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Trophallaxis network control approach to formation flight of multiple unmanned aerial vehicles

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A novel network control method based on trophallaxis mechanism is applied to the formation flight problem for multiple unmanned aerial vehicles (UAVs). Firstly, the multiple UAVs formation flight system based on trophallaxis network control is given. Then, the model of leader-follower formation flight with a virtual leader based on trophallaxis network control is presented, and the influence of time delays on the network performance is analyzed. A particle swarm optimization (PSO)-based formation controller is proposed for solving the leader-follower formation flight system. The proposed method is applied to five UAVs for achieving a 'V' formation, and a series of experimental results show its feasibility and validity. The proposed control algorithm is also a promising control strategy for formation flight of multiple unmanned underwater vehicles (UUVs), unmanned ground vehicles (UGVs), missiles and satellites.

unmanned aerial vehicle (UAV), trophallaxis, network control, formation flight, particle swarm optimization (PSO)

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1 Introduction

In recent years, formation control of multiple unmanned aerial vehicles (UAVs) has become a challenging interdisciplinary research topic, while autonomous formation flight is an important research area in the aerospace field [1, 2]. Several approaches that have been applied to the formation problem include artificial potential field method [3], hybrid supervisory control [4], and receding horizon control (RHC) [2].

In control systems, various kinds of signals transfer via the public data transmission network, and estimation, control and diagnosis are conducted in parallel and distributed executions. When the control loops in the control system are closed through a real-time network, it becomes a networked control system (NCS) [5, 6]. The most important characteristic of a NCS is that it connects cyberspace to physical space enabling the executions of several tasks in the distance far away. They can also be easily modified or upgraded by adding sensors, controllers and actuators to them with relatively low cost, and usually without major changes in their structures. Many researchers have done a lot of research on NCS. Wang et al. [7] developed several formation controllers for six-degrees-of-freedom (6-DOF) networked spacecraft considering constant and time-varying communication delays. Qiu et al. [8] investigated the H_2/H_∞ control problem for a class of discrete-time networked control systems with random communication time delays.

The stability of multiple UAVs formation flight depends largely on the information exchange and processing between the UAVs. The UAV group would perform their flight missions based on an existing database after each UAV has created the position and environment information

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data by using the navigation system and various sensors. Therefore, the stability of a UAV group is usually affected by the network characteristics, such as packet loss and time delay [6, 9].

Considering the communication requirements of the NCS, we investigated a new swarm search algorithm: Trophallactic. This new mechanism is based on the trophallactic behavior of social insects, animals and birds, such as ants, bees, wasps, sheep, dogs, sparrows and swallows. Trophallaxis is the exchange of fluid by direct mouth-to-mouth contact. By imitating that behavior, we proposed a method to reinforce the information exchanging and sharing between UAVs [10]. Our method was derived from the following example: A honey bee that finds the feeder fills its nectar crop with the offered sugar solution, and if the bee meets another bee on its way, there can be a trophallactic contact. The higher the metabolic rate of the bee is, the higher this consumption rate will be [11]. Kubo and Melhuish [12] showed an example in which the sharing of energy through trophallaxis can improve robot performance. Schmickl and Crailsheim [13] transferred the trophallaxis scenario into the context of a multi-robotic cleaning scenario and successfully tested and evaluated a new control strategy of a large-scale robot swarm. For the multiple UAVs formation flight, there are a lot of situations for the time delay to appear in the NCS and different types of time delay make it hard to directly apply existing methods to formation flight. To facilitate information sharing among UAVs, trophallaxis mechanism is employed. The major contribution of this paper is the formation controller design for a group of UAVs by using a trophallaxis network control; the particle swarm optimization (PSO) is also adopted for optimizing the parameters of proportional- derivative (PD) controller.

The rest of this paper is organized as follows. The next section describes the UAV model and formation structure, and the virtual leader is employed in our formation model. Section 3 designs a PSO-based PD controller, and the proposed network control method based on trophallaxis mechanism is also given in this section. Section 4 presents the experimental results for verifying the performance of the proposed formation flight approach. Our concluding remarks are contained in Section 5.

2 Leader-follower modeling for UAVs formation flight

A multiple UAVs formation flight system based on trophallaxis network control is shown in Figure 1.

