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ADAPTIVE FUZZY DISTRIBUTED FORMATION CONTROL FOR MULTIPLE UNMANNED HELICOPTERS

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Abstract. *This paper studies the adaptive fuzzy formation control problem for multiple unmanned helicopters. The desired ultimate position information is introduced into the consensus error; thus, the formation control can be carried out. The unknown dynamics in the modeling process is approximated by FLSs. Combining with backstepping recursive design, an adaptive fuzzy formation control algorithm is developed. Based on Lyapunov stability theory, the boundedness of the closed-loop signals and the formation error convergence can be guaranteed, respectively.*

Keywords: Fuzzy formation control, Unmanned helicopter, Backstepping recursive design

1. **Introduction.** The unmanned system is an important class of system, it is because many difficult and dangerous tasks can be completed by unmanned system, and thus humans do not need to take a risk to complete these tasks. Many unmanned systems have been widely used in practical engineering, such as the formation of unmanned aerial vehicle (UAV) [1], and the information consensus of multiple unmanned vehicle [2].

As the unmanned system becomes more and more attractive, the control study for unmanned system is also popular, especially for the formation control. The time-varying formation control design has been studied in [3] for unmanned vehicle, the formation information is introduced into the consensus error, and thus the convergence of consensus error can guarantee that the formation control can be achieved. Subsequently, the authors in [4] extend the work in [3] to the formation control problem under the switching topology. A leader-follower formation control problem has been investigated in [5] for unmanned aircraft systems, for which, the communication among all aircraft is not needed. The leader-follower fault-tolerant formation control problem is also studied in [6] for UAV, the actuator faults and potential collisions are all considered in the controlled system, and the developed controllers are divided into the outer-loop controller and inner-loop controller.

Recently, the intelligent control method has been recognized as an effective control method for the unmanned systems. The fuzzy logic systems (FLSs) and radial basis function neural networks (RBFNNs) can effectively deal with the unknown dynamics existing in the modeling process; thus, many adaptive fuzzy formation control results have been achieved in [7,8] for unmanned systems. In [7], the authors have studied the adaptive fuzzy formation control problem of unmanned surface vehicles, the considered unmanned surface vehicles contain unknown model nonlinearity and actuator saturation, and the unknown model nonlinearity and actuator saturation are solved by using the FLSs and auxiliary system, respectively. A neural network-based control method is proposed to achieve the formation control in [8] for second-order autonomous unmanned systems, and two cases are considered in the formation control design, that is, the velocity of leader is

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constant and time-varying function. Although many research achievements for the formation control of unmanned systems have been obtained, the formation control of unmanned helicopter is always ignored. The formation control study for unmanned helicopter is also necessary, and it plays an important role in search-and-rescue and war. The authors in [9] have studied the control problem of unmanned helicopter, but the control study is for single unmanned helicopter. Two classes of formation control problems have been investigated in [10] for multiple unmanned helicopters via sliding mode control, but the intelligent control approach to the formation for multiple unmanned helicopters is less reported. Motivated by the above works, an adaptive fuzzy formation control algorithm has been developed for multiple unmanned helicopters. Its main contributions can be summarized as the following.

1) With the help of the approximated technique benefiting from FLSs, the unknown dynamics existing in the modeling process have been handled successfully.

2) A novel formation control algorithm has been developed for unmanned vehicle by using intelligent control method instead of the sliding control one in [10]. Although the authors in [9] have studied the control problem of unmanned helicopter, the formation control problem cannot be solved.

2. **Problem Statement and Preliminaries.**

2.1. **The kinematics equations of attitude for helicopter.** As stated in [9], the attitude of helicopter can be expressed as a quaternion, and it has the following form

$$k = \lambda_1 i + \lambda_2 j + \lambda_3 k + \lambda_4 = [\lambda_1\ \lambda_2\ \lambda_3\ \lambda_4]^T = \begin{bmatrix} u \sin\dfrac{\beta}{2} \\ [0.6hl]\cos\dfrac{\beta}{2} \end{bmatrix} = \begin{bmatrix} \delta \\ \zeta \end{bmatrix} \tag{1}$$

where $u = [u_x\ u_y\ u_z]^T$ denotes the unite vector and its norm is equal to one. β denotes the direction angular, h and l are suitable constants with $hl = 5/3$, δ and ζ represent a vector and a scalar, respectively. Thus, the direction cosine matrix parameterized by quaternion k can be expressed as

