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• **Supplementary File** •

Distributed unmanned flocking inspired by the collective motion of pigeon flocks

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Appendix A Comparative simulation results

Fig. A1 depicts the simulation result of UAV flocking based on **Algorithm 1** under the obstacle environment, where **Fig. A1(a)-(e)** describe the top view of flight trajectory, altitude, altitude rate, horizontal airspeed, and yaw angle, respectively. In **Fig. A1(a)**, the area where UAVs could perceive obstacles is marked as shadows. As shown in **Fig. A1(a)**, the UAV swarm could safely pass through the complex obstacle environment without collisions between individuals, and could gradually achieve a formation in the process of approaching the target. As shown in **Fig. A1(b)-(e)**, the allowable error of dominant UAV reaching the target is satisfied at 74.8s. As shown in **Fig. A1(b) and (c)**, the altitude of the UAV swarm tends to the expected altitude h_{exp}=25m at about 5s, and the altitude rate tends to 0. As shown in **Fig. A1(d) and (e)**, the horizontal airspeed and yaw angle of the UAV swarm tend to be the same after fluctuating within the allowable range.

In order to further verify the superiority of **Algorithm 1**, the comparative simulation based on a traditional distributed method [1] is also carried out. Considering that there is no interactive pattern switching in traditional methods, each UAV is set to adopt only the egalitarian interaction pattern (i.e. α=∞ and $\beta < \infty$ to make $p_{\mathrm{h}} = 0$) in the contrast simulation. Considering the fairness and effectiveness of comparisons, the initial conditions and other parameters of the simulation without pattern switching are the same as those of the above simulation except that R_{c}^1=100m. **Fig. A2** displays the simulation result of UAV flocking based on the traditional distributed method under the obstacle environment, where **Fig. A2(a)-(c)** describe the top view of flight trajectory, horizontal airspeed, and yaw angle respectively. It should be noted that since pattern switching only acts on the horizontal plane, the curve of the altitude and altitude rate without switching is not different from that with switching. As shown in **Fig. A2(a)**, the UAV swarm could also safely cross the complex obstacle environment and gradually approach the target without collisions between individuals. However, there are some redundant trajectories in flight. Before the end of the simulation, the UAV swarm did not form a formation, and dominant UAVs did not meet the allowable error of reaching the target.

In order to compare the performance of the two algorithms, the order parameter V_{a} is introduced to measure the synchronization of the yaw angle:

$$V_{\mathrm{a}}=\left|\sum_{i=1}^{N} \boldsymbol{v}_i^*\right|/N \tag{A1}$$

The average distance d_{T} between the UAV swarm and the target is defined to measure the proximity of the swarm to the target:

$$d_{\mathrm{T}}=\sum_{i=1}^{N} \|\boldsymbol{x}_i - \boldsymbol{x}_{\mathrm{T}}\|/N \tag{A2}$$

Communication loss L_{s} is defined to measure the transmission loss in free space under ideal conditions:

$$L_{\mathrm{s}}\left(t\right)=\int_0^t \left(10^{\frac{P_0}{10}}+d^2\right)\mathrm{d}t \tag{A3}$$

where P_0 is the transmission loss power per unit distance, d is the transmission distance, and d is R_{c}^1 and R_{c}^2 in the egalitarian interaction pattern and the hierarchical interaction pattern, respectively.

Fig. A3 shows the comparative result with and without interaction pattern switching, where **Fig. A3 (a)-(c)** describe the order parameter, average distance between the UAV swarm and the target, and communication loss, respectively. In **Fig. A3**, the results with and without interaction pattern switching are marked with circular marker lines and square marker lines, respectively. As shown in **Fig. A3(a)**, the UAV swarm system with switching could achieve a higher level of synchronization faster than a non-switch system. Besides, the average synchronization of the switch system (as shown by the thick solid line) is also better than that of the non-switch system (as shown by the thin dashed line). As shown in **Fig. A3(b)**, the switch system is always closer to the target than the non-switch system at the same time. The distance between the dominant individual and the target in the switch system is less than the allowable error of reaching the target at about 74.8s, whereas the reaching error of the non-switch system fails to meet the requirement at this time before the end of simulation. As shown in **Fig. A3(c)**, the communication loss of the switch system is always less than that of non-switch, and the gap becomes more evident with the increase of simulation time.

