A CONNECTIONIST PARADIGM IN THE COORDINATION AND CONTROL OF MULTIPLE SELF-INTERESTED AGENTS

K. Alexiou (∗), **T. Zamenopoulos** (∗∗)

(∗) *UCL, Bartlett School of Graduate Studies, Centre for Advanced Spatial Analysis, 1-19 Torrington Place, Gower Street, e-mail:* a.alexiou@ucl.ac.uk
(∗∗) *London, WC1E 6BT, tel: +44 207 6791782, e-mail:* t.zamenopoulos@ucl.ac.uk

Abstract
Complex design and planning cases involve distributed knowledge conducted by self-interested agents. The multiplicity of interdependencies among goals, plans and activities emerged in design and planning, directs the necessity for coordination and consensus. We can distinguish two conditions where the importance for co-ordination among the parties involved, takes different forms. These are multi-agent collaborative planning and distributed problem solving. We introduce a connectionist approach to “co-ordination via control” and we discuss the formalization of a meta-model for knowledge representation that captures interdependencies among objects emerged in complex design and planning cases. We finally discuss the development of a Web-based tool for agent control and coordination.

Keywords: Distributed Multiple Agents, co-ordination, neurocontrol.

1. The system of interest

Architectural design and urban planning are complex procedures that handle complex artefacts and involve distributed knowledge conducted by self-interested agents. Those agents can be human-based (local authorities, architects, planners, citizens, etc) or artificial (plans, knowledge bases, decision support systems etc). In the evolution of such complex environments coordination and collaboration among distributed agents is paramount.

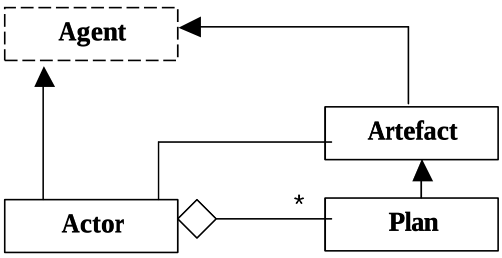

Figure 1: an abstract representation of our generic system of interest. Complex design and planning cases involve distributed agents

The three classes (Actor, Plan and Artefact) in (Figure 1) represent our generic system of interest, in design and planning. We often need to define more than one object in each of these classes; what characterises a “*complex design or planning case*” (Gebhardt, 1997). We consider as actors the people who are involved in architectural design or urban planning tasks and as plans the means that they use. The plans can differ among actors or can even be multiple for one individual actor. Plans are in general explicit or implicit models of the artefacts or the procedures that produce them. An artefact is the product in the real world of the actions involved in design and planning. In complex cases, knowledge is inherently distributed and the multiplicity of interdependencies among objects directs the necessity for "*co-ordination*" (Jennings, 1996; Malone, 1990; Weiβ, 1997; Gross et alii, 1998; Xiang, 1993; Zhang et alii, 1992).

We can consider the above scheme according to two different conditions (cases) regarding the objects that we can assign, their attributes and the scheme of interactions among them; which help us distinguish between two alternatives for co-ordination. The first condition explores the case of "*multi-agent collaborative planning (and design)*" and the second focuses on the theme of "*distributed problem solving in planning (and design)*". This distinction is drawn from the characterisations of Multi-Agent Systems and Distributed Problem Solving given by Ossowski and Jennings (Ossowski, 1999; Jennings, 1996).

These two conditions are explained below in more detail in order to specify the domains of interest covered in this project. In the following sections we will further elaborate a connectionist approach to "co-ordination via control". We will also discuss the formalization of a meta-model for knowledge representation that captures interdependencies among objects emerged in complex design and planning cases. Finally, we will introduce some ideas for the development of a web-based tool that supports co-ordination in multi-agent collaborative planning and distributed problem-solving environments.