The system shown in Figure 1 describes how the operator sends updated task commands and supervises changes of UAV states simultaneously. In this system, real-time data acquisition and processing are carried out through the trophallaxis network. Each UAV gets control sequence based on the task commands and its own states, and transfers underlying information to the trophallaxis network. In the information fusion and transfer process, there are many uncertainties and dangers which affect the quality of transmission, especially the time delay. Time delay is frequently encountered in network systems, it can easily reduce the

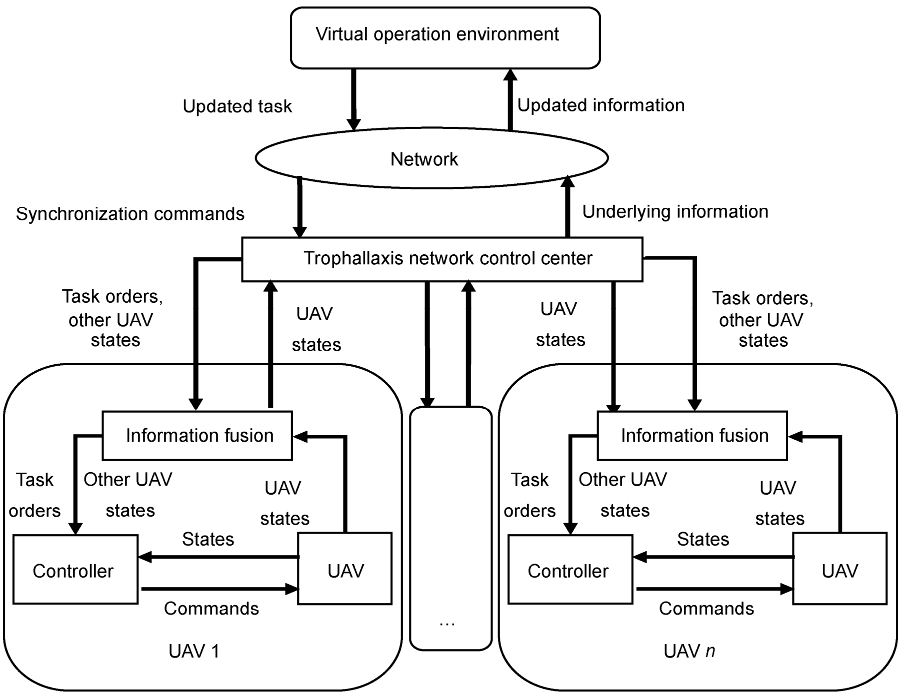

Figure 1 Multiple UAVs formation flight system based on trophallaxis network control.

transmission speed and even cause instability and oscillations in a system.

The virtual leader is employed in our model to track a desired flight trajectory so that UAVs can fulfil their mission by adjusting speed and heading angle based on the relative states of the virtual leader (see Figure 2). The closer the distance between a UAV and the virtual leader, the higher the UAV's priority. Each UAV will be a leader at the next level. If a UAV's leader is destroyed, then the UAV's priority will be boosted and replace its former leader. The virtual leader provides a stable, robust reference for formation control.

The point mass model is considered for the formation flight. Each UAV is assumed to fly at a constant altitude, parallel to the two-dimensional region to be surveyed [14]. A commonly used non-linear kinematics model that represents a UAV with zero or negligible velocity in the direction perpendicular to the UAV's heading is adopted by our model [15].

$$\begin{cases} \dot{x} = v\cos\psi, \\ \dot{y} = v\sin\psi, \\ \dot{v} = u, \\ \dot{\psi} = \omega, \end{cases} \tag{1}$$

where x and y are the Cartesian coordinates of the UAV, v is the velocity and ψ is the heading angle. The acceleration in the longitudinal direction u and angular turning rate ω are assumed to be the control inputs to the UAV.

In the leader-follower formation model, one UAV in the group is defined as a leader and the others the followers. Therefore, the problem of formation control is transformed into a position and direction tracking problem between followers and leader. The leader is responsible for tracking the desired task trajectory and followers simply need to keep a comfortable distance from the leader. The relative coordinates between virtual leader and follower is shown in Figure 2.

$$\begin{cases} x_r = (X_L - X_W)\cos(\Psi_W) + (Y_L - Y_W)\sin(\Psi_W), \\ y_r = (Y_L - Y_W)\cos(\Psi_W) + (X_L - X_W)\sin(\Psi_W). \end{cases} \tag{2}$$

The XOY in eq. (2) is geodetic coordinates, subscripts L and W mean the leader and follower. (X_L, Y_L) and (X_W, Y_W) represent the positions of the leader and follower in geodetic coordinates, respectively. V_L and V_W represent the speeds, Ψ_L and Ψ_W represent the heading angles. $X_rO_rY_r$ is the relative coordinates fixed in the follower according to the transformation between coordinates.

