Fixed-Time Fuzzy Adaptive Fault-Tolerant Control for Hypersonic Flight Vehicles Using a New Prescribed Performance Function

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Abstract This article proposes a new fixed-time fuzzy adaptive fault-tolerant control methodology for the longitudinal dynamics of hypersonic flight vehicles (HFVs) in the presence of actuator faults, uncertain dynamics and external disturbances. In contrast with the conventional fixed-time control schemes that typically contain the fractional powers of errors in their designs, this work develops a low-complexity control structure in the sense of removing the dependence on the need of above-mentioned fractional power terms by means of prescribed performance control (PPC) method. Different from the most existing PPC approaches where the initial conditions of tracking errors are required to be known, the newly proposed prescribed performance function (PPF) can relax such restrictions through choosing properly small initial values of PPF. Fuzzy logic systems (FLSs) are employed to handle unknown dynamics and minimal learning parameter (MLP) technique is incorporated into the design for the purpose of alleviating computation burden. Closed-loop stabil-

ity is rigorously proved via Lyapunov stability theory and simulation results are eventually given to validate the effectiveness of the proposed control strategy.

Keywords Fixed-Time Tracking Control · Hypersonic Flight Vehicles · Actuator Failure · Prescribed Performance Control

1 Introduction

Hypersonic flight vehicles have already attracted considerable attention due to their advantages of high flight speed, remarkable penetration ability and cost-effectiveness [1]-[3]. Nevertheless, the controller design for HFVs remains an intractable issue due to their peculiar features. For example, the engine-airframe structure results in strong couplings between propulsive and aerodynamic forces, and there exist intricate flexible deformation due to the slender geometry of vehicle structure, which influences the aerodynamic characteristics prominently [4]. In addition, the fast time-varying flight environment as well as the unknown external disturbances lead to frequent parameter variations and model uncertainties, dramatically increasing the difficulty of controller design for HFVs [5]. To address these problems, many effective methods have been presented, including robust control [4]-[6], neural/fuzzy control [7]-[9], prescribed performance control [10]-[12] and so on. Although these efforts solve the above-mentioned issues to some extent, these results rarely focus on the rate of convergence.

To be specific, only the exponential convergence of tracking error is guaranteed in the aforementioned work, which reveals the convergence time tends to be infinite. From a practical perspective, the rate of convergence is of great significance to the transient tracking performance [13]. Recently, the finite-time tracking control for HFVs is investigated in [13]-[16], which can make the tracking error converge into the predefined compact set within a finite time. Nevertheless, the convergence time, which is commonly achieved in [13]-[16], depends on the initial states of the system. It inevitably brings up a problem, that is, the convergence time can not be accurately settled when the initial states of the system are unknown. To solve such problem, the fixed-time control [17]-[20] is proposed skillfully, by which the tracking error can converge into a predefined impact set within a fixed time and the connection between the convergence time and initial states is eliminated.

However, there still exist some shortcomings with the conventional fixed-time tracking control scheme [17]-[20], where the inequation $\dot{V}(x) \leq -\tau V^p(x) - \varsigma V^q(x) + \kappa$ holds. On the one hand, the derivative of virtual and actual control laws will tend to infinite when the track-

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ing error approaches to zero, giving rise to singularity issues in the control design [20]. On the other hand, when the system encounters the unknown external disturbances [21]-[24] or the system faults [25]-[29], it is complicated to both ensure the fixed-time stability of the system and predetermine the convergence accuracy by selecting the design parameters. Furthermore, it is well known that the transient and steady-state performances are important to the controller design for HFVs [30]. Nonetheless, the existing PPC for HFVs commonly fails to explicitly contain a convergence time T in the performance function. Thus, it is urgent to develop a new low-complexity fixed-time fault-tolerant control (FTFTC) strategy for HFVs with the prescribed performance.

Motivated by these observations, we present a fixed-time adaptive fuzzy fault-tolerant control scheme for HFVs by utilizing a new prescribed performance function. The contributions mainly contain the follows:

1. This paper presents a structurally inexpensive FTFTC framework for HFVs in the sense that no fractional powers are involved in the design. Specifically, conventional fixed-time controllers in [18]-[20] need to satisfy the condition $\dot{V}(x) \leq -\tau V^p(x) - \varsigma V^q(x) + \kappa$. Nevertheless, merely the form $\dot{V}(x) \leq -\tau V(x) + \kappa$ is required in this work, which not only simplifies the control law but also removes the singularity problem caused by the derivative of fraction term.
2. As opposed to the state-of-the-art PPC methods [11]-[12] and [22], we propose a new PPC that not only enables us to obtain fixed-time convergence, but also removes the reliance on precise initial error values. This is done in combination with a newly proposed PPF.
3. By constructing the intermediate control laws and adaptive laws, the adverse impact of actuator faults of HFVs (e.g. loss of effectiveness, drift, etc.) is compensated effectively.

The remainder of the work is organized as follows. The HFV dynamics and preliminaries are introduced in Section 2. In Section 3, the FLSs-approximator-based FTFTC is designed and the closed-loop stability is verified in Section 4. Section 5 provides simulations to demonstrate the effectiveness of the proposed methods and the work is concluded in Section 6.

2 Problem formulation and preliminaries

2.1 Hypersonic flight vehicle dynamics

The longitudinal control-oriental model is originally developed by Parker [31], which can be formulated as

$$\begin{aligned}\dot{V} &= \frac{T \cos(\theta - \gamma) - D}{m} - g \sin \gamma, \quad \dot{h} = V \sin \gamma, \\ \dot{\gamma} &= \frac{T \sin(\theta - \gamma) + L}{mV} - \frac{g \cos \gamma}{V}, \quad \dot{\theta} = Q, \\ \dot{Q} &= \frac{M + \tilde{\psi}_1 \ddot{\eta}_1 + \tilde{\psi}_2 \ddot{\eta}_2}{I_{yy}}, \\ k_1 \ddot{\eta}_1 &= -2\zeta_1 \omega_1 \dot{\eta}_1 - \omega_1^2 \eta_1 + N_1 - \frac{\tilde{\psi}_1 M}{I_{yy}} - \frac{\tilde{\psi}_1 \tilde{\psi}_2 \ddot{\eta}_2}{I_{yy}}, \\ k_2 \ddot{\eta}_2 &= -2\zeta_2 \omega_2 \dot{\eta}_2 - \omega_2^2 \eta_2 + N_2 - \frac{\tilde{\psi}_2 M}{I_{yy}} - \frac{\tilde{\psi}_1 \tilde{\psi}_2 \ddot{\eta}_1}{I_{yy}},\end{aligned}\quad (1)$$

where T , D , L , M , N_1 and N_2 are defined as

$$\begin{aligned}T &= \beta_1(h, \bar{q}) \delta_\Phi \alpha^3 + \beta_2(h, \bar{q}) \alpha^3 + \beta_3(h, \bar{q}) \delta_\Phi \alpha^2 + \beta_4(h, \bar{q}) \alpha^2 \\ &\quad + \beta_5(h, \bar{q}) \delta_\Phi \alpha + \beta_6(h, \bar{q}) \alpha + \beta_7(h, \bar{q}) \delta_\Phi + \beta_8(h, \bar{q}), \\ D &= \bar{q} SC_D^\alpha \alpha^2 + \bar{q} SC_D^\alpha \alpha + \bar{q} SC_D^{\delta_e^2} \delta_e^2 + \bar{q} SC_D^{\delta_e} \delta_e + \bar{q} SC_D^0, \\ M &= z_T T + \bar{q} S \bar{c} C_{M, \alpha}^\alpha \alpha^2 + \bar{q} S \bar{c} C_{M, \alpha}^\alpha \alpha + \bar{q} S \bar{c} C_{M, \alpha}^0 + \bar{q} S \bar{c} c_e \delta_e, \\ L &= \bar{q} SC_L^\alpha \alpha + \bar{q} SC_L^{\delta_e} \delta_e + \bar{q} SC_L^0, \\ N_1 &= N_1^{\alpha^2} \alpha^2 + N_1^\alpha \alpha + N_1^0, \\ N_2 &= N_2^{\alpha^2} \alpha^2 + N_2^\alpha \alpha + N_2^{\delta_e} \delta_e + N_2^0, \\ \bar{q} &= \frac{\bar{\rho} V^2}{2}, \quad \bar{\rho} = \bar{\rho}_0 \exp\left(\frac{h_0 - h}{h_s}\right),\end{aligned}\quad (2)$$

and more detailed definitions can be found in [31].

2.2 The actuator-fault model

The actuator-fault model is developed by [26]

$$v(u) = \omega u + \varepsilon, \quad (3)$$

where u and $v(u)$ denote the input and output signals of actuator, and ω and ε represent the actual control effectiveness and drift distance, respectively.

Assumption 1 There exists an unknown positive constant $\bar{\varepsilon}$ such that $|\varepsilon| \leq \bar{\varepsilon}$, $0 < \omega \leq 1$.