1.1. Multi-agent collaborative planning

In multi-agent collaborative planning we assume that we have different stakeholders as members of the class Actor. The stakeholders are self-interested agents that participate in the planning procedure as a way to promote their individual goals. In participatory urban planning for example, it is strongly recognised the fact that the different stakeholders have different goals and different plans, which very often cause conflicts. There is a great need to support participation from the early stages of planning so that these conflicts can be expressed, and so that social interaction and deliberation takes place (Forester, 1998; Innes, 1996 and Innes et alii, 2000). This procedure reveals collective values and helps to produce indices for joint actions. Multi-agent collaborative planning can be seen as a search for common goals and is therefore focused on the effective interaction among the agents. Reasoning is a shared task developed on the basis of all-inclusive communication (Healey, 1996) and full access to the same sources of information (Batty, 1998). Interdependencies arise exactly from the fact that agents must equally share information. To that end, the establishment of trust among the collaborating parties is paramount (Kumar et alii, 2000). Within this framework co-ordination and consensus reflect on the activity of discovering and promoting mutual benefits out of the individual contributions. The same rule holds for example also in collaborative architectural design where the basic intention is sharing information and reasoning so as to discover productive paths for design solutions, which can be beneficial for each person individually (Craig et alii, 2000; Findlay et alii, 2000; Van Loon, 2000). If a measurement of efficiency is to be found, then this lies on the agents' evaluations regarding the effectiveness of the collaboration. (For more resources see also Gordon et alii, 1997; Klosterman, 1999).

1.2. Distributed Problem Solving

In distributed problem solving environments we assume that we have different experts as members of the class Actor, which try to combine their knowledge in order to achieve a common goal (Busseri et alii, 2000). They combine different expertise, often using different languages (i.e. different representations and meanings for the same objects, Haymaker et alii, 2000), and they try to pass their experience to the others in order to find an optimum solution. For example in a case of emergency in the city (e.g. an earthquake) different experts like city councillors, architects, engineers and planners have to communicate immediately and effectively to manage problems commonly defined (e.g. Dickey et alii, 1998). Another conventional example is in a design agency: experts from different fields employed in the same project need to communicate and combine their knowledge even when working from distance (Coyne et alii, 1996).

In contrast to the first condition, the goal of the collaboration is predefined, so the focus turns on the problem that has be solved and the appropriate distribution of tasks and roles among the agents. Reasoning unravels on the basis of combining expertise. (Branki et alii, 1993), Interdependencies arise due to the fact that partial requirements may conflict and that actors share routines and resources (Stubbs et alii, 2000). Within this framework co-ordination and consensus reflects on the organisational and problem-solving efficiency of the group. Reasoning is essentially distributed as in multi-agent collaborative planning, but in this case measuring the performance depends on the definition and the predefined expectations regarding the problem in hand. (For more resources see also Cheng et alii, 2000; Coyne et alii, 1993; Simoff et alii, 2000.)

In each case the issue of co-ordination refers not only to the actors, but also to every individual object that is defined within this scheme (plans, objects within plans, goals and sub-goals etc). In both cases co-ordination can be considered as a task involving distributed knowledge which need to be combined in order to optimise the performance of the actors and the artefacts, both individually and collectively. To that end, co-ordination can also be considered as an adaptive "control" assignment. Intelligent adaptive control deals with complex systems that possess not a-priori known, dynamic properties and exhibit complex behaviours and goals (Miller et alii, 1995; Jain et alii, 1999). In both cases a consensus is expected to be reached which does not mean elimination of conflicts but rather means recognition and elaboration of arguments and agreements, as a basis for building up decisions, solutions and indices for actions (Coyne et alii, 1993; and Innes, 1996).

2. The research problem: Co-ordination via Control

Having introduced the generic system of interest and the two research conditions we can now formalise the research problem as follows:

