Control of a Flexible Air-breathing Hypersonic Vehicle with Measurement Noises Using Adaptive Interval Type-2 Fuzzy Logic System

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Abstract—In this paper, a novel control scheme for the flexible air-breathing hypersonic vehicle (FAHV) using adaptive interval type-2 fuzzy logic system (AIT2-FLS) is proposed to reduce the side effects of measurement noises in the velocity channel and altitude channel as well as flexible dynamics in real applications. After input-output linearization of the longitudinal model of FAHV, the dynamic inversion controller is formulated to track the reference commands based on state feedback. The AIT2-FLS is further developed to deal with the model uncertainties and input errors. Besides, the state estimator is applied to estimate the true values of the corrupted outputs. The stability characteristics of both the controller and the state estimator are analyzed. The whole control scheme is finally obtained through combining the controller and the state estimator based on the separation principle. Simulation results demonstrate the robustness of our proposed control scheme against measurement noises and flexibilities.

Keywords—flexible air-breathing hypersonic vehicle; adaptive interval type-2 fuzzy logic system; state estimator; measurement noises

I. INTRODUCTION

Hypersonic vehicles, which refer to the ones at speeds over 5 Mach, have raised various interests for more than 50 years. Due to the complex design and severe flight conditions, hypersonic vehicles are sensitive to changes in the flight conditions as well as the aerodynamic parameters [1]. Besides, since the model itself is highly nonlinear and strongly coupled, the control system design becomes a real challenge. In 2007, the flexible air-breathing hypersonic vehicle (FAHV) model was introduced by Bolender and Doman [2]. Different from other general air-breathing hypersonic vehicle (AHV) models, this model constructs the dynamics of flexibilities, which may severely affect the flight safety. Therefore, how to suppress the flexible dynamics in real flight should be concerned.

Measurement noise, which is actually unavoidable in real applications, is another problem that should be taken into consideration. If the corrupted signals are directly utilized, the system may become unstable and the actuators may become broken. Although various Kalman filters have been proposed for control engineering [3, 4], these approaches may not be suitable for FAHV control because they mainly focus on the discrete systems. An adaptive non-singleton interval type-2 fuzzy logic control scheme was proposed in [5]. However, the results of the actuators may not be satisfactory under the effect of measurement noises. In [6], Peng and Wang developed a predictor together with a low-frequency learning-based neural updating law to reconstruct the corrupted states, which may be a promising way on noise reduction for nonlinear systems.

To deal with the uncertainties in real applications, fuzzy logic systems (FLSs) have been widely promoted for a long time. Although type-1 fuzzy logic system (T1-FLS) has been the first choice due to its convenience for design, it is not reasonable to use an accurate membership function (MF) for something uncertain [7]. Type-2 fuzzy logic system (T2-FLS), which uses at least one type-2 fuzzy set (T2-FS), with the structure presented in Fig. 1, is the extension of T1-FLS. Since T2-FSs can offer better capabilities of modeling vagueness and unreliability of information than type-1 fuzzy sets (T1-FSs), the amount of uncertainty in a system can be better reduced [8]. Meanwhile, considering the computational costs in real time control, interval type-2 fuzzy logic system (IT2-FLS), which uses interval type-2 fuzzy sets (IT2-FSs) instead, becomes more popular than general T2-FLS.

To the best of our knowledge, there are few investigations on the reduction of measurement noises for FAHV control. In this paper, a novel control scheme for FAHV using adaptive interval type-2 fuzzy logic system (AIT2-FLS) against measurement noises and flexible dynamics is proposed. First, the longitudinal model of FAHV is input-output linearized to obtain the tracking error dynamics in linear form. Then, a dynamic inversion controller is formulated to track the reference commands based on state feedback. An AIT2-FLS is further applied to approximate the uncertain terms in the controller. Besides, a state estimator is designed to reconstruct the exact velocity and altitude corrupted by measurement noises. The stability analyses of both the controller and the state estimator are explored. Based on the separation principle, the whole control scheme is finally obtained through combining the controller and the state estimator. Simulation results validate the effectiveness of our proposed control scheme on measurement noises and flexibilities reduction.

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The rest of this paper is organized as follows. Section 2 states the control objective as well as the preliminary information about the longitudinal model of the FAHV. From Section 3 to Section 5, we introduce the overall control scheme in details. Section 6 presents the simulation results, after which we draw our conclusions.

