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Tight formation control of multiple unmanned aerial vehicles through an adaptive control method

Yin WANG[1,2*] & Daobo WANG[3]

[1]*State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, Beijing* 100191*, China;*
[2]*College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing* 210016*, China;*
[3]*College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing* 210016*, China*

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Cooperative formation control for unmanned aerial vehicles (UAV) is a fundamental yet essential component toward the development of high-level autonomous flight control systems. When UAVs are flying in a tight formation, the power requirements for the following aircraft(s) can be significantly reduced because of the vortices effect of the leading aircraft. However, this also introduces an aerodynamic interaction to the formation dynamics, complicating the formation control problem. Formation control methods can be categorized into leader/follower-based algorithms, virtual structures [1], and behavioral approaches [2]. For a comprehensive review on the recent developments of formation control problem, refer to [3]. When the UAVs are flying in a tight formation, the aerodynamics coupling effect between each aircraft cannot be ignored [4]. Binetti et al. [5] proposed to model the formation dynamic interactions as nonlinear state feedbacks, and developed the inner-loop controller of the follower based on the extremum seeking algorithm. Dong et al. [6] analyzed the UAV control characteristics to the relative motion of the formation flight in the path-coordinated frame, and obtained the control law of the follower by using the Lyapunov stability theorem. Duan et al. [7] proposed solving the formation reconfiguration task as a parameter optimization problem, and presented a hybrid stochastic optimizer to determine the formation controller. In this study, a hybrid particle Swarm optimization and genetic algorithm is proposed to solve the multi-UAV formation reconfiguration problem, which is modeled as a parameter optimization problem. This new approach combines the advantages of particle swarm optimization and genetic algorithm to determine time-optimal solutions simultaneously.

The adaptive formation control scheme. We assume that the leader aircraft shares its motion parameters, i.e., the heading direction and speed to its followers. The follower then estimates the relative positions $(x,\ y)$ to the leader aircraft based on measured data (ψ_W, V_W). The formation controller calculates the motion commands (ψ_c, V_c) for each follower aircraft based on the desired formation distance (x_c, y_c). In the following section, we focus on the development of an adaptive control algorithm for the formation controller. In this paper, the vortices effects to the following aircraft can be defined as the drag incremental factor $\Delta f_v(\cdot)$ and lateral force factor $\Delta f_\psi(\cdot)$, respectively [8].

Let x_c, y_c denote the desired relative position of the leader and follower aircraft, and x, y represent

* Corresponding author (email: yinwangee@nuaa.edu.cn)
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the feedback positions, the formation error can be defined as

$$e = \begin{bmatrix} e_x \\ e_y \end{bmatrix} = \begin{bmatrix} x_c - x \\ y_c - y \end{bmatrix}. \quad (1)$$

The derivative of (1) can be calculated as

$$\begin{aligned} \dot{e} &= \begin{bmatrix} \dot{e}_x \\ \dot{e}_y \end{bmatrix} = A(\psi_{i-1}, \psi_i) + R(x, y) \begin{bmatrix} V_i \\ \dot{\psi}_i \end{bmatrix}, \\ A &= \begin{bmatrix} V_{i-1}\cos(\psi_{i-1} - \psi_i) \\ V_{i-1}\sin(\psi_{i-1} - \psi_i) \end{bmatrix}, \\ R &= \begin{bmatrix} -1, & y \\ 0, & -x \end{bmatrix} \begin{bmatrix} V_i \\ \dot{\psi}_i \end{bmatrix}. \end{aligned} \quad (2)$$

The formation position error in inertial reference coordinate is

$$\begin{aligned} E &= \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \cos\psi_i & -\sin\psi_i \\ \sin\psi_i & \cos\psi_i \end{bmatrix} \begin{bmatrix} e_x \\ e_y \end{bmatrix} \\ &= B(\psi_i) \begin{bmatrix} e_x \\ e_y \end{bmatrix}. \end{aligned} \quad (3)$$

The formation position error defined in inertial coordinate can be thus defined as

$$\dot{E} = BA + C \begin{bmatrix} V_i \\ \dot{\psi}_i \end{bmatrix}, \quad (4)$$

where

$$C = BR + \frac{\partial B}{\partial \dot{\psi}_i} \begin{bmatrix} \dot{e}_x \\ \dot{e}_y \end{bmatrix} [0 \quad 1].$$

