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Fully autonomous flying: from collective motion in bird flocks to unmanned aerial vehicle autonomous swarms

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1 Introduction

The unmanned aerial vehicle (UAV), an aircraft with no pilots on board, appeals to widespread applications in military and civil fields [1]. In complex and dynamic mission environments, a single UAV will suffer from fatal drawbacks, such as the limitation in sensing range, computing capacity, and weapon power. Therefore, the usage of UAV autonomous swarms for mission implementation will be a better choice for the dilemma single UAVs plunge in, which requires the capacity of precise real-time perception of emergency, autonomous decision making, and mission re-planning, based on pre-programmed flight plan or more complex dynamic automation system instead of remote control from ground control stations.

Several crucial issues exist in the deep studies for fully autonomous swarms from theoretical analyses to potential usages, such as, how to spread the local emergency information to the whole agent swarm, how to make a group decision based on the limited or redundant information and how to coordinate with each other to obey the group decision. As an added bonus, some of these problems have already appeared on the table of some researchers who focus on the self-organization in a variety of complex systems, especially the collective motion in bird flocks. Due to the similarity between UAV swarms and bird flocks in essence, establishing their mapping relation will provide a novel but feasible approach to the fully autonomous UAV swarm control.

2 Collective motion mechanisms in bird flocks

The organized flight of birds in the sky seems to be a well-rehearsed and magnificent dance. Large birds usually choose an orderly linear formation as their main flight mode, such as wild gooses and cormorants (Figure 1(a)). Meanwhile, small birds are more inclined to the cluster formation, such as pigeons and starlings (Figure 1(b)). Every small bird appears to know exactly when and where to change

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(a) (b) (c)

Figure 1 (Color online) Snapshots of flying on sky. (a) V-formation flight of birds; (b) airplanes in close formation; (c) flock of birds. @Copyright 201x Dreamstime (images are from Studio023, Yoderrm and Murat Erhan Okcu, respectively).

the direction so that the whole flock always maintains the fluency of motion without division. The mysterious mechanism behind this collective motion in bird flocks is attracting the attention of more and more researchers.

A computer animator named Craig Reynolds enabled the aggregate motion of a bird flock to enter the vision of people by computer animation in 1986. The behaviors of the boid model [2] obey three simple rules: collision avoidance, velocity matching, and flock centering. Other models begin to emerge in succession after the boid model, of which the comparatively familiar ones are the Vicsek model [3], the Couzin model [4] and the Cucker-Smale model [5]. Concretely, particles in the Vicsek model are driven with a constant absolute velocity, whose direction is assumed to be the average of those of the individuals in the neighborhood with some random perturbation added [3]. Couzin et al. [4] used a more biologically realistic model to simulate the aggregation behavior in bird flocks, which results from local repulsion, alignment and attractive tendencies based on the position and orientation of individuals relative to one another. Cucker and Smale [5] assumed that every bird adjusts its velocity by adding to it a weighted average of the differences of its velocity with those of the others and the weights are a function of the distance between birds.

All of the mentioned numerical models based on aprioristic assumptions seem to believe that the collective motion in bird flocks might arise from ordinary local rules of interactions among the individuals within a specified range. However, Cavagna et al. discovered that the interaction relies on the topological distance rather than the metric distance assumed in the above models by filming thousands of starlings and reconstructing the three-dimensional movements [6]. The attenuation of the interactional information that propagating across the flock was further confirmed to be extremely negligible, and a theory was formulated to reproduce the different phenomenon by considering the birds' behavioral inertia [7]. Latterly, a new dynamical field theory was proposed to unify the above mechanisms, where the birds are regarded as fluid elements in a large hydrodynamic system under the action of spin waves and density waves that are related to the velocity direction and positions of birds respectively [8].

