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Multi-level Holonification of Multi-agent Networks

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***Abstract*—A networked multi-agent system is a group of intelligent agents structured in a social network induced by agent interactions. As the size and diversity of the multi-agent system increase, the interactions and mutual influence of the agents in the structure become more complicated, and this makes the coordination of the system hard to deal with. Holonic models for multi-agent systems have been considered as one of promising models to manage large scale problems. This paper tackles one of the key problems in the design of holonic multi-agent systems. Here we propose a method to construct a multi-level holonic structure for a multi-agent network based on the centrality of the agents. The proposed method is applied to an urban traffic problem and the evaluation results prove its effectiveness.**

Keywords-component; holonification; multi-agent systems; holonic model;urban traffic control

I. INTRODUCTION

In recent decades, Multi-Agent Systems (MASs) have been excessively used, as one of very successful approaches, in the simulation and modeling of distributed systems [1]. An important concern in the design of MASs is the high load of interactions among the agents moving toward a common goal. This issue gets significant role in case of large scaled real world problems, due to the multiplicity and heterogeneity of the components. In such problems, when modeled by a MAS, on the one hand the agents need to operate in concert with each other in order to achieve system level goals, and on the other hand, they have a limited access to the computational resources and communication capabilities. The newly defined area of the networked systems has attracted wide research interests to cope with this problem [2]. In a multi-agent network the agents are organized towards a common goal where each agent interacts with the other agents according to a network topology [3].

The organizational structure of a multi-agent system, which is usually defined in terms of roles, relationships and authority structures, dictates the interactions among the agents, and can play a significant role in the overall performance of a society of agents. Many organizational models for MAS have been reported in the literature, among which, hierarchies, holarchies, coalitions, teams, congregation, societies, federations, markets, matrix organization and compound organizations are the most commonly used ones [4]. The contribution of this paper is on holarchies and holonic systems.

The holonification process in a holonic multi-agent system refers to the way that the agents are organized in self-similar nested groups, called holons. The organizational structure defined by holons is called holarchy and allows modeling of a MAS at several granularity levels [5]. This process is a very critical in the design of holonic multi-agent systems and extensively affects the efficiency and complexity of the system. Several methods, for the generating the holarchy and controlling it during the runtime, have been reported in literature, most of which are application dependent. Among the most related ones we could refer to [6] and [7]. In [6] the initial holonic structure is constructed through the negotiation and communication process among the basic components and in [7] a greedy approach, based on graph theory concepts, has been used.

This paper presents a holonification method for a population of interconnected homogeneous agents. In the proposed method, the importance of the agents in the flat network structure is evaluated using the centrality concept in social network research area. Having built the initial holons, the other agents of the network try to join these holons to form a multi-level holarchy. To assess our method, we have applied it to the urban traffic signal control problem and compared the results with a similar technique reported in [7].

The paper is organized as follows: in section 2, a brief introduction of holonic multi-agent systems is presented. The detailed explanation of the proposed method is given in section 3. In section 4, the proposed method is evaluated in a traffic signal control problem. Finally, a conclusion and future research directions are presented in section 5.

II. HOLONIC MULTI-AGETNT SYSTEMS

The word “holon” was proposed by Arthur Koestler to describe recursive and self-similar structures in biological and sociological entities [8]. This word is the combination of the Greek word “holos”, meaning whole, and the suffix “on”, meaning part of something. Based on the analysis that Koestler conducted on hierarchies and stable intermediate forms in both living organisms and social organizations, he found that “wholes” and “parts” do not exist in an absolute sense. In other words, none of components can be understood completely without their sub-components or without the super-component they are part of. According to Koestler, a holon is a self-similar or fractal structure that is stable and coherent. These structures consist of several holons as sub-structures (called sub-holons) and at the same time are parts of greater wholes (called super-holon).

Derived from the holonic concepts, a holonic organization is defined as a hybrid, recursive and hierarchical structure, which is able to generate dynamic linkages to control the parts. Some of the key characteristics of a holon are: stability, autonomy and cooperation capacity [9]. In the holonic terminology, a hierarchical structure of holons is called a holarchy [8]. A holarchy can be modelled using whole-part relationships and it is managed in a distributed manner by system elements or holons. A four-level holarchy is depicted in Fig. 1.

