A survey on Multi-Agent Systems (MAS)

Angjeliqi Anxhela Gjikopulli, Anubhab Banerjee*
*Chair of Network Architectures and Services, Department of Informatics
Technical University of Munich, Germany
Email: anxhela.gjikopulli@tum.de, anubhab.banerjee@tum.de

Abstract—**Multi-agent systems (MAS) got the attention of scholars and experts from various disciplines, from computer science to civil and electrical engineering, due to its capability of solving complex problems. The problem solving skill is achieved through the subdivision of the problem into smaller tasks and allocating them to specific agents within the system. Despite finding multiple applications across various disciplines, MAS still face numerous challenges related to the organizational issues among agents, security, task allocation, and so on. This paper provides a discussion on the diverse aspects of MAS starting with a definition of agents and their features. In addition, it tackles into details the application of MAS in three different fields: Cellular and Mobile Networks, Smart Cities and Ambient Technologies and Social Networks, the challenges faced in those fields and possible future works in respective fields.**

Index Terms—**Multi-Agent Systems (MAS), MAS applications,**

1. Introduction

Multi-agent systems is a subfield of Distributed Artificial Intelligence (DAI) [1] and has experienced rapid growth due to its ability to address complex computing problems. Multi-Agent Systems (MAS) are systems composed by an accumulation of autonomous entities, known as agents. Agents are computer systems with the important capabilities of learning and making autonomous decisions, and also interacting with neighbouring agents [2]. Their learning capabilities enable them to autonomously decide what they need to do in order to satisfy their design objectives [3] and solve their allocated tasks. The ability of interacting with other agents or with the environment enables them to learn new actions or contexts. The flexibility that such capabilities give to MAS, makes them suitable for problem-solving in a variety of disciplines, from computer science to civil or electrical engineering. At the same time there are various common challenges in building effective MAS, regardless of the application discipline, such as security [3], coordination within the system, task allocation, fault detection etc. In order to better understand and solve these challenges, it is neccessary to well-define agents and their features.

The content of this paper is organized as follows. First, we provide a theoretical overview of MAS, starting with a definition of agents and their features and the advantages of MAS to other systems in Section 1. Next, in Section 2, we give a detailed overview of three main areas of MAS applications, including the current developments and challenges in each field and some possible future work to improve each application. Finally, the conclusion of this MAS survey is given in Section 3.

2. Introduction to Agents

The most commonly agreed definition of agent is the one by Russell and Norvig [4] who define it as a flexible autonomous entity capable of perceiving the environment through the sensors connected to it. Unfortunately, the provided definition does not cover all the characteristics that an agent possesses. In this section we break down the definition presented in [2] where the authors define an agent as "an entity which is placed in an environment and senses different parameters that are used to make a decision based on the goal of the entity. The entity performs the necessary action on the environment based on this decision".

- Entity- the type of agent; could be a software, a hardware (sensor) or a combination of both (robot).
- Environment- the place where the agent senses the information for later decision making. The environment itself has multiple features that could affect the complexity of the system, mentioning here accessibility, determinism, dynamism and continuity [3].
- Parameters- the different types of data that an agent is responsible of sensing.
- Action- each agent is responsible of performing a set of continuous or discrete actions that result in changes to the environment.

When put together, *entities* sense and collect *parameters* from the *environment* or from neighbouring agents, in order for the agent to build up knowledge about the environment. Once the knowledge is built, the inference engine decides on the *actions* that need to be taken by the agent. Multi-Agent Systems (MAS) consist of numerous agents collaborating to solve a complex task.

2.1. Overview of MAS Features

MAS share numerous features and characteristics as outlined in [2]:

Leadership: As a leader in MAS we refer to a coordinator like role, that guides the other agents with the main target being the achievement of the system functions. Based on the presence of this role MAS follows

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two structural paradigms, leaderless and leader-follow. A leaderless system, as the name denotes, operates without this role resulting in its agents having to function on an autonomous basis. In a leader-follow MAS, in most cases, the source of the actions is the leader agent. In case of multiple leaders they communicate with each other to guide the followers.

