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Multiple UAV distributed close formation control based on in-flight leadership hierarchies of pigeon flocks ☆

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ABSTRACT

Owing to the similarity between bird flocks and unmanned aerial vehicle (UAV) swarms among intelligence, autonomy and local interactions, the collective motion mechanisms in bird flocks have reference significance for the design of distributed control algorithms for multiple UAVs. In this paper, a pigeon flocking model is proposed based on the in-flight leadership hierarchy in pigeon flocks. Graph theory is adopted to describe the transformation process from an arbitrary connected topology to the leadership hierarchy required for a line formation. The leader–follower relations are defined as the guidance from leaders to followers on the relative positions. On the basis of the pigeon flocking model, a distributed close formation control method to coordinate multiple UAVs to fly in a line close formation is presented. The simulation results based on the UAV close formation model, modified by the additional nonlinear aerodynamic interactions, are elaborated to show the feasibility and validity of our proposed method.

1. Introduction

Over the past few decades, unmanned aerial vehicles (UAVs) have been extensively utilized in military or civilian fields such as, surveillance, reconnaissance, search and rescue missions, mapping, and aerial cinematography [1–4]. In contrast to a single UAV, UAV swarms in formation will give better performance in complex and dynamic mission environments owing to the improvement in sensing range, computing capacity, and weapon power [5].

Besides traditional control methods [6–8], the self-organization mechanism in various complex systems, especially the collective motion in bird flocks, has provided a novel thought for UAV formation control due to the similarity between the two among intelligence, autonomy and local interactions [9]. In the literature, a few researchers have made some exploratory attempts. Hauert et al. [10] proposed a swarm of small fixed-wing UAVs in outdoor experiments based on a decentralized control framework with bio-inspiration from Reynolds' Boid model, the first flocking model, which reveals the basic rules of bird flocking. Vicsek et al. [11] presented a decentralized multi-copter flock that performs stable autonomous flight, and the control algorithm also has a structure analogous to that of the Boid model. Saska [12] introduced a stabilization and navigation method for swarms of UAVs along a predefined path through a complex environment with obstacles based on the bird flocking stabilization rules. However, these approaches will prompt the UAVs to fly in a parallel group rather than other desired formations, especially the line formation.

Pigeons with the remarkable navigation capabilities and complex group mechanisms, are highly favored by researchers due to the convenience in feeding and observation. In the aspect of the group flight, Nagy et al. [13,14] discovered a hierarchical structure in the in-flight leader–follower relations of pigeons by analyzing the pigeon flight data gathered by miniature GPS tracking. Each pigeon in a pigeon flock has its own place in the hierarchy, where the general leader is in an absolute leadership position and the other pigeons under the effect of individuals in upper ranks attempt to influence the flights of individuals in lower ranks. The flight impact from individuals in the adjacent upper rank is more direct and sensitive than the impact from the ones in other upper ranks. Every pigeon in a flock is tightly tied by the leader–follower relationships in the hierarchy arising in the air. The stable leadership hierarchy is hypothesized to be the resultant of group coordination based on different individual competences [15]. Speed [16], route fidelity [17] and individual experience [18] are inferred as three of the competences, which indicates that the pigeons, with

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higher speed, more faith to their own routes and more flight experience, will have more influence over the group direction changes. The leadership hierarchy is conjectured to process two advantages: one is that information spreads more effectively in a hierarchical structure than it spreads in other types of networks [15], the other is flocks with certain hierarchical structures compensate better for individual navigational error [19].

In this paper, a pigeon flocking model is proposed based on the in-flight leadership hierarchies in pigeon flocks. The established pigeon flocking model is composed of two parts. One is the hierarchy model based on graph theory which elaborates the hierarchical topology and the forming process via local interactions, and the other is the leader–follower relation model which depicts the effects of leaders to followers in a hierarchical structure. Owing to the similarity between pigeon flocks and UAV swarms in environmental interferences and mission requirements, the pigeon flocking model is applied to the control field to coordinate multiple UAVs to fly in a line close formation by establishing their mapping relations. Compared with the loose formation, the additional aerodynamic interactions created by the upwash and sidewash from the lead UAV is taken into account in the wing UAV close formation model.

