Properties Analysis of a Learning Method for Adaptive Systems

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KEY WORDS: *cooperation, self-organization, emergence, collective learning, multi-agent systems.*

ABSTRACT: *In order to build adaptive artificial systems, we suggest a thesis about the adequacy of a system relative to its relationships with the environment. We can tell it in this way: «Any system having a cooperative internal medium is functionally adequate». In our learning method, a global function emerges from the system unless this function is not explicitly dictated in each of its component. In fact, each component is always looking for maintaining a cooperative situation with others components in the system. The originality of our method is its facility of implementation because it's totally independent of the application field. Another property is that our method allows to suppress the classical component of control: the cooperation permits it implicitly.*

Introduction

Our work is situated in the multi-agent field: a society is viewed as an aggregation of autonomous interconnected agents. These agents interact directly or indirectly by the environment; they have heterogeneous skills and individual behavior. There is no global control.

Our aim is to build a multi-agent system functionally adequate, that is to say which realizes well the desired function, though the system is complex and immersed in a dynamic environment. In addition, this multi-agent system has to be independent from a particular application.

In such situation, the functional adequacy must be dynamically guaranteed during the system's life; the disturbances which may occur are solved by a reorganization of the agents, decided by the agents themselves. So we can talk about self-organization of the system and emergence of the global function.

The theorem we carried can be expressed like this: « Any system having a cooperative internal medium is functionally adequate ». Each part (agent) of the system is interacting with other parts. Each part has to be in cooperation with the others so that the totality would be in cooperative interaction. This means that each agent which locally detects uncooperative situations must try to change the organization in order to get a new cooperative state. For that, the agents' acts are always guided by a permanent research of cooperation with others.

International Journal of Computing Anticipatory Systems, Volume 1, 1998
Ed. by D. M. Dubois, Publ. by CHAOS, Liège, Belgium. ISSN 1373-5411 ISBN 2-9600179-1-9

After having detailed this theorem in a first part, we analyze in a second one the characteristics of systems based upon cooperative self-organization from a functional point of view (adaptive, homeostatic and emergent systems), and then from a systemic one in a third part (complex, self-organizing and autopoietic systems).

1. The Cooperative Self-Organization Theory

We developed a learning method based upon cooperation. Reorganizations are done in the system without any hypothesis about the semantic of emitted signals. The system's agents are only able to perceive these signals and then to influence their world. Cooperation occurs when a component receiving a signal is able to understand it, the integration of this information inside its knowledge leads it to some logical consequences and finally any conclusion must be useful to some other component inside the system.

Any other situations are detected as uncooperative by the component. They're called uncooperative because they damage the activity of the system. Because agents have incomplete and erroneous knowledge about the world, situations of competence, ambiguity, concurrence and conflict may then occur.

1.1. Definitions and Properties

Our work is based upon the notions of cooperation, internal medium and functional adequacy, which are defined below.

Definition ①: A system is *cooperative* if it has cooperative interactions with its environment, in others terms, when it gives good results; we mean when any signal perceived from its medium is understood and read without ambiguity. This information induces it to a reasoning process, and concluding results lead to act usefully in the medium.

Definition ②: A system consists of many components (physical structures or processes that are used to implement a mechanism) and the system's *internal medium* is the set of all these components and the physical support used for the internal exchanges.

Definition ③: A system is *functionally adequate* when it realizes the "right" function in its environment. The meaning of a "right" function is intended here as Maturana when he claims "everything said is said by an observer". To decide the truth of this "right" function, the observer must be external both to the system and the environment (a theoretically difficult thing in our physical world). It is this observer who judges if the given answers are right compared with the function the system has to carry out in its environment.

Hypothesis ①: An important property upon the system's structure remains for demonstrating the theorem. We consider an initial fixed set of components. This hypothesis can be overcome in considering each component as a whole system, in which the sub-components are using the same self-organization method described in the part 1.2. That way, all the uncooperative situations can be solved: if they can't be solved at the current level, they will be at the lower level.

It might be restrictive to use the principle of self-organization, that is to say the research of an optimum organization, as only learning mechanism. But, structuring a system in levels of different granularity allows a learning not only at the level of the organization but, also, at the level of skills. Indeed, the skill of an agent changes if its internal organization (the agents it is made of) is changed. So, the level's organization is chained to the one of the upper level.

We are going to prove our general theorem ❸: « Any system having a cooperative internal medium is functionally adequate ».

