International Journal of Innovative Research in Advanced Engineering (IJIRAE) ISSN: 2349-2163
Issue 4, Volume 2 (April 2015) www.ijirae.com

Applications of Multi Agent Systems in Control Engineering: A State-of-the-Art Survey

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Abstract*— Recent years have witnessed an increased interest in the field of distributed control. Multi Agent Systems are one of the strategies of implementing distributed control and have found application in several areas. This work attempts to present a comprehensive survey of the various applications of Multi Agent Systems in the field of control engineering.

Keywords*— Agent, Intelligent Agent, Multi Agent Systems, Distributed Control Systems, Hybrid Control, Congestion Control.

I. INTRODUCTION

Last few decades have witnessed an increased interest in research and development of distributed control. Distributed Control, also referred to as decentralized control, has found plethora of applications where it has been implemented successfully and yielded amazing results. Multi Agent Systems (MAS) is one of the several techniques/strategies used to implement and/or design distributed control systems. MAS is a technology comprising of one or more agents or intelligent agents. Each agent has specific goals and its actions are driven towards the completion of those goals. However, agent's actions depend, in some cases, on the actions of other nearby agents, for which nearby agents need to communicate with each other. Presently, MAS technology is finding wide range of applications in the field of control engineering. MAS has been used in distributed control [1-9], hybrid control [10-16], automation [17], congestion control [18-25], system restoration [26-36], network control [37, 59], to name a few out, of the many areas where it is being used and yielding amazing results.

Being a new technology, MAS faces a lot of challenges. Extensive research is under process on modelling, architecture and stability of multi agent systems. The design methodologies to be adopted and implementation approaches are also one of the several crucial issues which need to be resolved. Present ongoing research also focuses on developing platforms for easier implementation of agent based model or strategy. Design of proper communication protocols, to be followed by agents, is also under development. This paper attempts to present a comprehensive survey of the various applications, in the field of control engineering, where MAS is being implemented. At the outset, basic definitions and characteristics of agents and multi agent systems are presented, followed by detailed survey of the different control engineering applications.

II. DEFINITIONS

A. Agent

An agent has been defined in a number of ways in the past. [39-43]. A comparative analysis of these definitions can be found in [44]. According to Wooldridge, an agent is "a software (or hardware) entity that is situated in some environment and is able to autonomously react to changes in that environment." The environment, in the definition, may be physical or computing.

It is worth noting that the entity, in the definition, is an agent if it acts autonomously to environment changes. However, an agent is autonomous if it "exercises control over its own actions" [44].

In [45], Wooldridge and Jennings have classified agents in the following categories:

- Agents that execute straightforward tasks based on pre-specified rules and assumptions.
- Agents that execute a well defined task at a user's request.
- Agents that volunteer information or services to a user whenever it is deemed appropriate, without being explicitly asked to do so.

Pragmatically, the above classification does not clearly differentiate agents from many other existing systems. For example, a thermostat may be viewed as an agent as it also reacts to changes in its environment and has some degree of autonomy.

B. Intelligent Agent

According to Wooldridge [43], an intelligent agent exhibits flexible autonomy, which means the agent selects the most appropriate action, from a set of actions. An intelligent agent has the following characteristics:

- Reactivity: reacts to changes in environment in a timely manner
- Proactiveness: dynamically changes its behaviour in order to achieve its goals.
- Social ability: is able to communicate with other intelligent agents, in a cooperative manner. This is done using an Agent Communication Language (ACL).

C. Multi Agent Systems

A multi agent system is a system comprising of two or more agents. Agents have local goals, rather than having an overall goal [46]. In MAS, the agents have the ability to connect with each other. The communication is more than mere transfer of data between different software and hardware agents. It refers to the ability of negotiating and interacting in a cooperative manner. A multi agent system can therefore be defined as a collection of heterogeneous agents and/or computational entities, having their own problem solving capability and who are able to interact among themselves in order to reach a goal.

III.MAS IN CONTROL ENGINEERING APPLICATIONS

Due to the flexible, autonomous, distributed, fault tolerant behaviour and open architecture of MAS, it is being applied to a vast spectrum of applications. Basically, MAS has been implemented either for building extensible software/hardware systems or as a modelling approach.

A. Distributed Control Systems

A distributed control system (DCS) refers to a system or process, where the different components or elements of the system are not lumped but distributed throughout the system and each component is controlled by one or more controllers. In DCS, the entire system is networked for communication and monitoring [2].