Remark 1 Assumption 1 is commonly applied in FTC research to ensure the controllability of system when the actuator faults occur [26]. During flight, actuator fault inevitably occurs due to multiple factors such as aging and damage of components or screw shedding, which deteriorates the flight performance and even causes the serious flight accident in severe circumstance. Therefore, it is of great significance to consider the possible actuator faults when designing the control strategy. With different values of ω and ε , (3) can be divided into the following four cases

1. $\omega = 1$ and $\varepsilon = 0$, representing the fault-free case;
2. $0 < \underline{\omega} \leq \omega \leq \bar{\omega} < 1$ and $\varepsilon = 0$, where $\underline{\omega}$ and $\bar{\omega}$ are unknown positive constants, denoting partial loss of effectiveness;

V	Velocity.	h	Altitude.	$\bar{c}$	Mean aerodynamic chord.
θ	Pitch angle.	γ	Flight path angle.	η_i	i -th generalized flexible coordinate.
α	Angle of attack.	Q	Pitch rate.	S	Reference area.
T	Thrust.	D	Drag.	$\bar{q}$	Dynamic pressure.
L	Lift.	M	Pitching moment.	ζ_i	Damping ratio for flexible mode η_i .
I_{yy}	Moment of inertia.	m	Vehicle mass.	$C_D^{\delta_e^i}$	i -th order coefficient of δ_e in D .
Φ	Fuel equivalence ratio.	δ_e	Elevator angular deflection.	$C_D^{\alpha^i}$	i -th order coefficient of α in D .
z_T	Thrust moment arm.	N_i	i -th generalized force.	C_D^0	Constant term in D .
N_i^0	Constant term in N_i .	$N_i^{\delta_e}$	Contribution of δ_e to N_i .	$N_i^{\alpha^j}$	j -th order contribution of α to N_i .
C_L^0	Constant term in L .	$C_{M,\alpha}^0$	Constant term in M .	$C_{M,\alpha}^{\alpha^i}$	i -th order coefficient of α in M .
$C_L^{\delta_e}$	Coefficient of δ_e in L .	C_L^α	Coefficient of α in L .	ω_i	Natural frequency for η_i .

3. $\omega = 1$ and $\varepsilon \neq 0$, indicating the bias fault;
4. $0 < \underline{\omega} \leq \omega \leq \bar{\omega} < 1$ and $\varepsilon \neq 0$, where $\underline{\omega}$ and $\bar{\omega}$ are unknown positive constants, signifying that partial loss of effectiveness and bias fault occur at the same time.

2.3 Model transformation and decomposition

According to (1) and (2), V and h are mainly regulated by Φ and δ_e , respectively. To facilitate the controller design, the HFVs dynamics are decomposed into velocity subsystem and altitude subsystem.

Inspired by [32] and [33], the velocity subsystem is considered as

$$\dot{V} = f_V + g_V v(\Phi) + d_V, \quad (4)$$

where $f_V = \frac{\bar{q} S C_D^{\alpha^2} \alpha^2 + \bar{q} S C_D^0}{m} - g \sin \gamma + \frac{\cos \alpha}{m} [\beta_2(h, \bar{q}) \alpha^3 + \beta_4(h, \bar{q}) \alpha^2 + \beta_6(h, \bar{q}) \alpha + \beta_8(h, \bar{q})]$, $g_V = \frac{\cos \alpha}{m} [\beta_7(h, \bar{q}) + \beta_3(h, \bar{q}) \alpha^2 + \beta_1(h, \bar{q}) \alpha^3]$. f_V and g_V stand for unknown functions due to the time-varying aerodynamic parameters, while d_V represents the external disturbance on velocity.

Inspired by [34], we take the assumption $\sin(\gamma) \approx \gamma$ and $\cos(\gamma) \approx 1$, then the velocity subsystem can be considered as

$$\begin{cases} \dot{h} = V\gamma + d_h, & \dot{\gamma} = f_\gamma + g_\gamma \theta + d_\gamma, \\ \dot{\theta} = Q, & \dot{Q} = f_Q + g_Q v(\delta_e) + d_Q, \end{cases} \quad (5)$$

where $f_\gamma = \frac{\bar{q} S (C_L^0 - C_L^\alpha \gamma) + T \sin \alpha}{mV} - \frac{g}{V}$, $g_\gamma = \frac{\bar{q} S C_L^\alpha}{mV}$, $f_Q = z_T T + \frac{\bar{q} S \bar{c} C_{M,\alpha}(\alpha)}{I_{yy}}$ and $g_Q = \frac{\bar{q} S \bar{c} c_e}{I_{yy}}$. Similar to velocity subsystem, the functions f_γ , g_γ , f_Q and g_Q are unknown functions; d_h , d_γ and d_Q are the external disturbances of altitude subsystem. Along the standard ideas as [10]-[11], we assume there exist unknown positive functions g_{Vm} , $g_{\gamma m}$ and g_{Qm} such that $0 < g_{Vm} \leq g_V$, $0 < g_{\gamma m} \leq g_\gamma$ and $0 < g_{Qm} \leq g_Q$.

Remark 2 In practice, it is rather difficult to know the values of functions $f_\bullet, g_\bullet \in \{V, \gamma, Q\}$ accurately. There are mainly the following reasons: on the one hand, the aerodynamic parameters are constantly changing with the flight environment (i.e. velocity, altitude, attack of angle, etc.), where there inevitably exist measuring errors in the sensors of flight control system [1]. On the other hand, it is impossible to take all flight environment of HFVs into account in a wind tunnel, so that we have to rely on curve fitting technology to build the aerodynamic model [6]. Consequently, an exact model for HFVs is difficult to be obtained and in order to increase the robustness of flight control system, we regard $f_\bullet, g_\bullet \in \{V, \gamma, Q\}$ as unknown functions.

Assumption 2 [35] The reference trajectory $y_{ref}(t)$, together with its i -order derivative $y_{ref}^{(i)}(t)$ are continuous and bounded ($i = 1, 2 \dots n$).

2.4 A new fixed-time performance function

Definition 1 [35] A smooth function $\rho(t)$ is called fixed-time performance function (FTPF), if the following conditions are satisfied

1. $\rho(t) > 0$, i.e., $\rho(t)$ is ensured to be a positive function;
2. $\dot{\rho} \leq 0$, that is, $\rho(t)$ is monotonically decreasing;
3. $\lim_{t \rightarrow T} \rho(t) = \rho(T)$ and $\rho(t) = \rho(T)$ for any $t > T$, where $\rho(T)$ and T denote an arbitrarily small positive constant and settling time, respectively.

According to Definition 1, we construct an FTPF in the form of

$$\rho(t) = \begin{cases} \coth\left(\vartheta \frac{t}{T-t} + r\right) - 1 + \rho(T), & 0 \leq t < T \\ \rho(T), & t \geq T. \end{cases} \quad (6)$$

Proof In view of (6), it can be derived that

$$\begin{aligned}
\rho(T^-) &= \lim_{t \rightarrow T^-} \left[\coth \left(\vartheta \frac{t}{T-t} + r \right) - 1 + \rho(T) \right] \\
&= \lim_{t \rightarrow T^-} \frac{e^{\vartheta \frac{t}{T-t} + r} + e^{-\vartheta \frac{t}{T-t} - r}}{e^{\vartheta \frac{t}{T-t} + r} - e^{-\vartheta \frac{t}{T-t} - r}} - 1 + \rho(T) \\
&= \rho(T) = \rho(T^+),
\end{aligned}$$

that is, $\rho(t)$ is a continuous function. Furthermore, we can deduce that

$$\begin{aligned}
\dot{\rho}(t) &= -\frac{\vartheta}{T} \left(\frac{T}{T-t} \right)^2 \operatorname{csch}^2 \left(\vartheta \frac{t}{T-t} + r \right) \\
&= -\frac{\vartheta}{T} \left(\frac{T}{T-t} \right)^2 \left(\frac{2}{e^{\vartheta \frac{t}{T-t} + r} - e^{-\vartheta \frac{t}{T-t} - r}} \right)^2
\end{aligned}$$

when $t < T$, and $\dot{\rho}(t) = 0$ when $t \geq T$. For the sake of simplification, we denote $x = \frac{t}{T-t}$ and the fact $\lim_{t \rightarrow T^-} x = +\infty$ holds. Then, we can obtain

$$\lim_{t \rightarrow T^-} \dot{\rho}(t) = \lim_{x \rightarrow +\infty} -\frac{4\vartheta}{T} \left(\frac{1+x}{e^{\vartheta x+r} - e^{-\vartheta x-r}} \right)^2.$$

With the help of L'Hospital's rule, we get that

$$\lim_{t \rightarrow T^-} \dot{\rho}(t) = \lim_{x \rightarrow +\infty} -\frac{4}{T\vartheta} \left(\frac{1}{e^{\vartheta x+r} - e^{-\vartheta x-r}} \right)^2 = \dot{\rho}(T^+).$$