Decision function: In an MAS decisions can be linear or non-linear. Linearity is mainly determined by the source upon which its information is used to perform decisions. If the decisions of an agent are based on direct information then the MAS is linear. In case the agent's decisions are not affected by incoming information then this is considered as a non-linear MAS.

Heterogeneity: Based on the characteristics of its agents, a MAS is defined as either homogenous or heterogeneous. In a homogeneous MAS all agents have shared characteristics whereas in a heterogenous one the agents do not share the same functionalities.

Agreement parameters: In multiple MAS applications its agents must agree on certain metrics in order to further define the decision making progress. The number of these metrics determines the classification of a MAS namely: first, second or higher order.

Delay consideration: Given the co-dependence of the agents in various scenarios, delays might be faced. If the agents of a MAS expect delay and thus operate based on that, then the system is a system with delay. On the contrary, if the agents of a system cannot operate based on delays then the MAS is considered to be one without delay.

Topology: Based on the typology, agents can be divided into dynamic and static judging from their location and their relations to each-other. As dynamic, they move within a system or even in cases leave and rejoin. As static, they remain in place.

Data transmission frequency: Agents can either send data continuously resulting in a time-triggered MAS or requiring that other agents notify them to send information resulting in an event-triggered MAS.

Mobility: With the dynamicity of agents as the main focus, we can classify them as static or mobile. Static agents remain in their designated position whereas dynamic ones move based on the needs of the system.

2.2. MAS Advantages to Other Systems

MAS is comparatively assessed against other systems such as Object-oriented programming and Expert systems by Wooldridge [3], Zhao et al. [5], and Sadeghi et al. [6]. Expert systems observe and sense the environment, and then perform tasks based on the acquired knowledge. MAS is different due to the way it communicates between its agents in order for knowledge to be accumulated and tasks to be performed. An example of that would be having different results due to the sheer difference in the number of observers. In object-oriented programming objects deliver information and take decisions only from items immediately related to it by public functions. As a result, the frequency of interaction cannot be controlled, whereas in MAS agents can control the flow of information. Additionally, contrary to object orientation, agents in MAS can receive and propagate information from multiple sources.

3. MAS Applications

In this section we give an overview of some of the MAS applications: Smart Cities and Ambient Technologies (section 2.1), Social Networks (section 2.2) and Cellular and Mobile Networks (section 2.3). For each application we include the existing work suggested by the literature, possible voids in the topic and potential improvements or applications for future researchers to investigate further.

3.1. Smart Cities and Ambient Technologies

The Smart City (SC) refers to the place and territorial context where the planned usage of human and natural resources is properly managed and integrated through already available information and communications technology(ICT) [7]. In a city, properly integrated ICT within a network of fixed and mobile telecommunications, can improve the quality of life, can reduce unemployment, boost urbanization while being environmentally and socially sustainable and reduce extra costs and encourage development [8]. One of the technologies for a smart city grid that helps to achieve the mentioned scopes, is Distributed Intelligent Agents. The common goal of these systems is to always keep the network operational and the quality standards of the highest possible service. An ICT infrastructure with such purposes must be capable of providing instant bi-directional communications among devices, which can only be achieved through a distributed architectural framework. In the following section we address some of the main challenges of these systems, such as having increased costs, pollution and congestion etc.

3.1.1. Existing Research Works. In order to address the challenge of increasing costs, pollution and congestion due to unorganized distribution of freight, Khayyat and Awasthi [9] proposed an agent-based method which sheds light on a permanent solution by using six agents known as RFIDG (which stands for retailer, supplier, carrier, network, and city agents). The idea behind this proposal is the usage of RFID tags by the RFIDG agent, to easily handle and manage the supply of resources. When buying goods from a retailer or supplier, the buyer sends the request to one of their agents and upon receiving the request the same agent searches the database for the requested goods. As a next step, the goods are sent to the carrier agent which will ship them to the customer. In order to deliver the goods, the carrier agent follows the optimal path, which is determined by the network agent. Lastly, the city administrator agent informs both the supplier and the customer about relevant policies for the shipping goods.