- *Every actor k at time t is represented by a Plan $P_{k,t}$.* Actors' plans need to be expressed somehow so that social relation exists among them (Ossowski, 1999).
- *A plan $P_{k,t}$ represents a preferred state S_t for the artefact in time t.* In other words, every actor expresses her opinion about how things are, or how things should be, according to her knowledge, her experience and her goals. Every plan proposes a different state for the world or a different view of the world.
- *Every state S expresses interdependencies among individual objects proposed as parts of plans in the planning or problem solving procedure.* We will further discuss this subject in the light of our knowledge representation scheme.
- *An actor M produces a plan $P_{M,t+1}$ in response to state S_t and the plan $P_{l,t}$ as a means to control the resulting artefact.* In other words, the actors interact with each other in order to modify the plan towards their preferred state (Figure 2).
- *This process is modelled as a mapping o: P X S ® S. The semantic of the operator o is defined as an auto-associative memory.* A plan is a partial and "noisy" description that recalls a set of previous states on the basis of some common characteristics. In response to this association a new pattern state is formed. This is equivalent to the learning procedure that takes place in a collaborative environment (Forester, 1989; Faludi, 2000).
- *The critical issue is how to reach to a consensus (or equilibrium).* That means that the procedure shall go on until some consequent states prove to be identical in a specific period of time.

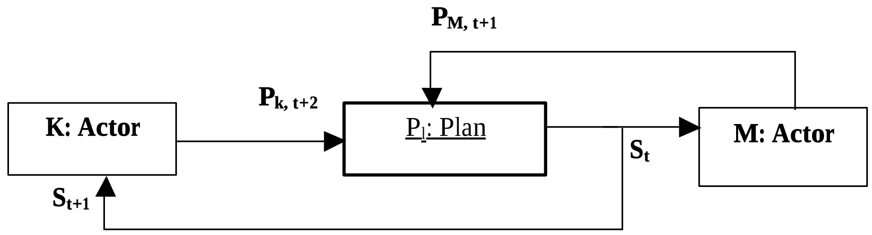

Figure 2: co-ordination via control. The actors interact in order to modify the plan towards their preferred state.

This scheme is actually a control model for co-ordination problems. In this description, actors behave as "controllers" trying to bring each other's plans within their objectives. As every actor develops the same controlling activity, the crucial issue is to find ways to reach equilibrium. It is as to say that we have a solution space and we try to reach an unknown state-point quickly and effectively.

Before we go on with the description of the connectionist paradigm we build for the co-ordination in complex design and planning cases, we need to clarify some issues regarding knowledge representation and knowledge acquisition.

3. Knowledge representation and knowledge acquisition

Co-ordination requires that the distributed agents (experts and stakeholders) share and exchange information in order to achieve their goals more efficiently. It is therefore a major issue to define what kind of information is transmitted among the agents and how this information is represented. In this context what matters most is to detect and manage the interdependencies between the activities, the goals and the plans followed by the agents (Gross et alii, 1998; Malone et alii, 1990). Acquisition and representation of knowledge consists in extracting, managing and producing information for the task in hand and the produced artefacts, in a coherent and comprehensive manner.

Distributed problem solving and multi-agent collaborative design and planning are complex procedures that involve diverse knowledge. The knowledge representation scheme must be therefore both flexible and robust (Gorti et alii, 1998). It must be able to work with different domain knowledge, associate alternative views and combine diverse data models; and it must be at the same time comprehensible to all. Moreover, since the informational and methodological needs of the agents usually change during the planning and design process, the knowledge representation model must be susceptible of dynamic adaptation. (Richter et alii, 1995) Traditional models are usually static and inflexible and typically suppose knowledge to be "something" that we could capture using a top down procedure. Some common solutions to this problem include the development of generic (all inclusive) models to adapt the existing models of the actors to the changing conditions, or the development of filters that transform the information given, to a uniform format (Haymaker et alii, 2000).

In this project we maintain that knowledge is distributed, temporal, uncertain, and case- based. Knowledge is a collective product emerging through the fertile combination of partial and imprecise knowledge transferred by the different participants in a complex activity. This emergent characteristic of knowledge is important even in design and planning activities conducted by an individual. Human reasoning is carried out on the basis of finding and learning connections among things and adapting to the changing conditions by recollecting similar cases (Gebhardt, 1997; Kolodner, 1993; Maher et alii, 1997; Ramsey et alii, 1991). Our aim is to construct a connectionist knowledge representation that inherits these characteristics and addresses the issues of co-ordination in a dynamic way. In contrast to the traditional solutions it does not create one standard model but it is intended to work as a meta-model

(Richter et alii, 1995) that encapsulates the different representation models of the agents and manages their interdependencies. This also gives the agents the opportunity to produce and use personalized representations.