In a previous work (Piquemal, 1996a), we showed the following thesis: « ❶ Any cooperative system is functionally adequate ». Let's suppose that a system doesn't carry out the right function (so it is not functionally adequate), there is, then, at least one situation in which the status given by the system is different from the one expected. This leads to a disturbance of the environment activity, and so consequently to a non-cooperative system.

So, any non functionally adequate system is uncooperative, which is equivalent to ❶.

Let's prove that « any system having a cooperative internal medium is cooperative ❷ ».

When an internal medium of a system is cooperative, all the interactions realized by its components are cooperative. These latter include the set of all the interactions between any components and the medium of the system. This set of cooperative interactions corresponds to the interactions between the system and the medium. Thus the system is cooperative in using the definition ①.

The points ❶ and❷ allow us to assert that any system having a cooperative internal medium is functionally adequate.

1.2. The Process of our Learning Method

In this part we present the process of our cooperative method for artificial system taking into account the previous theorem.

We dispose initially of a non structured set of given components included inside a system. The goal of the learning process is to find the right internal organization in order to be functionally adequate. The system must always be organized in order to be cooperative.

But in a dynamic environment, unpredictable events often occur and this can lead to uncooperative situations for some components. In this case, a component have to act toward the others to procure a new cooperative organization. The number of actions for this purpose is limited.

Inside our system, each component consists of skills (its knowledge about a field), beliefs (its knowledge about other components of the system) and social attitudes. These items allow the understanding of four uncooperative situations: incompetence, ambiguity, concurrence and conflict. We will now describe each uncooperative state and give the generic way to detect and act in this case.

1.2.1. Incompetence

Description: The receiving agent is inefficient to process data if there has been a sending mistake or if the transmitter gets a wrong belief about it.

Detection: The receiver can't extract any informative content from the message; it hasn't the necessary competence.

Action: If a component perceives an incomprehensible signal, it tries to find other components more able to take this information into account. If it doesn't know any, it sends it back to the transmitter. If it has a partial competence, the component deals with its part and tries to coordinate itself with others.

Interest: The misunderstood messages are not ignored. Their retransmission is useful to improve the group situation when a pertinent receiver is found. More than this, it sharpens the agent's mutual knowledge and therefore the organization especially during the integration of a new agent.

1.2.2. Ambiguity

Description: An ambiguity occurs when the content of a signal is incomplete either because the sender gets a bad description of the receiver's tasks or because the specification of the message is wrong.

Detection: If the perceived signal has got different meanings, all the possible interpretations lead to conflicting actions in the world and so to obtain several distinct states of the world.

Action: An agent is supposed to send intentionally and spontaneously understandable data for the others. So the receiver of an ambiguous message sends back all its interpretations of the received signal, so that the sender chooses the most pertinent and brings up to date its beliefs on the receiver's skills.

Interest: The ambiguities removal causes an adjustment of the agent's beliefs.

1.2.3. Concurrence

Description: A situation of concurrence may occur when two agents have got similarly skill for a given task (because of a previous redundancy or of a duplication of the agents).

Detection: An agent detects a situation of concurrence when it plans that another one wishes to act in order to transform the world in the same state it will do.

Action: First, redundancy is beneficial in two cases: when an agent hasn't been able to reach its aim or to accept a task it has been asked. In these cases, it refers the problem to its concurrent(s). Secondly, it can be useful to reach the current goal more efficiently by changing the concurrence in a cooperative situation.

Interest: To dispatch some activities is interesting in sharing the load between agents having similar skill, when they are too busy, or to accelerate the resolution process with cooperation. Eventually, dispatching permits to manage the agents' specialization by learning, avoiding useless duplications.

1.2.4. Conflict

Description: A conflict occurs when the plans of two agents are incompatible that is, the carrying out of an agent's plan would prevent another agent's carrying out its own one.

Detection: An agent detects a situation of conflict when it plans that another one wishes to act in order to transform the world in a state such that it can't reach the state it wanted to reach.

Action: The agent has to look for another plan.

Interest : Avoiding conflicts improves the resolution process rapidity.

Detecting and resolving the four previous uncooperative situations lead to the self-organization of the interaction links between agents. Self-organization is not a new concept: in the fields of artificial, numerous learning mechanisms have been drawn from patterns of cognition found in nature, especially with neural networks and genetic algorithm approaches.

It is necessary, in these approaches, to establish estimate's tests of the system's pertinence and viability.

