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Distributed UAV flocking control based on homing pigeon hierarchical strategies

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A B S T R A C T

The recent boom of animal collective motion investigation has attracted many researchers to the field of applying such intelligence to complicated distribute control problems in artificial systems, such as autonomous unmanned aerial vehicle (UAV) flocking. In this paper, a distributed control framework inspired by homing pigeon hierarchical strategies is proposed to solve the UAV flocking problem. This new approach combines the advantages of velocity correlation, leader-follower interaction and hierarchical leadership network observed in pigeon flock with altitude consensus control algorithm used in UAV flocking. The flocking control algorithm is implemented to achieve a stable performance by controlling local position and velocity of each UAV. The practical dynamic and constraints of fix-wing UAV are also taken into account. The distributed flocking algorithms are tested in several simulation cases, which verify the effectiveness and applicability of the proposed control framework.

1. Introduction

Unmanned aerial vehicle (UAV) is becoming an integral part to possess the future world of artificial intelligence. UAV will be used for complex tasks including surveillance, agriculture irrigation, forestry fire prevention, cargo transportation and coordinated rescue missions in the presence of disturbances, failures, and uncertainties [1–5]. Much effort is currently spent on various control problems associated with UAVs moving in formation with limited information. The advantages of performing formation flight include fuel saving at certain close formation positions, efficiency improving in cooperative task allocation and robustness increasing in a self-organizing system [6–8]. In addition to the research on the formation flight of multi-UAV systems, there have been some studies on the coordinated control of UAV flock. Flocking is a spectacular phenomenon in nature. In a natural flock, a large number of similar individuals achieve complex and fascinating motions based on local autonomous interactions. Generally, flocking is more effective and robust in solving complex tasks such as foraging, long-distance migration and defend environmental threats. Such coordinate mechanisms in nature provide bio-inspiration for developing efficient flocking of UAVs with distributed control. Furthermore, flocking flight can extend existing advantages and exploit potential advantages of coordinated UAVs [9,10].

Over the last decade, rapid progress in sensor technology leads to many advances in research of free-flying bird orientation strategies, especially pigeon hierarchical strategies. The collective route of pigeon flock emerges as a compromise between individual's preferred path and the leader's experience. Nagy et al. [11] record the pigeons' movements during spontaneous and homing flights to investigate the temporal relationship among the pigeon individual and its neighbors. They also present a well-defined hierarchy of pigeon flock and the experimental results demonstrate that the hierarchical organization can increase the efficiency of group flight. Furthermore, in [12] Pettit et al. investigate the collective intelligence of pigeon flock in social learning by adding a locally naive individual as a flight partner. They also find that there exists a feedback loop between leadership and learning in collective motion over time [13]. Pigeon flock's organizational structure can be transformed into unique components of the distributed system, and the leadership hierarchies can be implemented as the control framework of UAV flock.

There are a series of animal flocking principles, being able to perform coordinated control for autonomous UAVs. For example, a decentralized multi-copter flock is presented by Vásárhelyi et al. based on bio-inspired strategies with limited dynamic information [14]. An autonomous flock control algorithm is proposed by Hauert et al. for fixed-wing UAVs by integrating two Reynolds rules into the control system [15]. A remarkable flock of 20 quadcopters with a central controller calculating the navigational information for all agents is created by Kushleyev et al. [16]. Another quadcopter flock

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that is created by Bürkle et al. also implements the central processing at a ground station [17]. However, autonomous flock with decentralized control frameworks and self-organization capabilities needs to be further developed, and we take full advantages of animal flocking behaviors to achieve highly coherent motion.

Homing pigeons have been frequently used as a model in flocking strategies studies. Emerging evidence indicates that hierarchical leadership network dominates pigeon flock behavior, with most flock members following the decisions made by high level leaders in the network. Furthermore, in flocks composed of the same individuals the leadership hierarchy tends to be structurally stable. Pigeons may share navigational decisions and decide democratically on leadership when there is little conflict of opinion about the route to follow. These homing pigeon leadership hierarchies can be applied to solve complicated distribute control problems in UAV flocking.

In this paper, a distributed control framework is proposed to solve the UAV flocking problem. This framework contains various hierarchical strategies based on the pairwise leader-follower relations in pigeon flock and condenses those interactions into robust, fully transitive leadership hierarchies. This framework can be used to construct a stable flocking structure, and it can contain as many system-specific features as we can take into account, such as inertia, time delay, general noise and inner noise. The hierarchical features of pigeon flock can be useful in collective UAVs only if some specific aspects of realistic systems are considered. The principles of pigeon flock hierarchy can be transformed into unique control patterns of the UAV dynamical system. With simulations and further experiments on UAV flocking, the stability and efficiency of pigeon-inspired flocking control framework are studied.

The rest of this paper is organized as follows. Section 2 introduces the hierarchical strategies in pigeon flock, including velocity correlation, leader-follower interaction, and hierarchical leadership. Section 3 gives a description of the fix-wing UAV model and the transformation of control inputs. In Section 4, the proposed distributed control framework based on pigeon leadership hierarchies is implemented on the fix-wing UAV flocking. Series of simulation results and relevant analysis are discussed in Section 5, followed by our concluding remarks in Section 6.

