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Decentralized formation flight via PID and integral sliding mode control ☆

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ABSTRACT

This paper solves a formation control problem for a group of vehicles such as UAVs on a directed network subject to constant and time-varying disturbances or commands. A celebrated PID control is first proposed for constant disturbance rejection. A set of necessary and sufficient conditions for the vehicles to achieve a desired formation is proposed. Then, integral sliding mode control is introduced to tackle unknown but bounded time-varying disturbances or commands. In addition, the control sensitivity with respect to the network topology is analyzed. Finally, a quadcopter formation platform is introduced and used to verify all the presented theoretical results experimentally.

1. Introduction

Over the past years, the concept of decentralized formation control has been vastly studied with application to the coordination of multiple robots, unmanned air vehicles, underwater vehicle and spacecraft [1–7] for practical usage in a wide range of areas, i.e. surveillance and reconnaissance [8,9], radiation detection and contour mapping [10], target search [11], navigation [12–14], and so on. With the advancement of technology and the increasing demand for formation control of a multi-agent system, researchers have been trying to deal with more realistic problems such as time delays, model uncertainties, disturbances or external perturbations.

In this paper, formation flight in the presence of a disturbance that enters the control input is studied. Many systems are exposed to external perturbations that can disrupt the control input and subsequently the system's output. Motivated by numerous outstanding work, [15–17] proved the advantage of integral action that attenuates constant disturbances. In [15], the authors show that the integral action of a Proportional Integral Kalman Filter (PIKF) can effectively compensate for arbitrary disturbances. It allows a single Kalman filter to reject any type of input disturbances, including nonlinear disturbances. In [16], consensus protocols with integral control actions were presented to reject constant disturbances for the networks of both single-integrator and double integrator systems. For [17], a distributed control protocol with integral action was proposed to solve a robust output synchronization problem for a group of identical linear agents with constant external disturbances. Note that these results are mainly focused on consensus or regulation (zero reference) issues rather than formation control or tracking (nonzero, possibly time-varying, reference) of present interest.

Regarding the formation control problem, [18] recently proposed a time-varying formation protocol (essentially PD control) to let m second-order vehicles change their positions and velocities to achieve a desired formation with experimental validation. However, the situation with the presence of disturbances was not considered which may yield a steady-state tracking error in practice. Therefore in this present work, an integral action approach coupled with the PD control has been firstly introduced to address the constant disturbance rejection problem with experimental validation. Similar work using this method can also be found in [16, 17], but it is stressed again that the present work solves the formation control or tracking problem in which the vehicles on a network move to a prescribed (possibly time-varying) geometric shape with a desired relative distance, whereas [16,17] solve the synchronization problem in which the proposed protocols therein make the vehicles meet at the same place with zero relative distance. In addition, [16,17] considered constant disturbances only.

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Formation flight with an unknown time-varying disturbance or reference command is challenging. Since the integrator being employed for PID control is only capable of rejecting a constant disturbance, the formation flight performance using the existing PID control techniques may perform very poorly. As an alternative of PID, a nonlinear control technique can be considered to handle unknown but bounded time-varying disturbances or reference commands. Among many nonlinear control techniques, sliding mode control (SMC) is a well-developed one to deal with bounded parametric uncertainties and disturbances, so that the system can reach a desired state in finite time [21]. Using a high gain and fast switching actions, SMC can render the system reaching a prescribed sliding surface in finite time while being insensitive to the variation of uncertainties or disturbances in the control input channel. However, imperfect implementation of SMC in reality, e.g. slower switching actions than required, may fail to put the system on a desired sliding surface and subsequently yield a steady-state error as in the PD control case with no integral action.

For this reason, the integral sliding mode control (ISMC) technique has been deeply investigated [22,23]. In fact, the ISMC technique has been implemented in many applications [24–35]. It aims at improving the robustness of the motion equation in the whole state space. Using the ISMC approach, the (previously problematic) reaching phase is eliminated and the system trajectory starts immediately on the designed sliding surface. Therefore, this ISMC technique has been implemented in this paper to solve the formation control problem in the presence of unknown but bounded time-varying disturbances or reference commands. This paper presents an exposition of both methods (PID and ISMC) in tackling unknown constant as well as time-varying disturbances in the formation flight context and also shows the correlation of the network topology and the employed formation controller.

The main contribution of this paper is threefold. First, the control laws being discussed in [18,40] are further modified to account for unknown constant disturbances (bounded time-varying disturbances or reference commands) by PID (ISMC, respectively). In the course of this modification, a set of necessary and sufficient conditions to guarantee the networked dynamical system's stability is provided for the PID control. Furthermore, the characteristic of a wireless communication channel is considered in the ISMC design and analysis; it, in fact, helps to sort out the classical chattering issue of SMC. Second, real experimental results using three dynamic agents are presented. In the recent relevant works such as [25, 32–35], the theoretical ISMC results were demonstrated by means of computer simulations only. In contrast, this paper presents thorough experimental results that show the practical efficacy of ISMC. Third, control sensitivity of PID and ISMC with respect to the network topology is also studied.

