Non-fragile tracking control of constrained Waverider Vehicles with readjusting prescribed performance

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Abstract The purpose of this article is to solve the fragile problem of prescribed performance control (PPC) with application to Waverider Vehicles (WVs). By fragile problem, it denotes that tracking errors may break away from prescribed funnels if actuators are saturated. Firstly, we propose a new type of readjusting prescribed performance which adaptively readjusts its prescribed funnels such that the spurred transient performance and steady-state performance are still guaranteed for tracking errors in the presence of actuator saturation. Then, we extend the finite-time PPC into the non-affine model of WVs, ensuring that tracking errors always evolve within prescribed funnels. Furthermore, the improved back-stepping procedure without the derivation of virtual control law is utilized to develop non-fragile tracking controllers, and specially, there is no need of any fuzzy/neural approximation, avoiding the computational burden problem. Finally, compared simulation results are presented to verify the effectiveness and advantage.

Keywords Waverider Vehicles · Prescribed performance control · Fragile problem · Finite-time · Improved back-stepping

1 Introduction

Waverider Vehicles (WVs) have been regarded as the most promising technology for feasible and affordable hypersonic flight. The flight control design, which is the key technique to ensure safe flight and successful completion of flight missions, has caused worldwide concerns [1–5]. The special dynamics of WVs, including uncertainty, nonlinearity, non-affine property, saturation and coupling, leads to control challenges. The current focus of flight control for WVs is mainly on pursuing excellent robustness and accuracy under certain conditions such as actuator saturation/fault and uncertainties/disturbances via fuzzy/neural-based intelligent control [6–8], sliding mode control [9], back-stepping control [10–12], and fault-tolerant control [13,14]. However, all of them are unable to guarantee control system with satisfactory transient performance which is crucial to realize hypersonic maneuvering flight for WVs [15,16].

The prescribed performance control (PPC), firstly proposed by Bechlioulis et al. [17,18], is a pioneering methodology which is expected to provide an effective tool to ensure desired transient and steady-state performance. The main ideal of PPC is to devise a type of prescribed funnels called performance func-
tions whose shapes can be designed as needed [19–22].
The developed controllers based on PPC are capable of
guaranteeing that tracking errors always evolve within
prescribed funnels such that both the transient perform-
ance and the steady-state performance are satisfac-
tory. In the existing studies [23,24], prescribed perfor-
ance guaranteed tracking controllers were exploited for
WVs. Though tracking errors satisfy the desired
prescribed performance, those methods [23,24] require
that the models of WVs must have affine formulations,
which cannot be directly obtained owing to the nonlin-
ear characteristics. It is for this reason that non-affine-
model-based PPC schemes were investigated for WVs
in [7,15,16]. Furthermore, to reject system uncertain-
ties and disturbances, fuzzy/neural approximations are
commonly used methods [7,15,16,23,24] to enhance
the robustness performance. However, too much online
learning/computation burden caused by fuzzy/neural
approximations undoubtedly harms the real-time per-
fomance of control system, which is not conducive
to realize hypersonic maneuvering flight for WVs.
Besides, to improve the operability and practicability,
some researchers proposed improved versions of PPC
with finite-time convergence [16,22] such that the reg-
ulation time can be quantitatively designed as needed.

Despite the above developments of PPC, a facing
defect is the fragile problem. By fragile problem, we
mean that tracking errors may break away from pre-
scribed funnels if actuators are saturated. The flight
airspace of WVs is so high that it easily leads to actuator
saturation. The actuator saturation will inevitably result
in error increasing such that tracking errors show the
trend of breaking away from prescribed funnels, yield-
ing the fragile problem. Unfortunately, the existing PPC
strategies [3,8,16–24] did not take into consideration
actuator saturation since all of them couldn’t deal with
the fragile problem. In view of this, we propose a novel
non-fragile tracking controller with readjusting pre-
scribed performance for WVs subject to actuator satu-
ration. The addressed controllers are developed based
on non-affine models of WVs. Moreover, there is no
need of fuzzy/neural approximation, reducing online
learning computation burden. The main contributions
are listed as follows.

(1) The addressed method avoids the limitations of
previous finite-time PPC (FPPC) approaches [23,
24] that they are only suitable for affine dynamic
systems. In this article, FPPC is extended into the
non-affine model of WVs.
(2) The developed controller doesn’t require neu-
ral/fuzzy approximation [7,15,16,23] that may
cause lots of online learning parameters. As a
result, the computation burden of the design is sat-
sfactory.
(3) The proposed approach handles the fragile prob-
lem of PPC that the existing PPC strategies [8,16–
24] cannot deal with actuator saturation. In this
article, by proposing a new kind of readjusting pre-
scribed performance, both desired transient perfor-
ance and steady-state performance are guaran-
tee for tracking errors in finite time under actuator
saturation.

The rest of this paper is structured as follows. Sec-
tion 2 presents problem statement. Section 3 shows the
control design process. Section 4 provides the simula-
tion results, and Sect. 5 gives the conclusions.