Next, $\frac{d\rho^2(t)}{dt^2}$ can be derived as

$$\begin{aligned}
\frac{d\rho^2(t)}{dt^2} &= \frac{8\vartheta(1+x)}{T(e^{\vartheta x+r} - e^{-\vartheta x-r})^2} - \frac{8\vartheta^2(1+x)^2(e^{\vartheta x+r} + e^{-\vartheta x-r})}{T(e^{\vartheta x+r} - e^{-\vartheta x-r})^3} \\
&= \sqrt{|\dot{\rho}(t)|} \frac{4\sqrt{\vartheta/T}}{e^{\vartheta x+r} - e^{-\vartheta x-r}} + \frac{T}{4} \dot{\rho}(t) \left(1 + \frac{2e^{-\vartheta x-r}}{e^{\vartheta x+r} - e^{-\vartheta x-r}} \right).
\end{aligned}$$

Then, we have $\lim_{t \rightarrow T^-} \frac{d\rho^2(t)}{dt^2} = \frac{d\rho^2(T^+)}{dt^2} = 0$. Similarly,

it leads to that $\lim_{t \rightarrow T^-} \frac{d\rho^i(t)}{dt^i} = \frac{d\rho^i(T^+)}{dt^i} = 0, i = 3, \dots, n$.

That is to say, $\rho(t)$ is a smooth function. Furthermore, we can also see that $\dot{\rho}(t) \leq 0$ and the function $\rho(t)$ is continuous at T . Thus, we can conclude that the function $\rho(t)$ is a FTFP. This completes the proof. ■

Remark 3 We can easily obtain sufficiently large $\rho(0)$ by selecting a sufficiently small r , that is to say, the initial error need not to be known accurately. Consequently, the FTFP without initial error constraint is achieved. Furthermore, we can also conclude that, the convergence rate of the error depends on ϑ , which can be seen in Fig. 1 (a). By setting the steady-state error boundary as $\rho(T) = 1$ and choosing different values of ϑ , we can obtain that a larger ϑ means a faster convergence rate of the error.

Consider the following transformation

$$q(t) = \frac{e(t)}{\rho(t)}, \quad (7)$$

where the error transformation function is chosen as

$$z(q) = \frac{q}{1-q^2}, \quad (8)$$

and we abbreviate $q = q(t)$ there-in-after.

Remark 4 From (8), it can be observed that the inequality $-1 < q < 1$ holds if $z(q)$ is bounded. In view of (7), we conclude that $|e(t)| < |\rho(t)|$ holds as long as $|e(0)| < |\rho(0)|$. Choosing $\vartheta = 0.5$, $r = 0.1$, $T = 6$ and $\rho(T) = 1$, the convergence performance of the proposed FTFP is shown in Fig. 1 (b). In contrast to traditional PPC [10], where the prescribed performance function is in the form of $\rho(t) = \coth(\vartheta t + r) - 1 + \rho_\infty$, the proposed control scheme explicitly contains a convergence time T in the FTFP. By this means, we can easily pre-set the convergence time as needed.

Fig. 1: The convergence performance of the proposed FTFP

2.5 Fuzzy logic system

Define a set of fuzzy IF-THEN rules, where the l th IF-THEN rule is written as [21]-[22]

$\mathcal{R}^l$: If x_1 is F_1^l , and $\dots$ and x_n is F_n^l , then y is B^l .

where $\mathbf{x} = [x_1, \dots, x_n]^T \in \mathbb{R}^n$, and $y \in \mathbb{R}$ are the input and output of the FLSs respectively, and $F_1^l, \dots, F_n^l$ and B^l are fuzzy sets in $\mathbb{R}$. Let $F(\mathbf{x})$ be a continuous function defined on a compact set $\Omega_{\mathbf{x}}$. Then, for a given desired level of accuracy $\varepsilon > 0$, there exists a FLS $\mathbf{W}^T \mathbf{S}(\mathbf{x})$ such that $\sup_{\mathbf{x} \in \Omega_{\mathbf{x}}} |F(\mathbf{x}) - \mathbf{W}^T \mathbf{S}(\mathbf{x})| \leq \phi$, where

$\mathbf{W} = [w_1, \dots, w_p]^T$ is the adaptive fuzzy parameter vector in a compact set $\Omega_{\mathbf{W}}$, p is the number of the fuzzy rules, and $\mathbf{S}(\mathbf{x}) = [S_1(\mathbf{x}), \dots, S_p(\mathbf{x})]^T$ is the fuzzy basis function vector with $S_l(\mathbf{x}) = \prod_{j=1}^m \mu_{F_j^l}(x_j) / \sum_{l=1}^p (\prod_{j=1}^m \mu_{F_j^l}(x_j))$ where $\mu_{F_j^l}(x_j)$ is a fuzzy membership function of the variable x_j in IF-THEN rule. Let $\mathbf{W}^*$ be the optimal parameter vector, which is defined as

$$\mathbf{W}^* = \arg \min_{\mathbf{W} \in \Omega_{\mathbf{W}}} \left\{ \sup_{\mathbf{x} \in \Omega_{\mathbf{x}}} |F(\mathbf{x}) - \mathbf{W}^T \mathbf{S}(\mathbf{x})| \right\}. \quad (9)$$

Then, we can further obtain

$$F(\mathbf{x}) = \mathbf{W}^{*T} \mathbf{S}(\mathbf{x}) + \phi, \quad (10)$$

where ϕ is the minimum fuzzy approximation error.

Lemma 1 [36] The hyperbolic tangent function $\tanh(\bullet)$ is continuous and differentiable, for $\forall \varsigma \in R$ and $\forall \mu > 0$, it has

$$0 \leq |\varsigma| - \varsigma \tanh\left(\frac{\varsigma}{\mu}\right) \leq 0.2785\mu. \quad (11)$$

Lemma 2 [37] For any positive constants ω and δ , the following inequation holds

$$0 \leq |\omega| - \frac{\omega^2}{\sqrt{\omega^2 + \delta^2}} \leq \delta. \quad (12)$$

The control objective of this article is to design an fuzzy adaptive tracking controller such that

1. The velocity and altitude tracking errors are guaranteed to obey the prescribed performance boundaries at all times, and finally converge into the pre-defined residual sets within preassigned time T even in the presentence of actuator faults;
2. All signals of the closed-loop system remain bounded.

3 The FTFTC design

Corresponding to the decomposition in Sect. II.C, the control design is also decomposed into a velocity control design and an altitude control design.

3.1 Velocity controller design

We first define the velocity tracking error as

$$e_V = V - V_{ref}, \quad (13)$$

where V_{ref} is the velocity reference trajectory. In view of (4), (7) and (8), the time derivative of e_V is

$$\dot{e}_V = f_V + g_V \Phi + d_V - \dot{V}_{ref} = \dot{\rho}(t) q + \dot{z}_V \rho(t) \frac{\partial q}{\partial z}. \quad (14)$$

Then $\dot{z}_V$ can be rewritten as

$$\begin{aligned} \dot{z}_V &= \frac{f_V + g_V v(\Phi) + d_V - \dot{V}_{ref} - \dot{\rho}(t) q}{\rho(t) \frac{\partial q}{\partial z}} \\ &= \Upsilon_V + E_V \left(f_V + g_V(\Phi) + d_V - \dot{V}_{ref} \right), \end{aligned} \quad (15)$$

with $\Upsilon_V = -\dot{\rho}(t) q E_V$, $E_V = \frac{1}{\rho(t) \frac{\partial q}{\partial z}}$.

It can be deduced from (8) that $\frac{\partial q}{\partial z} = \frac{(1-q^2)^2}{1+q^2} \leq 1$ when $-1 < q < 1$, and noticing the fact $g_V \geq g_{Vm} > 0$ leads to

$$E_V g_V = \frac{g_V}{\rho(t) \frac{\partial q}{\partial z}} \geq \frac{g_{Vm}}{\rho(0)} = \tilde{g}_{Vm} > 0. \quad (16)$$

Choose the following quadratic function

$$L_V = \frac{1}{2} z_V^2 + \frac{1}{2\mu_V} \tilde{g}_{Vm} \tilde{\ell}_V^2, \quad (17)$$

with $\tilde{\ell}_V = \ell_V - \hat{\ell}_V$, in which $\hat{\ell}_V$ denotes the estimation of adaptive parameter ℓ_V , and μ_V is the positive user-defined parameter.