II. CONTROL OBJECTIVE AND PRELIMINARIES

In this study, the control objective is to design a control scheme which can make the velocity $V$ and altitude $h$ of the FAHV track their reference commands under the side effects of measurement noises in the velocity channel and altitude channel as well as flexibilities.

The longitudinal dynamics of the FAHV, which can be derived using Lagrange’s equations, consist of five rigid-body states and six flexible states [9]:

$$V = (T \cos \alpha - D)/m - g \sin \gamma$$  
$$\dot{\gamma} = (L + T \sin \alpha)/mV - g \cos \gamma/V$$  
$$\dot{h} = V \sin \gamma$$  
$$\dot{\alpha} = q - \gamma$$  
$$\dot{\dot{\eta}} = -2\zeta \omega \dot{\eta} - \omega^2 \eta + N_i, \quad i = 1, 2, 3$$

where $[V \gamma h \alpha q]^T$ indicates the velocity, flight path angle, altitude, angle of attack and pitch rate of FAHV respectively, while $\eta = [\eta_1 \eta_2 \eta_3]^T$ represents the first three vibrational modes. The approximations of lift $L$, drag $D$, thrust $T$, pitching moment $M_y$, and the three generalized forces $N_i$, $N_2$, and $N_3$ are given as follows:

$$L = 0.5 \rho V^2 s C_L(\alpha, \delta, \eta)$$  
$$D = 0.5 \rho V^2 s C_D(\alpha, \delta, \eta)$$  
$$T = 0.5 \rho V^2 s$$  
$$M_y = z_f T + 0.5 \rho \rho V^2 s C_M(\alpha, \delta, \eta)$$  
$$N_i = 0.5 \rho V^2 s [N_i \alpha^2 + N_i \alpha + N_i \delta + N_i \delta]$$

where

$$C_{L,\alpha}(\alpha, \delta, \eta) = C_{L,\alpha}^{\alpha^2} \alpha^2 + C_{L,\alpha}^{\alpha \delta} \alpha \delta + C_{L,\alpha}^{\delta^2} \delta^2$$  
$$C_{L,\alpha}(\alpha, \delta, \eta) = C_{L,\alpha}^{\alpha^2} \alpha^2 + C_{L,\alpha}^{\alpha \delta} \alpha \delta + C_{L,\alpha}^{\delta^2} \delta^2$$  
$$C_{L,\alpha}(\alpha, \delta, \eta) = C_{L,\alpha}^{\alpha^2} \alpha^2 + C_{L,\alpha}^{\alpha \delta} \alpha \delta + C_{L,\alpha}^{\delta^2} \delta^2$$

In (7)-(18), $\phi$ represents the throttle setting while $\delta_0$ stands for the canard deflection and elevator deflection respectively. At the same time, the canard deflection $\delta_0$ is set to be ganged with the elevator deflection $\delta$, with the relationship of $\delta = k_\delta \delta_0 = -\left(C_{L,\delta}^{\delta_0}\right) \delta_0$ [10]. The engine dynamics can be described through a second-order system:

$$\dot{\phi} = -2\zeta \omega \dot{\eta} - \omega^2 \eta + \alpha \phi + \omega \phi$$  

Other details in (1)-(19) can be seen in [11].

III. CONTROLLER DESIGN

In the following three sections, we will introduce our control scheme in details, including input-output linearization, dynamic inversion controller design, ART2-FLS design and state estimator design. The block diagram of the overall control scheme is displayed in Fig. 2. For the FAHV longitudinal model, the control inputs are chosen as $u = [\phi, \delta]^T$, while the outputs are $y = [V, h]^T$.

A. Input-Output Linearization

Input-output linearization is an effective way for control design in nonlinear systems. According to [1], if the nonlinear system satisfies the relative degree condition, then it can be completely linearized. Therefore, after differentiating $V$ and $h$ three times and four times respectively, we can obtain the following relationship:

$$\left[\begin{array}{c} \dot{V} \\ \dot{h} \end{array}\right] = \left[\begin{array}{cc} f_1 & b_1 \\ f_2 & b_2 \end{array}\right] \left[\begin{array}{c} \phi \\ \delta \end{array}\right]$$

where

$$f_1 = (a_1 x_0 + x^T \Omega \dot{x})/m$$  
$$f_2 = (a_1 x_0 + x^T \Omega \dot{x}) \sin \gamma/m + V (\pi, x_0 + x^T \Pi, x) \cos \gamma$$  
$$3V^2 \gamma \cos \gamma - 3V^2 \gamma^2 \sin \gamma + 3V^2 \gamma \cos \gamma$$  
$$-3V^2 \gamma \sin \gamma - V^2 \gamma \cos \gamma$$