3 Formation control based on trophallaxis mechanism

3.1 PSO-based formation controller

Proportional-integral-derivative (PID) control method is employed in our coordination controller, which is widely used in industrial control systems. In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller [16]. By tuning the three kinds of parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements [17].

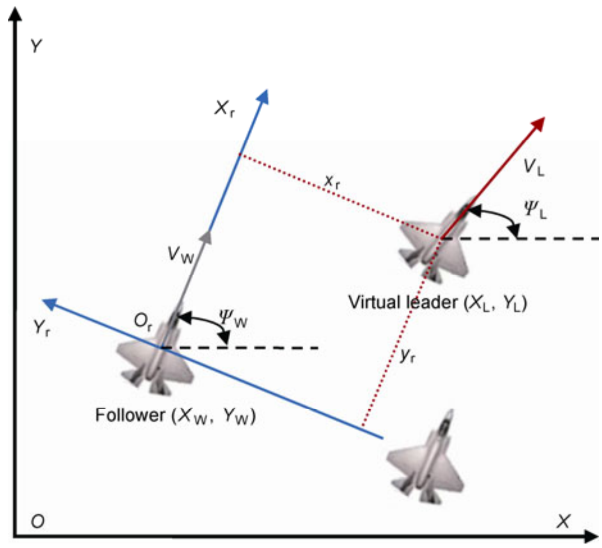

Figure 2 Relative coordinates of multiple UAVs formation flight.

We use linearized model described in eq. (1) to represent the leader and follower. Formation controller is deployed on the followers and the control input is the relative distance between the follower and leader. The control system framework for the leader-follower formation flight is shown in Figure 3.

The formation controller design is divided into two parts: Lateral channel and forward channel.

In the forward channel, the distance deviation $\Delta x = x - x_C$ and velocity deviation $\Delta v = V_L - V_W$ should be considered. At the same time it should also take into account the changing rate $\dot{x}$. Thus the control input can be expressed as

$$u = K_4 \cdot \Delta x + K_6 \cdot \Delta v + K_7 \cdot \dot{x}. \tag{3}$$

Similarly, the distance deviation $\Delta y = y - y_C$, heading angle error $\Delta\Psi = \Psi_L - \Psi_W$ and changing rate $\dot{y}$ should be considered in the lateral channel:

$$w = K_1 \cdot \Delta y + K_2 \cdot \Delta\Psi + K_3 \cdot \dot{y}. \tag{4}$$

The controller design problem is essentially a optimization problem based on a cost function. An optimum design method based on PSO algorithm is used for determining the PD controller parameters K_1, K_2, K_3, K_4, K_6 and K_7. In order to ensure the robustness and response speed of the system, overshoot and cumulative error are brought into our cost function.

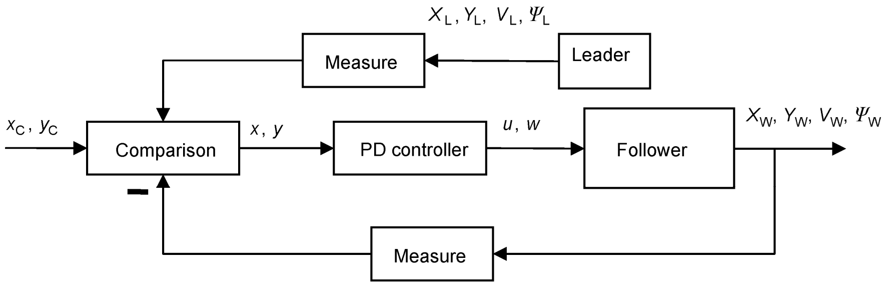

Figure 3 System structure for UAV leader-follower formation control, where x_C, y_C are expectations of relative distance, x and y denote the actual distance, u and w are control inputs generated by PD controller.

The overshoot is $\sigma = \frac{|y_p - y_{ref}|}{y_{ref}} \times 100\%$, where y_p and y_{ref} are the maximum output value and reference control input, respectively. The cumulative error is $e = \int |y(t) - y_{ref}| dt$. Thus, the cost function can be expressed as

$$\min J = w_1 \cdot \sigma + w_2 \cdot e, \tag{5}$$

where w_1 and w_2 are weight coefficients.

The procedure of PD parameters tuning based on PSO for solving multiple UAVs formation flight problem can be described as follows [18].

Step 1. Initialize PSO parameters on the basis of many experiments. Initialize a population of particles m=30 and the dimension of each particle n=6. Initialize the positions and velocities of the particles randomly. Set the maximum of iterations $N_{c\max}$=50, acceleration coefficients c_1=c_2=2, inertia weight factor $\omega = 0.2\exp[-10(N_c / N_{c\max})] + 0.4$, simulation time T=100 s. The parameter's up and down limit is [0, 10].

