Engineering Applications of Artificial Intelligence 55 (2016) 186–201

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

The impact of diversity on performance of holonic multi-agent systems

Ahmad Esmaeili [a,*], Nasser Mozayani [a], Mohammad Reza Jahed Motlagh [a], Eric T. Matson [b]

[a] School of Computer Engineering, Iran University of Science and Technology, Tehran, Iran
[b] Department of Computer and Information Technology, Purdue Polytechnic Institute, Purdue University, West Lafayette, IN, USA

ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form
13 May 2016
Accepted 18 June 2016

Keywords:
Multi-agent systems
Holonic multi-agent systems
Diversity
Optimization

ABSTRACT

There are Numerous researches in the fields of social sciences and multi-agent systems that are dedicated to studying the role of diversity vs. individual capabilities in design and performance of human and artificial societies. This paper addresses more complex multi-level structures, namely holarchies, in multi-agent systems, and conducts several analyses on the effect of individuals' behavioral diversities in the constitution and performance of the whole system. The hypothesis is that diversity directly affects the structure and performance of a holonic organization. In order to check this, we first proposed a diversity-based holonic model for multi-agent systems and then carried out a set of simulations in which a holonic multi-agent system is employed in a function optimization application. In these simulations, we manipulated the behavioral diversity of the agents in various ways and carefully observed the changes that occur on the effectiveness of the system. These observations include the quality of solutions, the height and composition of the constructed systems, and the time efficiency of the model. The empirical results show that as the diversity of intra-holon agents increases, the height of holarchy is reduced while the sizes of the holons tend to increase. On the other hand, this increase in diversity results in an increase in the performance of the system in situations that diversity of the initial population is high. However, when the diversity of the initial population is low, the diversities inside the holons need to be adjusted around 60 percent in order to boost the performance.

1. Introduction

Multi-Agent Systems (MASs) have had an excessive use in recent decades, thanks to their high success rate in modeling and simulation of distributed and/or complex systems (Weiss, 2013). In design of a MAS, interaction among the components toward a common goal plays an important role. This concern becomes even more significant in case of large scaled real world problems, where a high load of interactions is present due to the multiplicity and heterogeneity of the constituents. In a multi-agent approach to such problems, having limited computational and communication capabilities, the agents need to act towards a system level goal in concert with their counterparts. The new area of networked systems has attracted wide interest in the literature, under the term of networked multi-agent systems, to deal with this problem (Mesbahi and Egerstedt, 2010). The research on networked multi-agents systems mainly focuses on the agents organized to interact with each other according to a network topology (Karagiannis et al., 2010). On the other hand, an Organizational structure, as one of main characteristics of multi-agent systems, not only provides a framework for analyzing the roles the agents play, but also helps track the communication load in MASs and complement the concept of agents, with the aim of simplifying their models and reducing uncertainty (DeLoach and Matson, 2004). Numerous organizational models have been reported in the literature, among which, coalitions, teams, congregations, hierarchies, holarchies, federations, markets, matrix and compound organizations are the most commonly used ones (DeLoach and Matson, 2004; Irandoust and Benaskeur, 2008). By the design of an organizational multi-agent system as an open system, we allow the introduction of agents of various types and capabilities. In such a heterogeneous environment, different combination of the agents into teams or groups can lead to different performances, not necessarily outperforming the members of the group. Therefore, making a good understanding of the role of diversity has been considered as one of the first and critical steps in designing large-scale multi-agent systems.

The focus of this paper is on the study of holonic structures in multi-agent systems. In Holonic Multi-agent Systems (HMASs), the agents are organized in self-similar nested groups called holons, and the term holarchy refers to the multi-level structure composed of these holons. Such a hierarchical structure allows modeling of MASs at several granularity levels and has wide range of

* Corresponding author.
E-mail addresses: aesmaeili@iust.ac.ir (A. Esmaeili), mozayani@iust.ac.ir (N. Mozayani), jahedmr@iust.ac.ir (M.R.J. Motlagh), ematson@purdue.edu (E.T. Matson).

http://dx.doi.org/10.1016/j.engappai.2016.06.011

applications in dealing with complex systems (Rodriguez et al., 2007). Holonification, the problem of selecting the best possible holons to perform a certain goal, under limited resources, is very vital in the design of holonic multi-agent systems, and can substantially alter the efficiency and complexity of the systems. This fact has attracted many researches in organizational multi-agent systems and lead to various mechanisms in generating the holarchy and controlling its structure in dynamic environments such as the works in Jie et al. (2011), Abdoos et al. (2012), Esmaeili et al. (2014) to name a few. In Jie et al. (2011), a negotiation and communication process among the agents is used to build the initial holonic structure; and in Abdoos et al. (2012), Esmaeili et al. (2014) a greedy approach based on graph theory, and a multi-level centrality-based method are reported respectively.