![Fig. 2. The block diagram of the overall control system.](image-url)
and denote virtual control inputs, and are the parameters in (7)-(11) due to the existence of flexible dynamics in terms of \( \alpha \) and (27) may not be available in real applications. Since IT2-FLS is a universal approximator [14], in the next step, we use AIT2-FLS to approximate the uncertain term mentioned above, and (34) becomes:

\[
\mathbf{u} = \hat{\mathbf{B}}^{-1} (-\mathbf{F} + \mathbf{v}) = \hat{\mathbf{B}}^{-1} \left[ -f_h - \sum_{i=0}^{2} k_{i} e_i^{(i)} + \hat{\mathbf{v}}_h \right].
\]

In this study, the rule bases of our AIT2-FLS can be designed as follows:

\[
R_i^*: \text{If } x_i \text{ is } \tilde{F}^i, \text{ then } \hat{f}_i \text{ is } G^i, \quad s = 1, 2, \ldots, M
\]

where the inputs of AIT2-FLS \( x_i \) and \( x_s \) are chosen as \( V \) and \( \alpha \) respectively. The antecedent fuzzy sets \( \tilde{F}^i \) and \( \tilde{F}_s^i \) are Gaussian IT2-FSs, whose lower membership functions (LMFs) and upper membership functions (UMFs) are:

\[
\mu_{F^i}(x_i) = \exp\left( -\left( x_i - \bar{m}_{F^i} \right)^2 / 2\sigma_{F^i}^2 \right), \quad i = 1, 2
\]

\[
\bar{m}_{F^i}(x_i) = \exp\left( -\left( x_i - \bar{m}_{F^i} \right)^2 / 2\sigma_{F^i}^2 \right), \quad i = 1, 2
\]

respectively, while the consequent fuzzy sets \( G^i \) and \( G^i_s \) are Gaussian T1-FSs, with the corresponding centroids of \( \theta^i \) and \( \theta^i_s \). Next, applying singleton fuzzification and product inference, the degree of firing \( f^s(x_i, x_s) \) can be expressed as follows:

\[
f^s(x_i, x_s) = \prod_{i=1}^{M} \mu_{F^i}(x_i) \prod_{s=1}^{M} \bar{m}_{F^i}(x_s).
\]

Define the fuzzy basic function (FBF) as follows:

\[
\bar{x} = f^s(x_i, x_s) / \sum_{i=1}^{M} f^s(x_i, x_s).
\]
Then, if we use center-of-sets type reduction and center average defuzzification, we can obtain the crisp outputs of AIT2-FLS:

\[
\hat{y}_f = \left(\Theta^T \xi_a + \Theta^T \xi_n\right)/2 = \Theta^T \xi,
\]

\[
\hat{y}_s = \left(\Theta^T \xi_a + \Theta^T \xi_n\right)/2 = \Theta^T \xi,
\]

where \(\Theta = \begin{bmatrix} \Theta_1 \Theta_2 \ldots \Theta_n \end{bmatrix}^T\) and \(\xi = \begin{bmatrix} \xi_a \xi_n \ldots \xi_n \end{bmatrix}^T\).

Besides, \(\xi_a = [\xi_{a1}, \xi_{a2}, \ldots, \xi_{an}]^T\) and \(\xi_n = [\xi_{n1}, \xi_{n2}, \ldots, \xi_{nn}]^T\) are the predefined vectors whose elements are the positive definite matrices which satisfy the IT2-FLS as (41) or (42) such that

\[
\Theta = \begin{bmatrix} \Theta_1 \Theta_2 \ldots \Theta_n \end{bmatrix}^T
\]

and \(\xi = \begin{bmatrix} \xi_a \xi_n \ldots \xi_n \end{bmatrix}^T\) are the boundary FBF vectors derived by the Karnik-Mendel algorithm [15].

