Architecture for Multi-robot Systems with Emergent Behavior

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Abstract - *This paper describes the design of an architecture for multi-robots systems with emergent behavior. The platform must manage the dynamics in the system, so to enable the emergence therein. The architecture is divided into three levels. The first level provides local support to the robot, manages its processes of action, perception and communication, as well as its behavioral component. The behavioral component considers the reactive, cognitive, social and affective aspects of a robot, which influence its behavior and how it interacts with the environment and with the other robots in the system. The second level provides support to the collective processes of the system, as are the mechanisms of cooperation, collaboration, planning, and/or negotiation, which may be needed at any given time. This level of the architecture is based on the emerging coordination concept. The third level is responsible by the knowledge management and learning processes, both individually and collectively, that are occurring in the system.*

Keywords: multi-robots architecture, emergent behavior, multi-robots

1 Introduction

Multi-robots systems are used today in different tasks, particularly when using a single robot is not enough, or the task is not efficiently executed. In such systems several phenomena of interest to investigate are presented, such as studying the interactions between robots, and how behaviors can emerge in the system in an unstructured environment, with tasks, functions or objectives unallocated explicitly. The architecture proposed in this paper aims to support these systems, in which are emerging tasks, functions or objectives to be met by robots. It consists of three levels, a level for each robot, which consists of three modules: acting, perception and behavior, another level for the entire collective part, formed by a layer of emerging coordination; and a final level of knowledge management and learning processes. In particular, the collective level manages the processes of cooperation and/or collaboration in the system as well as the planning of agents.

In previous research, such as [1, 2, 3], proposals involving multi-robots systems with emergent behavior are presented, applied to problems such as robotic soccer, cooperative hunting and food search. However, generally homogeneous robots are used both in hardware and software, and for very specific tasks.

Our architecture doesn't arise from such assumptions, it presents a new structure for the characterization of the processes involved in the system, where they are managed by specific modules of collective and individual level to allow emergence; also, it implements a module of basic emotions in robots, which directly affects their behaviors in the environment and their interactions with the system.This article is divided into four sections, the first summarizes some initial considerations that contextualize the research, the second one presents the design of the proposed architecture. In the third one, a study case that allows looking at the operation of the architecture in an emergent process is presented, and finally, some final considerations regarding the research are presented.

2 Initial considerations

This section describes some concepts that help to contextualize the research presented in this paper.

2.1 Emergent Behavior

[4] is based on the premise that if a robot wants to have some autonomy in their operation, it should be able to display some basic behaviors, defining behavior from the biological point of view, as the processes that are carried out by the individual from the information taken from the environment and its own internal state, to eventually respond to the perceived changes. Furthermore, to do this it must recognize and interpret observed patterns of the physical phenomena occurring in its environment.

They describe from a functional point of view, some primitive behaviors for mobile robots, for example:

Evasion: behavior that allows a robot to avoid a collision, and thus preserve its integrity.

Attraction: towards an object, another robot, an environment.

From activation, concurrent or not, of these behaviors in different forms, can emerge more complex behaviors, such as: avoidance of an object, simple navigation, perimeter monitoring, among others.

On the other hand, in [5] emergent behavior is defined as that one which is not attributed to any individual in the group, but arises from the dynamics of the members of the system of which is part the individual.

In nature, there are multiple examples of living beings societies, which individually are simple organisms, and when they unite and work together a complex behavior can be observed, which arises from the interaction of individuals of the System. Ant colonies represent a clear example of occurrence of this type of behavior. In general, an emerging system is a complex system, adaptable, where behaviors that cannot be explained by explicit rules of operation appear [Aguilar, 2015].

2.2 Multi-robots Systems

[6] defines multi-robot systems as homogeneous or heterogeneous teams of robots, which are used in tasks where a single robot is not enough, or when the team becomes more efficient execution thereof. It generally has the following characteristics: cooperation, communication and coordination.

The emergent behavior of insect societies has inspired multi-robot systems, creating a whole area of research called swarm of robots. Swarms of robots usually are formed by simple individuals, and are designed to mimic the behavior of swarms of insects, thereby seeking to have robust and adaptable low-cost multi-robots systems.

