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Multi-agent distributed coordination control: Developments and directions via graph viewpoint☆

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ABSTRACT

In this paper, the recent developments of distributed coordination control problems are summarized in a graph-theory-based framework. Distributed coordination has attracted tremendous attention in control and robot communities because of its potential applications in the past decade. The graph is used to describe the interconnections among agents, and different distributed coordination control problems, such as consensus, formation control, rendezvous, alignment, swarming, flocking, containment control and circumnavigation control, are adopted to this description by considering different cooperative objects. Therefore it is natural to study the distributed coordination control problems via graph theory, and the graph-theory-based results on consensus, formation control, and some closely related issues, i.e., rendezvous/alignment, swarming/flocking, containment control and circumnavigation control, are reviewed, and provide a cohesive overview in the coordination control problems, in system modeling, control law designs and analysis, and structure transformation. Finally, towards the practical applications, some potential directions possibly deserving investigation in distributed coordination control are discussed.

1. Introduction

Researchers have long noticed and carried on detailed analysis on many coordinated behaviors, for example, the forage for food or defense against predators of insects, birds and fishes in nature, and self-organization or self-excitation of particles in physics [1–5]. These behaviors attracted researchers to consider seriously why the creature and particles take initiative to coordinate, and motivated the theoretical and applied studies on multi-agent coordination. With these inspirations, the coordination control in a network of mobile autonomous agents, such as unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs) and unmanned underwater vehicles (UUVs), was of interest in control and robotics in the past decade. Though it appears to be more complicated than single-agent systems, there are indeed many significant advantages in the coordinations of MAS (multi-agent system) over the single-agent system, for example, [6–13]:

- Distributed sensors and actuators, as well as inherent parallelism.
- Larger redundancy, higher robustness and greater fault tolerance. If one agent is destroyed, its task can be re-allocated and completed by others.
- Performing tasks that single-agent systems cannot do, such as in cargo transportation multiple vehicles can cooperate to put up big goods.
- Completing missions usually with higher performance and lower cost than single-agent systems, such as multiple mini-satellite formation can greatly reduce the cost in economy and enhance the accuracy in celestial observations that a single costly satellite.

No doubt that there are more advantages as well.

In general, two approaches are commonly adopted for coordination of multiple agents, i.e., a centralized control and a distributed control. In the centralized control, all computations and controls are completed in a global central station, which may result in high communication burden, high computational load and high memory requirement. On the contrary, the distributed approach requires no central controller, and all measures and controls are done in many local centers. Although both approaches are considered practical depending on the conditions of the real applications, the distributed approach is believed more promising due to many inevitable physical constraints such as narrow communication bandwidths, limited computing/memory resources,

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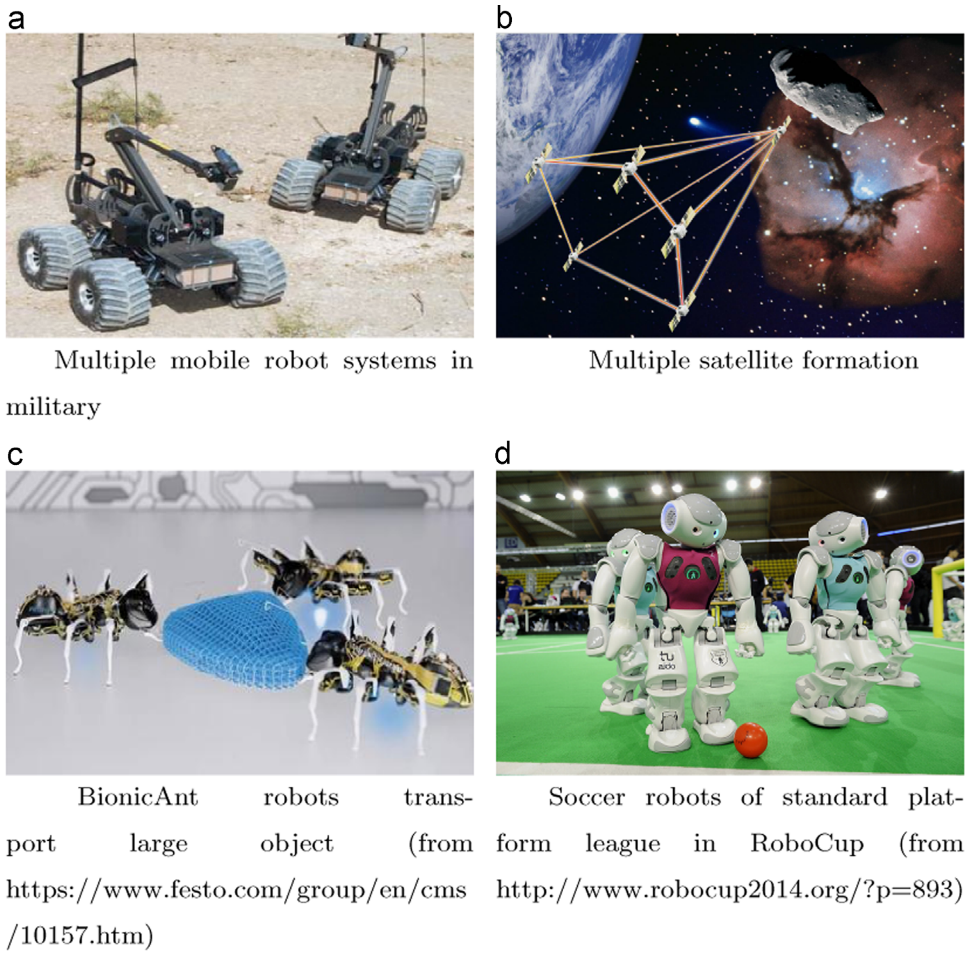

