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Survey Paper

A survey of multi-agent formation control☆

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ABSTRACT

We present a survey of formation control of multi-agent systems. Focusing on the sensing capability and the interaction topology of agents, we categorize the existing results into position-, displacement-, and distance-based control. We then summarize problem formulations, discuss distinctions, and review recent results of the formation control schemes. Further we review some other results that do not fit into the categorization.

1. Introduction

A significant amount of research efforts have been focused on the control of multi-agent systems due to both their practical potential in various applications and theoretical challenges arising in coordination and control of them. Theoretical challenges mainly arise from controlling multi-agent systems based on partial and relative information without an intervention of a central controller.

Formation control, which is one of the most actively studied topics within the realm of multi-agent systems, generally aims to drive multiple agents to achieve prescribed constraints on their states. Depending on the sensing capability and the interaction topology of agents, a variety of formation control problems have been studied in the literature.

Excellent surveys of formation control of multi-agent systems are found in Anderson, Yu, Fidan, and Hendrickx (2008); Chen and Wang (2005); Mesbahi and Egerstedt (2010); Olfati-Saber, Fax, and Murray (2007); Ren, Beard, and Atkins (2005); Ren, Beard, and Atkins (2007); Ren and Cao (2010) and Scharf, Hadaegh, and Ploen (2004). However, Chen and Wang (2005); Mesbahi and Egerstedt (2010); Olfati-Saber et al. (2007); Ren, Beard, and Atkins (2005); Ren, Beard et al. (2007) and Ren and Cao (2010) have mainly focused on consensus based formation control. Some important results, particularly on inter-agent distance based formation control, have not been extensively reviewed in those surveys. Scharf et al. (2004) have presented a survey of spacecraft formation flying rather than an extensive survey of general multi-agent systems. An excellent introduction of inter-agent distance based formation control is found in Anderson et al. (2008); however, a considerable amount of studies have been conducted thereafter. Thus we believe that it is timely and helpful to present an extensive survey of formation control of multi-agent systems.

Due to the vast amount of the literature, it would be challenging to exhaustively review the existing results on formation control. Rather than an exhaustive review, we thus focus on the characterization of formation control schemes in terms of the sensing capability and the interaction topology of agents because we believe that both of them are linked to the essential features of multi-agent formation control.

The characterization of formation control schemes in terms of the sensing capability and the interaction topology naturally leads to the question of what variables are sensed and what variables are actively controlled by multi-agent systems to achieve their desired formation. The types of sensed variables specify the requirement on the sensing capability of individual agents. Meanwhile, the types of controlled variables are essentially connected to the interaction topology. Specifically, if positions of individual agents are actively controlled, the agents can move to their desired positions without interacting with each other. In the case that inter-agent distances are actively controlled, the formation of agents can be treated as a rigid body. Then the agents need to interact with

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Table 1
Distinctions among position-, displacement-, and distance-based formation control.

	Position-based	Displacement-based	Distance-based
Sensed variables	Positions of agents	Relative positions of neighbors	Relative positions of neighbors
Controlled variables	Positions of agents	Relative positions of neighbors	Inter-agent distances
Coordinate systems	A global coordinate system	Orientation aligned local coordinate systems	Local coordinate systems
Interaction topology	Usually not required	Connectedness or existence of a spanning tree	Rigidity or persistence

each other to maintain their formation as a rigid body. In short, the types of controlled variables specify the best possible desired formation that can be achieved by agents, which in turn prescribes the requirement on the interaction topology of the agents.

Based on the aforementioned observation, we categorize the existing results on formation control into position-, displacement-, and distance-based according to types of sensed and controlled variables:

- Position-based control: Agents sense their own positions with respect to a global coordinate system. They actively control their own positions to achieve the desired formation, which is prescribed by the desired positions with respect to the global coordinate system.
- Displacement-based control: Agents actively control displacements of their neighboring agents to achieve the desired formation, which is specified by the desired displacements with respect to a global coordinate system under the assumption that each agent is able to sense relative positions of its neighboring agents with respect to the global coordinate system. This implies that the agents need to know the orientation of the global coordinate system. However, the agents require neither knowledge on the global coordinate system itself nor their positions with respect to the coordinate system.
- Distance-based control: Inter-agent distances are actively controlled to achieve the desired formation, which is given by the desired inter-agent distances. Individual agents are assumed to be able to sense relative positions of their neighboring agents with respect to their own local coordinate systems. The orientations of local coordinate systems are not necessarily aligned with each other.