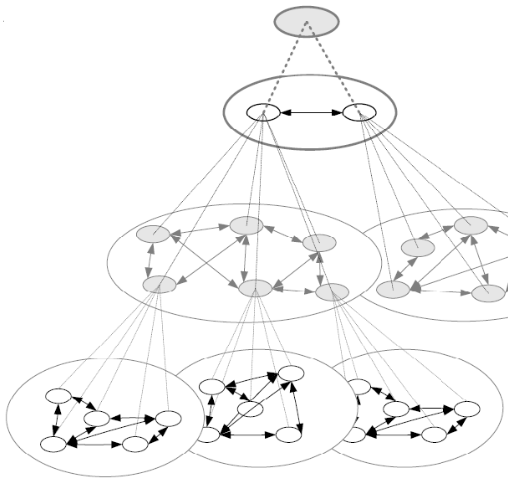


Figure 1. A holarchy composed of four holarchical levels [10].

In HMAS, holons are, by definition, composed of other holons in super- and sub-holon relationship.

In Holonic Multi-Agent System (HMAS) the structure can be seen as a set of hierarchical levels, in which the holons are, by definition, composed of other holons in super- and sub-holon relationships. In a HMAS, the holons of any level can interact only with the ones in the same level, and the ones in their immediate upper or lower levels through an especial holon, called head. In these systems, any individual holon is considered as semi-autonomous entities in the way that their actions and behaviors are based on their own local knowledge under the control of their super-holon.

Holonic organizations have proven to be effective solutions to several problems associated with hierarchical and self-organizing structures [11] and have been successfully applied in a wide range of complex real world systems ranging from flexible manufacturing systems [12] to transportation [10] and health organizations [13].

III. THE PROPOSED METHOD

In this section, our proposed method for extracting the holarchy based on the relationship characteristics between the agents is discussed. As mentioned before, the proposed algorithm makes use of the concepts in social networks and network theory domain. Therefore, in this section, modeling a multi-agent system as a network of agents is explained at first and then the proposed multi-level holonification method, based on the relative importance of the agents in the network, is presented in detail.

A. Network Modeling of Multi-agent Systems

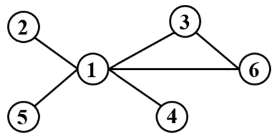
In recent years, with the growth of the scale of multi-agents systems, agents are most likely to get organized in a networked structure in which each agent interacts only with its immediate neighbors. This way, regardless of the size of system and its networked model, the agents merely need some local information about the network and as a result the complexity of the systems is reduced significantly.

A networked multi-agent system can be presented as a graph. In this graph, the vertices are the agents and edges are the interaction relationships between the agents in the MAS. A multi-agent network, based on the application domain they are used in, can be directed or undirected; and weighted or unweighted. In this article, we will focus on the undirected unweighted model of multi-agent networks.

Formally, through this article, a multi-agent network is presented by the pair $MAN = < A, I >$, in which A is the set of agents of MAS and I refers to the set of interaction relationships between the agents. Such a network can be represented by an adjacency matrix $\mathbf{\Lambda}$, in which the rows and the columns are the indexes of the agents and the items are defined as follows:

$$\mathbf{\Lambda}(a_i, a_j) = \begin{cases} 1 & if\ (a_i, a_j) \in I \\ 0 & otherwise \end{cases} \quad ; \quad a_i, a_j \in A \qquad (1)$$

In Fig. 2 an example multi-agent network consisting of 6 agents is illustrated.



$$A = \{1,2,3,4,5,6\}$$

$$I = \{(1,2),(1,3),(1,4), (1,5),(1,6),(3,6)\}$$

$$\mathbf{\Lambda} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Figure 2. An example multi-agent network

Having a multi-agent network, holonification is task of partitioning the network based on some specific criteria. Here we concentrate on the position of the agents in the network to holonify the MAS. This makes our method to be mapped and easily used in a wide range of applications and problems.

Formally, the holonification problem in each level of a holarchy is finding a set, H, of subsets h_i such that:

$$H = \{h_1, h_2, ..., h_k\} \mid \; h_i \subset A; \; \bigcup_i h_i = A \qquad (2)$$

where, k is the total number of holons and h_i , $i = 1,2,3…,k$ are the holons themselves. In the general definition of holonic multi-agent systems, the members of different holons, i.e. h_i, might overlap; however, since overlapping holons will impose an extra degree of complexity in coordination of agents, we have assumed that in each level of a holarchy, the holons are disjoint. That is:

$$\forall h_i, h_j \in H; \, l(h_i) = l(h_j) \rightarrow h_i \cap h_j = \phi \qquad (3)$$

where, $l(h_i)$ is a function that returns the level of holon h_i in the holarchy.