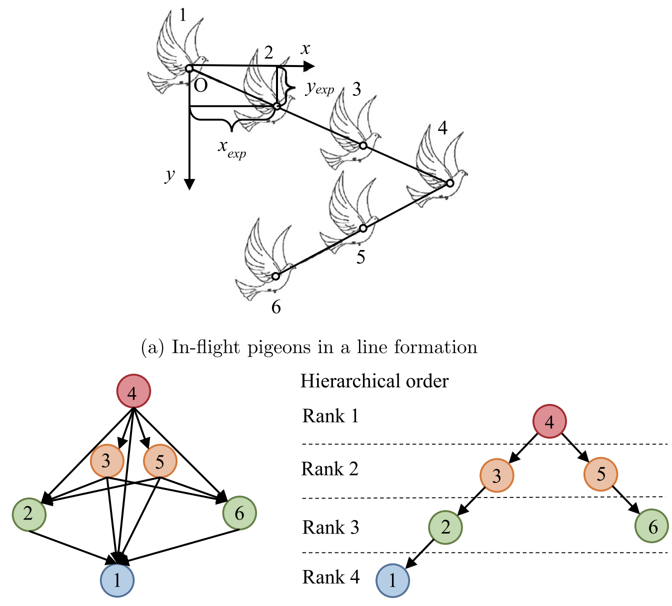
The main contribution of this paper is to propose a UAV distributed close formation control method based on in-flight leadership hierarchies of pigeon flocks. The proposed method could allow a UAV flock not only to fly in a line close formation under conditions with delay, noise and accidents, but also to reconfigure formation. The core of the proposed method is to build a hierarchy model of pigeon flocks to transform an arbitrary connected graph into a binary directed tree in which only the root node has two child nodes. It means that the built hierarchy model could enable individuals in a pigeon flock to self-organize into a hierarchical leadership network, a topology required in UAV close formation, based on local interactions. In our previous work [20], the leadership hierarchy of pigeon flocks has been applied to UAV formation control under ideal conditions, and the hierarchical leadership network is predefined and fixed. However, the hierarchical leadership network in this paper is produced by local interactions among individuals and will change voluntarily with group states, which is the major innovation of this paper.

The rest of the paper is organized as follows. Section 2 models the mechanism of pigeon flocking by describing the hierarchical topology and leader–follower relation in pigeon flocks. Section 3 depicts the UAV close formation model modified by the additional aerodynamic interactions from the lead UAV. Section 4 proposes a distributed line close formation control method for multiple UAVs based on the pigeon flocking model in Section 2. Simulation validation is elaborated in Section 5, and our concluding remarks are drawn in Section 6.

2. Pigeon flocking model

2.1. Hierarchy model of pigeon flocks

The pigeon flock can be conveniently expressed as an undirected graph $G_u = (\hat{V}, E_u)$, where the set of vertices $\hat{V} = \{v_1, v_2, \ldots, v_n\}$ represents n pigeons, the set of edges $E_u = \{e_1^u, e_2^u, \ldots, e_m^u\}$ represents lines joining certain unordered pairs of these pigeons. In the vertical direction, assume that each pigeon i with the position $P_i = (X_i, Y_i, h_i)$, horizontal velocity V_i, horizontal velocity direction ψ_i and altitude rate ζ_i is available to communicate with any individual. In the horizontal direction, if $R^{ij} \le R_{comm.}$, a communication connection e_k^u exists between individual i and j, and $e_k^u = (v_i, v_j)$ belongs to the set E_u, where R^{ij} is the horizontal distance between individual i and j, and $R_{comm.}$ is the horizontal



(a) In-flight pigeons in a line formation

(b) Leadership network G

(c) The minimalist leadership network T

Fig. 1. Pigeons in a line formation and the leadership network.

communication range. In a pigeon flock, if no one drops out, the undirected graph G_u must be a connected graph.

If individual i and j can communicate with each other and individual i attempts to adjust its own states based on the information obtained from individual j, a leadership line e_k exists between the ordered pair (v_j, v_i), where vertex v_j is the initial vertex representing the leader j and vertex v_i is the terminal vertex representing the follower i. Accordingly, the leadership network in a pigeon flock can be described by a digraph $G = (\hat{V}, E)$. As shown in Fig. 1, when the pigeon flock flies in a line formation depicted in Fig. 1(a) where x_{exp} and y_{exp} represent the expected forward distance and lateral distance respectively and the pigeons in front of the formation will lead pigeons in behind, the digraph G reflecting the leadership network of the pigeon flock without considering the communication range constraint is presented in Fig. 1(b). In this paper, taking into account a condition that $R_{comm.} \in [R_{\text{exp}}, 2R_{\text{exp}})$ which means that the leadership only exists in individuals with adjacent hierarchical order, the digraph G is a binary directed tree T in which only the root node has two child nodes, where $R_{\text{exp}} = \sqrt{x_{\text{exp}}^2 + y_{\text{exp}}^2}$ is the expected horizontal distance. The directed tree T is the minimalist leadership network in the pigeon flock.

In this paper, a distributed algorithm is proposed to coordinate a pigeon flock to fly in a line formation through local interactions. In other words, the algorithm aims to transform an arbitrary connected graph G_u into a binary directed tree T in which only the root node has two child nodes. A specific example is cited to illustrate the flow and realization of the algorithm, and the specific steps are as follows:

Step 1 Establish communication relationship network G_u. Each individual i attempts to identify the set $N_{comm.}^i$ of individuals within communication range. The number of individuals in $N_{comm.}^i$ is $n_{comm.}^i$. The undirected graph G_u describing the communication relationship of the pigeon flock shown in Fig. 2(a) is given in Fig. 2(b). For example, $N_{comm.}^7 = \{9, 8, 6, 3\}$. Afterwards each individual will share communication information by the following method:

1) A set CI_i for storing two-bit communication information (i, j) is respectively built, where the first bit is the personal index