Step 2. Set $w_1 = 0.7$ and $w_2 = 0.3$. Evaluate the value of each particle by computing the cost eq. (5). Record the best position P_i of each particle and the global best particle P_g.

Step 3. Update the velocity and the new position of each particle in the swarm by using eqs. (6) and (7):

$$v_{p_i(t+1)} = \omega v_{p_i(t)} + c_1 rand_1(t)[P_i(t) - p_i(t)] + c_2 rand_2(t)[P_g - p_i(t)], \tag{6}$$

$$p_i(t+1) = p_i(t) + v_{p_i(t+1)}. \tag{7}$$

Step 4. Evaluate the cost function of updated particle. Detect the PSO terminating conditions (reaching the maximal generation or finding the idea optimum). If the terminating condition is met, end the PSO algorithm and return the global best particle P_g; else go to Step 3.

Step 5. Record the PD controller parameters K={K_1, K_2, K_3, K_4, K_6, K_7}, and change the up and down limit to K±5. Go to Step 1 for further optimization.

3.2 Time delay analysis of trophallaxis network

In the trophallaxis network environment, communication lines are shared and information flow changes irregularly. Therefore, information exchange between sensors, controllers and actuators in the NCS would result in uncertain time delays. The trophallaxis network analysis becomes very complicated for the existence of time delay. Although investigators have made considerable progress over the past few years in analyzing and modeling the NCS, different types of time delay make it hard to directly apply existing methods to different network environments [19]. So it is quite important to analyze trophallaxis network features correctly.

Time delay in the trophallaxis network includes sensor-controller delay τ_{sc} and controller-actuator delay τ_{ca}, and they are divided into short time delay and long time delay according to sampling period T.

1) Short time delay: Time delay distributes on [0 α], and $\alpha \leqslant T$.

2) Long time delay: Time delay distributes on [0 α], and $\alpha > T$.

Generally, delayed feedback is able to stabilize the systems with short time delay. However, for systems with long time delay, feedback compensation should be adopted to stabilize the system [20].

In NCS, the sensor node is time-driven, and the controller and actuator could be time-driven or event-driven.

Time-driven: If the controller (or actuator) is time-driven and calculates its control value based on input value at sampling time, and if there is no new control data arriving at the controller (or actuator) node during [t_k, t_{k+1}), the system would keep using the control input of the last cycle during [t_{k+1}, t_{k+2}). If the controller (or actuator) node receives 1,2,$\cdots$, or m data packets, it keeps the newest packet and cleans out large volume of obsolete data (see Figure 4).

Event-driven: If the controller (or actuator) is event-driven and updates its control value once a new data packet is received. Therefore, the control system may have variable of control inputs during a sampling period T. If there is no new control data arriving at the controller (or actuator) node during [t_k, t_{k+1}), the system would not change its control input during [t_{k+1}, t_{k+2}) unless it receives a new data packet [21].

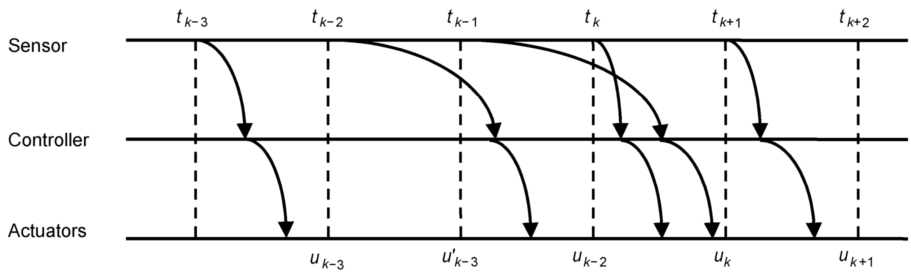

Figure 4 Timing diagram of NCS.

For the multiple UAVs formation flight network control system, there are a lot of reasons for the time delay to appear in the trophallaxis process such as: UAVs send state information to network control center, and the network control center sends task information and command to UAVs. As the controller node of the NCS, the network control center is set to be time-driven. We also change UAVs to be event-driven though they are the sensor nodes of the NCS because the time-driven mode requires strict synchronization between nodes. It's impossible to guarantee a strictly synchronous sampling in the presence of uncertain time delays in the trophallaxis network, and the event-driven mode also improves utilization of the feedback.