3 Description of the proposed architecture

The architecture consists of three levels, where each one has specific tasks, but their integration is what allows giving support to emerging processes. Emergence is possible, since the three levels provide through their components the required elements: deployment of interactions, management of distributed processes, management of local decision rules, mechanisms of local and collective learning, and shared memory spaces. The levels of the architecture are (see Figure 1).

- **Collective level**

Supports the processes of interaction of the robots with others individuals within the system and with the environment. It has mechanisms that enable emerging processes of coordination among robots.

- **Individual level**

Provides support to the individual processes of the robot; manages the perception abilities of each robot, control of its actuators and their local decision-making, as well as aspects related to the robot's conduct and *emotions.*

- **Level of knowledge management and learning processes**

Manages the Knowledge, both individual and collective, as well as learning processes that occur in the system (individual and collective).

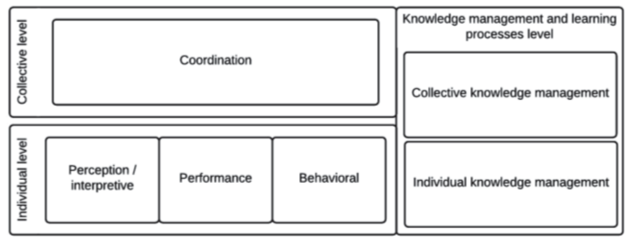


Figure1.Proposed Architecture

The following section explains in detail each one.

3.1 Collective Level

In [7, 8] is described the conceptual design of an adaptive architecture for cooperative multi-robot systems, which inhibits or activates its levels according to the expected behavior of the system, with planning and coordinating tasks as the core of its structure. In this paper (inspired in that work), is described an architecture that supports an emerging self-organized system composed of general purpose robots.

The essential level for this task is the Collective. This level comprises a coordination module. This module manages the dynamics of the interactions between the robots and of the robots with the environment, and the processes that arise from them. Next, we give an overview of how is the operation of the coordination module.

In this module, processes involved in the management of the interactions among individuals working in the system occur, such as inform their tasks, look for information they are interested, etc. Coordination in this module is manage under the emerging approach, such as a priori actions to be performed aren't established, but when decisions are made.

Under this approach, the division and allocation of tasks and negotiation emerge naturally in the system [9, 10]. Depending on the need of the community of agents in a given moment (collective goal), can be carried out information processes (direct or indirect), recruitment, search, among others. This module facilitates the occurrence of these processes.

3.2 Level of knowledge management and

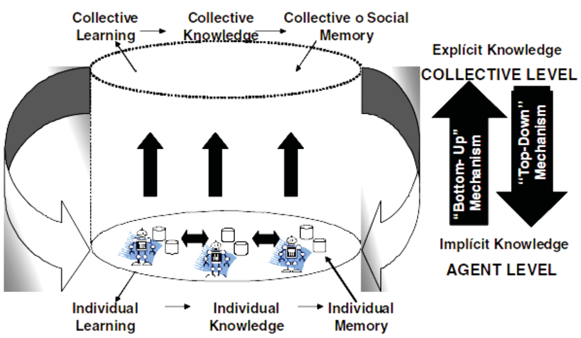
learning

The behavioral component of the robot governs the behavior of itself during its interactions with the environment and with other individuals; for which use their local knowledge as well as collective knowledge, which are acquired (learned) based on the performances of the robots in the system.

This level is responsible for the management of this knowledge, and facilitates the learning process. In Figure 2 is described the process of learning and knowledge management, based on the work presented in [11, 12], as is required by our self-organized emergent system.

Figure 2. Types of knowledge and learning in MASOES. [12]

According to this model, the robot increases their knowledge through a process of individual learning, and its interaction with other individuals and the environment. To do this, this level has a collective knowledge base and several locals, one for each robot. It also enables the processes of individual and collective learning, which feed off each other,



through three phases:

- Socialization: mechanisms to share individual knowledge with the group.
- Aggregation: mechanisms to sort, filter and merge that knowledge.
- Appropriation: mechanisms for converting the collective knowledge in individual knowledge.

In particular, this level is structured in two layers:

- *Management Module of individual knowledge*: in this layer individual learning mechanisms are implemented, and the management of knowledge bases of each robot is performed. The mechanisms of socialization and appropriation are in this layer.