3.1. A meta-model for knowledge representation

In this section we attempt to portray some ideas for representing and storing knowledge coming from the actors in different formats. It is intended to clarify the way the different models of representation can be formatted and encapsulated in a meta- model in a fashion that serves the requirements of the connectionist approach. We will further show how we can manage interdependencies among objects that emerge in complex design and planning cases.

In any relational or object oriented representation we can identify three explicitly modelled components: entities, attributes and values. (Richter et alii, 1995) In a relational database we can store information about an artefact (entity), say a "building", in a table, as a combination of the attributes "shape" and "land use". In each record we store the values for the corresponding artefacts; for example "square" and "residential". Under an object oriented perspective we would create a class "building" with the attributes "shape" and "land use" and associate those with some methods. An instance of this class would be an object (entity) that has specific values for the attributes, i.e. "square" and "residential". In general, object oriented representations are much more flexible in modelling complex relations but still rather static to be able to capture ill-defined, changing conditions.

Starting with the idea of a fully connected world we attempt to build a connectionist meta-model to handle entities, attributes and values and represent their interdependencies in a dynamic way. Each entity can be defined and/or evaluated in relation to all the others as a set of connections with different strengths. If we apply this same idea to attributes and values, we have a universe of interconnected "objects". We define each object Oj as a fuzzy set containing the other objects in different degrees (Figure 3):

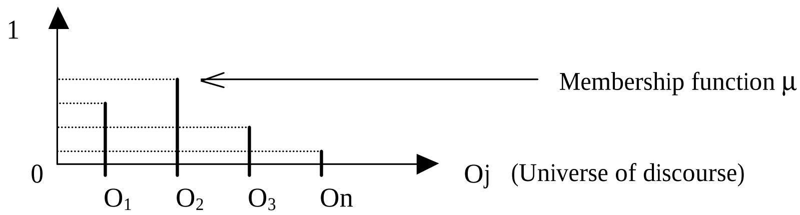

Figure 3: fuzzy connectionist representation. An object contains all the other objects in different degrees.

Using the fuzzy set theory we can incorporate uncertainty to our meta-model using intuitive descriptions. We envisage that we can define a degree of self-similarity by iteratively expressing each component in the fuzzy set as another fuzzy set and so on. This idea is still in a primitive form, but we consider two ways of elaborating this suggestion. In the above diagram the universe of discourse Oj is defined as a set of n objects and it is mapped in the closed unit interval [0,1]. The membership function μ is defined as μ: Oj $\rightarrow$ [0,1]. The first alternative is to consider the universe of discourse as being a "weighted" Oj (which represents the fact that the object Oj is partially "true") and define the membership as a mapping μ: Woj $\rightarrow$ (W_{O1} x W_{O2} x …x Won) $\in$ [0,1]. The second alternative is to consider a universe of discourse consisting of the product (W_{O1} x W_{O2} x …x Won = Wi) and produce a mapping μ: Wi $\rightarrow$ Woj $\in$ [0,1].

We can now continue with the formal description of the meta-model by focusing on the subsethood theorem introduced by Kosko (Kosko, 1992; Young, 1996) and elaborating the description of interdependencies by means of logical connectives.

Let us consider a situation where an object O ("square") given the positions of its two opposite angles $P_1(x_1,y_1)$ and $P_2(x_2,y_2)$, has an attribute L "Land use" assigned to it and some attached "Comments" C. Each of these components is a fuzzy set and can be represented as a point in an n-dimensional Euclidean space. The object O can be represented as a point in a unit two-dimensional cube; where the co-ordinates represent the membership of the object P_1 and P_2 to the set O denoted $m_O(P_1)$ and $m_O(P_2)$ respectively. (Figure 4(a)) The object L can be also represented in the same system (Figure 4(b)): the sets O and L indicate two different (fuzzy) relations between the sets P_1 and P_2.