Controlling the transport system and managing the ongrowing traffic in metropolitan cities is another important challenge. A proposed solution through agent-based methods from Hager [10] suggests that parameters such as fare and people satisfaction are used for analyzing the transportation model. This would be feasible through two groups of agents: travellers and vehicles. The agents would then share knowledge about traffic which is used by other agents at the same time, to decide on the shortest and fastest way toward their destination.

Similarly, MAS is applied in building management. The suggested literature [11] reviews an agent-based method for heating management in buildings, through heterogeneous heating appliances and sensors distributed around the building. The demand agents check the building temperature and pass the collected data to the heater, buffer and heat pump agents. The data from the demand agents are later used by the latter agents to adjust the temperature in the building if needed. After testing this method in an apartment and comparing the results with the centralized heating method, it was noticed that the daily consumption was significantly reduced when using the agent method.

3.1.2. Possible Future Works. With all the technological advancements in almost every industrial field, the number of integrated sensors into building materials is increasing by the day. Market-leading companies in glass and aluminium processing, engaged in the production of doors, windows and facades have started integrating sensors capable of capturing data related to air humidity levels, pollution indexes, noise levels etc. in the outdoor environment as well as in the inside spaces. Yet, these data are currently being used only for product optimization purposes. Our recommendation would be that there is a great research potential in further looking into how using these agents in the context of MAS could be useful for optimizing pollution and traffic levels in cities, as well as for weather forecasting purposes.

3.2. Social Networks

The number of social networks is increasing on a daily bases in terms of users, daily session-time spent and even in terms of available networks in the market. When put it in a bigger scale, this growth would be attributed to the continuously increasing number of Internet users. According to the literature [11], a social network is comprised of a set of autonomous social actors like users, groups and services, all of which act as agents. The complexity of social networks comes from the large number of users leaving or entering the network, which comes with an exponential growth of connections. Thus, the need to effectively manage such systems arises and MAS is seen as a potential solution to overcoming the complexity of social networks [11]. Through the years, researchers have come up with the three following main views for understanding social networks from a MAS point of view [11]:

1. The structure-oriented view: the main focus is on analysing the characteristics of the social actors' interaction of a network's topological structure.

2. The actor-oriented view: the main focus is on analysing the characteristics and effects of the behaviour of social actors within the social network environment.

3. The actor-structure crossing view: both structure oriented and actor-oriented views are in focus and researchers study how the behaviour of actors shape the network structures and how the network structure can shape user behaviours.

All three of the views find different applications among disciplines, but in this paper, we focus in some of the application areas of the actor-oriented view, where the structure of social networks is not quite strengthened.

3.2.1. Existing Research Works. Many researchers argue that social networks are an effective structure for multi-agent systems [11], [12]. One of them is also Gatti et al. [13], who proposes a similar approach on how MAS can be used to predict various aspects and functionalities of a social network. The researchers propose the introduction of agents throughout the social network that will collect information related to user behaviour. After performing topic and semantic classification to build specific user profiles, this information can be used to forecast future user behaviours, related to their activities within the network. Yet, social networks do not necessarily need to occur in the cyberspace. Ma and Zhang [14] considered the school system as a social network. The authors attempted the use of MAS in order to adequately allocate funds to various extra-curricular school programs. They modelled every role such as professor and student or other authorities within the system as an agent. Then, the system would assess, based on academic performance, whether the funds were adequately allocated.