So, in neural networks, the learning law of one neuron describes the law of its connections' weight changes. In our pattern, the learning is done by modifying only the inter-agents links; so weight assignment and their change are useless.

For artificial life, the individual survival function selects the most able for reproduction. So, survival criteria have to be arbitrarily established. Well in our pattern, criteria of action setting are independent of applications and are defined inside the behavior of the agent.

Our cooperation method is different from both two previous approaches because it leaves free the agents and doesn't need any « first-given » (there is no need for it to statically fix the characteristics of the application during its conceiving).

2. Functional Viewpoint Analysis

The main factors to evaluate a software are reusability, compatibility, validity, reliability and extensibility, (Meyer, 1990)... The validity is the aptitude of a system to realize a task defined at its specification phase in others terms it is the aptitude to realize a particular function. The reliability is its aptitude to continue to realize its function in unexpected conditions. The extensibility is the capability of the system to take specification changes into account. These three last properties are very important for adaptive systems. So we can study a system with a functional viewpoint. If we consider that each component of the system is the physical support for a defined function, modifying the organization between these components leads very generally to the transformation of the previously global function of the system. That's why we analyze in this part the functional properties like adaptivity, homeostasis and emergence in accordance to the theorems of the part one.

2.1. Adaptivity

An adaptive system is able to automatically improve its performances over time in response to what has been encountered previously (Mitchell, 93). In a biology viewpoint, the adaptation is the properties of a system to maintain its essential parameters in fixed limits. This allows the system to survive in an environment. In artificial system area, the adaptation is covered by the learning aptitudes of agents (Weiss, 1996). A system adapts itself, if it can learn knowledge to improve its behavior when changes occur in its environment.

In our case, we want to show that when the environment evolves, the capacity of adaptation allows the system to evolve to a best functional adequacy. Suppose a system cooperative and functionally adequate. When the environment evolves, two cases can be observed: either the medium of the system is cooperative or it is not cooperative. In the first case, a cooperative situation occurs, the system realizes a task without modifying its relational structure. That is because no agent in the system detects a uncooperative situation. Therefore, the system is still cooperative. By the thesis ❶, we can conclude that it is still functionally adequate. In the other case, the evolution leads at least one agent to detect a uncooperative situation. We are going to inspect what is happening for the four uncooperative situations to show that our method allows the system to adapt itself in response to an evolution of its environment.

2.1.1. Incompetence or ambiguity situations

If the situation is an incompetence or an ambiguity, this is local to the agent. As we have said in the first part of this paper, the agent searches others agents' help. According to the hypothesis ①, we can affirm it exists in the system, agents who have or are going to have skills to satisfy the incompetence or to remove the ambiguity. So the agent is again in a cooperative situation and the system too and by the theorem ❸, we can conclude the system is functionally adequate.

2.1.2. Concurrence situations

The concurrence situation implies that the system has not an optimal behavior because redundancies exist. So, in view of a concurrence, the behavior followed by the agent is to use the concurrence to move a challenge situation in a cooperative situation or to improve the collective behavior. The agent with its knowledge about the others, can try to act in a more cooperative manner.

2.1.3. Conflict situations

In a conflict situation, either the agent can solve the conflict or not. If it can, the situation becomes again cooperative between the components of the system. If it cannot solve it, the implemented behavior of the agent allows itself to try to solve the conflict in propagating it towards others agents or to refuse it.

The method ensures that the system can take away the conflict because each agent locally searches to have cooperative interactions. So the system with conflicts evolves towards an organization where there is no more conflict. In this case too, the internal medium has cooperative interactions and so the system is functionally adequate.

So, the system changes its organization and especially the relationships between its components in order to suppress or to use this uncooperativeness. The system does not try to converge towards attractors, but simply tries to find an internal organization which allows it to be permanently in cooperation. If this ideal situation occurs, according to the theorem ❸ stated in the first part, the system is functionally adequate. It has well adapted itself to the dynamic of the environment. So a really cooperative system has the property of adaptivity.

2.2. Homeostasis

There is homeostasis when it exists a process which balances various influences and effects such that a stable state or a stable behavior is maintained. A learning system can undergo a continuous structural change in order to act adequately in its medium. But an underlying question remains "what are the conditions under which the system stays in or falls out of stability?" In other words, what are the conditions of stability of a complex system for being homeostatic ?