$$\begin{aligned} M(k) &= I - 2\delta^T\delta I + 2\delta\delta^T + 2\zeta\Lambda(\delta) \\ &= I + 2\zeta\Lambda(\delta) + 2\Lambda^2(\delta) \\ &= \begin{bmatrix} \lambda_1^2+\lambda_4^2-\lambda_2^2-\lambda_3^2 & 2(\lambda_1\lambda_2+\lambda_3\lambda_4) & 2(\lambda_1\lambda_3-\lambda_2\lambda_4) \\ 2(\lambda_1\lambda_2-\lambda_3\lambda_4) & \lambda_2^2+\lambda_4^2-\lambda_1^2-\lambda_3^2 & 2(\lambda_2\lambda_3+\lambda_1\lambda_4) \\ 2(\lambda_1\lambda_3-\lambda_2\lambda_4) & 2(\lambda_2\lambda_3-\lambda_1\lambda_4) & \lambda_3^2+\lambda_4^2-\lambda_1^2-\lambda_2^2 \end{bmatrix} \end{aligned} \tag{2}$$

where $I \in R^{3\times3}$ is an identity matrix. $\Lambda \in R^{3\times3}$ represents a skew symmetric matrix, which can be described as

$$\Lambda(\delta) = \begin{bmatrix} 0 & -\delta_3 & \delta_2 \\ \delta_3 & 0 & -\delta_1 \\ -\delta_2 & \delta_1 & 0 \end{bmatrix} \tag{3}$$

The derivative of the quaternion can be written as

$$\dot{k} = \begin{bmatrix} \dot{\delta} \\ \dot{\zeta} \end{bmatrix} = \frac{1}{2}K(k)w \tag{4}$$

with $K(k) = \begin{bmatrix} \zeta I + \Lambda(\delta) \\ -\delta^T \end{bmatrix} = \begin{bmatrix} K_1(k) \\ -\delta^T \end{bmatrix} = \begin{bmatrix} \lambda_4 & -\lambda_3 & -\lambda_2 \\ \lambda_3 & \lambda_4 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & \lambda_4 \\ -\lambda_1 & -\lambda_2 & -\lambda_3 \end{bmatrix}$. $w = [w_x\ w_y\ w_z]^T \in R^3$ is the angular velocity in the body-fixed frame. The error attitude matrix is given as

$K_e = K_d K^T$, and the unit quaternion of K_e is expressed as $k_e = [\delta_e, \zeta_e]^T$. Similar to [10], the error kinematic is defined as

$$\dot{k}_e = \frac{1}{2} K(k_e) w = \frac{1}{2} \begin{bmatrix} K_1(k_e) \\ -\delta_e^T \end{bmatrix} w \tag{5}$$

The key control objective is to design a controller ω which can guarantee the stability of quaternion error dynamics and $k_e = [0\ 0\ 0\ 1]^T$ with $\|\delta_e\| = 0$ and $\|\zeta_e\| = 1$.

Lemma 2.1. [9] *With respect to the error kinematics (5), if the controller ω is designed as*

$$\omega = -c_w \left(K_1^T(k_e) + (1 - \zeta_e) I \right) \delta_e = -c_w \delta_e \tag{6}$$

then, for any given positive constant c_w, k_e will converge to $[0\ 0\ 0\ 1]^T$.

Lemma 2.2. [7] *For any continuous function $\rho(\upsilon)$ defined over a compact set Λ, and any given positive constant ψ, there always exists an FLS $\hat{\rho}(\upsilon|\mu^*) = \mu^{*T}\phi(\upsilon)$ such that*

$$\sup_{\upsilon \in \Lambda} \left| \rho(\upsilon) - \mu^{*T}\phi(\upsilon) \right| \leq \psi \tag{7}$$

where $\phi_i(\upsilon)$ are fuzzy basis functions, and they are usually chosen as Gaussian functions. $\phi(\upsilon) = [\phi_1(\upsilon), \phi_2(\upsilon), \ldots, \phi_N(\upsilon)]^T \big/ \sum_1^N \phi_i(\upsilon)$ are the fuzzy basis function vectors and satisfy that $0 < \phi^T(\upsilon)\phi(\upsilon) \leq 1$. $\mu^* = [\mu_1^*, \mu_2^*, \ldots, \mu_N^*]^T$ denotes the ideal weight vector and N is the fuzzy rules number.