3.2.2. Possible Future Works. The opportunities that come with implementing multi-agent systems in the context of social networks are endless. When focusing in the cyberspace, due to the undeniable growth of the smart-devices industry, everyone who owns such a device transmits endless amounts of data on a daily basis. In the context of search engines or other mobile applications, these data could be used to improve the overall user experience through further personalization and content improvement. To summarize, our recommendation would be to further look into how MAS could be useful for optimizing user experience in the cyberspace.

3.3. Mobile and Cellular Network Applications

Mobile Applications are amongst the most important utility tools in our everyday life and have tremendously upgraded our daily communication. The continuously increasing number of mobile network users and the extensive online activities performed daily, require the implementation of new technologies to improve the quality of the already offered services in mobile and cellular networks. The range of available agents in this context extends from weak (reactive) agents that respond in a stimulus response manner and have minimal need for a representational model of the agent environment, to strong and highly sophisticated agents that need to support rational reasoning in collaborative contexts in order to maintain complex mental states [15]. Multi-agent system approaches have proven to be particularly effective when applied for systems that are comprised by many dynamically interacting components [16], although in the mobile computing arena the utilized agents are of a weak variety.

On the other hand, when it comes to cellular networks, although wireless communication is extensive nowadays, there are still numerous challenges faced starting from the

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wide variety of data rates, to the high traffic data asymmetry, high energy consumption, low latency requirements in crowded areas etc. [17], [18]. The fifth-generation wireless communication systems (5G) is expected to address some of these challenges due to the integration of different types of cellular networks into a holistic network system, with the primary goal of providing quality of service to its users in an energy efficient manner [19]. Yet, with the emergence of 5G as heterogeneous networks, wireless radio spectrum resources are in high demand, causing a shortage of resources. This means that it is very important to look into new methods of improving the spectrum utilization [20]. One of the most promising solutions that is based on multi-agent architecture, is explained below.

3.3.1. Existing Research Works. *Cognitive Radio (CR) Spectrum Sensing Framework*: According to a 2014 study [20], changing the design of traditional Cognitive Radio Spectrum Sensing based on a multi-agent architecture, would meet the 5G network requirements. Alleviating the problem of scarce radio spectrum is attempted through the Cognitive Radio technology, by using radio spectrum resource management techniques [21]. Spectrum sensing itself is one of the key functions of cognitive radio that prevents the harmful interference between secondary users and primary users and improved the spectrum utilization by identifying the available spectrum [22]. In the traditional technology, the secondary user has the cognitive capability that performs spectrum sensing. The new approach consists on removing this capability from second users and assign the spectrum sensing duty to a new communication entity known as a spectrum agent (SA), with the ultimate goal of reducing energy consumption and wasteful resources, and improving the overall spectrum efficiency [20]. The introduction of SA as a third agent would not only reduce the design complexity of network equipment and improve spectrum utilization in 5G networks, but it would also minimize the cost of hardware. The spectrum agent (SA) itself is thought as independent of the number of users and as part of its function it collaborates with other detection points for an efficient collaborative spectrum sensing. According to the researchers, spectrum agents could be several tiny-base or micro-base stations.

3.3.2. Possible Future Works. Although the proposed multi-agent framework brings great improvements into the spectrum utilization and not only, there are still some voids that remain open for further research. Some of these issues would include: SA deployment, SA detection period and delay, SA scalability, Inter-SA handoff and sensing tasks assignment.

4. Conclusion and future work

Multi-agent systems have a wide application domain due to their high flexibility and as such, the challenges faced are also numerous. In this survey we discussed the diverse aspects of MAS and gave an overview of few MAS applications and challenges encountered in Cellular and Mobile Networks, Smart Cities and Ambient Technologies and Social Networks. We concluded each application with a discussion on the possible future studies that could improve the current voids in the respective applications. We believe that there is great potential in further researching the implementation of MAS in the mentioned areas. We expect this article to serve as an insightful resource to further investigate the possibilities of extending MAS applications beyond their current scope.

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