2. Homing pigeon leadership hierarchies

This section presents three typical hierarchical strategies in pigeon flock, including velocity correlation, leader-follower interaction and hierarchical leadership network. Direction and velocity choice dynamics within flocks of up to 8 homing pigeons, which are obtained by high-resolution lightweight GPS devices [18], are considered. The relationship between individual pigeon's velocity performance during free flights and homing flights are examined. In general, considering about a pigeon flock of N individuals, each individual is represented by the position vector $p_i(t)$ and the velocity vector $v_i(t)$. The projected distance $d_{ij}(t)$ is defined as the distance between pigeons i and j on the motion direction of the whole flock. The velocity correlation function $C_{ij}(\tau)$ can be defined as:

$$C_{ij}(\tau) = \left\langle \boldsymbol{v}_i(t) \cdot \boldsymbol{v}_j(t+\tau) \right\rangle \tag{1}$$

where $\langle \bullet \rangle$ denotes the time average, τ represents the time delay of velocity correlation behavior between pigeons i and j. The directional correlation delay time is defined as τ_{ij}^*, and the maximum value of velocity correlation function $C_{ij}(\tau)$ is $C_{ij}(\tau_{ij}^*)$. The directional correlation delay time represents the strength of pairwise leader-follower relationship between individuals. The velocity correlation behavior can be considered as a basic "velocity copy" motion related to pigeon flock hierarchical leadership. A pigeon is defined as a leader when its velocity is 'copied' by another pigeon delayed in time. About two-thirds of pairwise comparisons between pigeons produced clearly directed velocity correlation edges, and the average delay time of this behavior is 0.3 s. The characteristic delay time of each individual can be presented as pigeons' hierarchical reaction performance in the context of following a persistent change in the direction of motion of leaders.

According to the velocity correlation analysis, pigeons tend to copy the direction and velocity of particular individuals (neighbors) consistently. In order to examine the effects of pigeon hierarchical organization on stability and robustness, we extend an existing collective motion model [19] by further incorporating the pigeon inspired leader-follower interaction and hierarchical leadership network. In this model, individuals interact with their neighbors within a fixed communicating range, these neighbors should be higher leaders in the flock. We divide the communicating area into three specific interaction zones: the avoidance zone (r_R), the alignment zone (r_O) and the attraction zone (r_A). At all times, each pigeon tries to maintain a minimum distance between itself and other pigeons by turning away from individuals within the avoidance zone. The preferred turning direction of pigeon i can be expressed as:

$$\psi_i(t+\Delta t) = -\sum_{j \neq i} \frac{p_j(t) - p_i(t)}{|p_j(t) - p_i(t)|} \tag{2}$$

where $\psi_i(t+\Delta t)$ is the individual's desired direction of travel at $t+\Delta t$. The leader-follower interaction in pigeon flock mainly occurs within the attraction zone and the alignment zone. Individuals are attracted to and align with their leaders based on the velocity correlation. Then the turning direction can be calculated as:

$$\psi_i(t+\Delta t) = \sum_{j \neq i} \frac{p_j(t) - p_i(t)}{|p_j(t) - p_i(t)|} + \sum_{j=1}^{N} \frac{v_j(t)}{|v_j(t)|} \tag{3}$$

While navigating towards a fixed target location, leaders must balance their preference to maintain flock cohesion with their global navigation behavior. Then the direction can be calculated as:

$$\psi_i'(t+\Delta t) = \frac{(1-\omega)\psi_i'(t+\Delta t) + \omega\psi_{ig}}{|(1-\omega)\psi_i'(t+\Delta t) + \omega\psi_{ig}|} \tag{4}$$

where $\psi_i'(t+\Delta t)$ represents the leader's preferred direction at $t+\Delta t$. ω is a weighting factor ranges from 0 to 1. $\omega = 0$ implies no navigation towards the preferred direction and $\omega = 1$ represents only the use of navigational information and no social interactions. In order to select a suitable value of weighting factor ω, series of simulations are implemented on the basis of the global navigation behavior with ω varying from 0 to 1. A higher value of ω is better in the premise of maintaining the integrality of pigeon flock. ψ_{ig} is the direction towards the global target. The factor represents the balance between leader's social interaction and its navigation towards the target.

Crucially, the velocity correlation and leader-follower interaction in pigeon flock are based on a robust hierarchical leadership network, containing only directed transitive leader-follower relationships [20,21]. The hierarchical leadership network is divided into several levels, and pigeons in higher hierarchy level are more influential in determining the flock's movement. Furthermore, leaders in higher level of the network have more followers. Therefore, the first level leader can contribute with relatively most weight to the movement decisions of the flock, as it has most followers who consistently copy its movement. With multiple leaders in the second and the third levels of the hierarchically organized network, pairwise leader-follower relations among flock members remain stable in emergency situations. Leadership ranks within

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