In order to obtain a system which is wholly stable, relationships between its components must keep unchanged. In fact, if the environment realizes an unexpected exchange with the system, it is like a perturbation which is perceived by some agents as an uncooperative situation. So the system reacts in modifying its organization, in adapting itself. And when no agent detects a uncooperative situation, this implies that no more reorganization can be done so the system has reached a stable state. We can deduce a necessary condition to have instability which is that the system and its environment have uncooperative interactions. In the method that we recommend, a sufficient condition to guarantee the organization stability is that interactions between the system and its environment must be cooperative. By consequence the interactions between the components will be cooperative.

A consequence is that a system which is in a stable state will see its global function to be stable, we mean that when a same situation occurs several times, the system will give the same answer.

2.3. Emergent Phenomena

Emergent systems involve a system and its environment and the emergence rises of the interactions between them. Three characteristics of a multi-agent system are necessary to define the emergence in this kind of artificial systems:

- the first is that no agent controls globally the dynamic of all the system. The agents are limited and they are unaware of some parts of the global system. So each agent has a local environment.
- the second is that the agents act and modify locally this environment.
- the last is that in an agent's environment there is other agents.

The system dynamic is an iteration between interpretation of their local environment by agents, action of agents on this environment, new interpretation of the modified environment, new actions... When such dynamic is stable, we can talk about emergence of a structure or of a global functionality (M. R. Jean, 1997). When a phenomenon emerges, new categories are needed to describe this underlying regularity which are not previously used to describe the characteristics of the component's behaviors.

In our cooperative method, only two behaviors must be specified: the skills of each component and the conditions in which a local reorganization process to a component is triggered. Thus, no component of the system needs to see more than a fraction of the rest of the system or the environment and we have many local processes unaware of any global function. When the global system is closed to an homeostatic organization, it seems to have a regular behavior which can be assigned as emergent by an observer.

3. Systemic Viewpoint Analysis

When someone wishes to realize a function, he conceives a physical or virtual entity to support it. We now feature our adaptive system from the physical characteristics viewpoint. To do this, our work is based upon the systems' theory. We can find three main characteristics for such systems : self-organization, complexity and autopoiesis.

3.1. Self-Organization

The term organization refers commonly to relationships between the components of a system. Self-organization of a system consists in the autonomous transformation of the topology (i.e. network connections) of its components as result of this network's functioning, which is dynamic in this view (MARCIA, 1995). This is based on the notion of autopoiesis where the distinction between structure and organization is very clear. Maturana and Varela say "Therefore, the organization of a system as the set of relations between its components that define it as a system of a particular class, is a subset of the relations included in its structure. It follows that any given organization may be realized through many different structures, and that different subsets of relations included in the structure of a given entity, may be abstracted by an observer (or its operational equivalent) as organizations that define different classes of composite unities" (Maturana, 1980). According to Maturana, each particular system is a member of class: the class of systems having the same components but having their structures possibly different due to the history of structural coupling with the environment.

We use here the latter notions, that is: we consider the organization as the set of interaction links between the agents of the system.

Our learning process leads to avoid all perturbations that could occur between components. Clearly, because links between components are dynamic the structure evolves. But the set of relations between components is limited by the permanent goal : to avoid non cooperation. This constraint remains constant in what we call organization even self-structuring.

We propose a method which allows the self-organization of the system: agents of the system modify their skills (internal structure) and their believes (interaction links) according to the uncooperative situations detected and to the current state of the resolution. Our method confers the agents the ability of adaptivity which is not momentary but on the contrary, memorized by learning on organization. This learning is autonomous and local; it allows the agents to position themselves in the organization in order to be permanently in cooperative situations with others. With the dynamic and autonomous modification of interaction links (self-organization), the system becomes reliable, robust, evolutive and resistant in the case of failures.

3.2. Complex System

If a system is identifiable, it is organized according an objective and one limit defines a frontier with the outside (the substrate in which it is immersed). Despite this identification, it can be difficult to understand the system's role; that's its complexity. We can characterize the complexity of a system by an apparent disorder in which an order that we don't know exists. A system is complex if "a great many independent agents are interacting with each other in a great many ways" (Waldrop, 1992).

Our method can be applied to complex systems, that is, systems for which it's impossible to determinate the state at a given moment because:

- the number of agents which compose the system is important,
- each agent has only a partial view of others and the environment in which it's immersed,
- no agent has a global view of the whole system,
- the agents are autonomous and interact according to their perception and their presupposition about others (believes),
- the system is strongly dynamic...

