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Distributed game strategy for unmanned aerial vehicle formation with external disturbances and obstacles

Key words: Distributed game strategy; Unmanned aerial vehicle (UAV); Distributed model predictive control (MPC); Levy flight based pigeon inspired optimization (LFPIO); Non-singular fast terminal sliding-mode observer (NFTSMO); Obstacle avoidance strategy

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Motivation

1. The unmanned aerial vehicle (UAV) swarm can expand the field of application, and has more reliable, more robust, and more durable task execution capabilities. Formation control is a key technology for UAVs to realize the collaborative work of a swarm system.

2. The target of a single UAV should be concerned with in some situations. UAV formation can be regarded as a game problem in the case of different individual objectives.

Main idea

1. A non-singular fast terminal sliding mode observer (NFTSMO) is proposed to observe the disturbance. The robustness against disturbance is provided by NFTSMO, and fast convergence of the observer is achieved.

2. A distributed UAV obstacle avoidance strategy is proposed with topology reconstruction. More energy of a single UAV can be retained during the process of obstacle avoidance by the developed obstacle avoidance strategy.

3. The cost function of each UAV is established in the distributed MPC framework, and a Levy flight based pigeon inspired optimization (LFPIO) algorithm is proposed to solve the distributed cost function to achieve the Nash equilibrium.

Non-singular fast terminal sliding mode observer

Particle model system

$$\dot{z} = Az + Bu + d$$

Non-singular fast terminal sliding surface

$$s = e + \Pi_1 \mathrm{sig}^{\lambda_1}(e) + \Pi_2 \mathrm{sig}^{\lambda_2}(\dot{e})$$

Disturbance observer

$$\begin{cases} \dot{\hat{z}} = Az + Bu + s_0 + \hat{d} \\ \dot{s}_0 = \left(\Pi_2 \lambda_2 \mathrm{diag}\left(|\dot{e}|^{\lambda_2 - 1}\right)\right)^{-1} \left[\dot{e} + \Pi_1 \lambda_1 \mathrm{diag}\left(|e|^{\lambda_1 - 1}\right)\dot{e}\right] \\ \dot{\hat{d}} = \eta \mathrm{si}g(s) + \rho \mathrm{sig}(s) \end{cases}$$

Obstacle avoidance strategy

An obstacle avoidance method based on topology reconstruction is proposed. As shown in Fig. 2, a safe circle is set to ensure a safe distance. There are two cases in which the UAV formation encounters obstacles, and the three dashed lines in the figure are in the same direction as the ideal speed of the formation.

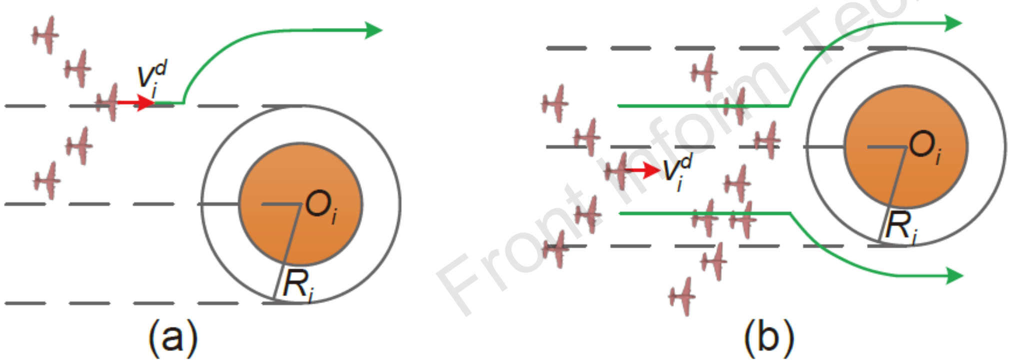


Fig. 2 Two cases in which UAVs encounter obstacles: (a) first case; (b) second case