In social science, diversity of a group refers to demographic and cultural differences together with variations in training and expertise (Page, 2008). Inspired from social sciences, diversity is also one of the fundamental concepts in disciplines such as sociobiology, statistics, genetics, and robotics. When it is mapped to the world of intelligent agents, diversity is translated in form of capability of the agent to perform a task and their various behaviors in different circumstances. In other words, in the context of multi-agent systems, diversity may be due to differences in knowledge, positions, characteristics, capabilities, and behaviors of the agent components (Lyback, 1999). In this article, we define diversity as the difference in capabilities of the agents, resulting in various behaviors towards the introduced problem. In an application in which a large number of agents with various skills are cooperating towards a pre-specified common goal, one can arrange the agents in abundant ways into any cooperative group. This circumstance raises the question whether the designer should concentrate on the diversity inside the groups or the strength of the members. This issue becomes even more critical when we are devising solutions based on holonic multi-agent systems, due to flexibility and adaptability of the structures in different levels. Assuming an already present network topology among the agents, current paper studies the effect of diversity on the efficiency of holonic multi-agent systems.

This paper is organized as follows: in Section 2, a review on the effects of diversity in artificial agent societies are given. Section 3 presents a brief introduction to holonic multi-agent systems and the concepts and terminologies that are used throughout this paper. The detailed explanation of the proposed diversity-based HMAS model is provided in Section 4. Section 5 presents a concrete case study to show how the proposed model can be applied to an arbitrary application and to provide a the test bed for this study. Section 5 is dedicated to the empirical results and the discussion about how to use these results to build more efficient holarchies. And finally, the article concludes in Section 6, with some suggestions for the future research.

2. Literature review

To the best of our knowledge, there is no research reported on the role of diversity in structuring holonic multi-agent systems. Nevertheless, there are numerous works in multi-agent systems that are noteworthy. As mentioned before, there is a direct relationship between the concept of diversity and capability, and there is an extensive amount of research in many disciplines about the capability of human and animal groups in solving problems (King et al., 2011; Krause et al., 2010; Lorenz et al., 2010). The studies show that two factors play significant roles in the performance of the groups: the diversity of the group members and the ability of individuals (Krause et al., 2010; Lorenz et al., 2010; Grofman et al., 1983). However, it is often unclear which factor surpasses the other. According to various empirical results presented in Lorenz et al. (2010), Krause et al. (2011), in the applications that a specific continuous variable is to be estimated, diversity has more influence, while in the problems that need a high degree of theoretical knowledge, the capabilities of the individuals become more important (Lorenz et al., 2010; Krause et al., 2011). Furthermore, in Luan et al. (2012), the authors try to analyze the contribution of these two parameters in decision-making tasks through altering the factors in various simulations to find situations that each of these two parameters outdoes the other.

Regarding organizational structures, the concept of diversity has been considered as a significant factor for team formation in social sciences and economics (Hong and Page, 2004; LiCalzi and Surucu, 2012; Marcolino et al., 2013). In these works, the diversity of the system is modeled by the information they bring, and converges to the best options familiar to the group. One of the earliest works on the study of the effect of diversity in artificial societies is the work by Hong and Page (2004). They used a series of computer simulations and theoretical analyses to show how a group of randomly selected agents (diverse) surpass a group of skillful agents, in solution searching problems. In their model, they assigned a set of local minima to each agent, which can be improved with the help of other team members. Furthermore, they showed that with an increase in the number of diverse agents, the system converges to the optimal solution. In book (Page, 2008), Page also popularized the importance of diversity through sets of computational simulations and theories. The works by Page and Hong has been followed by many other works, such as Krause et al. (2011), Luan et al. (2012), Lakhani et al. (2007), which try to show the effect of diversity on the quality of the solution in different settings. For instance, in Grofman et al. (1983), the authors study diversity in swarm intelligence. According to their experiments and empirical results, groups of high capable individuals can be outcompeted by groups of same size but with lower capable members, and adding diversity to the group can be more beneficial than making the members more capable. Nevertheless, the diversity, while being necessary and beneficial for the performance of swarm intelligence, does not solely guarantee the performance without the use of other factors. Furthermore, in Marcolino et al. (2013), the authors suggest a voting mechanism for the agents to use in order to avoid being trapped in the local minima of the agents. In Marcolino et al. (2014), a detailed analysis of diversity in multi-agent systems is given by proposing a new model of strength and diversity in teams of voting agents. In this work, the authors have shown that under specific conditions, a divers team of agents beats a uniform team of strong agents, in multiple world states.

Apart from individual capabilities, there are some other factors that may affect the relationship between diversity and system performance. For instance, In Balch (1999), Balch has used behavioral diversity to propose a cooperative strategy. According to the empirical results achieved in robotic soccer and multi-robot foraging tasks, they showed how the utility of diversity depends on the task the agents try to solve. They show through various evidences that diverse groups tend to outperform highly-skilled ones on intellective tasks (Hastie, 1986; Levine and Moreland, 2008).

The entire over-mentioned researches, study the effect of diversity on a single level of human or artificial societies, while an increased number of problem solvers in a society demands more complex structures, such as hierarchies. In such systems, any change in the combination of subgroups, not only affects the performance of that group, but also has indirect influence on the performance of the other parts. In this paper we study the effect of diversity in multi-level holonic structures through various simulations. In these simulations, the diversity of the system is controlled using a parameter, called "diversity factor", which alongside