Utilizing (3) and (14), the time derivative of L_V is

$$\begin{aligned} \dot{L}_V &= z_V \left(\Upsilon_V + E_V f_V + E_V g_V \omega_V \Phi + E_V g_V \varepsilon_V \right. \\ &\quad \left. + E_V d_V - E_V \dot{V}_{ref} \right) - \frac{1}{\mu_V} \tilde{g}_{Vm} \tilde{\ell}_V \dot{\hat{\ell}}_V. \end{aligned} \quad (18)$$

Define the nonlinear function

$$F_V = \Upsilon_V + E_V f_V + E_V d_V - E_V \dot{V}_{ref} + \frac{1}{2} z_V, \quad (19)$$

where f_V and d_V are unknown due to the existence of unknown external disturbances and fast time-varying flight environment. A FLSs-approximator is constructed to estimate F_V as

$$F_V = \mathbf{W}_V^T \mathbf{S}_V(\mathbf{x}_V) + \phi_V, \quad (20)$$

where $\mathbf{x}_V = [V, V_{ref}, \dot{V}_{ref}]^T$. Substituting (19) and (20) into (18), we have

$$\begin{aligned} \dot{L}_V &= z_V \left(\mathbf{W}_V^T \mathbf{S}_V + \phi_V + E_V g_V \omega_V \Phi + E_V g_V \varepsilon_V \right) \\ &\quad - \frac{1}{\mu_V} \tilde{g}_{Vm} \tilde{\ell}_V \dot{\hat{\ell}}_V - \frac{1}{2} z_V^2. \end{aligned} \quad (21)$$

According to Young's inequation, we can further have

$$z_V \mathbf{W}_V^T \mathbf{S}_V \leq \frac{z_V^2 \|\mathbf{W}_V\|^2 \mathbf{S}_V^T \mathbf{S}_V}{4\tau_V} + \tau_V, \quad (22)$$

$$z_V \phi_V \leq \frac{1}{2} z_V^2 + \frac{1}{2} \phi_V^2, \quad (23)$$

where τ_V is a positive constant, then we can rewrite (21) as

$$\begin{aligned} \dot{L}_V &\leq z_V (E_V g_V \omega_V \Phi + E_V g_V \varepsilon_V) + \frac{z_V^2 \|\mathbf{W}_V\|^2 \mathbf{S}_V^T \mathbf{S}_V}{4\tau_V} \\ &\quad + \tau_V + \frac{1}{2} \phi_V^2 - \frac{1}{\mu_V} \tilde{g}_{Vm} \tilde{\ell}_V \dot{\hat{\ell}}_V. \end{aligned} \quad (24)$$

According to Assumption 1, ω_V and ε_V are unknown. Therefore, we define the upper and lower bounds of fault parameters to achieve robustness, which are expressed as

$$\underline{\omega}_V = \inf(E_V g_V \omega_V), \quad \vartheta_V = \frac{1}{\underline{\omega}_V}, \quad (25)$$

$$\xi_V = \sup(E_V g_V \varepsilon_V). \quad (26)$$

Consider the Lyapunov function candidate

$$L_{\bar{V}} = L_V + \frac{1}{2l_V} \omega_V \tilde{\vartheta}_V^2 + \frac{1}{2r_V} \tilde{\xi}_V^2, \quad (27)$$

where $l_V \geq 0$ and $r_V > 0$ are the parameters to be designed, $\tilde{\vartheta}_V = \vartheta_V - \hat{\vartheta}_V$ and $\tilde{\xi}_V = \xi_V - \hat{\xi}_V$ represent estimation errors with $\hat{\vartheta}_V$ and $\hat{\xi}_V$ being the estimations of ϑ_V as ξ_V , respectively.

The time derivative of $L_{\bar{V}}$ gives

$$\dot{L}_{\bar{V}} = \dot{L}_V - \frac{1}{l_V} \omega_V \tilde{\vartheta}_V \dot{\tilde{\vartheta}}_V - \frac{1}{r_V} \tilde{\xi}_V \dot{\tilde{\xi}}_V. \quad (28)$$

Define $\ell_V = \frac{\|\mathbf{w}_V\|^2}{\tilde{g}_{Vm}}$ and choose the intermediate control law as

$$\bar{\Phi} = k_V z_V + \frac{z_V \hat{\ell}_V \mathbf{S}_V^T \mathbf{S}_V}{4\tau_V} + \hat{\xi}_V \tanh\left(\frac{z_V}{a_V}\right). \quad (29)$$

It can be induced that

$$\begin{aligned} \dot{L}_{\bar{V}} \leq & z_V E_V g_V \omega_V \bar{\Phi} + \frac{z_V^2 \ell_V \tilde{g}_{Vm} \mathbf{S}_V^T \mathbf{S}_V}{4\tau_V} + \tau_V + \frac{1}{2} \phi_V^2 \\ & - \frac{\omega_V}{l_V} \tilde{\vartheta}_V \dot{\tilde{\vartheta}}_V + z_V \bar{\Phi} - k_V z_V^2 - \frac{z_V^2 \hat{\ell}_V \tilde{g}_{Vm} \mathbf{S}_V^T \mathbf{S}_V}{4\tau_V} \\ & + \xi_V \left(|z_V| - z_V \tanh\left(\frac{z_V}{a_V}\right) \right) - \frac{\tilde{g}_{Vm}}{\mu_V} \tilde{\ell}_V \dot{\tilde{\ell}}_V \\ & + \frac{1}{r_V} \tilde{\xi}_V \left(r_V z_V \tanh\left(\frac{z_V}{a_V}\right) - \dot{\tilde{\xi}}_V \right). \end{aligned} \quad (30)$$

Choose the adaptive laws as follows

$$\dot{\hat{\ell}}_V = \frac{\mu_V z_V^2 \mathbf{S}_V^T \mathbf{S}_V}{4\tau_V} - \Gamma_V \hat{\ell}_V, \quad (31)$$

$$\dot{\hat{\xi}}_V = r_V z_V \tanh\left(\frac{z_V}{a_V}\right) - b_V \hat{\xi}_V, \quad (32)$$

$$\dot{\hat{\vartheta}}_V = l_V z_V \bar{\Phi} - c_V \hat{\vartheta}_V, \quad (33)$$

where $a_V > 0$, $b_V > 0$ and $c_V > 0$ are the parameters to be designed.

Substituting (31)-(33) into (30) yields

$$\begin{aligned} \dot{L}_{\bar{V}} \leq & z_V E_V g_V \omega_V \bar{\Phi} + \tau_V + \frac{1}{2} \phi_V^2 + \frac{\Gamma_V \tilde{g}_{Vm}}{\mu_V} \tilde{\ell}_V \hat{\ell}_V \\ & - \omega_V \tilde{\vartheta}_V z_V \bar{\Phi} + \frac{\omega_V c_V}{l_V} \tilde{\vartheta}_V \hat{\vartheta}_V + z_V \bar{\Phi} - k_V z_V^2 \\ & + \xi_V \left(|z_V| - z_V \tanh\left(\frac{z_V}{a_V}\right) \right) + \frac{b_V}{r_V} \tilde{\xi}_V \hat{\xi}_V. \end{aligned} \quad (34)$$

Now we design the actual control law as

$$\Phi = -\frac{z_V \hat{\vartheta}_V^2 \bar{\Phi}^2}{\sqrt{z_V^2 \hat{\vartheta}_V^2 \bar{\Phi}^2 + \sigma_V^2}}, \quad (35)$$

where $\sigma_V > 0$ is a predefined constant. According to Young's inequality, one has

$$\tilde{\ell}_V \hat{\ell}_V = (\ell_V - \tilde{\ell}_V) \tilde{\ell}_V \leq -\frac{1}{2} \tilde{\ell}_V^2 + \frac{1}{2} \ell_V^2, \quad (36)$$

$$\tilde{\vartheta}_V \hat{\vartheta}_V = (\vartheta_V - \tilde{\vartheta}_V) \tilde{\vartheta}_V \leq -\frac{1}{2} \tilde{\vartheta}_V^2 + \frac{1}{2} \vartheta_V^2, \quad (37)$$

$$\tilde{\xi}_V \hat{\xi}_V = (\xi_V - \tilde{\xi}_V) \tilde{\xi}_V \leq -\frac{1}{2} \tilde{\xi}_V^2 + \frac{1}{2} \xi_V^2. \quad (38)$$

Substituting (35)-(38) into (34) and applying Lemma 1 and Lemma 2, we can rewrite (34) as

$$\begin{aligned} \dot{L}_{\bar{V}} \leq & -k_V z_V^2 - \frac{1}{2\mu_V} \Gamma_V \tilde{g}_{Vm} \tilde{\ell}_V^2 - \frac{1}{2l_V} \omega_V c_V \tilde{\vartheta}_V^2 - \frac{1}{2r_V} b_V \tilde{\xi}_V^2 \\ & + \frac{1}{2\mu_V} \Gamma_V \tilde{g}_{Vm} \ell_V^2 + \frac{1}{2l_V} \omega_V c_V \vartheta_V^2 + \frac{1}{2r_V} b_V \xi_V^2 + \tau_V \\ & + \frac{1}{2} \phi_V^2 + \omega_V \sigma_V + 0.2785 a_V \xi_V. \end{aligned} \quad (39)$$

3.2 Altitude controller design

In the process of altitude controller design, the backstepping methodology is adopted to deal with complex dynamics. The virtual controllers will be designed at first, and then the intermediate control law the actual control law will be constructed to counteract the impact of actuator fault. To initiate the design process, we first define the following tracking errors

$$\begin{cases} e_h = h - h_{ref}, & z_\gamma = \gamma - \chi_\gamma, \\ z_\theta = \theta - \chi_\theta, & z_Q = Q - \chi_Q, \end{cases} \quad (40)$$

with χ_γ , χ_θ and χ_Q representing the virtual control laws.