Let

\[
A_e = \begin{bmatrix} 0 & 1 & 0 \\ -k_{i1} & -k_{i2} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad b_e = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},
\]

\[
A_s = \begin{bmatrix} 0 & 1 & 0 \\ -k_{s1} & -k_{s2} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad b_s = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},
\]

Then substituting (41) and (42) into (35), it becomes:

\[
u = B^{-1} \begin{bmatrix} -\Theta^T \xi - \sum_{j=1}^3 k_j e_j + \tilde{V} \\ -\Theta^T \xi - \sum_{j=1}^3 k_j e_j + \tilde{V} \end{bmatrix}
\]

where \(\Theta, \Theta_1, \Theta_2\) update as follows:

\[
\Theta = \gamma \epsilon e_P b_P \xi - \sigma (\Theta - \Theta_1)
\]

\[
\Theta_1 = \gamma \epsilon e_P b_P \xi - \sigma (\Theta - \Theta_2)
\]

with \(\gamma > 0, \gamma > 0, \sigma > 0\) and \(\sigma > 0\). In addition, \(P_e\) and \(P_s\) are the positive definite matrices which satisfy the following Lyapunov functions:

\[
A_e^T P_e + P_e A_e = -Q_e, \quad A_s^T P_s + P_s A_s = -Q_s
\]

in which \(Q_e\) and \(Q_s\) are appropriate positive definite square matrices. \(\Theta_1\) and \(\Theta_2\) are the predefined vectors whose dimensions are the same as those of \(\Theta\) and \(\Theta_1\), respectively.

D. Stability Analysis

Lemma 1 [14]: The IT2-FLS can uniformly approximate any function \(f(x)\) which is continuous in \(C[-1,1]\) to any degree of accuracy. In other words, for \(\forall \epsilon > 0\), there exists an IT2-FLS as (41) or (42) such that

\[
\sup_{x \in [-1,1]} |f(x) - \Theta^T \xi(x)| < \epsilon.
\]

Define \(\Theta_1\) and \(\Theta_2\) as the optimal estimation parameters, while \(\epsilon_1\) and \(\epsilon_2\) as the minimal estimation errors. Then \(f_e\) and \(f_s\) can be expressed in the following form:

\[
f_e = \Theta_1^T \xi_a + \epsilon_1, \quad f_s = \Theta_2^T \xi_n + \epsilon_2.
\]

Combining (31), (45) and (50), we can obtain the overall error dynamics as follows:

\[
\dot{e}_f = A_e e_e + b_e \left(\Theta^T \xi_a + \epsilon_1\right)
\]

\[
\dot{e}_s = A_s e_s + b_s \left(\Theta^T \xi_n + \epsilon_2\right)
\]

where \(\dot{\Theta} = \Theta - \Theta_2\) and \(\dot{\Theta}_1 = \Theta - \Theta_1\). The following theorem shows the stability characteristics of our proposed controller.

Theorem 1: Consider the closed-loop system consisting of the FAHV longitudinal model (1)-(6), the control law (45), together with the adaptive laws (46) and (47). Then, the tracking errors in both the velocity channel and altitude channel are uniformly ultimately bounded (UUB).

Proof: Consider the following Lyapunov function candidate:

\[
V_i = \frac{1}{2} e_i^T P_e e_i + \frac{1}{2} e_i^T P_s e_i + \frac{1}{2} \gamma^T \hat{\Theta} - \frac{1}{2} \gamma^T \Theta_2
\]

Differentiating (53), we can get

\[
\dot{V}_i = -\frac{1}{2} e_i^T Q_e e_i + \frac{1}{2} e_i^T P_e b_P \xi - e_i^T P_e b_P \xi - e_i^T P_s b_P \xi - e_i^T P_s b_P \xi
\]

\[
-\frac{\sigma_1}{\gamma} \Theta^T (\Theta - \Theta_1) - \frac{\sigma_2}{\gamma} \Theta^T (\Theta - \Theta_2)
\]

Note that

\[
\Theta^T (\Theta - (\Theta - \Theta_1)) \leq \frac{1}{2} \Theta^T \Theta + \frac{1}{2} \Theta^T \Theta
\]

Then (54) follows that

\[
\dot{V}_i \leq -\frac{1}{2} e_i^T Q_e e_i + \frac{1}{2} e_i^T P_e b_P \xi + e_i^T P_s b_P \xi + \frac{\sigma_1}{\gamma} \Theta^T (\Theta - \Theta_1) + \frac{\sigma_2}{\gamma} \Theta^T (\Theta - \Theta_2)
\]

where

\[
W_i = e_i^T P_e b_P \xi + e_i^T P_s b_P \xi + \frac{\sigma_1}{2 \gamma} \Theta^T (\Theta - \Theta_1) + \frac{\sigma_2}{2 \gamma} \Theta^T (\Theta - \Theta_2)
\]

is a bounded term. By choosing \(\mu_1 = \lambda(Q_s)/\lambda(P_s)\) and \(\mu_2 = \lambda(Q_s)/\lambda(P_s)\), \(\mu_1 = \sigma\) and \(\mu_2 = \sigma\), where \(\lambda\) and \(\lambda\) denote the minimum and maximum eigenvalues respectively, we have

\[
\dot{V}_i \leq -\mu_i V_i + W_i
\]

with \(\mu_i = \min(\mu_1, \mu_2, \mu_3, \mu_4)\). Thus, the tracking errors in both the velocity channel and altitude channel are UUB.
IV. STATE ESTIMATOR DESIGN