2 Problem statement

2.1 Vehicle model

We consider the following nonlinear model of an WV
[25] whose map of geometry and force is shown in
Fig. 1.

\[
m\ddot{V} = T \cos(\theta - \gamma) - D - g \sin \gamma, \quad (1)
\]
\[
\dot{h} = V \sin \gamma, \quad (2)
\]
\[
mV \dot{\gamma} = L + T \sin(\theta - \gamma) - mg \cos \gamma, \quad (3)
\]
\[
\dot{Q} = \dot{\psi}, \quad (4)
\]
\[
I_{yy} \ddot{\psi} = M + \dot{\psi}_1 \dot{\eta}_1 + \dot{\psi}_2 \dot{\eta}_2, \quad (5)
\]
\[
k_1 I_{yy} \dot{\eta}_1 = -2I_{yy} \dot{\psi}_1(\omega_1 \dot{\eta}_1 - I_{yy} \omega_1^2 \eta_1)
\]
\[
+ I_{yy} N_1 - \dot{\psi}_1 \left(M + \dot{\psi}_2 \dot{\eta}_2\right), \quad (6)
\]
\[
k_2 I_{yy} \dot{\eta}_2 = -2I_{yy} \dot{\psi}_2(\omega_2 \dot{\eta}_2 - I_{yy} \omega_2^2 \eta_2)
\]
\[
+ I_{yy} N_2 - \dot{\psi}_2 \left(M + \dot{\psi}_1 \dot{\eta}_1\right). \quad (7)
\]

The vehicle model has five rigid-body states, i.e.,
velocity (\(V \in \Re_{>0}\)), altitude (\(h \in \Re_{>0}\)), flight-path
angle(\(\gamma \in \Re\)), pitch angle (\(\theta \in \Re\)) and pitch rate
(\(Q \in \Re\)), and two flexible states (\(\eta_1 \in \Re\) and
\(\eta_2 \in \Re\)). The control inputs (fuel equivalence ratio
\(\Phi \in \Re_{>0}\) and elevator angular deflection \(\delta_e \in \Re\)) are implied in trust
force \(T\), drag force \(D\), lift force \(L\), pitching moment
M, and generalized forces $N_1$ and $N_2$ [25], given by

$$
T \approx \beta_1 \Phi \alpha^3 + \beta_2 \alpha^3 + \beta_3 \Phi \alpha^2 + \beta_4 \alpha^2 \\
+ \beta_5 \Phi \alpha + \beta_6 \alpha + \beta_7 \Phi + \beta_8,
$$

$$
D \approx \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 D \alpha^2 \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 D \delta \alpha^2 \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 D \delta \alpha \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 D \delta e,
$$

$$
L \approx \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 L \alpha \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 L \delta \alpha \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 L \delta e.
$$

$$
N_1 = N_{10}^2 \alpha^2 + N_{1}^2 \alpha + N_{10}^0, \\
N_2 = N_{20}^2 \alpha^2 + N_{2}^2 \alpha + N_{20}^0 \delta e + N_{20}^0,
$$

$$
M \approx z_T T + \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 C_{M,0} \alpha^2 \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c^2 C_{M,0} \alpha \\
+ \frac{1}{2} \exp\left(\frac{h_0 - h}{h_s}\right) \rho_0 V^2 S c c e \delta e.
$$

All the coefficients and variables in the above equations are clearly defined in [25] and also are listed in the Nomenclature (See the Appendix).

2.2 The Fragility of prescribed performance

By prescribed performance we mean that the tracking error $e(t) : \mathbb{R} \rightarrow \mathbb{R}$ evolves within prescribed funnels $p_L(t) : \mathbb{R} \rightarrow \mathbb{R}$ and $p_R(t) : \mathbb{R} \rightarrow \mathbb{R}$ that are also called performance functions, that is, $p_L(t) < e(t) < p_R(t)$ holds for all $t \geq 0$ if $e(0)$ satisfies $p_L(0) < e(0) < p_R(0)$, as depicted in Fig. 2a. The overshoot of $e(t)$ is no more than $\max\{-p_L(0), p_R(0)\}$ and the steady-state value of $e(t)$ is less than $\max\{-p_L(\infty), p_R(\infty)\}$. Thus, prescribed behaviours including the transient performance (i.e., overshoot and convergence time) and the steady-state performance (i.e., steady-state error) can be guaranteed for $e(t)$.