3.3 Trophallaxis network design

A distributed communication scheme is essential for multiple UAVs formation flight to ensure identity and consistency. The attractive aspect of the trophallaxis mechanism is the ability to incorporate information transfer as a biological process and utilize global information to generate an optimal control sequence at each time step.

In the process of formation, all the UAVs, including the virtual leader have the ability to conduct trophallaxis. The virtual leader sends updated task information and other UAVs accomplish task information update during their sampling period through the trophallaxis network [22].

In this work we consider two trophallaxis strategies to implement information transfer; the Empty call and Donation mechanisms. When a UAV has received the latest task information, it is capable of donating information to neighbors, then it becomes a donor UAV. When a UAV's current information is not fresh enough, it becomes a recipient UAV and calls for help (empty call) until its information freshness level increases again. An exchange of information (trophallaxis) can only occur between a donor and a recipient in their communication range. D_i=1, D_i=−1, and D_i=0 represent donor UAV, recipient UAV, and idle UAV, respectively.

$$D_i = \begin{cases} 1\ , & (\eta_{ij} > 0) \text{ and } (rand \leqslant 0.3), \\ -1\ , & (\eta_{ji} > 0) \text{ or } (rand > 0.3), \\ 0\ , & \text{otherwise}, \end{cases} \tag{8}$$

where η_{ij} represents UAV i's willingness to donate information to UAV j, and if its value is bigger, the tendency toward donation is higher.

$$\eta_{ij} = \frac{1}{d_{ij}}(\eta_{sij} + \eta_{tij}), \tag{9}$$

where η_{sij} is UAV i's aspiration to update the state information, and if UAV i's update time is later than UAV j, the value is bigger. Similarly, η_{tij} is UAV i's aspiration to update the task information.

$$\begin{cases} \eta_{sij} = \sum\limits_{(k=1)}^{N} \left[0.5(T_{si} - T_{sk})\lambda_1 + 0.1(\Delta t)\lambda_2\right], \\ \eta_{tij} = \sum\limits_{(k=1)}^{N} \left[0.8(T_{ti} - T_{tk})\lambda_3 + 0.3(\Delta t)\lambda_4\right], \end{cases} \tag{10}$$

where T_{si} and T_{ti} indicate the state update time and the task update time of UAV, respectively. N is the number of UAVs and Δt is the sampling period.

$$\lambda_1 = \begin{cases} 1, & T_{si} > T_{sk}, \\ 0, & \text{otherwise}, \end{cases} \tag{11}$$

$$\lambda_2 = \begin{cases} 1, & T_{si} = T_{sk}, \\ 0, & \text{otherwise}, \end{cases} \tag{12}$$

$$\lambda_3 = \begin{cases} 1, & T_{ti} > T_{tk}, \\ 0, & \text{otherwise}, \end{cases} \tag{13}$$

$$\lambda_4 = \begin{cases} 1, & T_{ti} = T_{tk}, \\ 0, & \text{otherwise}. \end{cases} \tag{14}$$

Recipient UAVs observe the following rules when receiving donated information.

1) All the task information and state information during the trophallaxis process must include sending time and arrival time.

2) Time delay should be taken into account for evaluating the arrival time.

3) When new data arrive, they are stored in a data pool in chronological order.

4) If and only if the information in the data pool is newer, the recipient UAVs will perform information updating.

The information exchange flowchat for multiple UAVs formation flight based on the trophallaxis mechanisms is shown in Figure 5.

4 Experimental results

A series of experiments have been performed to investigate the performance of the proposed trophallaxis network based formation control scheme for multiple UAVs formation flight. We use eq. (1) to represent states of UAV model, with input limit ±0.05 km/s for the acceleration u and ±30°/s for the turning rate w. The speed limit of UAV is [0.05 km/s, 0.3 km/s]. Both the formation flight model and designed formation controller are established on the Matlab/Simulink platform. The UAV states in the PD parameters optimization are initialized as shown in Table 1. The desired relative distances of leader-follower formation flight are x_C=2 km, y_C=2 km. In the 2nd second, the leader changes its heading angle to 10° and keeps its speed as 0.2 km/s.

The final result of PD controller parameters optimized by PSO are shown in Table 2. Figure 6 describes the relationship of the payoff function and iteration count of PSO. Figure 7 shows the formation reconfiguration trajectory and relative distances of UAVs.

In Figure 7, the follower finally follows the leader with a constant velocity and the final distance between UAVs is 2 km in both the x and y directions. Figures 7(a)–(f) display the responses of flight trajectory, relative distance, deviation distance and heading angle, respectievly. It converges in 50 s because of the input restriction.