B. Holonification

The holonification process at the lowest part of a holarchy can be considered as a variant of graph clustering problem and hence suffers from NP-hardness [14]. In the proposed method, a bottom-up approach is followed to construct the holarchy. Given a multi-agent network as introduced before, the process of extracting the holarchy begins with locating the agents that are eligible to play the role of the head. These head agents construct a basic holon in the lowest level in the holarchy. Then, the other agents of the network attempt to join these basic holons, based on their position in the network and the eligibility of their neighbors. This process can be repeated to build the upper levels of the holarchy. For this purpose, the lower level holons together with the interaction relationships between their member agents, make an abstract multi-agent network, i.e. a network of lower level holons as abstract agents. Now the holonification process is repeated on this network to build another level. This process is repeated until a single holon, as a root, is created such that it contains all the other holons in the holarchy.

The algorithm that is used to recognize and select the important agents as the heads in the network, is based on the concept of centrality in network theory and social network analysis domains. There are various kinds of centrality defined in social network research community, each of which focuses on a specific aspect of importance among the individuals [15]. In this article, we recognize the potential head of the holons as the agents that not only have many connections with the other ones, but also the one in close distance to the other important agents. Accordingly, adopting the concept of eigenvector centrality in social networks, we define the eligibility of the agent a_i to become a head as follows:

$$elig(a_i) = \lambda_{\max}^{-1} \sum_j \mathbf{\Lambda}(a_i, a_j) \cdot elig(a_j) \qquad (4)$$

where, the λ_i are the eigenvalues of the adjacency matrix $\mathbf{\Lambda}$, and $\lambda_{\max}$ is the largest of them. This equation can also be written in matrix notations as:

$$\mathbf{\Lambda} \; \mathbf{elig} = \lambda_{\max} \; \mathbf{elig} \qquad (5)$$

where, **elig** is the vector with the elements $elig(a_i)$.

Now let us present the proposed algorithm to extract the holarchy for a given multi-agent network, as follows:

1) Compute the eligibility of the agents using the Eq. 4 above.

2) Select the heads as the agents with eligibility value greater that the average eligibility values of all agents. That is:

$$Head = \left\{ a_i \in A \mid elig(a_i) > \frac{\sum_j elig(a_j)}{|A|} \right\} \qquad (6)$$

where, $Head$ is the set of selected head agents and $|A|$ refers to the number of members of the agents set A.

3) Create a basic holon for each of the agents selected as head. These heads are the only members of the corresponding created holons.

4) For each of the non-head agents, find the neighbor with higher eligibility value:

$$BN(a_i) = \underset{a_j \in Neighbor(a_i)}{\arg\max} \; (elig(a_j)) \qquad (7)$$

where, $BN(a_i)$ is the function to find the most eligible neighbor of agent a_i, and $Neighbor(a_i)$ is set of all neighbors of a_i in the network.

5) For all the agents not currently member of any holon, Add them to the holon of which their most eligible neighbor is a member. Formally:

$$Holon(a_i) = \begin{cases} h_{a_j} & a_j \in Head \\ Holon(a_j) & otherwise \end{cases} \; ; a_j = BN(a_i) \qquad (8)$$

where, $Holon(a_i)$ specifies the holon that a_i should join, and h_{a_j} is the holon that a_j is a head in.

6) Stop the algorithm if there is only a single holon created in the current level (the root holon).

7) Once the holonification of the current level completes (all the agents of the network are members of created holons), build an abstract multi-agent network. The

vertices of this new abstract network are the holons created in current level; and the edges are the interaction relationships linking the members of different holons.

8) Repeat the steps above, to construct the upper levels of the holarchy.

In the following section, we will evaluate the proposed method.

IV. Experimental Results

Intelligent traffic control problem is one of very sophisticated domains tackled by the researchers in artificial intelligence. The complexity of the problem together with its dynamics, have made the central solutions almost intractable. Agent-based urban traffic models, as one of distributed approaches, have been found as efficient tools for traffic planning and deploying more intelligent traffic management. There are a considerable number of works reported in the literature which have used multi-agent and holonic systems to provide a flexible and robust control mechanism in urban traffic domain. Among the most recent researches in the use of holonic multi-agents in this field, we direct the readers to [7] and [10].

In this paper, we have chosen the problem of controlling traffic signals to evaluate our proposed method. For this purpose, first, the urban traffic system is modeled as a multi-agent network. In this network, the signal controllers in the intersections are the agents, and the roads connecting these intersections are the interaction edges. The resulting network is *connected* in the sense that always there is at list a path between two randomly selected agents (intersections); and *planner* since the network has an intersection wherever two interaction edges cross. Fig. 3 shows an example traffic network with its corresponding multi-agent network model.