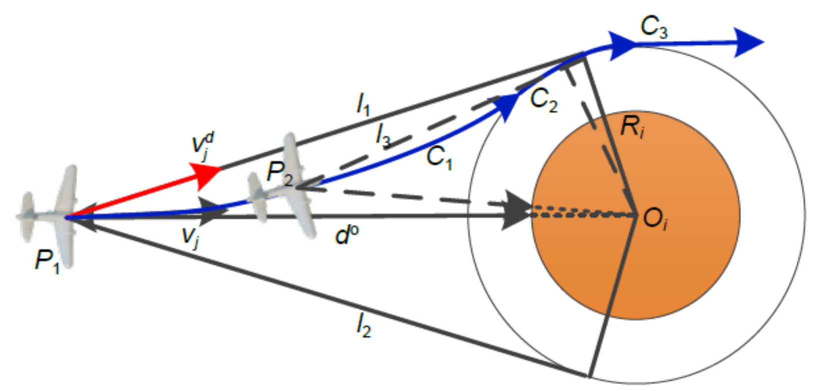
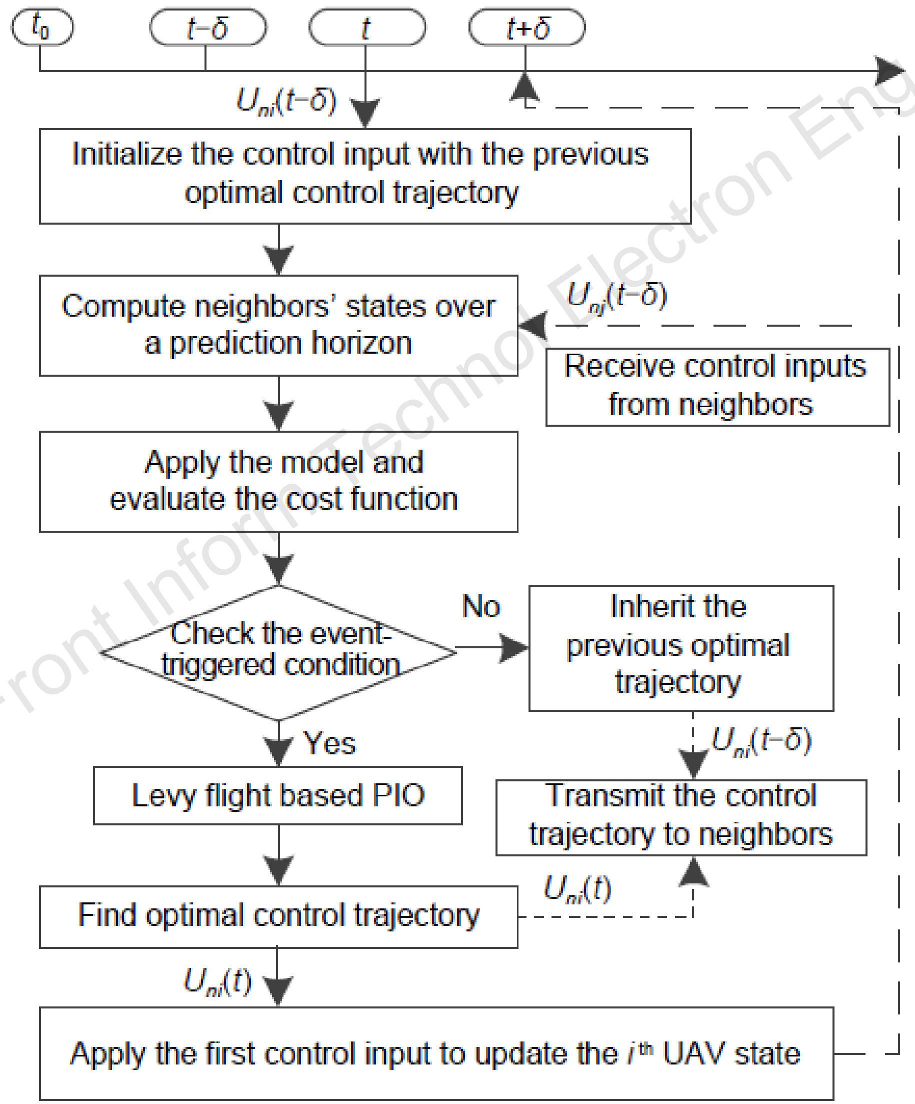
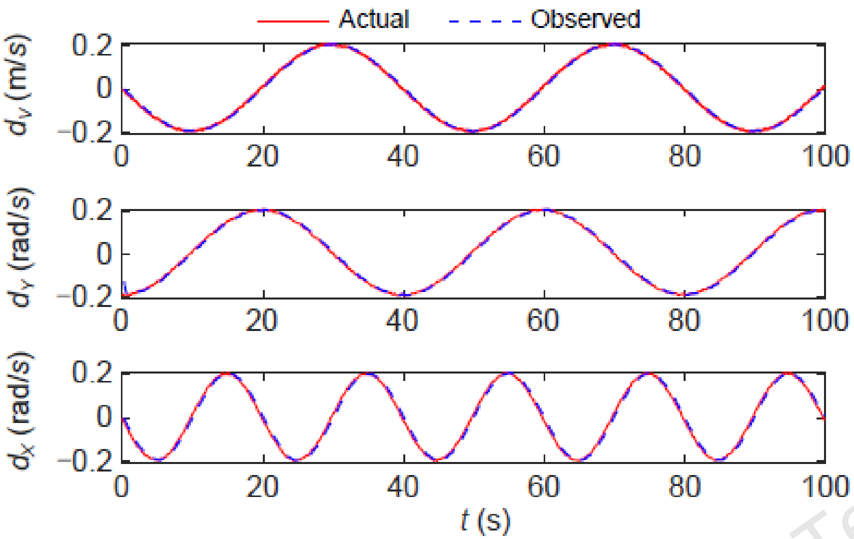