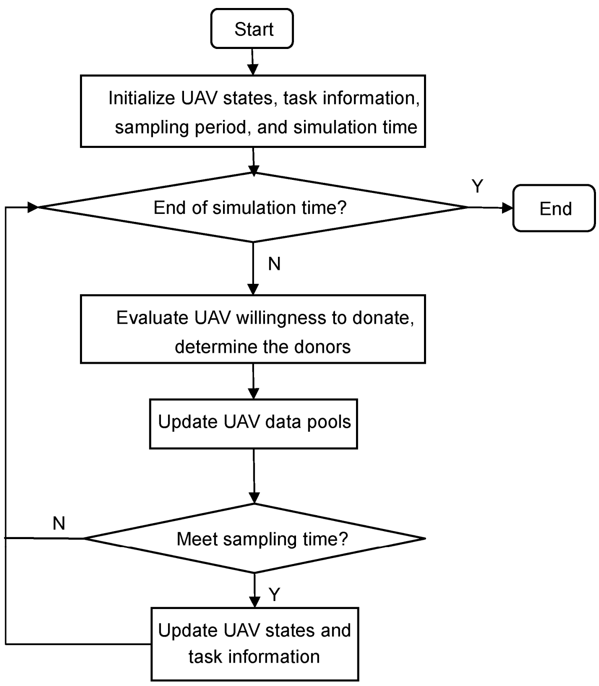

Figure 5 The flowchart of trophallaxis network based information exchange for UAV.

Table 1 UAV initial states

	Position (km)	Heading angle (°)	Speed (km/s)
Leader	(2, 0)	0	0.2
Follower	(0, −10)	0	0.2

Table 2 PD controller parameters

K_1	K_2	K_3	K_4	K_6	K_7
10	2.6693	2.1241	0.6858	0.5470	10

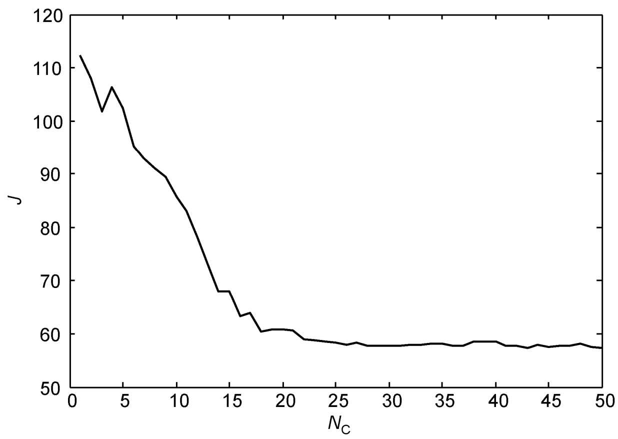

Figure 6 The evolution curve of PSO.

The flight formation in the multiple UAVs flight simulation consists of one virtual leader and five UAVs, and the UAVs initial states are shown in Table 3. The sampling period Δt is 0.1 s.

The virtual leader changes its heading angel to 0° at 5th second, and then the UAVs are required to form a 'V' formation. The desired relative distances to achieve the 'V' formation are shown in Table 4. The speed of virtual leader is set as 0.2 km/s and the simulation time is 200 s.

The UAV group follows the virtual leader as seen in Figure 8. The five UAVs reconfigure from a '|' initial shape into g a 'V' formation and the UAV group is travelling from left to right in the figure. Under the control inputs generated by trophallaxis network, the multiple UAVs successfully achieved the task of formation keeping. Figures 8 (b)–(e) show the responses of UAVs relative distance, speed and heading angle, respectively. It is obvious that the group converges in 150 s.

5 Conclusion

In this paper, we have proposed a novel multiple UAVs formation flight scheme, which is based on the trophallaxis