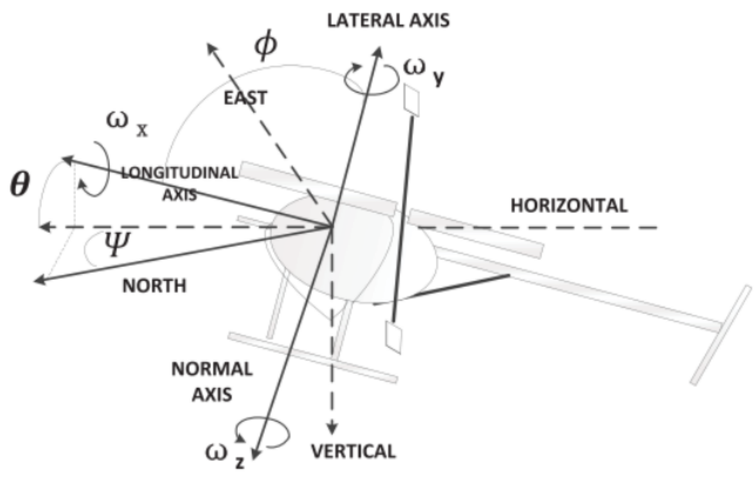

FIGURE 1. The structure of unmanned helicopter

2.2. **The developed dynamic model structure.** As shown in Figure 1, the unmanned helicopter contains six degrees of freedom, that is, the position $d = [d_x\ d_y\ d_z]^T \in R^3$ and the attitude $[\theta\ \phi\ \varphi]^T \in R^3$. The linear velocity and the angular velocity are expressed as $v = [v_x\ v_y\ v_z]^T \in R^3$ and $w = [w_x\ w_y\ w_z]^T \in R^3$, respectively. Therefore, the kinematic model of helicopter can be written as

$$\dot{d} = K(k)v \tag{8}$$

and

$$\dot{k} = \frac{1}{2} K(k) w \tag{9}$$

where $K(k)$ is the direction cosine matrix, and it satisfies $\|K(k)\|_2 \leq \beta$. With the help of (8) and (9), the proposed linear and angular accelerations of our model contain the following relationship:

$$\dot{v} = -S(w)v + M^T f + Gv + B_1 u_1 + \Delta_1 + d_v(s, \theta_1)$$

$$\dot{w} = A^{-1}S(Aw)w + Cw + B_2u_2 + \Delta_2 + d_w(s, \theta_2) \tag{10}$$

where $f = [0\ 0\ f_0]^T \in R^3$ is the gravity, $A \in R^{3\times3}$ denotes a symmetric positive define inertial matrix. $u_1 = [0\ 0\ u_4]^T \in R^3$ and $u_2 = [u_1\ u_2\ u_3]^T \in R^3$ are the control input to drive the unmanned helicopter. $G = diag[g_1\ g_2\ g_3] \in R^{3\times3}$, $C = diag[c_1\ c_2\ c_3] \in R^{3\times3}$, $B_1 \in R$, and $B_2 = diag[b_{21}\ b_{22}\ b_{23}] \in R^{3\times3}$, $\Delta_1 = diag[0\ 0\ \Delta_{13}] \in R^{3\times3}$ and $\Delta_2 = diag[\Delta_{21}\ \Delta_{22}\ \Delta_{23}] \in R^{3\times3}$ are the coefficients confirmed by flight data through the method in [10]. $d_v \in R^3$ and $d_w \in R^3$ denote the uncertainties in the modeling process, which can be approximated by the FLSs.

3. **Distributed Adaptive Fuzzy Formation Control of Unmanned Helicopter and Stability Analysis.** In this section, the desired position information of each unmanned helicopter is introduced into the consensus error, and the nonlinear dynamics caused by modeling process are approximated by using FLSs. Combining with backstepping recursive design, an adaptive fuzzy controller is developed to achieve the formation of unmanned helicopters. Based on the Lyapunov stability theorem, all the signals in closed-loop are guaranteed to be bounded, and the formation error convergence can be guaranteed.

