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Brief paper

Shape and orientation control of moving formation in multi-agent systems without global reference frame ☆

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ABSTRACT

In this paper, distance-based formation control laws for the multi-agent systems are proposed when the reference velocity is unknown to the followers. Especially, not only the shape but the orientation of formation is also controlled. Each agent measures only the relative positions of neighbors with respect to their own local coordinate system. The local coordinate systems in each agent are not aligned and unknown to the other agents; thus the control laws are completely decentralized. Using the measured local information, the unknown reference velocity is estimated by applying an adaptive method. The shape and orientation of formation are controlled based on the estimated reference velocity. The stability and convergence of the system are analyzed mathematically and verified through numerical simulation.

1. Introduction

The research on the formation control of unmanned multi-agent systems has recently received significant attention. The formation control problems are classified according to control variables as shown in Oh, Park, and Ahn (2015); for example, displacement-based and distance-based formation control problems have been popularly investigated. In the displacement-based formation control, the desired formation is specified by the desired displacements. To achieve the desired formation, each agent measures and controls relative positions of neighbors in the orientation aligned local coordinate system. This implies that the agents should know the orientation information of other agents, which is a shortcoming (e.g. Anderson, Yu, Dasgupta, & Morse, 2007; Consolini, Morbidi, Prattichizzo, & Tosques, 2008; Lin, Francis, & Maggiore, 2005; Ren & Atkins, 2007). On the other hand, in the case of the distance-based formation control, the desired formation is specified by desired inter-agent distances. Each agent measures relative positions of neighbors in local coordinate system and controls distances to the neighbors for achieving the desired formation. Thus, the orientations of local coordinate system of agents do not need to be aligned with a global coordinate system. Furthermore, it is unnecessary to obtain orientation of other coordinate system (e.g. Cao, Anderson, Morse, & Yu, 2008; Dimarogonas & Johansson, 2008; Guo, Lin, Cao, & Yan, 2010; Krick, Broucke, & Francis, 2009; Oh & Ahn, 2011). The distance-based formation control problem is quite complicated and difficult to solve in general because of limited available information. However, there are several reasons why research on the distance-based formation control attracts attention. In the distance-based formation control, only the relative positions of neighbors with respect to their own local coordinate systems are necessary. This implies that each agent does not have to sense orientations of other coordinate systems and requires less equipment in implementation. Furthermore, the distance-based approach offers better cost-effectiveness, scalability, and robustness because the control laws are perfectly decentralized. Even though there are difficulties in the design and analysis of control laws, the distance-based formation control is considered in this paper because it has several advantages as mentioned in the above.

In the existing distance-based formation control research, only the shape of formation in stationary situation has been widely considered (e.g. Cao et al., 2008; Dimarogonas & Johansson, 2008; Krick et al., 2009; Park, Oh, & Ahn, 2012). The movement and orientation of formation have been less studied because of complexity. Although the movement of formation was handled re-

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cently in several articles such as Guo, Lin, et al. (2010), Guo, Yan, and Lin (2010), Kang and Ahn (2016), Kang, Park, Lee, and Ahn (2014), the orientation of formation has not been considered. From our experimental tests, however, we have observed that, when a group of agents moves with a reference velocity, the orientation of formation with respect to the direction of movement should be considered. If the orientation is not considered, the orientation of formation may not be as desired in terms of moving direction. For example, when only the inter-agent distances are constrained, the follower might be continuously moving around the leader,[1] which makes the follower rotate around the leader in a circle. It is similar as the problem considered in Mou, Morse, Belabbas, and Anderson (2014). Thus, it is important to consider the orientation of formation when a distance-based formation control law is designed.

This paper is dedicated to this orientation problem including an estimation of the unknown reference velocity. Each agent measures only relative positions of their neighbors with respect to their own local coordinate system. Because the local coordinate systems of agents are not aligned and unknown to each other, it is not simple to design the velocity estimator and formation control laws for shape and orientation control. Unlikely the previous papers studying the movement of distance-based formation, the unknown constant reference velocity is exponentially estimated and orientation of formation is also controlled.

2. Problem statement

Directed graph is represented by a pair $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{1, \ldots, N\}$ is the set of vertices and $\mathcal{E} = \{\ldots, (i, j), \ldots\} \subset \mathcal{V} \times \mathcal{V}$ is the set of directed edges. The notation N denotes the number of vertices, and an edge (i, j) is considered to be directed from j to i. The direction from j to i is graphically depicted as $j \longrightarrow i$. The set of neighbors of $i \in \mathcal{V}$ is defined as $\mathcal{N}_i = \{j \in \mathcal{V} | (j, i) \in \mathcal{E}\}$. To denote the kth neighbor of the agent i, we use the symbol $\mathcal{N}_i(k)$. The pair $(\mathcal{G}, p)$ is called a framework, where $p_i \in \mathbb{R}^2$ is the position of vertex i and $p = \left[p_1^T \cdots p_N^T\right]^T \in \mathbb{R}^{2N}$ is a realization of graph $\mathcal{G}$ in two-dimensional space. In this paper, all of the coordinate systems are expressed in the Cartesian coordinate system. The cardinality of a set is denoted as $|\cdot|$. Assuming that agents are ordered as $1, 2, \ldots, N$, the subset of vertices composed of j to N is denoted as $\mathcal{V}_{j:N}$. The symbol $\mathbf{I}_i$ represents $i \times i$ identity matrix and $\mathbf{O}_{i \times j}$ represents $i \times j$ matrix with all zero components.