Note that the above categorization is useful in characterizing formation control schemes in terms of the requirement on the sensing capability and the interaction topology. As summarized in Table 1, position-based control is particularly beneficial in terms of the interaction topology though it requires agents to be equipped with more advanced sensors than the other approaches. Conversely, distance-based control is advantageous in terms of the sensing capability, but it requires more interactions among agents. Displacement-based control is moderate in terms of both sensing capability and interaction topology compared to the other approaches. Roughly speaking, this reveals a trade-off between the amount of interactions among agents and the requirement on the sensing capability of individual agents as illustrated in Fig. 1.

Though decentralization is one of important themes in multi-agent formation control, we avoid characterizing the existing results into centralized and decentralized due to the following two reasons. First, a formation control scheme may be classified into centralized or decentralized according to whether or not it requires a global coordinator[2]; however, such a categorization is not appropriate for an overview of various formation control schemes. Indeed, under this criterion, we find that most of formation

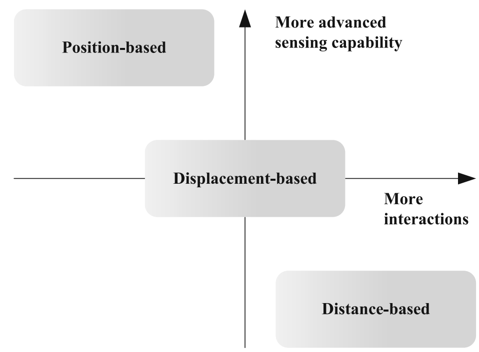

Fig. 1. Sensing capability vs. interaction topology.

control schemes found in the literature fall into decentralized control because they do not explicitly require a global coordinator. Second, meanings of decentralized formation control are not exactly the same in the literature and rather subjective. Thus a characterization in terms of decentralization may cause further confusion, which is not desirable.

On the other hand, the concepts of the terms, *local* and *relative*, which are often used for describing features of formation control schemes, can be clearly described based on the requirement on the sensing capability and the interaction topology. In the following, we attempt to sort out several concepts associated with the terms:

- *Relative*: Every formation control scheme requires agents to sense variables such as positions and attitudes with respect to either local coordinate systems associated with individual agents or a global coordinate system associated with the multi-agent system. The term *relative* is usually taken to mean that a variable is sensed with respect to a local coordinate system, not a global one. Conversely, a variable that is sensed with respect to a global coordinate system is called *absolute*. One may associate *relative* with *decentralized*. In this respect, distance-based formation control can be considered more *decentralized* than position- and displacement-based control. However, such a characterization may cause confusion because *decentralized* has other meanings. Nevertheless, we emphasize that the concept of *relative* can be clearly described in terms of the sensing capability of individual agents.
- *Local*: The term *local* can be understood in several ways. First, it can be associated with interactions among agents. A formation control scheme that requires agents to interact with all the other agents can be considered *non-local*. Otherwise, as it requires less interactions, it can be considered more *local*. This concept can be clearly described by the interaction topology. Second, *local* can be taken to mean that a variable is sensed with respect to a local coordinate system. That is, *local* means *relative* in terms of sensing of variables. In this case, the concept of *local* can be clearly described by the sensing topology. Finally, it involves with the non-existence of a global coordinator as mentioned above.

Based on the above discussions, once again, we try to avoid characterizing the existing results into centralized and decentralized because it may cause confusion. Rather than centralized and decentralized control, we categorize the existing results into

[2] By a global coordinator, we mean an entity that gathers information from all agents, makes some decision, and then distributes some coordination command to the agents. In this respect, *decentralized* control is compatible with *local* control in the sense that a global coordinator is not required.

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