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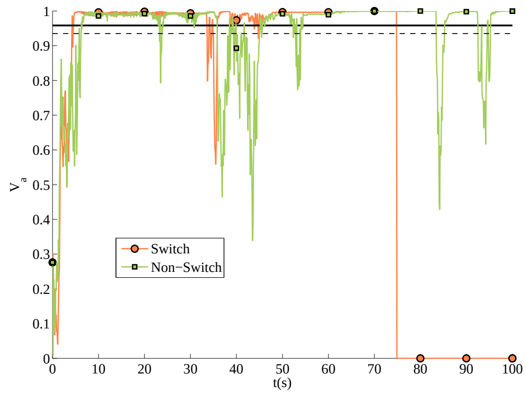
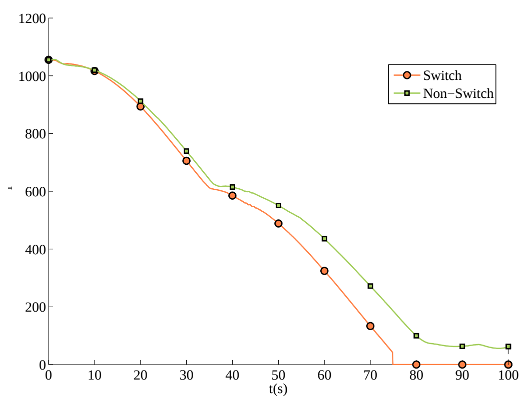
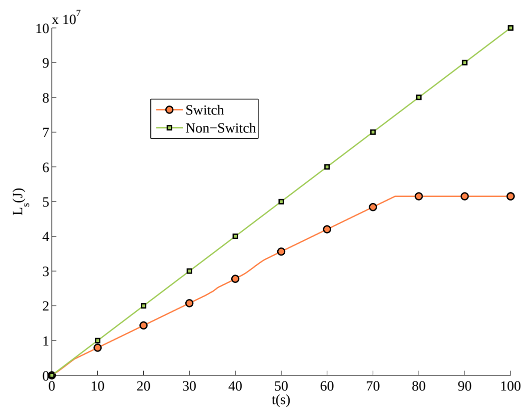


(a) Order parameter



(b) Average distance between the UAV swarm and the target



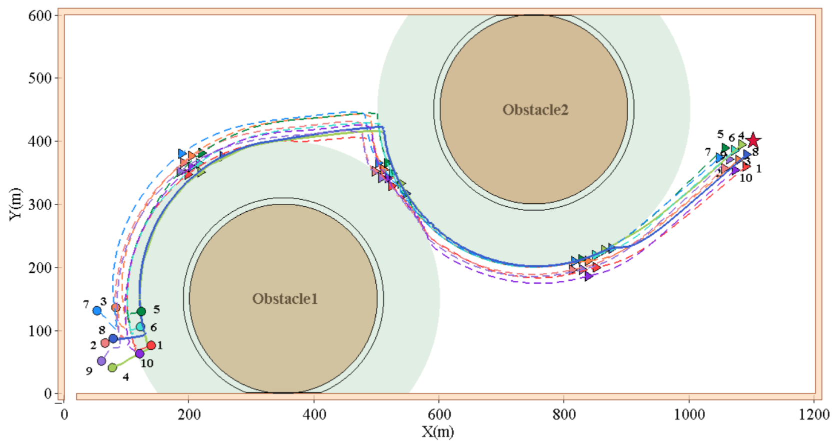
(c) Communication loss

Figure A3 Comparison between **Algorithm 1** (Switch) and the traditional algorithm (non-switch).

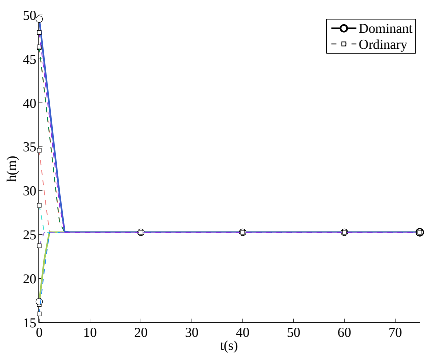
In summary, a UAV swarm based on **Algorithm 1** could reach a target without clustering under the environment with obstacles. Compared with systems without interactive pattern switching, the switch system based on **Algorithm 1** has advantages in the synchronization, approaching rapidity and communication loss.