Actually, when measurement noises exist in the velocity channel and altitude channel, \( V \) and \( h \) are not able to be obtained accurately in state feedback control. Therefore, we propose a state estimator to reconstruct the exact states of the velocity and altitude.

Assumption 1: The measurement noises \( w_1 \) and \( w_2 \) are bounded white Gaussian noises (WGNs). In other words, there exist positive constants \( w_1^* \) and \( w_2^* \) such that \( |w_1| \leq w_1^* \) and \( |w_2| \leq w_2^* \).

Inspired by [6], the state estimator can be designed as follows:

\[
\dot{\hat{V}} = (\hat{\dot{T}} \cos \alpha - \hat{D})/m - g \sin \gamma - \sigma_1 (\hat{\dot{V}} - V_n) \tag{60}
\]

\[
\dot{\hat{h}} = \hat{V} \sin \gamma - \sigma_2 (\hat{\dot{h}} - h_n) \tag{61}
\]

where \( \hat{V} \) and \( \hat{h} \) are the estimation values of \( V \) and \( h \), \( V_n = V + w_1 \) and \( h_n = h + w_2 \) are the measured outputs, while \( \sigma_1 \) and \( \sigma_2 \) are positive constants. Then, according to (60), (61), (1) and (3), the estimation error dynamics can be obtained:

\[
\dot{\tilde{V}} = \hat{V} - \tilde{V} = (\hat{\dot{T}} \cos \alpha - \hat{D})/m - \sigma_1 (\hat{\dot{V}} - V_n) \tag{62}
\]

\[
\dot{\tilde{h}} = \hat{h} - \tilde{h} = \hat{V} \sin \gamma - \sigma_2 (\hat{\dot{h}} - h_n) \tag{63}
\]

where \( \hat{T} = \hat{T} - T \) and \( \hat{D} = \hat{D} - D \) are bounded terms. Next, we will give the stability analysis of our state estimator.

Theorem 2: Consider the system (60) and (61). Then under the effect of measurement noises, the estimation errors are UUB.

Proof: Consider the following Lyapunov function candidate:

\[
V_2 = \frac{1}{2} \tilde{V}^2 + \frac{1}{2} \tilde{h}^2. \tag{64}
\]

Differentiating (64), we can obtain

\[
\dot{V}_2 = \dot{V} \left[ (\hat{T} \cos \alpha - \hat{D})/m - \sigma_1 (\hat{\dot{V}} - V_n) \right] + \dot{\hat{V}} \left[ \hat{V} \sin \gamma - \sigma_2 (\hat{\dot{h}} - h_n) \right]. \tag{65}
\]

Since \( \hat{T} \) and \( \hat{D} \) are bounded terms, and \( \gamma \) is usually very small in real flight, \( (\hat{T} \cos \alpha - \hat{D})/m \) and \( \sin \gamma \) are bounded, that is, \( |(\hat{T} \cos \alpha - \hat{D})/m| \leq W_{21}, \) and \( |\sin \gamma| \leq W_{22} \), with \( W_{21} > 0 \) and \( W_{22} > 0 \). Then, applying Young’s inequality, we have

\[
\dot{V}_2 \leq W_{21} V - \sigma_1 \tilde{V}^2 + \sigma_2 \dot{\hat{V}} \tilde{V} + \sigma_2 \dot{\hat{h}} \tilde{h} + \sigma_2 \hat{h} \tilde{h} + \frac{1}{4} \tilde{V}^2 + \frac{\sigma_2}{4} \tilde{V}^2 + \frac{\sigma_2}{4} \tilde{V}^2 + \frac{W_{22}}{2} \tilde{V}^2 + \frac{W_{22}}{2} \tilde{V}^2 - \sigma_1 \tilde{h}^2 - \frac{\sigma_2}{4} \tilde{h}^2 + w_2 \tag{66}
\]

where \( W_{21} = W_{22}^* + \tilde{w}_1^* + \tilde{w}_2^* \) is bounded. By choosing

\[
\mu_{21} = \sigma_1 - \frac{1}{4} \frac{\sigma_2^2}{4} - \frac{W_{22}}{2} > 0, \quad \mu_{22} = \sigma_2 - \frac{W_{22}}{4} - \sigma_2^2 > 0 \tag{67}
\]

we have

\[
\dot{V}_2 \leq -\mu_2 V + W_2 \tag{68}
\]

with \( \mu_2 = \min(2\mu_{21}, 2\mu_{22}) \). Therefore, the estimation errors are UUB. This completes the proof.