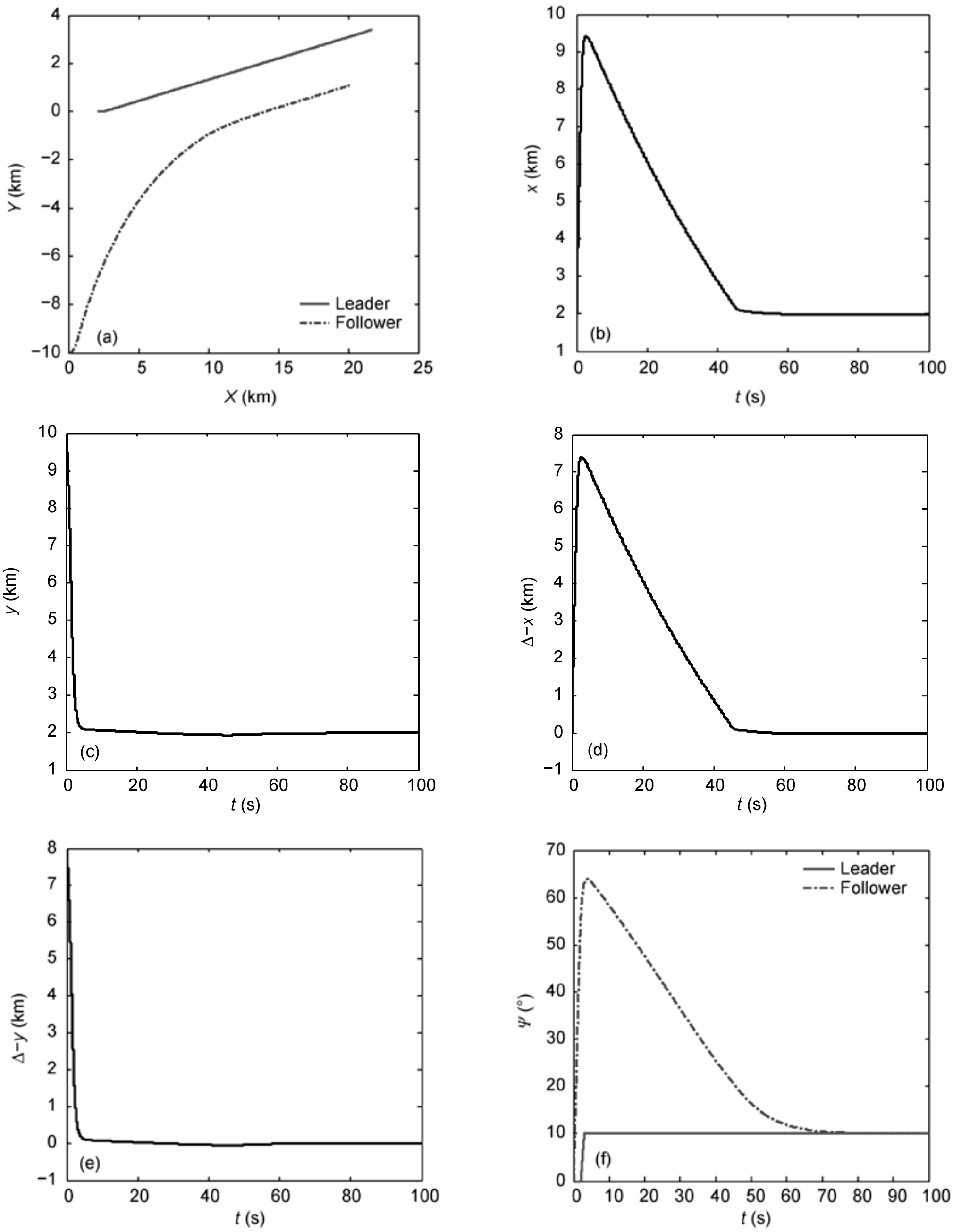

Figure 7 Experimental results of formation based on PD controller. (a) Flight trajectories of leader-follower formation; (b) Relative distance (x) of X-axis; (c) Relative distance (y) of Y-axis; (d) Deviation distance (Δx) of X-axis; (e) Deviation distance (Δy) of Y-axis; (f) Responses of heading angle (Ψ).

Table 3 UAVs initial states

	Position (km)	Speed (km/s)	Heading angle (°)	Sample time (s)	Network transmission time (s)
Virtual leader	(2, 100)	0.2	–0.5	0.1	0
UAV 1	(0, 95)	0.2	0.5	0.1	0.05
UAV 2	(0, 115)	0.2	–0.5	0.2	0.1
UAV 3	(0, 80)	0.2	–0.5	0.1	0.12
UAV 4	(0, 125)	0.2	–0.1	0.2	0.05
UAV 5	(0, 70)	0.2	0.1	0.1	0.1

Table 4 Formation flight requirements

	Leader	Relative distance in the X direction (km)	Relative distance in the Y direction (km)
UAV 1	Virtual leader	2	0
UAV 2	UAV 1	2	–2
UAV 3	UAV 1	2	2
UAV 4	UAV 2	2	–2
UAV 5	UAV 3	2	2