Step 1 Similarly to velocity controller design, one reaches

$$\dot{e}_h = V\gamma + d_h - \dot{h}_{ref} = \dot{\rho}(t)q + \dot{z}_h\rho(t) \frac{\partial q}{\partial z}. \quad (41)$$

Then we have

$$\dot{z}_h = \frac{V\gamma + d_h - \dot{h}_{ref} - \dot{\rho}(t)q}{\rho(t) \frac{\partial q}{\partial z}} = \Upsilon_h + E_h \left(V\gamma + d_h - \dot{h}_{ref} \right) \quad (42)$$

with

$$\Upsilon_h = -\dot{\rho}(t)qE_h, \quad E_h = \frac{1}{\rho(t) \frac{\partial q}{\partial z}}. \quad (43)$$

Noting that $\frac{\partial q}{\partial z} = \frac{(1-q^2)^2}{1+q^2} \leq 1$ when $-1 < q < 1$ and the fact that $V \geq V_m > 0$ where V_m is minimum permissible flight velocity, yields

$$E_h V = \frac{V}{\rho(t) \frac{\partial q}{\partial z}} \geq \frac{V_m}{\rho(0)} = \tilde{V}_m > 0. \quad (44)$$

Consider the following Lyapunov function candidate

$$L_h = \frac{1}{2}z_h^2 + \frac{1}{2\mu_h}\tilde{V}_m\tilde{\ell}_h^2, \quad (45)$$

with $\tilde{\ell}_h = \ell_h - \hat{\ell}_h$, in which $\hat{\ell}_h$ denotes the estimation of adaptive parameter ℓ_h , μ_h is the positive design parameter.

The time derivative of L_h gives

$$\dot{L}_h = z_h (\mathbf{W}_h^T \mathbf{S}_h + \phi_h + E_h V \gamma) - \frac{1}{\mu_h} \tilde{V}_m \tilde{\ell}_h \dot{\hat{\ell}}_h - \frac{1}{2} z_h^2, \quad (46)$$

with $F_h = \Upsilon_h + E_h d_h - E_h \dot{h}_{ref} + \frac{1}{2} z_h$ being approximated by FLS $\mathbf{W}_h^T \mathbf{S}_h(\mathbf{x}_h) + \phi_h$, where $\mathbf{x}_h = [h, h_{ref}, \dot{h}_{ref}]^T$.

Applying Young's inequation, it gives

$$z_h \mathbf{W}_h^T \mathbf{S}_h \leq \frac{z_h^2 \|\mathbf{W}_h\|^2 \mathbf{S}_h^T \mathbf{S}_h}{4\tau_h} + \tau_h, \quad (47)$$

$$z_h \phi_h \leq \frac{1}{2} z_h^2 + \frac{1}{2} \phi_h^2, \quad (48)$$

where τ_h is a positive constant, noting that $\gamma = z_\gamma + \chi_\gamma$ we can further rewrite (46) as

$$\begin{aligned} \dot{L}_h \leq & E_h V z_h z_\gamma + z_h E_h V \chi_\gamma + \frac{z_h^2 \ell_h \tilde{V}_m \mathbf{S}_h^T \mathbf{S}_h}{4\tau_h} \\ & + \tau_h + \frac{1}{2} \phi_h^2 - \frac{1}{\mu_h} \tilde{V}_m \tilde{\ell}_h \dot{\hat{\ell}}_h, \end{aligned} \quad (49)$$

with the definition of $\ell_h = \frac{\|\mathbf{W}_h\|^2}{\tilde{V}_m}$. Choose the virtual control law and updating law as follows

$$\chi_\gamma = -k_h z_h - \frac{z_h \hat{\ell}_h \mathbf{S}_h^T \mathbf{S}_h}{4\tau_h}, \quad (50)$$

$$\dot{\hat{\ell}}_h = \frac{\mu_h z_h^2 \mathbf{S}_h^T \mathbf{S}_h}{4\tau_h} - \Gamma_h \hat{\ell}_h. \quad (51)$$

Substituting (50)-(51) into (49) yields

$$\dot{L}_h \leq -k_h z_h^2 + \frac{1}{\mu_h} \Gamma_h \tilde{V}_m \tilde{\ell}_h \hat{\ell}_h + E_h V z_h z_\gamma + \frac{1}{2} \phi_h^2 + \tau_h. \quad (52)$$

Step 2 Take the Lyapunov function candidate as

$$L_\gamma = L_h + \frac{1}{2} z_\gamma^2 + \frac{1}{2\mu_\gamma} g_{\gamma m} \tilde{\ell}_\gamma^2. \quad (53)$$

Similar to step 1, by defining $\ell_\gamma = \frac{\|\mathbf{W}_\gamma\|^2}{g_{\gamma m}}$, the time derivative of L_γ can be formulated as

$$\begin{aligned} \dot{L}_\gamma = & \dot{L}_h + z_\gamma (\mathbf{W}_\gamma^T \mathbf{S}_\gamma + \phi_\gamma + g_\gamma \theta) - \frac{1}{\mu_\gamma} g_{\gamma m} \tilde{\ell}_\gamma \dot{\hat{\ell}}_\gamma \\ & - E_h V z_h z_\gamma - \frac{1}{2} z_\gamma^2, \end{aligned} \quad (54)$$

with $F_\gamma = f_\gamma + E_h V z_h + d_\gamma - \dot{\chi}_\gamma + \frac{1}{2} z_\gamma$ being approximated by FLS $\mathbf{W}_\gamma^T \mathbf{S}_\gamma(\mathbf{x}_\gamma) + \phi_\gamma$, where $\dot{\chi}_\gamma = \frac{\partial \chi_\gamma}{\partial h} \dot{h} +$

$$\frac{\partial \chi_\gamma}{\partial \ell_h} \dot{\hat{\ell}}_h + \frac{\partial \chi_\gamma}{\partial h_{ref}} \dot{h}_{ref} \text{ and } \mathbf{x}_\gamma = [h, \gamma, h_{ref}, \dot{h}_{ref}, h_{ref}^{(2)}, \hat{\ell}_h]^T.$$

Design the virtual control law and adaptive law as

$$\chi_\theta = -k_\gamma z_\gamma - \frac{z_\gamma \hat{\ell}_\gamma \mathbf{S}_\gamma^T \mathbf{S}_\gamma}{4\tau_\gamma}, \quad (55)$$

$$\dot{\hat{\ell}}_\gamma = \frac{\mu_\gamma z_\gamma^2 \mathbf{S}_\gamma^T \mathbf{S}_\gamma}{4\tau_\gamma} - \Gamma_\gamma \hat{\ell}_\gamma. \quad (56)$$

Based on (52)-(56), we obtain

$$\begin{aligned} \dot{L}_\gamma \leq & -k_h z_h^2 - k_\gamma z_\gamma^2 + \frac{1}{\mu_h} \Gamma_h \tilde{V}_m \tilde{\ell}_h \hat{\ell}_h + \frac{1}{\mu_\gamma} \Gamma_\gamma g_{\gamma m} \tilde{\ell}_\gamma \hat{\ell}_\gamma \\ & + g_\gamma z_\gamma z_\theta + \frac{1}{2} \phi_h^2 + \frac{1}{2} \phi_\gamma^2 + \tau_h + \tau_\gamma. \end{aligned} \quad (57)$$

Step 3 Consider the following Lyapunov function candidate

$$L_\theta = L_\gamma + \frac{1}{2} z_\theta^2 + \frac{1}{2\mu_\theta} \tilde{\ell}_\theta^2. \quad (58)$$

Defining $\ell_\theta = \|\mathbf{W}_\theta\|^2$, the time derivative of L_θ gives

$$\begin{aligned} \dot{L}_\theta = & \dot{L}_\gamma + z_\theta (\mathbf{W}_\theta^T \mathbf{S}_\theta + \phi_\theta + Q) - \frac{1}{\mu_\theta} \tilde{\ell}_\theta \dot{\hat{\ell}}_\theta \\ & - g_\gamma z_\gamma z_\theta - \frac{1}{2} z_\theta^2, \end{aligned} \quad (59)$$

with $F_\theta = g_\gamma z_\gamma - \dot{\chi}_\theta + \frac{1}{2} z_\theta$ being approximated by FLS $\mathbf{W}_\theta^T \mathbf{S}_\theta(\mathbf{x}_\theta) + \phi_\theta$, where $\dot{\chi}_\theta = \sum_{x=h,\gamma} \frac{\partial \chi_\theta}{\partial x} \dot{x} + \sum_{x=h,\gamma} \frac{\partial \chi_\theta}{\partial \ell_x} \dot{\hat{\ell}}_x + \sum_{i=0}^2 \frac{\partial \chi_\theta}{\partial h_{ref}^{(i)}} h_{ref}^{(i+1)}$ and $\mathbf{x}_\theta = [h, \gamma, \theta, h_{ref}, \dot{h}_{ref}, h_{ref}^{(2)}, h_{ref}^{(3)}, \hat{\ell}_h, \hat{\ell}_\gamma]^T$.