The second order derivative of formation position error defined in inertial coordinate is

$$\begin{aligned} \ddot{E} &= CG\left(\begin{bmatrix} V_{ci} \\ \psi_{ci} \end{bmatrix} - \begin{bmatrix} V_i \\ \psi_i \end{bmatrix}\right) + D + C \begin{bmatrix} \Delta f_v(\cdot) \\ \Delta f_\psi(\cdot) \end{bmatrix}, \\ D &= \begin{bmatrix} \dot{V}_i - \dot{\psi}_{i-1} V_{i-1} \\ \dot{V}_i + \dot{\psi}_{i-1} V_{i-1} \end{bmatrix} B(\psi_{i-1}) + \dot{C} \begin{bmatrix} V_i \\ \dot{\psi}_i \end{bmatrix}, \\ G &= \mathrm{diag}(g_v, g_\psi), \end{aligned} \quad (5)$$

where (ψ_{W_C}, V_{W_C}) denote the input heading and speed command of the follower to its autopilot, (g_v, g_ψ) are the gain of speed and heading control loop, respectively. In this paper, we consider the vortices effect is unknown and design an adaptive formation control law that is capable of estimating the changing disturbance. We assume the aerodynamic coupling effects $\Delta f_v(\cdot)$ and $\Delta f_\psi(\cdot)$ are unknown but bounded functions,

$$|\Delta f_v(\cdot) - \Delta f_{vN}(\cdot)| \leqslant \Delta \tilde{f}_v,$$

$$|\Delta f_\psi(\cdot) - \Delta f_{\psi N}(\cdot)| \leqslant \Delta \tilde{f}_\psi. \quad (6)$$

We define the input commands $\boldsymbol{u}$ for the formation control as

$$\begin{aligned} u = \begin{bmatrix} V_{ci} \\ \psi_{ci} \end{bmatrix} &= -(CG)^{-1}\left[D + k_1\dot{E} + k_2 E\right] \\ &\quad - (CG)^{-1}\left[CG \begin{bmatrix} -V_i \\ -\psi_i \end{bmatrix} \right. \\ &\quad \left. + C \begin{bmatrix} \Delta f_v(\cdot) \\ \Delta f_\psi(\cdot) \end{bmatrix}\right]. \end{aligned} \quad (7)$$

According to (5),

$$\ddot{E} + k_1\dot{E} + k_2 E = 0,$$

where k_1 and k_2 are positive constants, we need to design the command inputs $\boldsymbol{u}$ such that the formation position tracking error can be converge to zero,

$$\ddot{E} = CG\left(\begin{bmatrix} V_{ci} \\ \psi_{ci} \end{bmatrix} - \begin{bmatrix} V_i \\ \psi_i \end{bmatrix}\right) + D + C \begin{bmatrix} \Delta f_v \\ \Delta f_\psi \end{bmatrix}. \quad (8)$$

Since $\det(\boldsymbol{CG}) = g_v g_\psi x_c$ and $g_v g_\psi x_c \neq 0$, $(\boldsymbol{CG})^{-1}$is computable, thus the control inputs $\boldsymbol{u}$ can be determined. As shown in (6), the control inputs contains unknown components, we therefore need to estimate the unknown vortices effects,

$$\begin{aligned} u = \begin{bmatrix} V_{ci} \\ \psi_{ci} \end{bmatrix} &= -(CG)^{-1}\left[D + k_1\dot{E} + k_2 E\right] \\ &\quad - (CG)^{-1}\left[C \begin{bmatrix} \Delta \hat{f}_v(\cdot) \\ \Delta \hat{f}_\psi(\cdot) \end{bmatrix} \right. \\ &\quad \left. + CG \begin{bmatrix} -V_i \\ -\psi_i \end{bmatrix}\right]. \end{aligned} \quad (9)$$

According to (7) and (8), the formation position error,

$$\begin{aligned} \bar{E} &= [\dot{E} \quad \ddot{\mathrm{E}}]^{\mathrm{T}} \\ &= A\bar{E} + C_v(\Delta \hat{f}_v(\cdot) - \Delta f_v(\cdot)) \\ &\quad + C_\psi(\Delta \hat{f}_\psi(\cdot) - \Delta f_\psi(\cdot)), \end{aligned} \quad (10)$$

where

$$A = \begin{bmatrix} 0_{2\times2} & I_{2\times2} \\ -k_2 I_{2\times2} & -k_1 I_{2\times2} \end{bmatrix} C_v = \begin{bmatrix} 0 \\ 0 \\ \cos\psi \\ \sin\psi \end{bmatrix},$$

$$C_\psi = \begin{bmatrix} 0 \\ 0 \\ -x_c\sin\psi_i - y_c\cos\psi_i \\ -x_c\cos\psi_i - y_c\sin\psi_i \end{bmatrix}. \quad (11)$$