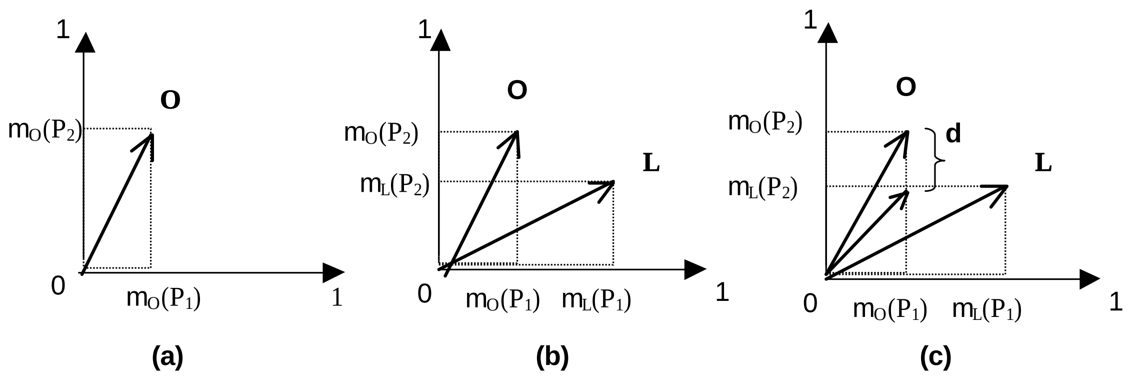

Figure 4: (a), (b) a representation of objects (fuzzy sets) as points in the Euclidean space. **(c)** The subsethood degree defines subset relations by means of the distance among fuzzy sets

We can further evaluate the interdependency of the two sets by means of logical connectives. In our example the existence of object O is strongly related to the positions P_1 and P_2. By viewing these objects as fuzzy sets we can express intuitive perceptions about their interrelation. What fuzzy logic suggests is that we do not see, for example, the "square" existing on the strict basis of the conjunction of P_1 and P_2. Rather we can consider that a slight displacement of, say, P_1 would still evaluate the square as a reasonable possibility. This corresponds to the way people evaluate and connect objects and events, and offers a resourceful means of managing ambiguous interdependencies. Additionally, if we take into consideration the fact that the objects introduced by the actors in a complex planning or design procedure are continually changing, then we can picture a fuzzy measurement that changes over time as the interconnections among the objects grow.

In order to clarify the logical implication and equivalence we must reflect on the subsethood theorem in detail. The subsethood theorem starts with the hypothesis that a set can be partly subset and partly superset of another fuzzy set. In (Figure 4(b)) the objects O and L apart from the fact that relate the objects P_1 and P_2, they are also related themselves.

If the $m_O(P_2)$ is slightly higher than $m_L(P_2)$ then the set O is also slightly superset of the set L. In this case the object O violates slightly the fact that O is subset of L (because $m_O(P_1)$ is less than $m_L(P_1)$). Kosko starts with the hypothesis: the greater the violation in magnitude and the greater the number of violations relative to the rectangular of L, the less O is subset of L and the more O is a superset of L. So, he relates superset and subset measures as follows:

Supersethood (O,L)= 1- subsethood (O, L)

The subsethood (O, L) measure should approach 1 as O approaches the closest subset of L. So, the key idea is metrical: we need to measure the Euclidean distance of O with the closest