One of the characteristics of complex systems is their ability to adapt themselves to external constraints by adopting a new equilibrium phase (an attractor). It's the typical case of our learning method: it allows the system to adapt itself to an external perturbation which leads it in an uncooperative state (ambiguity, incompetence, conflict, concurrence) by coming back to a cooperative situation once the proposed generic situations applied (c.f. 1.2. part).

3.3. Enaction and Autopoiesis

A system is autopoietic (Maturana, 1980) if its whole components represents at every time the system's organization despite the changes involved by the interactions. Enaction theory is about learning by acting: a system progresses with its own experience about the interactions with the surrounding. The components of autopoietic systems "must be dynamically related in a network of ongoing interactions": the components interact in ways which are continually changing. But at the same time these ways allow for the continuation of interactions so that the

system continues to exist. In addition, the interactions of the components are responsible for the production of the components themselves. An operational closure is made between the system (which stays the same) and the surrounding (which changes).
In summary, an autopoietic system is an emergent phenomenon arising from the interaction of components which, by way of these interactions, give rise to new interactions and new components, while preserving the system's autopoietic character. An adaptive system should be autopoietic: it adapts itself in order to have the right organization at every moment.

With our method, the system is autopoietic in the sense that all the modifications of relations between agents at the level N lead to modifications of relations between agents at the level N+1. To be more precise, when an uncooperative situation occurs at the level N, the actions we recommend in the case of the detected situations are applied. That induces some modifications of the system's organization at the level N. As the level N+1 of the system highly depends of the level N, every interaction arising after the self-organization of the level N leads consequently to a self-organization of the level N+1, as we can see on the figure below. The reciprocity is available too.

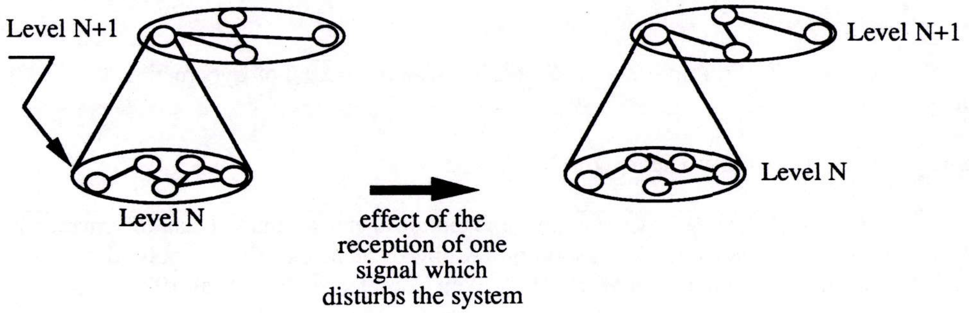

Figure 3.3: Autopoietic phenomena

4. Conclusion

In this article we've proposed an original method of learning based on self-organization.
For that, we have demonstrated the following theorem saying that when a system has its internal medium cooperative, it gives the right results. The internal medium of a system is cooperative when its components (agents) are in cooperative situations. We have defined four uncooperative situations which can occur when a signal is perceived by an agent: incompetence, ambiguity, concurrence, conflict and four actions that agents must apply when such situations occur. So agents are autonomous and they always try to be cooperative with others. Consequently they adapt themselves to the environment by learning according the interactions they had with others.
We have then study our learning method on functional and systemic viewpoints. We've shown that our method is adaptive, homeostatic and that good results emerge from the system. It's also a self-organizing method which is well suited to complex systems.

The originality of our method is twofold : it's independent of the application field, so it can be easily implemented whatever the application is. We just have to instanciate the uncooperative situations and to implement the algorithms of detection and action in the four uncooperative situations. Another property is that it allows to suppress the classical component of control. In fact, it's not necessary to know the finality of the system before its conception, we just need to know that all its components have to cooperate. Indeed, if all agents cooperate effectively, the community will give a good global function.
This learning method has been applied in two applications :

- a game we called « tileworld » where agents have to push tiles in holes while avoiding obstacles and being the more effective as they can (Piquemal, 1996b).
- a project called ARCADIA whose aim is to find relevant information in distributed network, where information is distributed, heterogeneous by their content and in constant evolution (Camps, 1996).

ARCADIA is still under development but results we obtained with the tileworld let us suppose that our project is promising and will be a serious rival to actual information research engines.

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