V. CONTROLLER-ESTIMATOR SYNTHESIS

In the previous sections, we have separately finished the controller design as well as the state estimator design based on the separation principle. In this section, we synthesize the controller and the state estimator into a whole control scheme as follows:

\[
u = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \end{bmatrix}^T \begin{bmatrix} -\Theta_1 \phi_1 - \sum_{i=0}^2 k_i \Theta_i^o + \hat{V}_c \\ -\Theta_2 \phi_2 - \sum_{i=0}^2 k_i \Theta_i^o + \hat{h}_c \end{bmatrix} \tag{69}
\]

\[
\dot{\hat{V}} = (\hat{T} \cos \alpha - \hat{D})/m - g \sin \gamma - \sigma_1 (\hat{\dot{V}} - V_n) \tag{70}
\]

\[
\dot{\hat{h}} = \hat{V} \sin \gamma - \sigma_2 (\hat{\dot{h}} - h_n) \tag{71}
\]

\[
\Theta_1 = \gamma \epsilon_1 \phi_1 \beta_1, \Theta_2 = \gamma \epsilon_1 \phi_2 \beta_2 \tag{72}
\]

\[
\epsilon_1 = \hat{V} - \tilde{V}, \quad \epsilon_2 = \hat{h} - \tilde{h}, \quad \hat{\epsilon}_1 = \left( \epsilon_1, \epsilon_2, \epsilon_3 \right)^T \tag{73}
\]

VI. SIMULATIONS

Simulations are conducted to validate the effectiveness of our proposed control scheme against measurement noises and flexibilities in this section. The trimmed conditions of the simulations are selected as \( V_0 = 7846.4 \text{ ft/s} \), \( \gamma_0 = 0 \text{ rad} \), \( h_0 = 85000 \text{ ft} \), \( q_0 = 0.0219 \text{ rad} \), \( q_0 = 0.0012 \text{ ft/s} \), \( \eta_0 = 0.594 \text{ ft/s} \). \( \eta_0 = -0.0976 \text{ ft/s} \), \( \eta_0 = -0.0335 \text{ ft/s} \), \( \eta_0 = 0 \text{ ft/s} \). Command signals are set as 300 ft/s step signal in the velocity channel and 4000 ft/s step signal in the altitude channel. In order to arrange a better transition process as well as to obtain the high-order derivatives of the command signals, we use the tracking differentiators which can be seen in [5, 16].

In the AFT2-FLS, each of the antecedent fuzzy sets \( \tilde{F}_1 \) and \( \tilde{F}_2 \) has 5 MFs, namely NB, NS, ZO, PS and PB. The parameters of \( \tilde{F}_1 \) and \( \tilde{F}_2 \) are shown in Table I. Besides, the initial values of the consequent centroids are set as the desired

<table>
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<th>( \alpha_1 )</th>
<th>( \alpha_2 )</th>
<th>( \alpha_3 )</th>
<th>( \alpha_4 )</th>
<th>( \alpha_5 )</th>
<th>( \sigma_1 )</th>
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<td>32</td>
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<td>0.0022</td>
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<tr>
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<td>0.0374</td>
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<td>0.0022</td>
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</table>
noises and flexibilities. Fig. 4 depicts the measured and has a good tracking performance in both the velocity channel.

3-6. In Fig. 3, we can see that in our control scheme, the FAHV state estimator on noise reduction. The control inputs, errors still exist, this figure validates the good property of our estimate of the velocity and altitude. Although the estimation shown in Fig. 6, which verifies the convergence and effectiveness of our method.

The proposed method as the basic controller to track the reference commands, while the AIT2-FLS is applied to approximate the uncertainties in the longitudinal dynamics of FAHV. Furthermore, the state estimator is utilized for estimating the true values which are corrupted by measurement noises. Afterwards, the overall control scheme is obtained by synthesizing the controller and the state estimator based on the separation principle. Simulations conducted at last verify the effectiveness of our proposed control scheme.

REFERENCES