Construct the virtual control law and adaptive law

$$\chi_Q = -k_\theta z_\theta - \frac{z_\theta \hat{\ell}_\theta \mathbf{S}_\theta^T \mathbf{S}_\theta}{4\tau_\theta}, \quad (60)$$

$$\dot{\hat{\ell}}_\theta = \frac{\mu_\theta z_\theta^2 \mathbf{S}_\theta^T \mathbf{S}_\theta}{4\tau_\theta} - \Gamma_\theta \hat{\ell}_\theta. \quad (61)$$

From (58)-(61), one has

$$\begin{aligned} \dot{L}_\theta \leq & -k_h z_h^2 - k_\gamma z_\gamma^2 - k_\theta z_\theta^2 + \frac{\Gamma_h \tilde{V}_m \tilde{\ell}_h \hat{\ell}_h}{\mu_h} + \frac{\Gamma_\gamma g_{\gamma m} \tilde{\ell}_\gamma \hat{\ell}_\gamma}{\mu_\gamma} + z_\theta z_Q \\ & + \frac{\Gamma_\theta \tilde{\ell}_\theta \hat{\ell}_\theta}{\mu_\theta} + \frac{1}{2} \phi_h^2 + \frac{1}{2} \phi_\gamma^2 + \frac{1}{2} \phi_\theta^2 + \tau_h + \tau_\gamma + \tau_\theta. \end{aligned} \quad (62)$$

Step 4 Choose the following Lyapunov function candidate

$$L_Q = L_\theta + \frac{1}{2} z_Q^2 + \frac{1}{2\mu_Q} g_{Qm} \tilde{\ell}_Q^2. \quad (63)$$

Constructing $\ell_Q = \frac{\|\mathbf{W}_Q\|^2}{g_{Qm}}$ and taking the derivative of L_Q yield

$$\begin{aligned} \dot{L}_Q = & \dot{L}_\theta + z_Q (\mathbf{W}_Q^T \mathbf{S}_Q + \phi_Q + g_Q \omega_Q \delta_e + g_Q \varepsilon_Q) \\ & - \frac{1}{\mu_Q} g_{Qm} \tilde{\ell}_Q \hat{\ell}_Q - z_\theta z_Q - \frac{1}{2} z_Q^2, \end{aligned} \quad (64)$$

with $F_Q = f_Q + z_\theta + d_Q - \dot{\chi}_\theta + \frac{1}{2} z_Q$ being approximated by FLS $\mathbf{W}_Q^T \mathbf{S}_Q(\mathbf{x}_Q) + \phi_Q$, where $\dot{\chi}_Q = \sum_{x=h,\gamma,\theta} \frac{\partial \chi_Q}{\partial x} \dot{x} +$

$$\sum_{x=h,\gamma,\theta} \frac{\partial \chi_Q}{\partial \hat{\ell}_x} \dot{\hat{\ell}}_x + \sum_{i=0}^3 \frac{\partial \chi_Q}{\partial h_{ref}^{(i)}} h_{ref}^{(i+1)} \text{ and } \mathbf{x}_Q = [h, \gamma, \theta, Q, h_{ref}, \dot{h}_{ref}, h_{ref}^{(2)}, h_{ref}^{(3)}, h_{ref}^{(4)}, \hat{\ell}_h, \hat{\ell}_\gamma, \hat{\ell}_\theta]^T.$$

The upper and lower bounds of fault parameters are defined as

$$\underline{\omega}_Q = \inf(g_Q \omega_Q), \vartheta_Q = \frac{1}{\underline{\omega}_Q}, \quad (65)$$

$$\xi_Q = \sup(g_Q \varepsilon_Q). \quad (66)$$

Construct the Lyapunov function

$$L_Q = L_Q + \frac{1}{2l_Q} \omega_Q \tilde{\vartheta}_Q^2 + \frac{1}{2r_Q} \tilde{\xi}_Q^2, \quad (67)$$

where $l_Q > 0$ and $r_Q > 0$ are designed parameters, $\tilde{\vartheta}_Q = \vartheta_Q - \hat{\vartheta}_Q$ and $\tilde{\xi}_Q = \xi_Q - \hat{\xi}_Q$ represent estimation errors with $\hat{\vartheta}_Q$ and $\hat{\xi}_Q$ being the estimations of ϑ_Q and ξ_Q , respectively. Choose the intermediate control law and adaptive laws as follows

$$\bar{\delta}_e = k_Q z_Q + \frac{z_Q \hat{\ell}_Q \mathbf{S}_Q^T \mathbf{S}_Q}{4\tau_Q} + \hat{\xi}_Q \tanh\left(\frac{z_Q}{a_Q}\right), \quad (68)$$

$$\dot{\hat{\ell}}_Q = \frac{\mu_Q z_Q^2 \mathbf{S}_Q^T \mathbf{S}_Q}{4\tau_Q} - \Gamma_Q \hat{\ell}_Q, \quad (69)$$

$$\dot{\hat{\xi}}_Q = r_Q z_Q \tanh\left(\frac{z_Q}{a_Q}\right) - b_Q \hat{\xi}_Q, \quad (70)$$

$$\dot{\hat{\vartheta}}_Q = l_Q z_Q \bar{\delta}_e - c_Q \hat{\vartheta}_Q, \quad (71)$$

where k_Q, τ_Q, a_Q, b_Q and c_Q are designed positive parameters.

Finally, we choose the actual control law as

$$\delta_e = -\frac{z_Q \hat{\vartheta}_Q^2 \bar{\delta}_e^2}{\sqrt{z_Q^2 \hat{\vartheta}_Q^2 \bar{\delta}_e^2 + \sigma_Q^2}}, \quad (72)$$

where $\sigma_Q > 0$ is a predefined constant. Following similar analysis to velocity subsystem, we can further de-

duce that

$$\begin{aligned} \dot{L}_{\bar{Q}} \leq & -k_h z_h^2 - k_\gamma z_\gamma^2 - k_\theta z_\theta^2 - k_Q z_Q^2 - \frac{\Gamma_h \tilde{V}_m}{\mu_h} \tilde{\ell}_h^2 \\ & - \frac{\Gamma_\gamma g_{\gamma m}}{\mu_\gamma} \tilde{\ell}_\gamma^2 - \frac{\Gamma_\theta}{\mu_\theta} \tilde{\ell}_\theta^2 - \frac{\Gamma_Q \tilde{g}_{Qm}}{2\mu_Q} \tilde{\ell}_Q^2 - \frac{\omega_Q c_Q}{2l_Q} \tilde{\vartheta}_Q^2 \\ & - \frac{b_Q}{2r_Q} \tilde{\xi}_Q^2 + \frac{\Gamma_h \tilde{V}_m}{\mu_h} \ell_h^2 + \frac{\Gamma_\gamma g_{\gamma m}}{\mu_\gamma} \ell_\gamma^2 + \frac{\Gamma_\theta}{\mu_\theta} \ell_\theta^2 \\ & + \frac{\Gamma_Q \tilde{g}_{Qm}}{2\mu_Q} \ell_Q^2 + \frac{\omega_Q c_Q}{2l_Q} \vartheta_Q^2 + \frac{b_Q}{2r_Q} \xi_Q^2 + \frac{1}{2} \phi_h^2 \\ & + \frac{1}{2} \phi_\gamma^2 + \frac{1}{2} \phi_\theta^2 + \frac{1}{2} \phi_Q^2 + \tau_h + \tau_\gamma + \tau_\theta \\ & + \tau_Q + \underline{\omega}_Q \sigma_Q + 0.2785 a_Q \xi_Q. \end{aligned} \quad (73)$$

The whole FTFTC design for HFVs is shown in Fig.2.

4 Closed-loop stability analysis

Theorem 1 Despite the occurrence of unknown actuator fault (3), consider the closed-loop system composed by (4) and (5), the virtual control laws (50), (55) and (60), the intermediate control laws (29) and (68), the actual control laws (35) and (72), and the parameter adaptation laws (31)-(33), (51), (56), (61) and (69)-(71). Let Assumptions 1-2 hold. By designing the parameters properly, it therefore holds that

1. The tracking errors e_V and e_h can converge into a predefined residual set within an user-defined time T .
2. The overshoot and convergence rate are guaranteed by FTTPF and all signals of the closed-loop system are SGPFs.