subset of L as illustrated in the figure. This distance measured by the subsethood degree is expressed in a scale from [0,1] for normalisation (Figure 4(c)).
In terms of logical connectives, we have an evaluation for the logical implication as a function of the distance among the fuzzy sets, or of their subset and superset relation. In our example as the subsethood degree approaches 1, the relation of O with L is, more O $\Rightarrow$ L and less L $\Rightarrow$ O. As a result, implication and by extension equivalence, are defined in a continuous way.
However, what we really need is to define logical connectives in an evolutionary way according to the changes occurring to the initial network of objects and relations, because of the actors' interaction and altering conditions. We need to redefine logical connectives according to the changing "context" of connected objects. As shown above, it is important to develop a description that not only manages the interdependencies among objects in terms of relations among fuzzy sets, but also in terms of distance measurements among fuzzy sets. Our conjecture is that the subsethood measurement could be elaborated to describe emergent properties and connections among objects, on the basis of distributing local connections to manage global interdependencies. If we manage to incorporate a self-similar, iterative description of the fuzzy sets -what proposes the existence of a "fractal" space rather than the homogeneous isotropic Euclidean space - then we can elaborate a distance measurement that expresses changes resulting in time and in different scales.
In this section we have described a meta-model for representing knowledge from a connectionist perspective and within the framework of fuzzy logic. We have also shown how we can facilitate the representation of logical connectives to be expressed in an evolutionary manner. "Capturing" logical connectives is of significant importance for co-ordination, because they give us insight into how different agents unravel their reasoning in a specific design or planning case, and they can reveal interdependencies among objects, plans, preferences and goals.

4. A connectionist paradigm in co-ordination

If common logical patterns can be detected among the information exchanged by the different agents, then we can assume that these patterns form an effective indicator (a prototype) towards consensus and co-ordination. The basic idea is to create a controller-filter that learns the patterns generated by the agents' participation and interaction and use them back as a platform for co-ordination.
We argue that the principles and tools of self-organised associative neural networks for pattern recognition and clustering could be implemented to address the issues of agent co-ordination and control.

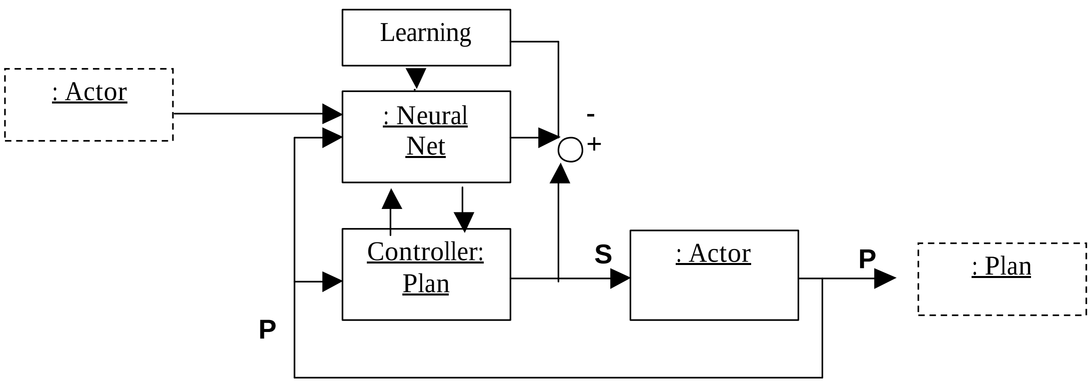

Figure 5: a neurofuzzy controller for coordination

The architecture of the controller is illustrated in Figure 5. We have already described in our generic view of co-ordination, the interaction of the actors via the modification of the plan towards their preferred state (Figure 2). The controller works by assigning an associative memory to the introduced plan-state. The neural network discovers patterns of interdependencies among objects and plans, and trains the system towards these patterns. The target (or the reaction of the controller) is re-evaluated continuously- and in real time- by means of the differences among emerging states. Instead of thinking about a central controlling mechanism we distribute the controlling behaviour among plans. More analytically the key points are:

- Every plan $P_{k,\ t}$ expressed by an actor K is defined as an "agent" whose behaviour is triggered by an associatively recalling previous states (Figure 6).
- Every plan performs as a micro-controller for all the other plans with a target formed according to collective patters that are discovered through time.

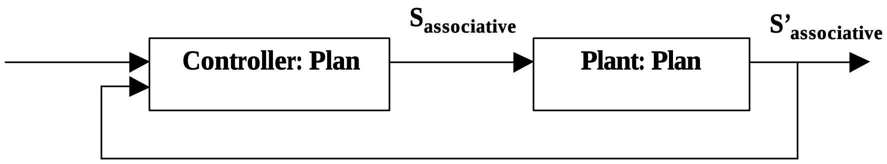

Figure 6: every plan recalls associated states in response to a stimulus

- A set of plans P={$P_{1,}$ P_2,…, P_n} drawn from different actors at different times could be seen as a training set, which acts as co-ordinator (Figure 7(a)). At the same time, every plan is a micro-controller itself that trains the other plans towards the preferred direction of the actor that proposed it (Figure 7(b)). The essence of the neuro-controller is that it makes feasible an interaction among current and existing plans so that each of them evaluates and constrains the others towards a solution that satisfies local and global requirements.