- *Management Module of collective knowledge*: This layer manages the collective knowledge base of the system, so that it is available to all individuals. Aggregation mechanism is in this layer.

3.3 Individual Level

In particular, the emergent behavior of insect societies and the appearance of swarms of robots have inspired a new class of robots, called swarm of robots [13].

A robot swarm has two parts, one being related to the hardware that shapes it and another related to the software, which controls its operation and behavior.

On the hardware side, for this research was designed a prototype robot swarm, inexpensive, with hardware architecture of four layers (see Figure 3):

Control: This component is responsible for the control process of the devices of the robot. It features an Arduino board, based on a micro-controller ATmega 328.

Locomotion / Performance: This component is responsible for managing the robot locomotion system, and the management of actuators that could be incorporated into its design. The robot has a system of differential locomotion idler, implemented through a gearbox, which transmits the power of two DC motors to the wheels.

Perception: It’s responsible for managing the perception of the robot. The robot has infrared sensors to capture information from the ground, and a sound that allows it to capture information on distances to objects that are in front of it.It also has a virtual sensor that is provided by an artificial vision system, which allows it to capture information from the world, which isn’t possible to grasp with their physical sensors.

Communication: This component does all the management communication process of the robot. The robot has a Xbee® device based on the IEEE 802.15.4 protocol, which allows communication point to point or multipoint with devices of the same class.

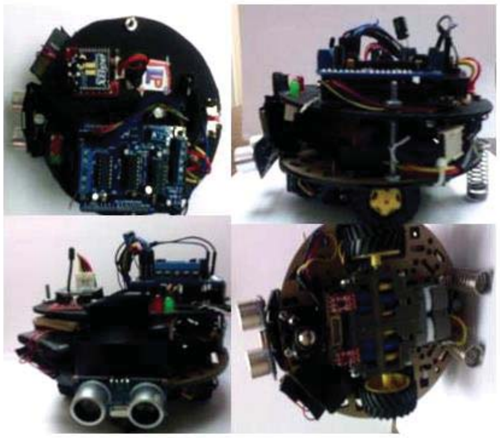


Figure 3.Robot of general purpose

The robot also has a software architecture that allows it to manage its tasks. This local architecture consists of a set of libraries that allow it to control the sensors and actuators of the robot, as well as communication between the robot and other devices. It is organized into modules:

3.3.1 Module of perception/interpretation

This module is responsible for obtaining the information from the sensors of the robot, both physical and virtual. These data are pre-processed and can cause activation of reactive or deliberate behaviors, as appropriate, the latter are managed by a sub-module of interpretation, which receives sensory information from the robot, it interprets it, and activates deliberative behaviors of the robot. These can lead to planning and/or cooperation needs, managed by the collective level of architecture. In other words, external or internal stimuli are processed at a t time which is received by the robot, and lead to a change in its internal state or its environment at a t+1 time. This module basically gives the robot capabilities of perceiving information from the environment, and interpreting it to generate appropriate responses to stimulus received.

3.3.2 Executing Module

It manages the operation of the actuators of the robot. Particularly, manages the locomotion system of the robot, in order to allow its movement in the environment as well as it controls any other actuator that could be implemented in it. This level is implemented locally on the robot.

3.3.3 Behavioral Module

The behavioral part of the robot is more complex. In [11] is proposed an architecture for non-formal modeling of emergent self-organized systems (MASOES), which includes individual and collective aspects involved in this type of system.

For individual aspects, it describes a series of internal components of each agent, which through their interactions generate the behavior itself, which are activated by other modules of the architecture. These are:

Behavioral component: it is responsible for regulating the conscious and emotional behavior of the agent.

Reactive component: it is responsible for generating the reactive behavior of the agent.

Cognitive component: it generates cognitive behavior through reasoning mechanisms.

Social component: it promotes aware in the agents about what made the other agents. Here collective knowledge is used.

Based on this model is proposed the behavioral module for the robot, which takes the individual components proposed in MASOES, and are modified in order to suit them to the architecture proposed in this paper. Figure 4 shows the proposed design for behavior on the robot module:

Reactive Layer: This component interacts directly with the components of perception and performance of the hardware architecture of the robot, and it is responsible for generating reactive behaviors in the robot. It is understood by reactive behaviors, actions that execute the robot directly from a stimulus received, without first going through a deliberative process, are actions resulting from a process of stimulus - reaction. This layer manages survival behaviors of the individual, and has priority over any other behavior that can be generated.