Proof Take the Lyapunov function candidate as

$$L = L_V + L_{\bar{Q}}. \quad (74)$$

Applying (39) and (73), the derivative of L gives

$$\begin{aligned} \dot{L} \leq & -k_V z_V^2 - k_h z_h^2 - k_\gamma z_\gamma^2 - k_\theta z_\theta^2 - k_Q z_Q^2 - \frac{\Gamma_V \tilde{g}_{Vm}}{2\mu_V} \tilde{\ell}_V^2 \\ & - \frac{\Gamma_h \tilde{V}_m}{\mu_h} \tilde{\ell}_h^2 - \frac{\Gamma_\gamma g_{\gamma m}}{\mu_\gamma} \tilde{\ell}_\gamma^2 - \frac{\Gamma_\theta}{\mu_\theta} \tilde{\ell}_\theta^2 - \frac{\Gamma_Q \tilde{g}_{Qm}}{2\mu_Q} \tilde{\ell}_Q^2 \\ & - \frac{\omega_V c_V}{2l_V} \tilde{\vartheta}_V^2 - \frac{\omega_Q c_Q}{2l_Q} \tilde{\vartheta}_Q^2 - \frac{b_V}{2r_V} \tilde{\xi}_V^2 - \frac{b_Q}{2r_Q} \tilde{\xi}_Q^2 \\ & + \frac{\Gamma_h \tilde{V}_m}{\mu_h} \ell_h^2 + \frac{\Gamma_\gamma g_{\gamma m}}{\mu_\gamma} \ell_\gamma^2 + \frac{\Gamma_\theta}{\mu_\theta} \ell_\theta^2 + \frac{\Gamma_V \tilde{g}_{Vm}}{2\mu_V} \ell_V^2 \end{aligned}$$

Fig. 2: Overall fixed-time tolerant-control scheme for HFVs

$$\begin{aligned}
& + \frac{\Gamma_Q \tilde{g}_{Qm} \ell_Q^2}{2\mu_Q} + \frac{\omega_V c_V}{2l_V} \vartheta_V^2 + \frac{\omega_Q c_Q}{2l_Q} \vartheta_Q^2 + \frac{b_V}{2r_V} \xi_V^2 \\
& + \frac{b_Q}{2r_Q} \xi_Q^2 + \frac{1}{2} \phi_V^2 + \frac{1}{2} \phi_h^2 + \frac{1}{2} \phi_\gamma^2 + \frac{1}{2} \phi_\theta^2 + \frac{1}{2} \phi_Q^2 \\
& + \tau_V + \tau_h + \tau_\gamma + \tau_\theta + \tau_Q + \underline{\omega}_V \sigma_V + \underline{\omega}_Q \sigma_Q \\
& + 0.2785a_V \xi_V + 0.2785a_Q \xi_Q.
\end{aligned} \quad (75)$$

Recalling the definitions of L_V and L_Q , the following inequation holds

$$\dot{L} \leq -kL + C, \quad (76)$$

where $k = \min\{2k_V, 2k_h, 2k_\gamma, 2k_\theta, 2k_Q, \Gamma_V, \Gamma_h, \Gamma_\gamma, \Gamma_\theta, \Gamma_Q, b_V, b_Q, c_V, c_Q\}$, $C = \frac{\Gamma_h \tilde{V}_m}{\mu_h} \ell_h^2 + \frac{\Gamma_\gamma g_{\gamma m}}{\mu_\gamma} \ell_\gamma^2 + \frac{\Gamma_\theta}{\mu_\theta} \ell_\theta^2 + \frac{\Gamma_V \tilde{g}_{Vm}}{2\mu_V} \ell_V^2 + \frac{\Gamma_Q \tilde{g}_{Qm}}{2\mu_Q} \ell_Q^2 + \frac{\omega_V c_V}{2l_V} \vartheta_V^2 + \frac{\omega_Q c_Q}{2l_Q} \vartheta_Q^2 + \frac{b_V}{2r_V} \xi_V^2 + \frac{b_Q}{2r_Q} \xi_Q^2 + \frac{1}{2} \phi_V^2 + \frac{1}{2} \phi_h^2 + \frac{1}{2} \phi_\gamma^2 + \frac{1}{2} \phi_\theta^2 + \frac{1}{2} \phi_Q^2 + \tau_V + \tau_h + \tau_\gamma + \tau_\theta + \tau_Q + \underline{\omega}_V \sigma_V + \underline{\omega}_Q \sigma_Q + 0.2785a_V \xi_V + 0.2785a_Q \xi_Q$.

Integrating both sides of (76) yields

$$L \leq L(0) + \frac{C}{k}. \quad (77)$$

In accordance with (17), (27), (45), (53), (58), (63), (67), (74) and (77), we have

$$z_V \leq \sqrt{2L(0) + \frac{C}{k}}, \quad z_h \leq \sqrt{2L(0) + \frac{C}{k}}, \quad (78)$$

and the estimation errors of the adaptive parameters will converge to the following compact sets

$$\left\{ \begin{array}{l} \tilde{\ell}_V \leq \sqrt{2\mu_V (L(0) + \frac{C}{k})} \\ \tilde{\ell}_h \leq \sqrt{2\mu_h (L(0) + \frac{C}{k})} \\ \tilde{\ell}_\gamma \leq \sqrt{2\mu_\gamma (L(0) + \frac{C}{k})} \\ \tilde{\ell}_\theta \leq \sqrt{2\mu_\theta (L(0) + \frac{C}{k})} \\ \tilde{\ell}_Q \leq \sqrt{2\mu_Q (L(0) + \frac{C}{k})} \end{array} \right\}, \quad \left\{ \begin{array}{l} \tilde{\vartheta}_V \leq \sqrt{\frac{2l_V}{\omega_V} (L(0) + \frac{C}{k})} \\ \tilde{\vartheta}_Q \leq \sqrt{\frac{2l_Q}{\omega_Q} (L(0) + \frac{C}{k})} \\ \tilde{\xi}_V \leq \sqrt{2r_V (L(0) + \frac{C}{k})} \\ \tilde{\xi}_Q \leq \sqrt{2r_Q (L(0) + \frac{C}{k})} \end{array} \right\}.$$

Therefore, the transformational errors z_V and z_h are bounded. By reviewing (6)-(8), we can conclude that the velocity and altitude tracking errors converge

to a residual set within a fixed time T and the prescribed performances are guaranteed. Besides, all signals of closed-loop system are SGPFs. This completes the proof. ■

Remark 5 The existing fixed-time control strategies for HFVs [17]-[19] fail to take system transient and steady-state performances into account and it is fairly complicated to make tracking error convergence into a preassigned compact set within the fixed-time by selecting design parameters. It is worth noting that the fixed-time tracking control is achieved as long as the bounded condition is satisfied in the proposed design. Consequently, the complexity of the control structure is reduced and the initial states need not to be known accurately via the proposed control approach.

Remark 6 It is worth mentioning that the control performance is depended closely on the designed parameters of prescribed function. In (6), large initial errors are allowed by choosing a small enough r , larger ϑ and smaller T will increase the convergence rate. However, too large ϑ or too small T will give rise to actuator input saturations. In (29), (50), (55), (60) and (68), designed parameters $k_V, \tau_V, a_V, k_h, \tau_h, k_\gamma, \tau_\gamma, k_\theta, \tau_\theta, k_Q, \tau_Q$ and a_Q determine the convergence rate and convergence accuracy. In (31)-(33), (51), (56), (61) and (69)-(71), designed parameters $\mu_V, \Gamma_V, r_V, b_V, l_V, c_V, \mu_h, \Gamma_h, \mu_\gamma, \Gamma_\gamma, \mu_\theta, \Gamma_\theta, \mu_Q, \Gamma_Q, r_Q, b_Q, l_Q$ and c_Q effect convergence rate of the adaptive parameters. In the controller design, we need to design the parameters properly to improve the tracking performance and avoid the saturation phenomenon.