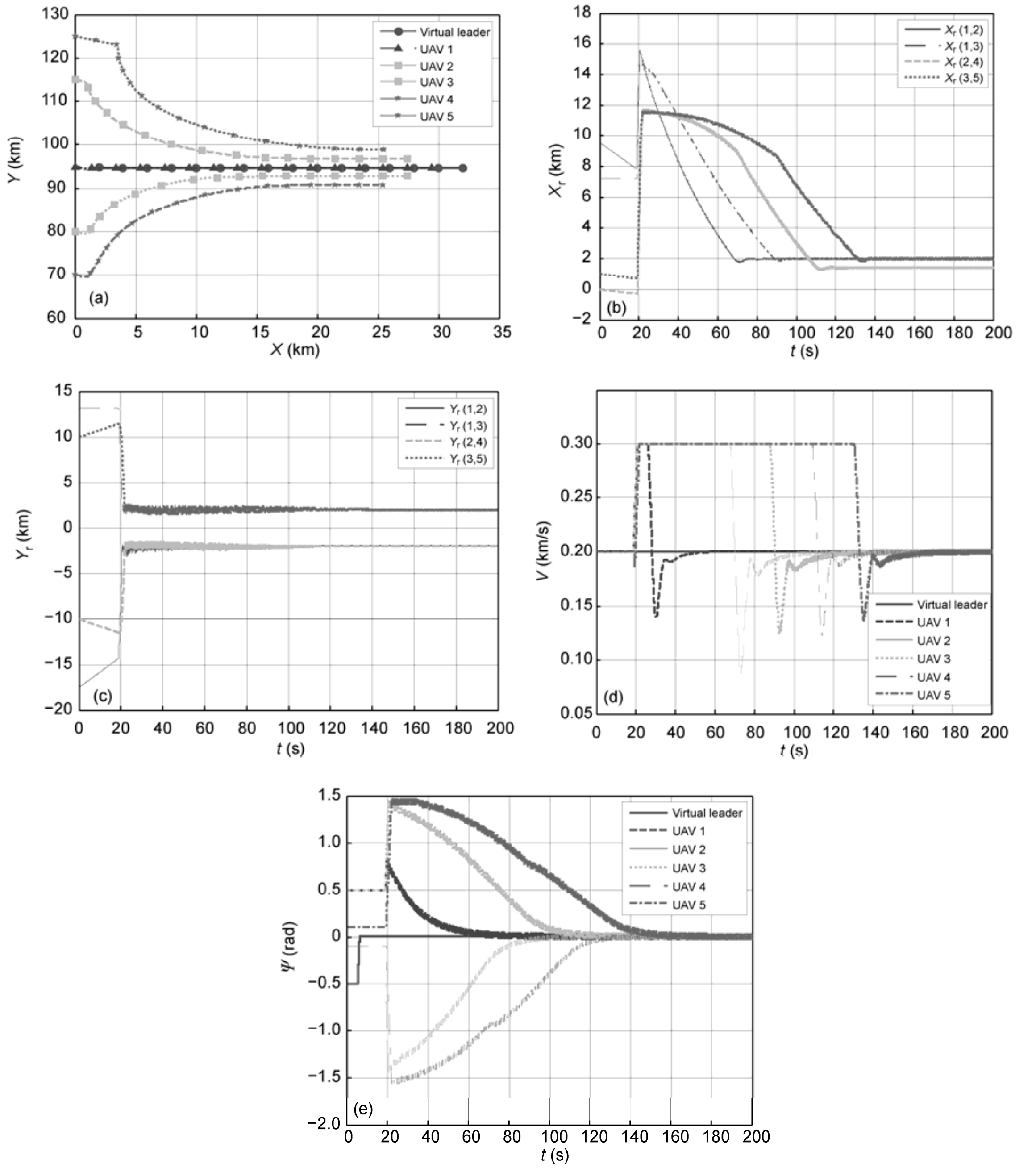

Figure 8 Experimental results of formation flight. (a) Five UAVs merge to a *V*-formation while following a virtual leader; (b) Relative distances (X_r) of *X*-axis; (c) Relative distances (Y_r) of *Y*-axis; (d) Velocity (*V*) responses of five UAVs; (e) Heading angle (Ψ) responses of five UAVs.

network control. The effect of network induced delay on the multiple UAVs control system performance is analyzed, and experimental results show the feasibility and effectiveness of our proposed approach. In the experiments, the proposed method was applied to five UAVs for achieving a 'V' formation by tracking the virtual leader.

Our future work will focus on applying the new approach in this paper to real-world multiple UAVs formation flight. The proposed approach can also be applied to formation flight of unmanned ground vehicles, satellites and unmanned underwater vehicles.

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