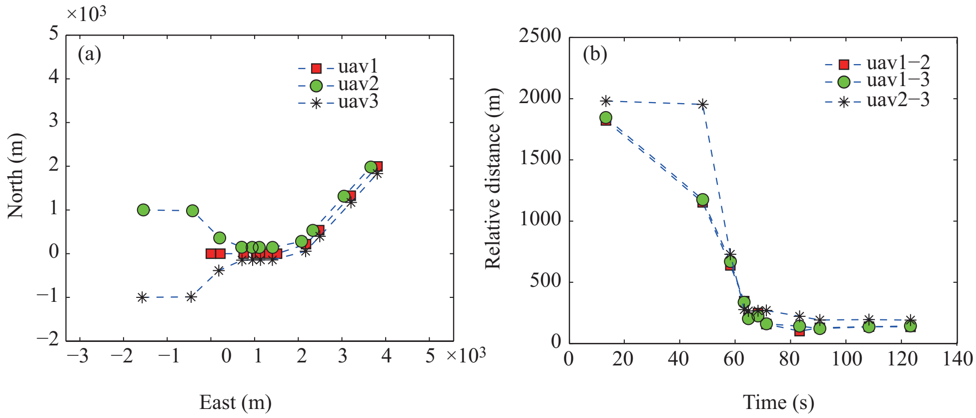

Figure 1 (Color online) The top view of the formation flight trace (a) and the relative distances (b) between UAVs.

If the formation error $\bar{E} = [\dot{E} \quad \ddot{E}]^{\mathrm{T}}$ approaches to zero, the formation of the UAVs is able to form the desired geometry. Assuming that P and Q are positive definite matrices. P is the solution to the Lyapunov function $A^{\mathrm{T}}P + PA = -Q$, if $\Delta\hat{f}_v$ and $\Delta\hat{f}_\psi$ satisfy the following conditions:

$$\begin{aligned}\Delta\hat{f}_v &= \Delta f_{vN} - \Delta\tilde{f}_v \mathrm{sign}(C_v^{\mathrm{T}} P\bar{E}),\\ \Delta\hat{f}_\psi &= \Delta f_{\psi N} - \Delta\tilde{f}_\psi \mathrm{sign}(C_\psi^{\mathrm{T}} P\bar{E}).\end{aligned} \tag{12}$$

Let the Lyapunov function with the following form:

$$V = \frac{1}{2}\bar{E}^{\mathrm{T}} P\bar{E}. \tag{13}$$

The gradient of the associated Lyapunov function can be computed as

$$\begin{aligned}V \leqslant & -\frac{1}{2}\bar{E}^{\mathrm{T}}Q\bar{E} - \left|\bar{E}^{\mathrm{T}}PC_v\Delta\tilde{f}_v\right| - \left|\bar{E}^{\mathrm{T}}PC_\psi\Delta\tilde{f}_\psi\right|\\ & + \left|\bar{E}^{\mathrm{T}}PC_v\Delta\tilde{f}_v\right| + \left|\bar{E}^{\mathrm{T}}PC_\psi\Delta\tilde{f}_\psi\right|\\ \leqslant & -\frac{1}{2}\bar{E}^{\mathrm{T}}Q\bar{E} < 0.\end{aligned}$$

Thus, the formation position error can converge to zero, i.e., $\bar{E} \to 0, E \to 0$, which indicates the proposed adaptive control law is able to enforce the formation to desired geometric pattern.

Simulation and analysis. Assuming that a group of UAVs consists of three aircrafts, a leader and two followers, forming a triangular formation. The initial relative positions between each UAV are 1000 m. During the simulation, the leader aircraft is flying according to the pre-defined path, and the followers are required to track the leading aircraft to form a tight formation. The required formation distance between each UAV is 150 m. The simulation results are shown in Figures 1(a) and (b). In the first segment of the path, the leader is flying with constant speed and heading, while the followers are far away behind the leader aircraft. It can be seen from these figures that the proposed formation controller is able to form a desired geometric pattern of the formation. In the second segment of flight, the leader aircraft makes a left turn by 50° to the north, the proposed formation controller can adjust the speeds of two followers to track the path of the leader and keep the geometric pattern of the formation.

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