(a) Multiple mobile robot systems in military

(b) Multiple satellite formation

(c) BionicAnt robots transport large object (from https://www.festo.com/group/en/cms/10157.htm)

(d) Soccer robots of standard platform league in RoboCup (from http://www.robocup2014.org/?p=893)

Fig. 1. Some typical applications of multi-agent distributed coordinations.

and large sizes of vehicles to manage and control [12]. In addition, with the improvements of the embedded computing and communicating technologies, the distributed coordinations of MAS have become easy to materialize.

Generally speaking, distributed coordination uses *local* interactions between agents to achieve *collective* behaviors of multiple agents, and therefore to accomplish *global* tasks. It has a broad range of potential applications, such as in military, aerospace, industry, and entertainment. Fig. 1 shows some typical applications of multi-agent distributed coordinations. In the military field, multiple mobile robot systems shown in Fig. 1(a) can adopt a proper geometric pattern to perform military tasks for taking the place of human soldiers, such as reconnaissance, searching, mine clearance, and patrol under adverse/hazardous circumstances. Taking the reconnaissance mission as an example, a single robot has limited ability to gain environmental information. However, if multiple robots keep proper formation to cooperatively apperceive the surrounding, they are likely to rapidly and accurately obtain the environmental information. In the aerospace field, satellite formation shown in Fig. 1(b) is the leading technique in the space application in 21st century, which opens up a brand-new direction for the application of satellites, especially for mini-satellites. Satellite formation can not only greatly reduce the cost and enhance the reliability and survivability, but also broaden and override the function of individual satellites and achieve the tasks that multiple single spacecrafts cannot finish. In the industrial field, multiple mobile robots can deal with the dull, dirty and dangerous work in coordination. For example, when multiple robots cooperatively carry large scale goods in a poisonous environment, their positions and orientations are strictly restricted in order to meet the requirements of load balance shown in Fig. 1(c). In the entertainment field, for example, in Fig. 1(d), multiple soccer robots, in order to keep neat or meet tactical needs, must keep some special patterns, and may dynamically switch the patterns for avoiding obstacles.

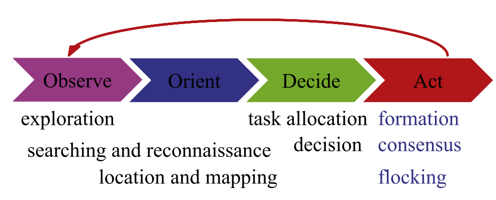

Fig. 2. Typical researches on multi-agent coordination in the view of the OODA (observe–orient–decide–act) loop.

Because of huge advantages and wide applications, all phrases in Boyd's OODA (observe–orient–decide–act) loop [14], which is clearly the dominant model of control and command today, are apt to be accomplished by distributed coordination. Fig. 2 provides some typical researches on multi-agent coordinations in the view of the OODA loop, such as cooperative exploration, searching and reconnaissance, location and mapping, decision, task assignment, formation, consensus, flocking, and to name a few.

In this survey, we mainly pay attentions to coordination control oriented problems in the last cycle, i.e., "act", in the OODA loop. Only the control problems of multi-agent distributed coordination are reviewed, in which the control inputs are designed by utilizing local information to drive the agents moving, and achieving collective