The aforementioned contributions could be further extended if adaptive intelligent control techniques were implemented along with PID or ISMC. In fact, there exist several pieces of research work on flight control using ANFIS (Adaptive Neuro-Fuzzy Inference System) or its variants [36–38]; see [39] for a recent survey on this topic. It is certainly expected to improve the formation flight performance using those ideas of properly adapting PID gains or ISMC parameters with respect to flight conditions. However, this gain adaptation is not pursued in this paper due to its downside as suggested in [39], including difficulty in guaranteeing analytical stability and possible failure under unknown disturbance characteristics. Note that one recent comparison report between online fuzzy PD controllers [36] testifies that an ANFIS approach could be unsatisfactory in transporting an object via a group of quadcopters in the presence of a time-varying disturbance of particular frequency, if the required off-line training was not done in a way to take into account the particular range of frequencies.

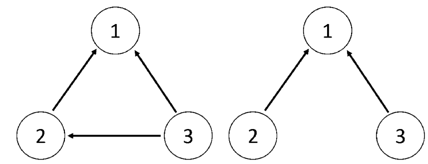

Fig. 1. Network topology of three nodes: Case 1 (left) and Case 2 (right).

The rest of this paper is organized as follows. In Section 2, basic concepts and useful results on graph theory are introduced and the problem formulation is presented. Sections 3 and 4 introduce the design of the formation controllers, PID and ISMC, respectively. The connection between the network topology and those controllers is presented in Section 5 and experimental results are shown in Section 6. Finally, conclusions are drawn in Section 7.

2. Preliminaries and problem formulation

2.1. Graph theory

Multiple vehicles can be modeled using a graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ with a node set $\mathcal{V} = \{v_i : i \in 1, 2, ..., m\}$ and an edge set $\mathcal{E} = \{e_{ij} = (v_i, v_j) : v_i, v_j \in \mathcal{V}\}$, where the nodes and the edges represent the vehicles and the communication links among them, respectively. Each e_{ij} represents a directed edge from v_i to v_j. The set of neighbors of node v_i is denoted by $\mathcal{N}_i = \{v_j \in \mathcal{V} : e_{ij} \in \mathcal{E}\}$. Associated with $\mathcal{G}$, the graph Laplacian matrix $L_{\mathcal{G}} = [l_{ij}]$ is defined as:

$$l_{ij} = \begin{cases} |\mathcal{N}_i|, & \text{for } i = j; \\ -1, & \text{for } j \in \mathcal{N}_i; \\ 0, & \text{for } j \notin \mathcal{N}_i. \end{cases}$$

For example, Fig. 1 shows two directed graphs of three vehicles for two cases. The associated Laplacian matrix for Case 1 is given below:

$$L_{\mathcal{G}} = \begin{bmatrix} 0 & 0 & 0 \\ -1 & 1 & 0 \\ -1 & -1 & 2 \end{bmatrix},$$

and the set of neighbors of each vehicle is $\mathcal{N}_1 = \{\ \}$, $\mathcal{N}_2 = \{1\}$ and $\mathcal{N}_3 = \{1, 2\}$. Similarly, the Laplacian matrix for Case 2 is

$$L_{\mathcal{G}} = \begin{bmatrix} 0 & 0 & 0 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}.$$

In this paper, $\mathcal{G}$ being considered is a directed graph with at least one globally reachable node or the rank of $L_{\mathcal{G}}$ is $m-1$. A graph possesses a globally reachable node (e.g. node 1 for the two cases in Fig. 1) if one of its nodes can be reached from each of any other nodes via a directed path. A directed path in the graph is an ordered sequence of nodes such that any pair of consecutive nodes in the sequence is an edge of the graph. The following lemma summarizes well-known properties of the Laplacian matrix.

Lemma 1. *Let $L_{\mathcal{G}} \in \mathbb{R}^{m\times m}$ be the Laplacian matrix of a directed graph $\mathcal{G}$. Then,*

1) *$L_{\mathcal{G}}$ has at least one zero eigenvalue, and $\boldsymbol{1}_m$ (a column vector of size m with an '1' as its elements) is the associated eigenvector, i.e. $L_{\mathcal{G}}\boldsymbol{1}_m = 0$.*
2) *If $\mathcal{G}$ has a globally reachable node, then 0 is a simple eigenvalue of $L_{\mathcal{G}}$, and all the other $m-1$ eigenvalues have positive real parts.*

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