The developed control algorithm is based on two steps backstepping technique, its basic coordinate transformation is defined as

$$z_{i,1} = \sum_{j=1}^{N} a_{i,j}(d_i + \rho_i - d_j - \rho_j) + b_{i,0}(d_i + \rho_i - y_r) \tag{11}$$

$$z_{i,2} = v_i - \alpha_{i,1} \tag{12}$$

$$e_i = w - k_w\zeta_e \tag{13}$$

where $z_{i,1} \in R^3$ denotes the formation error, and $e_i \in R^3$ represents the attitude error. $\alpha_{i,1} \in R^3$ is an immediate control signal.

Step 1: From (8), the derivative of position of unmanned helicopter r_i can be expressed as

$$\dot{d}_i = Mv_i = M(z_{i,2} + \alpha_{i,1}) \tag{14}$$

Consider the following Lyapunov function as

$$V_1 = \frac{1}{2}\sum_{i=1}^{N} z_{i,1}^T z_{i,1} \tag{15}$$

Combining (14) and (15), it can be shown that

$$\begin{aligned}\dot{V}_1 &= \sum_{i=1}^{N} z_{i,1}^T \dot{z}_{i,1} \\ &= \sum_{i=1}^{N} z_{i,1}^T \left(\sum_{j=1}^{N} a_{i,j}\left(Mz_{i,2} + M\alpha_{i,1} + \dot{\rho}_i - Mv_j - \dot{\rho}_j\right) + b_{i,0}\left(Mz_{i,2} + M\alpha_{i,1} - \dot{y}_r\right)\right)\end{aligned} \tag{16}$$

Design the virtual controller $\alpha_{i,1}$ as

$$\alpha_{i,1} = (pM)^{-1}\left[-c_{i,1}z_{i,1} - \sum_{j=1}^{N} a_{i,j}\left(\dot{\rho}_i - Mv_j - \dot{\rho}_j\right) + b_{i,0}\dot{y}_r\right] \tag{17}$$

where $c_{i,1} \in R^3$ is positive design parameter vector, $p = \sum_{j=1}^{N} a_{i,j} + b_{i,0}$.

The derivative of V_1 satisfies

$$\dot{V}_1 \le \sum_{i=1}^{N} \left\{-c_{i,1}z_{i,1}^T z_{i,1} + pz_{i,1}^T Mz_{i,2}\right\} \tag{18}$$

Step 2: With the help of (10) and (12), the derivative of v_i can be written as

$$\dot{v}_i = -A^{-1}S(Aw_i)w_i + M^T f + Gv + B_i u_1 + \Delta_1 + d_v(s, \theta_1) \tag{19}$$

Since the nonlinear dynamics $d_v(s, \theta_1) \in R^3$ is unknown, an FLS is utilized to approximate it as

$$d_v(s, \theta_1) = W_i^T \varphi_i(s, \theta_1) + \varepsilon_i \tag{20}$$

where $\varepsilon_i \in R^3$ denotes the approximate error, and there exists an unknown constant ε_i^* such that $\|\varepsilon_i\| \leq \varepsilon_i^*$.

Construct the following Lyapunov function as

$$V_2 = V_1 + \sum_{i=1}^{N} \left\{ \frac{1}{2} z_{i,2}^T z_{i,2} + \frac{1}{2} tr \left\{ \tilde{W}_i^T \gamma_i^{-1} \tilde{W}_i \right\} \right\} \tag{21}$$

with γ_i being a design parameter matrix.

Then the derivative of V_2 satisfies

$$\begin{aligned} V_2 &= \dot{V}_1 + \sum_{i=1}^{N} \left\{ z_{i,2}^T \dot{z}_{i,2} - tr \left\{ \tilde{W}_i^T \gamma_i^{-1} \dot{\hat{W}}_i \right\} \right\} \\ &= \dot{V}_1 + \sum_{i=1}^{N} \left\{ z_{i,2}^T \left(-S(w_i)v_i + M^T f + Gv + B_i u_1 + \Delta_1 + W_i^T \varphi_i(s, \theta_1) + \varepsilon_i \right) \right. \\ &\quad \left. - tr \left\{ \tilde{W}_i^T \gamma_i^{-1} \dot{\hat{W}}_i \right\} \right\} \end{aligned} \tag{22}$$