5 Simulations

In this section, simulation results are used to demonstrate the effectiveness and superiority of the proposed methodology. The model parameters of HFVs can be consulted from [31]. HFVs are expected to climb a maneuver from the initial trim conditions, depicted in Ta-

Fig. 3: The velocity, altitude tracking performance and attitude angles under different initial states

Fig. 4: The flexible states, control inputs and adaptive parameters under different initial states

ble 1, to the final values $V = 8700\text{ft/s}$ and $h = 88000\text{ft}$. The uncertain aerodynamic coefficients are modelled as $C_i = C_i^*(1 + \Delta_i)$, where C_i^* represents the nominal coefficient and Δ_i represents the uncertain factor ranging from -20% to 20% . The external disturbances in velocity subsystem and altitude subsystem are set as $d_V = 10 \sin(t) \text{ ft/s}$, $d_h = 5 \sin(0.1t) \text{ ft}$, $d_\gamma = 0.05 \sin(t) \text{ deg}$, $d_Q = 0.5 \sin(0.1t) \text{ deg/s}$. The reference trajectories of velocity and altitude are generated via the following filters [10]

$$\frac{V_{ref}(s)}{V_c(s)} = \frac{0.03^2}{s^2 + 2 \times 0.95 \times 0.03 \times s + 0.03^2}, \quad (79)$$

$$\frac{h_{ref}(s)}{h_c(s)} = \frac{0.03^2}{s^2 + 2 \times 0.95 \times 0.03 \times s + 0.03^2}, \quad (80)$$

where $V_{ref}(s)$ and $h_{ref}(s)$ represent the inputs of filters, $V_c(s)$ and $h_c(s)$ represent the outputs of filters, respectively. It is assumed that HFVs actuators failed at 100s, and the details of failure are formulated in the

Table 1: The initial states

States	Value	Units
V	7700	ft/s
h	85000	ft
γ	0	deg
θ	1.6325	deg
Q	0	deg/s
η_1	0.97	ft slugs ^{0.5} /ft
$\dot{\eta}_1$	0	ft/s slugs ^{0.5} /ft
η_2	0.7967	ft slugs ^{0.5} /ft
$\dot{\eta}_2$	0	ft/s slugs ^{0.5} /ft

form of

$$v(\Phi) = 0.8\Phi - 0.1, \quad (81)$$

$$v(\delta_e) = 0.8\delta_e + 0.0349. \quad (82)$$

Fig. 5: The velocity, altitude tracking performance and attitude angles via different methodologies

Fig. 6: The flexible states, control inputs and performance indexes via different methodologies

The FTPFs are selected as

$$\rho_V(t) = \begin{cases} \coth\left(\frac{t}{50-t} + 0.4\right) - 0.9, & 0 \leq t < 50 \\ 0.1, & t \geq 50, \end{cases} \quad (83)$$

$$\rho_h(t) = \begin{cases} \coth\left(\frac{t}{50-t} + 0.4\right) - 0.5, & 0 \leq t < 50 \\ 0.5, & t \geq 50. \end{cases} \quad (84)$$

The fuzzy rules in $\mathbf{W}_V^{*T} \mathbf{S}_V$ are listed as

$\mathcal{R}^l$: If V is F_V^i , then y is B^l , where $i = 1, 2, 3$; $l = 1, 2, 3$.

The fuzzy rules in $\mathbf{W}_\gamma^{*T} \mathbf{S}_\gamma$ are listed as

$\mathcal{R}^l$: If h is F_h^i , and γ is F_γ^j , then y is B^l , where $i = 1, 2, 3$; $j = 1, 2, 3$; $l = 1, 2, \dots, 9$.

Then, the fuzzy rules in $\mathbf{W}_\theta^{*T} \mathbf{S}_\theta$ are listed as

$\mathcal{R}^l$: If h is F_h^i , and γ is F_γ^j , and θ is F_θ^k , then y is B^l , where $i = 1, 2, 3$; $j = 1, 2, 3$; $k = 1, 2, 3$; $l = 1, 2, \dots, 27$.

The fuzzy rules in $\mathbf{W}_Q^{*T} \mathbf{S}_Q$ are listed as

$\mathcal{R}^l$: If h is F_h^i , and γ is F_γ^j , and θ is F_θ^k , and Q is F_Q^p , then y is B^l , where $i = 1, 2, 3$; $j = 1, 2, 3$; $k = 1, 2, 3$; $p = 1, 2, 3$; $l = 1, 2, \dots, 81$.

The fuzzy membership function is given as follows

$$\begin{aligned} \mu_{F_V^1} &= \exp\left[-(V-7500)^2/300\right], & \mu_{F_h^1} &= \exp\left[-(h-85000)^2/1000\right], \\ \mu_{F_V^2} &= \exp\left[-(V-8100)^2/300\right], & \mu_{F_h^2} &= \exp\left[-(h-87000)^2/1000\right], \\ \mu_{F_V^3} &= \exp\left[-(V-8700)^2/300\right], & \mu_{F_h^3} &= \exp\left[-(h-89000)^2/1000\right], \\ \mu_{F_Q^1} &= \exp\left[-(Q+0.03)^2/0.002\right], & \mu_{F_\theta^1} &= \exp\left[-(\theta-0)^2/0.002\right], \\ \mu_{F_Q^2} &= \exp\left[-(Q-0)^2/0.002\right], & \mu_{F_\theta^2} &= \exp\left[-(\theta-0.02)^2/0.002\right], \\ \mu_{F_Q^3} &= \exp\left[-(Q-0.03)^2/0.002\right], & \mu_{F_\theta^3} &= \exp\left[-(\theta-0.04)^2/0.002\right], \\ \mu_{F_\gamma^1} &= \exp\left[-(\gamma-0)^2/0.0005\right], & \mu_{F_\gamma^2} &= \exp\left[-(\gamma-0.005)^2/0.0005\right], \\ \mu_{F_\gamma^3} &= \exp\left[-(\gamma-0.01)^2/0.0005\right]. \end{aligned}$$

The controller parameters are selected as $k_V = \mu_V = r_V = l_V = \mu_h = \mu_\gamma = \mu_\theta = \mu_Q = r_Q = l_Q = 1$, $\tilde{g}_{Vm} = 0.00001$, $\tilde{g}_{Qm} = 1$, $\tau_V = \Gamma_V = c_V = b_V = \tau_h = \Gamma_h = \tau_\gamma = \Gamma_\gamma = \tau_\theta = \Gamma_\theta = \tau_Q = \Gamma_Q = c_Q = b_Q = 0.1$, $a_V = 0.2$, $a_Q = 0.25$, $\sigma_V = \sigma_Q = \frac{1}{t^2+0.01}$, $k_h = 10$, $k_\gamma = 2$, $k_\theta = 10$, $k_Q = 50$. To prove that the proposed FTFTC is realizable and independent of the initial states, the first example is taken, while the superiority

of the proposed FTFTC over the conventional fixed-time control (CFTC) in [38] is explained in the second example.

Example 1 In this example, two different initial states cases, i.e., case 1 ($e_V(0) = e_h(0) = 0$) and case 2 ($e_V(0) = e_h(0) = 1$) are considered respectively.

The obtained simulation results, depicted in Figs. 3-4, reveal that the proposed FTFTC has full capabilities to deal with the condition that aerodynamic parameters are perturbed and initial states are uncertain. It can be observed from Figs. 3 (a)-(b) that the velocity and altitude tracking errors are guaranteed not to exceed the prescribed bounds. Furthermore, the velocity and altitude can rapidly track their reference trajectories even if the actuator fails. Fig. 3 (c) and Fig. 4 (a) depict there is no high-frequency chattering in the attitude angles as well as the flexible states, and they can converge to their steady values rapidly. Fig. 4 (b) shows that the control inputs are smooth and within realistic limits. The estimated values of adaptive parameters are bounded, which is presented in Fig. 4 (c).

Example 2 In this example, simulations via the CFTC [38] and the proposed FTFTC are demonstrated, where the initial states are set as $e_V(0) = e_h(0) = 1$. In order to expound the advantages of tracking performances of the proposed FTFTC, the performance index $E = \int_0^t e^2 dt$ is introduced where e denotes the tracking error.

Simulation results are depicted in Figs. 5-6. Figs. 5 (a)-(b) shows the velocity and altitude tracking performance, in which the velocity and altitude tracking errors are limited in the preset bounds by the proposed FTFTC and the proposed FTFTC can provide higher rate of convergence compared with the CFTC. Besides, the attitude angles and flexible states are shown in Fig. 5 (c) and Fig. 6 (a), indicating that smaller oscillation amplitudes of attitude angles and flexible states are achieved in the presence of actuator failures by means of the proposed FTFTC. In addition, Fig. 6 (c) gives that less error energy is produced via the proposed FTFTC in contrast with the CFTC. That is to say, the proposed FTFTC can achieve more accurate tracking.

6 Conclusions

A novel fixed-time fuzzy adaptive fault-tolerant control methodology based on performance function is developed for hypersonic flight vehicles in this work. In contrast with the conventional fixed-time control, the proposed approach not only guarantees that the velocity and altitude tracking errors converge into a pre-assigned compact set, but also satisfies both the prescribed transient and steady performance. In addition,

the proposed scheme can avoid the singularity problem caused by the differential of fractional order tracking error and remain valid in spite of actuator faults. Comparative simulation results confirm the validity and superiority of the presented control strategy.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Figures

Figure 1

The convergence performance of the proposed FTPF

Figure 2

Overall fixed-time tolerant-control scheme for HFVs

Figure 3

The velocity, altitude tracking performance and attitude angles under different initial states

Figure 4

The flexible states, control inputs and adaptive parameters under different initial states

Figure 5

The velocity, altitude tracking performance and attitude angles via different methodologies

Figure 6

The flexible states, control inputs and performance indexes via different methodologies