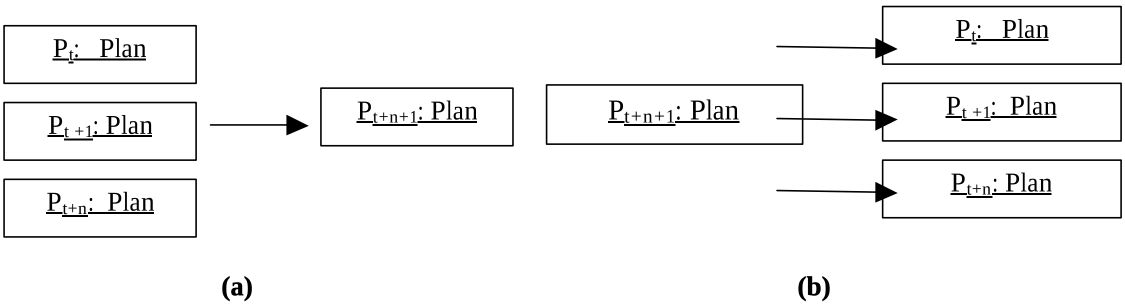

Figure 7: feedback among "training" and "trained" plans.

The technique that we employ for this model is on an early stage, however we can introduce some of the key points:

- Every proposed plan is received as a (fuzzy) distinct agent that has access to an array of all the proposed objects in the system.

- Every plan-agent represents a case. That is, every agent is characterised by a matrix of weights (membership functions), which describe fuzzy objects and their interdependencies.
- A neural network computes the matrix of weights: every plan is a Hopfield-like network of connected neurones. The connections among neurones describe the interdependencies.
- Different plans-agents form layers (clusters) of units laterally connected. Each unit is governed by leaky- integrator dynamics and receives the same set of inputs from a layer of plans (Figure 8).
- The training algorithm will most probably be a hybrid form of the Fuzzy ART proposed by (Carpenter et alii, 1991; Georgiopoulos et alii, 1995) for unsupervised learning.

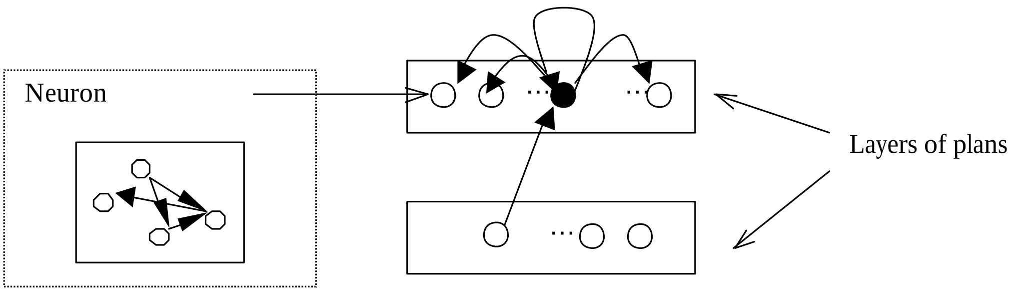

Figure 8: a neural network computes the weights of interconnections among plans and among the objects within the plans