3 UAV autonomous swarms inspired by bird flocks

The UAV swarm is a group with one common purpose composed by tens of or more UAVs, which is the product of complex mission environment and the boost of UAV autonomous control. The concrete missions of UAVs in a swarm not only include the collective behavior, such as aggregation, separation, state uniform, and external obstacle (static or dynamic) avoidance, but also contain the individual behavior to avoid conflict with each other. Due to the large amount of computational cost and the high complexity of the whole UAV swarm system when fusing the numerous local environment information and making individual decisions to agree with the group decision, traditional centralized control [9,10] shrinks back at the sight of this complex mission and gives way to distributed control [11,12] with relaxed autonomy. The distributed control in a UAV swarm is a process of individual autocephalous perception and decision making to achieve a global objective. Nevertheless, the design of the distributed control algorithm is still a serious and challenging problem on account of the following difficulties: (1) The local information of external threats and neighbors' states sensed by an individual is limited, while a single UAV has to make its own decision to submit to a global mission; (2) The changes of the external environment (obstacles, hostile threats, atmospheric turbulence, etc.) are rapid, which makes that the distributed network topology in UAV system transform accordingly due to the real-time re-planning.

Inspiration from evolution characteristics and behavior patterns has been an effective way to solve the key technical problems of UAVs. For example, the optimal close formation geometry is inspired by the linear formation in large birds, for which the close formation's induced drag is minimized (Figure 1(c)). Owing to the similarity between UAV swarms and birds flocks in mission requirements and environmental interferences, the collective motion mechanisms in bird flocks have reference significance for the design of distributed control algorithms for UAV swarms, especially for the distributed topological structure and its transformation rules. It implies that the behaviors of individual UAVs following some simple rules as outlined in Section 1 are probably to result in a swarm that satisfies the desired requirements. There is no doubt that simple individual rules mean the robustness, scalability and flexibility of the UAV swarm, which is crucial in improving the execution efficiency facing to the complex missions.

Many obstacles exist in the way to establishing the mapping relations and converting the collective motion mechanism in bird flocks into a distributed control algorithm of the UAV autonomous swarm. Fortunately, we could occasionally hear the gospel that the first decentralized multi-copter flock that performs stable autonomous outdoor flight with up to 10 flying agents was presented based on a decentralized control framework with bio-inspiration from the boid model [13]. Accompanied by the gradual exposure of the mystery of bird flocks, the UAV autonomous swarms based on the collective motion mechanisms will become a reality in the future.

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References

1 Liu X C, Wang H, Fu D, et al. An area-based position and attitude estimation for unmanned aerial vehicle navigation. Sci China Tech Sci, 2015, 58: 916–926
2 Reynolds C W. Flocks, herds and schools: a distributed behavioral model. In: Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques. New York: ACM, 1987. 25–34
3 Vicsek T, Czirók A, Ben-Jacob E, et al. Novel type of phase transition in a system of self-driven particles. Phys Rev Lett, 1995, 75: 1226–1229
4 Couzin I D, Krause J, James R, et al. Collective memory and spatial sorting in animal groups. J Theor Biol, 2002, 218: 1–11
5 Cucker F, Smale S. Emergent behavior in flocks. IEEE Trans Automat Contr, 2007, 52: 852–862
6 Ballerini M, Abibbo N, Candelier R, et al. Interaction ruling animal collective behavior depends on topological rather than metric distance: evidence from a field study. Proc Natl Acad Sci, 2008, 105: 1232–1237
7 Attanasi A, Cavagna A, Del Castello L, et al. Information transfer and behavioural inertia in starling flocks. Nat Phys, 2014, 10: 691–696
8 Cavagna A, Giardina I, Grigera T S, et al. Silent flocks: constraints on signal propagation across biological groups. Phys Rev Lett, 2015, 114: 218101
9 Duan H B, Luo Q N, Yu Y X. Trophallaxis network control approach to formation flight of multiple unmanned aerial vehicles. Sci China Tech Sci, 2013, 56: 1066–1074
10 Guo S P, Li D X, Meng Y H, et al. Task space control of free-floating space robots using constrained adaptive RBF-NTSM. Sci China Tech Sci, 2014, 57: 828–837
11 Luo Q N, Duan H B, Yu Y X. An improved artificial physics approach to multiple UAVs/UGVs heterogeneous coordination. Sci China Tech Sci, 2013, 56: 2473–2479
12 Zhou J, Wu X J, Liu Z R. Distributed coordinated adaptive tracking in networked redundant robotic systems with a dynamic leader. Sci China Tech Sci, 2014, 57: 905–913
13 Vásárhelyi G, Virágh C, Somorjai G, et al. Outdoor flocking and formation flight with autonomous aerial robots. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, 2014. 3866–3873