Cognitive Layer: This layer generates deliberative behaviors in the robot, based on its local knowledge. We define deliberative behaviors those actions that occur after the stimulus received by the robot has been processed and interpreted; in order to generate an analyzed action (there are implicit reasoning processes). Here it generates complex behaviors, built from primitive behaviors, which allows running specific and more complex actions.

Social layer: It explodes the collective knowledge in decision-making processes of the robot. It interacts closely with the other two levels (collective and knowledge management), for the planning, coordination and/or cooperation processes in the system to generate behaviors that allow the robot to interact with others within the system, either directly or indirectly. Basically, manages how the robot interacts with other individuals of the group.

Affective layer: based on [12] is proposed an affective model, which considers a set of positive or negative emotions involved in generating behavior of robots, which affects the level of self-organization and emergence of the system. These emotions directly affect the individual and collective behavior of the robots. In the behavioral model proposed in this paper, the affective component is transverse to the cognitive and social components, and consists of a set of basic emotions that affect the behavior of the robot in the environment and its willingness to the execution of the tasks to be executed. Mainly, the affective component inhibits or activates the behaviors generated by the cognitive and social layers.

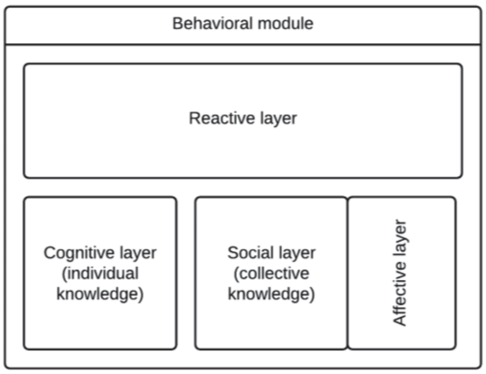


Figure 4.Behavioral model proposed

In general, the behavioral component provides a set of behaviors, which allow the operation of the robot and the emergence of collective behaviors in the system.

At the implementation level, almost everything is made in a shared computing cloud between robots, which allow them to perform highly complex processes. What is implemented in the robot are basically: libraries to control actuators, sensors, and the primitive behaviors, and management of the communication device.

4 Case of study

In this section is described the performance of our architecture for transporting objects.

4.1 Transport of an object

A classic case of study in multi-robot systems is the transport of objects. In [14, 15, 16] some related works are presented, where different solutions to the problem are shown. For example, a solution poses a leader in the system that centralizes planning task; another raised by the use of bio-inspired algorithms in solving the problem, as in the proposal presented in [17], the last taking as a reference the behavior of ant societies to establish a set of primitive behaviors for each agent, where a simple coordination mechanism between them is achieved.

However, a solution based in emerging systems consists of:

- The group of individuals explores the environment in pursuit of its goal,
- When one finds the object, it tries to move it and take it to the place prepared for deposit,
- If it can’t do it, it recruits others,
- Then, a cooperative mechanism is activated in order to organize the group of individuals to move the object collectively.

This solution is inspired by the behavior of ant colonies, and the key is a pattern of formation around the object that allows its transport. The operation of our architecture is described in this last case of transport of an object; in particular, it shows how the architecture provides support to the emergent behavior displayed during the process.

4.2 Our architecture supporting the transport task

Following is described step by step, in general, the operation of the architecture, for the case of transporting an object seen as an emergent process:

1) System configuration: three robots, an object, and a point of deposit (where leave the object), are located at random positions.
2) Initialization of the emotional state of each robot: in the affective layer of the behavioral module of each robot, an *emotional* state and *an activation threshold* is randomly defined. This threshold and state will influence its disposition towards the execution of tasks in the environment, and its relationship with other individuals.
3) *Activation of primitive behaviors*: Once the robots are in the environment a primitive behavior, from the set of robot's behaviors, is activated in the reactive layer of behavior module. In this particular case is *search*, which focuses on moving through the environment without a predefined plan, searching for the object.
4) Detection of an element in the environment: When it detects an element in the front (it is based on the perception module, in its virtual sensor), it parses it through the cognitive layer, to determine one of the following situations:

- *Detects an obstacle:* it activates an evasion behavior thereof through the cognitive layer. The robot analyzes (reasons) a number of actions required to avoid the obstacle and move on. The Individual knowledge base is updated and the action is shared collectively, to be used by other individuals.
- *Detects a robot*: the reactive layer of the behavioral module activates a primitive behavior: collision avoidance. The robot immediately stops its movement to a safe distance.
- *Detects pheromone:* it activates the coordination layer to allow them to manage these interactions. The robot recognizes the type of stimulus, its intensity, etc., and on that basis it takes the decision to act (follows the stimulus) or not, that decision is also affected by its emotional state. The robot updates its individual knowledge base, and if action is carried out, the collective knowledge base (pheromone) is updated.
- *Detects the object to be transported (to push):* after the object is detected, the reactive layer is responsible for

generating a behavior through which the robot tries to push the object. In the first instance it will try to do it individually, depending on its emotional state. If the result is negative and fails, the cognitive layer is activated for the robot to try other alternatives to move it, for example, reposition. If the result remains negative, the robot will seek to recruit others, using the behavioral module (to know its environment), the layer of emergent coordination, and the knowledge management level (for example, to leave traces in the environment through the virtual sensor, or to send messages of help (broadcast)). In this way, the robot tries to attract other individuals to the object in order to generate a collective action. In all cases, individual knowledge is updated through knowledge management level, and in the case of seeking help, the collective knowledge.

5) Several robots around the object: in this case, more than one robot tries to transport the object, either because they got almost simultaneously or they were recruited. In this case the collective level is activated, as well as the social layer of behavioral module, in order to coordinate the actions of the robots around of the object. They solve the situations of conflict as the direction of the movement, positioning of the robots around of the object, and the number of individuals needed to execute the task. To solve it, it activates repositioning mechanisms around the object, negotiating to reach a common direction, and adjustment in the number of individuals. That is, the transport task is coordinated, emerging *an organizational pattern* that allows transport the objet.

6) End of task: the robot or the robots which are carrying out the transport detect the destination of the object, such that it is deposited. The level of coordination is inhibited if there aren't interactions at that moment, and the individual level activates its behavioral component, in order to activate new individual behaviors. All databases of knowledge are updated (local and collective) as the result of the task (the learning mechanism is activated).

5 Final Considerations

The proposed architecture provides a framework to facilitate the emergence in multi-robot systems, through its three layers. They manage the processes at individual and collective levels that occur in the system, as well as knowledge that is built during the performance of robots.

The architecture allows the individual performance of each robot, allows local decision-making of each, and supports the interactions of the robot with the environment and with other robots. Its modular structure facilitates the addition of new components, and the update of the mechanisms used. The behavioral component of the robots allows different behaviors and intentions towards the execution of a task, or the interaction with other robots, enabling the study of their behaviors at the collective level, and how this affects the emergence in the system. This component will be based on a range of *emotions*, represented by indices of satisfaction or rejection to carry out a task.

The architecture allows the management of key aspects of emerging systems, such as the execution of the processes of the swarm in a distributed way (for robots), the local decision-making for each robot, facilitates the interactions between robots (through the use of shared memory spaces or messages), and allows the construction of individual and collective knowledge.

To show the behavior of the architecture, we have used the case of study of transportation of an object in an emerging form. In this particular case, the architecture is capable of supporting the emergence of the organizational pattern of the swarm for transport. To do this, it enables collective typical tasks of this emerging process, such as determining the number of individuals needed to perform the task, recruit other robots when one can´t move the object, etc. It also allows the resolution of conflicts that arise at the time of the movement of the object, or the conflicts of the interaction of multiple individuals in the same space.

The architecture is scalable in the number of robots, this is because each individual acts independently in the environment, and collective processes appear by the own dynamics of the system and not a priori defined configurations. Whenever a robot is included in the system, it is instantiated in the architecture individually. The architecture also allows the inclusion of robots with different hardware (there are not assumptions about it). The system is robust and flexible, since the failure, replacement or addition of a robot, does not affect the overall structure of the system.

Future works will be devoted to the specific problem of implementing of each level, and analyze the processes of emergence when there are specialized individuals (robots). Also, we will study the emotions in the system, to include behavioral and emotional aspects of greater complexity.

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