5. The tool

Having discussed the idea of co-ordination via control, using a connectionist paradigm, we must also investigate ways of implementing this idea to multi-agent collaborative planning and distributed problem solving, which form our motivation in the first place. At the outset, we have tried to build a model to capture and manage diverse and uncertain information coming from multiple agents. In parallel to this, we must seek for ways to assist open communication and wide information exchange. The use of the World Wide Web as a platform for the implementation of our model appears to be a very promising alternative for different reasons. One reason is that the WWW and the Internet are themselves a powerful source of information and knowledge, plus the fact that are widely distributed and accessible. The growth of the Internet has called for the development of large repositories of information for planning and design based tasks, as well as for the development of on-line decision support tools, often aiming to support communication within the public realm (Batty, 1998; Gordon et alii, 1997; Sharma et alii, 1998; Shiffer, 1992; Shiffer 1995).
To begin with, we are planning to implement the neuro-controller described in the previous sections, to be available on the web. The interface will be based on an Internet-GIS application. One of the basic targets is to incorporate and exchange information from different applications. The purpose is to bring together experts from different domains and also to facilitate the participation of a wider public. A possible solution to this problem is to use XML to transfer and model data coming from the different applications in various formats. We could also describe XML as a general format – a "meta-language" that implements the scheme of knowledge representation we have already discussed, and facilitates the management and computation of diverse information provided by the actors. The principal components of our Web-based tool are illustrated in the Figure 9, which also explains the tasks involved in a sequential order.

The process described in Figure 9 is a process similar to that in Case-Based Reasoning. Briefly, the actor first identifies a system of interest (selects at minimum a geographical position) and forms a query that retrieves a case according to the interdependencies of the objects in the selection. A case is a network of plans linked according to expressed interdependencies, and it is stored in a database. Editing includes selection of the appropriate plans and their modification. The submission of the modified plan is considered by the system as a new plan, and is exposed to the process of co-ordination described in the previous sections. When the system reaches a minimum of deviation among plans-states, stores the new interconnection of plans as a new case. For reasons of stability we consider applying a measurement of maximum deviation among proposed and stored cases to help us maintain the case base.

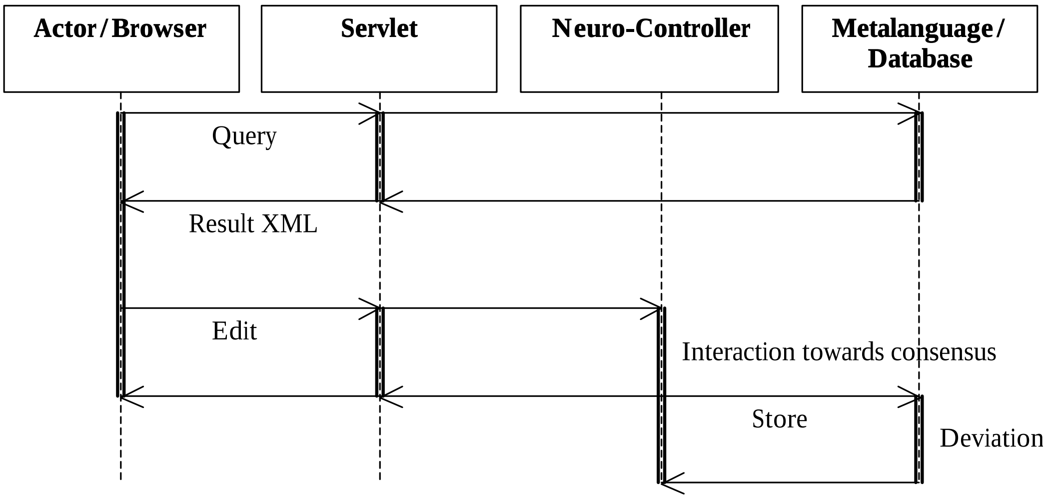

Figure 9: a sequence diagram for the basic components of the Web-based tool for coordination

6. Conclusion

In this paper we described a model for co-ordination adopting a connectionist point of view and we elaborated a model of co-ordination via a control. The possible application areas of this paradigm are in multi-agent collaborative planning and in distributed problem solving. We also formalised a meta-model for knowledge representation to facilitate computation and management of diverse information. Testing those ideas in the construction of a Web-based tool to assist co-ordination of multiple distributed agents is the next step. It is a strong conviction of the authors that all effort has to be put to implement new tools to support collaboration in a wide area of domains where public interest is at stake. Planning and design are social activities and if we devise tools to support them, then these tools have to be pragmatic.

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