Few examples of DCS may be listed as:

- traffic signals,
- electric power grids and power plants,
- sensor networks,
- oil refining plants,
- water management system.

In [3], the authors define four levels of DCS:

(i) technological level, represented by sensors, controllers and other specific components of system.

(ii) supervisory level, interacting between operators and technological processes with real conditions.

(iii) information level, containing all information and data of the technological processes as a database.

(iv) management level, containing tools for online analyses processing.

In [1], Ligus and Horanska, discuss the principles of direct communication in the design of DCS, which are:

(i) First principle, called the principle of direct communication of elements, states that the technological level should have direct communication with the higher levels.

(ii) Gateway principle is extension of the first principle which states that if the supervisory level is large scale, then it is better to use a gateway server for communication.

In [4], the authors present a modelling framework for developing multi agent systems comprising of networked identical agents that can communicate and interact to perform the assigned task. Bidram et al implement distributed cooperative control of multi agent system, using one-way communication links, for frequency control of micro-grids [5]. Their work aims at synchronizing the distributed generators to nominal frequency and share the active power among DGs as per their ratings. Of late much has been done, for the reactive power control of smart grids using distributed MAS [6]. Multi agent systems, due to their inherent decentralized configuration and open architecture can show their potential in this area of control engineering.

B. Hybrid Control

A hybrid system is a dynamic system that shows both continuous and discrete dynamic behaviour. Generally, the term "hybrid dynamic system" is used in order to differentiate it from systems that combine neural network and fuzzy logic. The discrete part of the system makes decision to switch from one control law to the other, while the continuous part acts as per the law. Thus, such a system models the interaction between logical and continuous elements of a system. Hybrid systems are not only hard to model but also hard to analyse. However, nowadays MAS is used to decompose the hybrid structure of such systems and model it as multiple interacting agents. In [10], the possible/required modifications in the agent paradigm have been discussed, which can make the multi agent modelling of hybrid system easy for mathematical analysis.

Integration of cognitive capabilities can make the implementation of multi agent system even more realistic. In [11], the authors present some general considerations about introduction of cognitive capability into social MAS simulations. It points out the most relevant cognitive requirements of social simulations of a great amount of real scenarios where some agents carry out cognitive processing while others (a great majority) behave in reactive way.MAS has also been successfully implemented, for the hybrid control of micro-grids and smart micro-grids, for energy management and also hierarchy control [12, 13]. Hybrid control, using MAS, has also been applied for power distribution and system restoration [14] as will be discussed shortly in the upcoming sub-section.MAS architecture is well suited for control of hybrid dynamic systems. This advantage of MAS over other control strategies has helped in modelling and analysis of hybrid systems.

C. Congestion Control

Congestion is a situation in communication networks, in which too many packets are present in a part of the subnet, due to which the performance degrades. Congestion in a network may occur when the load on the network (i.e. the number of packets sent to the network) is greater than the capacity of the network (i.e. the number of packets a network can handle). This phenomenon generally occurs in communication networks, urban and air traffic network and all networks consisting of links and switches. Congestion control helps in controlling the traffic entry into a networked system, and avoids congestion, by controlling the rate at which data packets are sent and received. If the network is distributed geographically, a decentralized controller, such as multi agent system, will prove to be more efficient and reliable, providing good solution to the flow control and hence preventing congestion. Each node can be controlled by an intelligent agent that acts autonomously and is related to the network. Also, the agents may communicate with each other to reach a consensus on the data transfer rate, to resolve the congestion issue.

In [20], the authors study the resolution of conflict in air traffic management. The method models the aircraft and manoeuvres as a hybrid control system and calculates the maximal set of safe initial conditions for each aircraft so that separation is assured in the presence of uncertainties in the actions of the other aircraft. Explicit Congestion Notifications (ECN) have been used to signal congestion and eliminate losses in a network by choosing the ECN mar levels independently for each node [21].Congestion control has been implemented for networks represented by nonlinear fluid flow model in [22]. The proposed congestion controller takes into account the associated physical network resource limitations and is shown to be robust to the unknown and time-varying network delays. A linear matrix inequality (LMI) condition is obtained to guarantee ruggedness of the closed-loop system. Electrical power generation, transmission and distribution networks are also vast and complex. With advent of smart grid, communication in power system networks has increased. With frequent data transfer between various elements/loads of such a network, congestion creates a problem. In [23], a congestion management scheme has been proposed for smart grid infrastructures, to control the power absorption from a grid, in presence of plug-in hybrid electric vehicles. The achieved solution, based on the principles of game theory, converges to a pure Nash equilibrium solution.