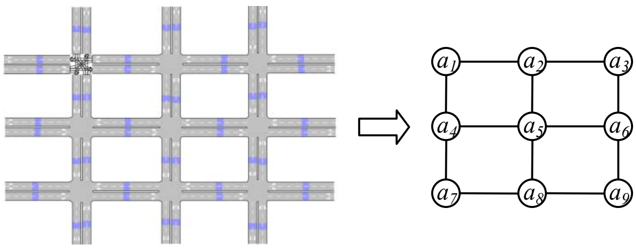


Figure 3. Multi-agent network model of a urban traffic network

The proposed method has been tested on an urban traffic network consisting of 25 intersections and 31 connecting roads. We are going to compare our results with the results from the method proposed in [7]. In the urban network that is used, the roads are designed to be of same length and capacity. This causes the weights of the links that are used in [7] all of the same value, and provide a fair condition for the two methods to be compared. The multi-agent network model of the designed urban traffic network is depicted in Fig. 4 using spring layout. It should be noted the distances between the agents are unreal and this is due to the layout algorithm that is used to illustrate the network.

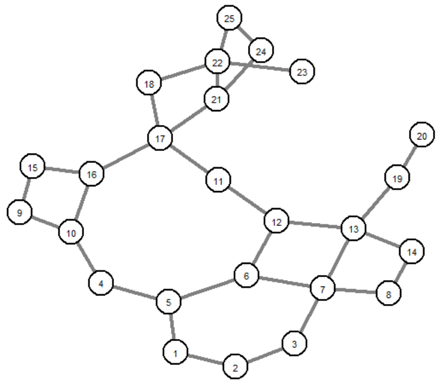


Figure 4. Multi-agent network model of the experimental urban traffic environment

The experiment was carried out using the Aimsun[1] traffic simulation environment. The traffic network configuration parameters are listed in Table 1.

TABLE I. Traffic Network Configuration

Property	Value
Number of intersections	25
Number of links	31
Length of each link	436.72m
Maximum speed	60km/h
Number of lanes per link	2
Arrival distribution	uniform
Simulation duration	5 hours
Traffic demand	30000 veh/hour

During the experiments, the mechanism used for scheduling the traffic lights inside of a holon is the same as the one explained in [7]. Average traffic delay time is the measure that is used to compare our holonification method with the greedy one reported in [7]. Fig. 5 shows the resulted traffic delay time, averaged over 10 runs. As it can be seen, the proposed method in this article has caused relatively lower delay time for the vehicles in the traffic network and postponed the saturation time of the traffic.

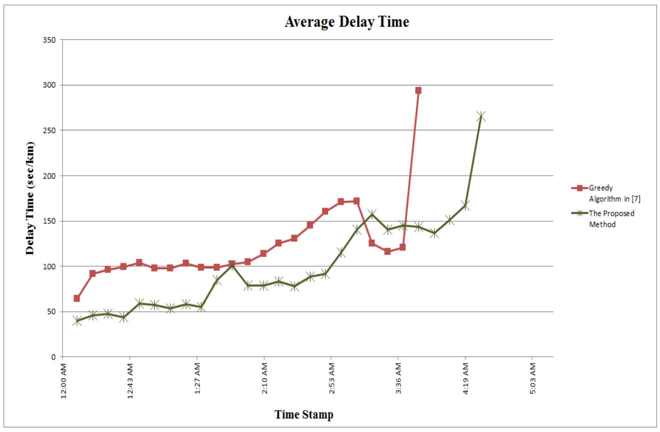


Figure 5. Delay time of the compared methods in the experiment

[1] http://www.aimsun.com

V. CONCLUSION AND FURURE WORKS

Holonic multi-agent systems are considered as one of very effective tools for dealing with real-world large scaled and complex problems. One of the key concerns in holonic approaches is the way that the holarchy is structured. In this paper we proposed a method, inspired from social networks, to build the holonic structures in a bottom-up approach. It was tried to define the method in a way that it can be used for wide ranges of applications. The only prerequisite of this method is an un-weighted undirected multi-agent network model of the problem which can be easily provided in many real-world applications. In order to evaluate the quality of the holons constructed in the proposed method, we applied it to the problem of urban traffic signal control and compared the results with one of recently reported holonification method. The empirical result proved the effectiveness of the holarchy generated by our method. Future works include extending our algorithm to weighted multi-agent networks and considering the characteristics of the agents in the holonification process.

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