Fig. 3 Ideal speed for obstacle avoidance

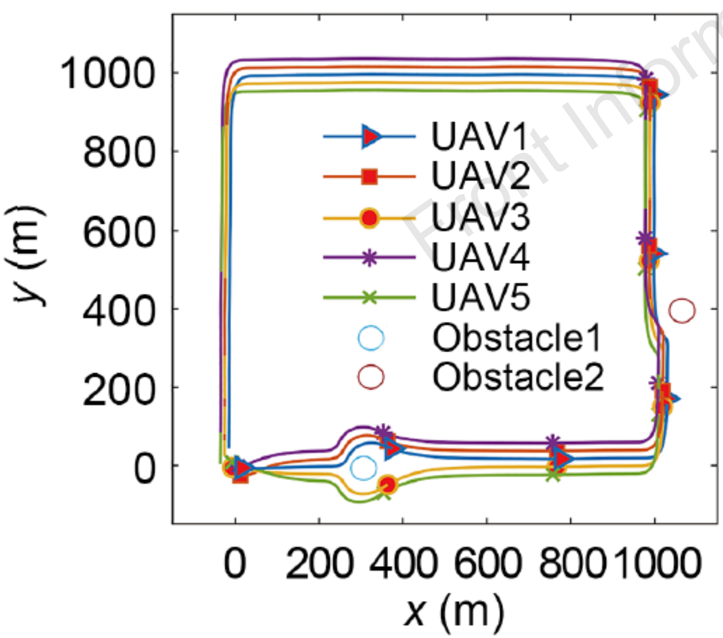
LFPIO based Nash equilibrium strategy for distributed MPC



Simulation results



The observation results of the disturbance are shown in Fig. 6, in which the observed value and the actual value were essentially the same in three channels.



The UAV formation can successfully complete the task and navigate through all obstacles with the obstacle avoidance strategy proposed in this paper. When crossing the first obstacle (Fig. 2b), the UAVs were automatically divided into two sub-formations. When facing the second obstacle (Fig. 2a), the UAVs chose to keep the formation, flying from one side.

Simulation results

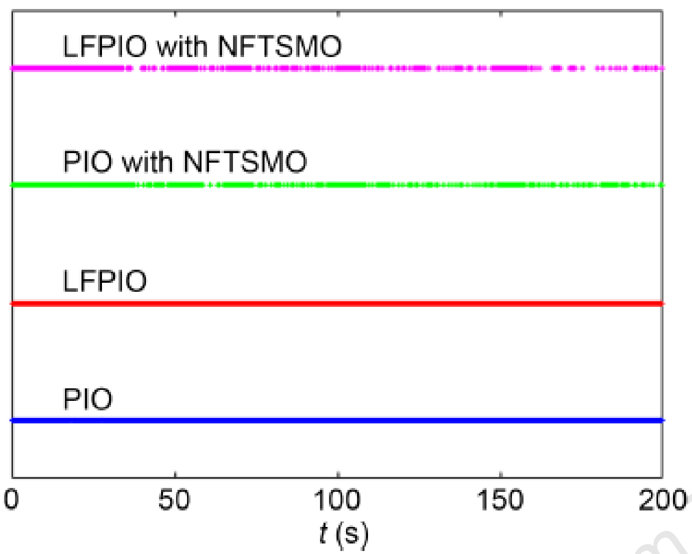


Fig. 9 Triggered times of UAV5 with different methods

Fig. 9 shows the triggered times of UAV5 with different methods. The triggered threshold was set as 10. The effects of the disturbance cannot be ignored, for which PIO and LFPIO were still triggered at every moment. Corresponding to Fig. 5, the control input was updated less without encountering obstacles and changing direction, and the triggered times were reduced (Fig. 9).

Table 2 Triggered times of UAVs with different methods

Algorithm	Triggered times					
	UAV1	UAV2	UAV3	UAV4	UAV5	Mean
PIO	1000	1000	1000	1000	1000	1000
LFPIO	1000	1000	1000	1000	1000	1000
PIO with NFTSMO	513	632	578	598	539	572
LFPIO with NFTSMO	455	560	501	518	459	498.6

Conclusions

1. We propose a non-singular fast terminal sliding mode observer to estimate the influence of disturbances, and prove that the observer converges in fixed time using a Lyapunov function.

2. We design an obstacle avoidance strategy based on topology reconstruction, by which the UAV can save energy and safely pass obstacles.

3. The cost function of each UAV is designed, by which the UAV formation problem is transformed into a game problem in the MPC framework. LFPIO is developed to solve the Nash equilibrium. The efficiency of the LFPIO based distributed MPC is verified through comparative simulations.

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