A real life problem of pedestrian evacuation in a stadium is also a case of congestion control. A multi agent based congestion evacuation model has been proposed in [24] to simulate the previously mentioned problem, with or without obstacles. Recharging electric vehicles (EV) by connecting to the distribution network, during peak hours, also causes congestion and overloading of transformers and cables. This congestion management problem has been solved using, market based, hierarchical, multi agent approach [25].

D. System Restoration

Restoration after a blackout is a complex task that requires effective coordination, communication, and decision making in the face of rarely seen grid configurations and operating conditions. Every disturbance is unique to the conditions of the day and the initiating cause. Exactly how the power system will respond, or the extent of any blackout following a disturbance cannot be predicted. MAS have found application in connectivity restoration [27], power system restoration [29] and also restoration of smart grid [30]. Zenqiang Mi, Yang Yang and Guangjun Liu worked on developing a hybrid connectivity restoration framework, named HERO, in a multi agent network [27]. Nguyen and Flueck, present a new and completely distributed algorithm for service restoration with distributed energy storage support following fault detection, location, and isolation. Their distributed algorithm makes use of intelligent agents, which possess three typical characteristics, namely autonomy, local view, and decentralization [28]. The restoration problem, however, can also be viewed as a multi level, multi-objective optimization problem [35]. The application of MAS, for protection and control of smart distribution grid (SDG), has been demonstrated by H. Gao et al, in their work which includes modelling of 10kV distribution network with distributed generation (DG) and fault simulations [36]. J Ghorbani et al [14] showed that hybrid structure of MAS provides the capability of solving the restoration problem with taking the advantages of both centralized and distributed agent structures. Bottom-up order of agents, in power system restoration problem, constructing the MAS is zone agents, feeder and substation agents. In this architecture, agents have the permission to execute a function based on their hierarchy level and the control central supervisory is not always required. MAS agents, classified as Bus Agent, Feeder Agent, Substation Agent or Device Agent have been frequently used to develop multi agent system models, across several software platforms such as JADE, for efficient power system restoration [29, 30]. These models have been able to locate and isolate the fault and thereby restore the system.

Grid restoration using MAS has been done numerous times. However, the experimental duplicity of the results has been done in [31] by R. Belkacemi and A. Bababola. The technology has been implemented through the use of a six-bus experimental test bed set up using Tennessee Technological University Smart Grid Laboratory and the results matched those of simulation. The solution of distribution power system restoration, using multi agent approach, has been compared with the mathematical programming approach in [32]. The proposed approach, using only local information, proved to be promising even for large scale distribution networks.Design and development of Belief-Desire-Intention (BDI) agent based approach for system restoration has been proposed in [34]. The proposed BDI multi-agent approach can be applied to any size or structure of the multi-bus power systems. It has been shown, on the basis of results, that the proposed approach becomes more effective and efficient when the scale of the power system expands. Restoration of distributed power systems, proves to be a promising area of application, wherein the distributed nature and property of multi agent approach can be exploited

IV. DISCUSSIONS AND FUTURE SCOPE

MAS have been accepted, worldwide, as a new approach for system modelling and control system design. Its inherent distributed nature has been used to solve complex, multi objective problems. Multi agent approach has been extensively used in distributed control, hybrid control, network control, automation, congestion control, to name a few. The inherent decentralized nature of MAS helps to solve several problems, with much more efficiency than centralized techniques or algorithms. However, development of MAS is not an easy task. The design, of multi agent control strategy, is limited by several factors, such as, choice of topology, problems in inter-operability, choice of agent structure, implementation strategy and choice of development platform [60].

Current research is directed towards finding answers to the above mentioned limitations, so as to bolster the implementation of MAS in appropriate areas of application. Nonetheless, the research area is open with plethora of opportunities and scope. The issue of security in multi agent systems [52] and use of MAS for protection of critical infrastructures [53] are imminent areas for further research. Development of strategy to apply multi agent approach for smart grids [55], micro grids [57], networked control systems [59], formation control [54], intruder detection [56], to name a few, are research areas which have been surveyed, to identify crucial issues, regarding MAS design and development and still need to be explored further.

V. CONCLUSIONS

Multi Agent Systems, in the past few decades, have attracted immense attention in the scientific research community. However, the complexity of design and other several factors are the stumbling blocks for the technology. Also, there have always been questions regarding the choice of application area and suitability of MAS.

This work attempted to present a survey of the various areas, in control engineering, where multi agent systems have been successfully and efficiently implemented.

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