References

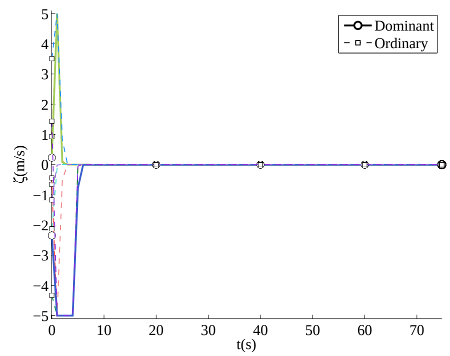
1 Zhang X, Duan H. Altitude consensus based 3D flocking control for fixed-wing unmanned aerial vehicle swarm trajectory tracking. P I Mech Eng G-J Aer, 2016, 230(14): 2628-2638



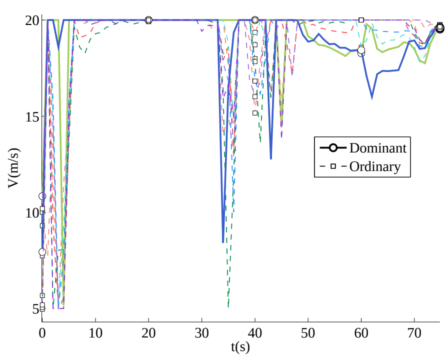
(a) Top view of flight trajectories



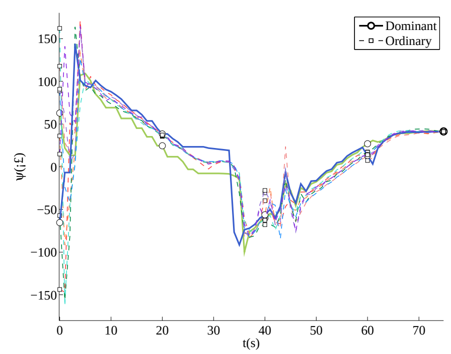
(b) Altitude



(c) Altitude rate

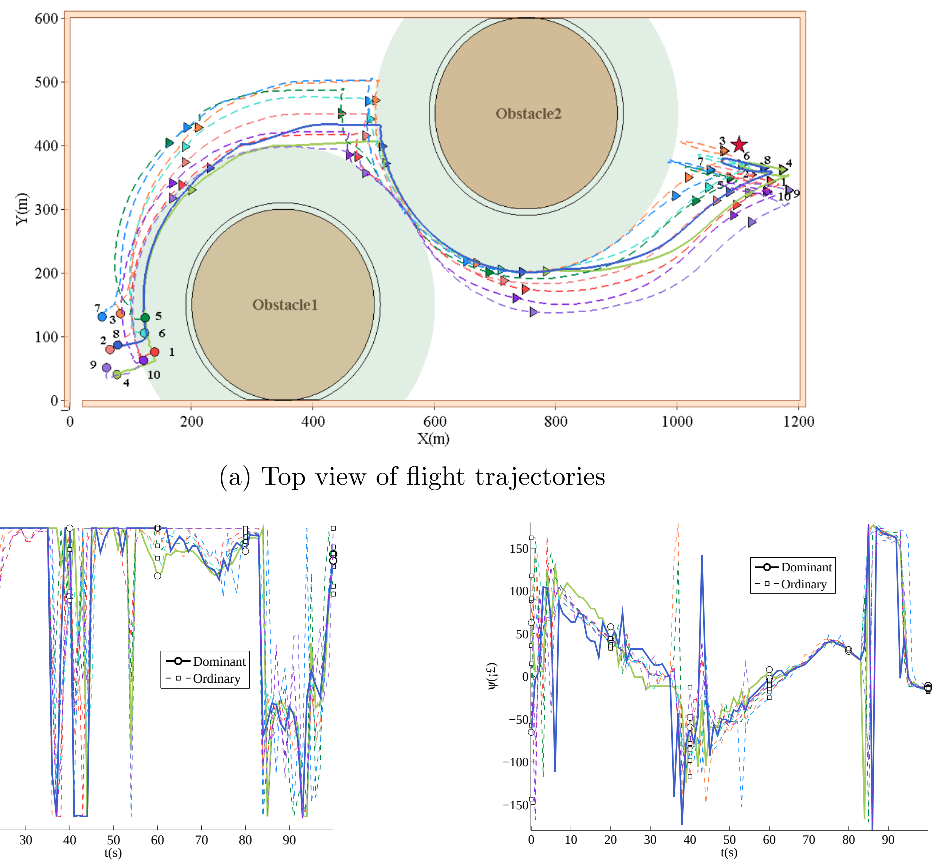


(d) Horizontal airspeed



(e) Yaw angle

Figure A1 UAV flocking based on **Algorithm 1** (with switch).



(a) Top view of flight trajectories

(b) Horizontal airspeed

(c) Yaw angle

Figure A2 UAV flocking based on a traditional algorithm (without switch).