Design the controller $u_{i,1}$ and the parameter adaptive law of $\hat{W}_i$ as

$$\begin{aligned} u_1 &= B_1^T \left(-c_{i,2} z_{i,2}^2 - z_{i,2}/2 - z_{i,1} \left(\sum_{j=1}^{N} a_{i,j} + b_{i,0} \right) M + S(w_i)v_i - M^T f - Gv - \Delta_1 \right. \\ &\quad \left. - \hat{W}_i^T \varphi_i(s, \theta_1) \right) \end{aligned} \tag{23}$$

$$\dot{\hat{W}}_i = \gamma_i \varphi_i(s, \theta_1) z_{i,2}^T - \sigma_i \hat{W}_i \tag{24}$$

where $c_{i,2} > 0$ and $\sigma_i > 0$ are positive parameters.

Substituting (23) and (24) into (22) yields

$$V_2 \leq \sum_{i=1}^{N} \left\{ \sum_{j=1}^{2} -c_{i,j} z_{i,j}^T z_{i,j} + tr \left\{ \tilde{W}_i^T \gamma_i^{-1} \sigma_i \hat{W}_i \right\} + \Upsilon_i \right\} \tag{25}$$

where $\Upsilon_i = \frac{1}{2}\varepsilon_i^{*2}$.

Taking (10) and (13) into account, the derivative of w can be expressed as

$$\dot{w}_i = A^{-1}S(Aw)w + Cw + B_2 u_2 + \Delta_2 + \tilde{\Theta}_i^T \varphi_i(s, \theta_2) + \bar{\varepsilon}_i \tag{26}$$

To prove the stability of attitude error system, construct the following Lyapunov function

$$V_3 = \sum_{i=1}^{N} \left\{ \frac{1}{2} e_i^T e_i + \frac{1}{2} tr \left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \tilde{\Theta}_i \right\} \right\} \tag{27}$$

where ς_i is a design parameter matrix.

From (26) and (27), we can obtain

$$\dot{V}_3 = \sum_{i=1}^{N} \left\{ e_i^T \dot{e}_i - tr \left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \dot{\hat{\Theta}}_i \right\} \right\}$$

$$= \sum_{i=1}^{N} \left\{ e_i^T \left(A^{-1}S(Aw)w + Cw + B_2u_2 + \Delta_2 + \Theta_i^T \varphi_i(s,\theta_2) + \bar{\varepsilon}_i \right) - tr\left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \dot{\hat{\Theta}}_i \right\} \right\} \tag{28}$$

Since the nonlinear dynamics $d_w(s,\theta_1) \in R^3$ is unknown, an FLS is utilized to approximate it as

$$d_w(s,\theta_1) = \Theta_i^T \varphi_i(s,\theta_2) + \bar{\varepsilon}_i \tag{29}$$

where $\bar{\varepsilon}_i \in R^3$ denotes the approximate error, and there exists an unknown constant $\bar{\varepsilon}_i^*$ such that $\|\bar{\varepsilon}_i\| \le \bar{\varepsilon}_i^*$.

Design the controller u_2 and the adaptive law of $\hat{\Theta}_i$ as

$$u_2 = B_2^{-1}\left(-\bar{c}_i e_i - A^{-1}S(Aw)w - Cw - \Delta_2 - \hat{\Theta}_i^T \varphi_i(s,\theta_2) \right) \tag{30}$$

$$\dot{\hat{\Theta}}_i = \varsigma_i \varphi_i(s,\theta_2) e_i^T - \bar{\sigma}_i \hat{\Theta}_i \tag{31}$$

where $\bar{c}_i$ and $\bar{\sigma}_i$ are positive design parameters.

Substituting (30) and (31) into (28) yields

$$\dot{V}_3 \le \sum_{i=1}^{N} \left\{ -\bar{c}_i e_i^T e_i + tr\left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \bar{\sigma}_i \hat{\Theta}_i \right\} + \bar{d}_i \right\} \tag{32}$$

where $\bar{d}_i = \frac{1}{2}\|\bar{\varepsilon}_i\|^{*2}$.