In this paper, it is assumed that the system is considered in two-dimensional space and the motion of each agent is a single integrator model dynamics:

$$\dot{p}_i = u_i, \quad \forall i \in \mathcal{V} \tag{1}$$

where $u_i \in \mathbb{R}^2$ is the control input for agent i. The notations of relative position $z_{j,i} \in \mathbb{R}^2$ and distance error $e_{j,i} \in \mathbb{R}$ are defined as:

$$z_{j,i} = p_j - p_i, \qquad \forall (j, i) \in \mathcal{E} \tag{2}$$

$$e_{j,i} = \left\|z_{j,i}\right\|^2 - d_{j,i}^2, \qquad \forall (j, i) \in \mathcal{E} \tag{3}$$

where $d_{j,i}$ is the desired distance between agents j and i. From the definition of distance error (3), the convergence of distance error $e_{j,i}$ to zero means that the distance between agent j and i converges to the desired value. Therefore, to obtain the desired formation, the control laws should make all of the distance errors converge to zero.

[1] In our experimental test using the existing formation control laws as shown in the video (https://youtu.be/szVORcRGWcw), the orientation of formation was changing gradually as time passed due to the fact that the existing formation control laws consider only the maintenance of desired inter-agent distances.

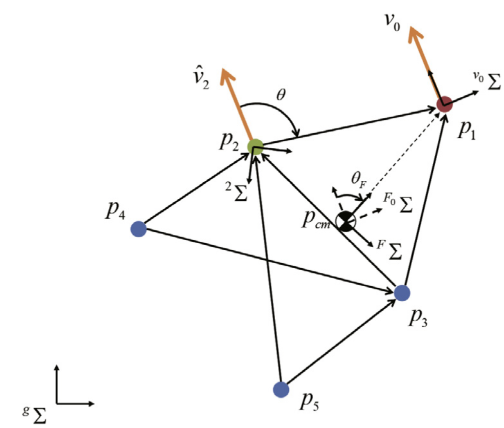

Fig. 1. In the multi-agent systems, the orientation of formation θ_F represents angular difference between the coordinate systems $^{F_0}\Sigma$ and $^F\Sigma$.

This paper studies the orientation of formation that is angle of rotation with respect to the direction of reference velocity v_0. To strictly define the orientation of formation, some notations are necessary. The coordinate system $^{v_0}\Sigma$, as shown in Fig. 1, is defined to represent the direction of reference velocity. The coordinate system $^{v_0}\Sigma$ is attached to the first agent and y-axis is aligned to the direction of reference velocity. As shown in Fig. 1, θ is the angle between the estimated reference velocity at the agent 2 and the line connecting the agents 1 and 2. The coordinate systems of formation $^{F_0}\Sigma$ and $^F\Sigma$ are attached to the center of mass p_{cm} that is obtained as $p_{cm} = \frac{\sum p_i}{|\mathcal{V}|}$. The y-axis of coordinate system $^F\Sigma$ is aligned to the vector $z_{1,cm} = p_1 - p_{cm}$. By moving the origin of the coordinate system $^{v_0}\Sigma$ to the center of mass point p_{cm}, we define another coordinate system $^{F_0}\Sigma$.

Definition 1 (*Orientation of Formation*)**.** In the multi-agent systems, the orientation of formation is represented by an angle θ_F that is angular difference between the coordinate systems $^{F_0}\Sigma$ and $^F\Sigma$. That is, the angle θ_F from the y-axis of $^{F_0}\Sigma$ to the y-axis of $^F\Sigma$ is orientation of formation.

In this paper, two problems are simultaneously handled.

Problem 2. The first problem handled in this paper is to design the control laws that make all agents maintain the desired formation dispersively and independently. This problem can be simply expressed as follows:

$$\text{The shape problem}: \dot{p}_i \to v_0, \qquad \forall i \in \mathcal{V}$$
$$\left\|z_{i,j}\right\| \to d_{i,j}, \qquad \forall (i, j) \in \mathcal{E}$$

where $v_0 \in \mathbb{R}^2$ is the reference velocity. The second problem is to control the orientation of formation defined as Definition 1. Orientation problem is expressed as follows:

$$\text{The orientation problem}: \theta_F \to \theta_{F_d}$$

where $\theta_{F_d} \in \mathbb{R}$ is the desired angle for desired orientation of formation.

These problems are solved in the following assumptions.

Assumption 3. The graph topology is given as cycle-free persistent graph and consistent at all times. The cycle-free persistent graph can be obtained as the result of a Henneberg sequence containing only vertex additions as shown in Hendrickx, Anderson, Delvenne, and Blondel (2007).