Theorem 3.1. *For unmanned helicopter system (10), under Lemma 2.1, and Lemma 2.2, if the virtual controller is designed as (23) and (30), the actual controllers are designed as (17), and the parameter adaptive laws are designed as (24) and (31), the developed control scheme can guarantee that all the signals in closed-loop system are bounded, and the formation error will converge to zero.*

Proof: Consider the following Lyapunov function

$$V = V_2 + V_3 \tag{33}$$

From (25) and (32), we have

$$\dot{V} \le \sum_{i=1}^{N} \left\{ -\bar{c} e_i^T e_i + tr\left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \bar{\sigma}_i \hat{\Theta}_i \right\} + \bar{d} - \sum_{j=1}^{2} c_{i,j} z_{i,j}^T z_{i,j} + tr\left\{ \tilde{W}_i^T \gamma_i^{-1} \sigma_i \hat{W}_i \right\} + \Upsilon_i \right\} \tag{34}$$

Based on Young's inequality, one has

$$tr\left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \bar{\sigma}_i \hat{\Theta}_i \right\} \le -\frac{1}{2} tr\left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \bar{\sigma}_i \tilde{\Theta}_i \right\} + \frac{1}{2} tr\left\{ \Theta_i^T \varsigma_i^{-1} \bar{\sigma}_i \Theta_i \right\} \tag{35}$$

$$tr\left\{ \tilde{W}_i^T \gamma_i^{-1} \sigma_i \hat{W}_i \right\} \le -\frac{1}{2} tr\left\{ \tilde{W}_i^T \gamma_i^{-1} \sigma_i \tilde{W}_i \right\} + \frac{1}{2} tr\left\{ W_i^T \gamma_i^{-1} \sigma_i W_i \right\} \tag{36}$$

Substituting (35) and (36) into (34) yields

$$\dot{V} \le \sum_{i=1}^{N} \left\{ -\bar{c}_i e_i^T e_i - \frac{1}{2} tr\left\{ \tilde{\Theta}_i^T \varsigma_i^{-1} \bar{\sigma}_i \tilde{\Theta}_i \right\} - \sum_{j=1}^{2} c_{i,j} z_{i,j}^2 - \frac{1}{2} tr\left\{ \tilde{W}_i^T \gamma_i^{-1} \sigma_i \tilde{W}_i \right\} + D_i \right\} \tag{37}$$

where $D_i = \frac{1}{2} tr\left\{ W_i^T \gamma_i^{-1} \sigma_i W_i \right\} + \frac{1}{2} tr\left\{ \Theta_i^T \varsigma_i^{-1} \bar{\sigma}_i \Theta_i \right\} + \Upsilon_i + \bar{d}_i$.

Choose $C_i = \min\left\{ \bar{c}_i, c_{i,j}, \sigma_i, \bar{\sigma}_i \right\}$ and $C = \min_{1 \le i \le N}\{C_i\}$, and define $D = \sum_{i=1}^{N} D_i$. (37) can be written as

$$\dot{V} \le -CV + D \tag{38}$$

Integrating two sides of (38) on $[0,t]$ yields

$$V(t) \le (V(0) - D/C)e^{-Ct} + D/C \tag{39}$$

From (39), it can be concluded that the closed-loop signals $z_{i,1}$, $z_{i,2}$, $\hat{W}_i$, and $\hat{\Theta}_i$ are all bounded. Furthermore, the formation error satisfies

$$\|z_{i,1}\| \leq \sqrt{2[(V(0) - D/C)e^{-Ct} + D/C]} \tag{40}$$

which means that the formation error will converge to a compact set, and the compact set can be adjusted arbitrary small by increasing the parameters $c_{i,1}$, $c_{i,2}$, $\bar{c}_{i,1}$, γ_i, and ς_i.

However, the small error will lead to large control action, and the parameters should be selected to satisfy the desired performance. Thus, the proof of Theorem 3.1 has been completed.

4. **Conclusions.** In this paper, a novel adaptive fuzzy formation control scheme has been developed for multiple unmanned helicopters. FLSs are utilized to identify the unknown dynamic existing in the modeling process. The formation information is introduced into the consensus error to achieve the formation control. Combining with backstepping technique, an adaptive fuzzy formation controller is developed. Based on Lyapunov stability theorem, it is proven the boundedness of closed-loop signals and formation error convergence. The future work is aimed at studying the fault-tolerant formation control for multiple unmanned helicopters with unknown actuator faults.

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