It is impossible to devise feed-back controllers by directly using the constraint formulation $p_L(t) < e(t) < p_R(t)$. In order to facilitate controller design, we introduce the following equivalent form

$$
e(t) = S_c^e (\varepsilon_c(t)) (p_R(t) - p_L(t)) + p_L(t) \quad (8)
$$

with $S_c^e (\varepsilon_c(t)) = \frac{e^{\varepsilon_c(t)}}{1 + e^{\varepsilon_c(t)}} : \mathbb{R} \rightarrow (0, 1)$. The transformed error $\varepsilon_c(t) \in \mathbb{R}$ is derived from (8) as

$$
\varepsilon_c(t) = \ln \left( \frac{e(t) - p_L(t)}{p_R(t) - e(t)} \right). \quad (9)
$$

The transformed error $\varepsilon_c(t) \in \mathbb{R}$, instead of the initial tracking error $e(t)$, will be utilized for control feedback. Hereon, we stress the fragile problem of the existing PPC methodologies when there exists actuator saturation. When actuator is saturated, the tracking error $e(t)$ will inevitably increase [26], making $e(t)$ close to (even exceed) the prescribed funnels $p_L(t)$ and $p_R(t)$, as shown in Fig. 2b. From (9), we know that $\varepsilon_c(t) \rightarrow -\infty$ as $e(t) \rightarrow p_L(t)$ and $\varepsilon_c(t) \rightarrow +\infty$ as $e(t) \rightarrow p_R(t)$. The non-convergence of $\varepsilon_c(t)$ will cause control singularity problem.

2.3 Readjusting prescribed performance

To handle the singularity problem, we propose an alternative PPC approach that is able to adaptively readjust its prescribed funnel, namely the Readjusting Prescribed Performance, given by

$$
p_{\text{lower}}^c(t) < e(t) < p_{\text{upper}}^c(t), \quad (10)
$$
where \( p_{\text{lower}}^e(t) : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0} \) and \( p_{\text{upper}}^e(t) : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{>0} \) are newly developed performance functions

\[
p_{\text{upper}}^e(t) = \begin{cases} 
\left( \frac{T_{\text{FF}}}{T_{\text{FF}}} \right)^{\frac{b}{c}} \left( p_0^e - p_{T_{\text{FF}}}^e \right) + p_{T_{\text{FF}}}^e + p^e(t), & 0 < t \leq T_{\text{FF}}^e, \\
p_{T_{\text{FF}}}^e + p^e(t), & t > T_{\text{FF}}^e,
\end{cases}
\]

(11)

with \( p_{\text{lower}}^e(t) = -p_{\text{upper}}^e(t), \) \( p_0^e(\in \mathbb{R}_{>0}) > p_{T_{\text{FF}}}^e(\in \mathbb{R}_{>0}), T_{\text{FF}}^e \in \mathbb{R}_{>0}, \) \( p^e(t) = \kappa_1^e \tanh (\kappa_2^e \text{abs}(u - u_d)), \) \( \kappa_1^e \in \mathbb{R}_{>0} \) and \( \kappa_2^e \in \mathbb{R}_{>0}, \) where \( u_d \in \mathbb{R} \) is the ideal value of the control input \( u \in \mathbb{R}, \) and \( \text{abs}(u - u_d) \) denotes the saturation of actuator \( u. \)

**Remark 1** Unlike the exiting performance functions \([8, 16–24],\) the newly designed \( p_{\text{lower}}^e(t) \) and \( p_{\text{upper}}^e(t) \) contain the readjusting term \( p^e(t) = \kappa_1^e \tanh (\kappa_2^e \text{abs}(u - u_d)) \) that is capable of adaptively regulating the prescribed funnels (i.e., decrease \( p_{\text{lower}}^e(t) \) and increase \( p_{\text{upper}}^e(t) \) when \( u - u_d \neq 0 \)) according to the saturation abs \((u - u_d)\), being expected to avoid the singularity problem.

**Remark 2** It is clearly concluded that \( p_{\text{lower}}^e(t) \) and \( p_{\text{upper}}^e(t) \) are bounded since \( p_{\text{upper}}^e(t) \in \left[p_0^e + \kappa_2^e, p_{T_{\text{FF}}}^e + \kappa_2^e \right] \) and \( p_{\text{lower}}^e(t) = -p_{\text{upper}}^e(t). \)

### 2.4 Control objective

Due to the nonlinearity of vehicle model, (1)–(5) can be rewritten as the following non-affine formulation \([3, 5],\)

#### Velocity subsystem

\[
\dot{x}_V = f^V_{\Phi} (x_V, \Phi) = F^V_{\Phi} (x_V, \Phi) + \iota^V_{\Phi} \Phi.
\]

(12)

In (12) and (13), \([x_V, x_V^h, y_V, y_V^h, x_Q, y_Q] : = [V, h, \gamma, \theta, Q] \) are system states. \( V > \frac{1}{2} \frac{\partial f^V_{\Phi}(x_V, \Phi)}{\partial \Phi}, h > \frac{1}{2} \frac{\partial f^h_{\Phi}(x_Q, \Phi)}{\partial \Phi}, \) \( e > 0, i > 0, \) and \( 0 < \delta_\Phi < 1 \) are constants \([3, 5].\)

### Altitude subsystem

\[
\dot{x}_h^V = f_h^V (x_h^V, \gamma^V) = F_h^V (x_h^V, \gamma^V) + \iota_h^V \gamma^V.
\]

\[
\dot{x}_h^\theta = f_h^\theta (x_h^\theta, \theta^\theta) = F_h^\theta (x_h^\theta, \theta^\theta) + \iota_h^\theta \theta^\theta.
\]

(13)

\[\begin{align*}
\dot{x}_V^h &= f^h_{\Phi} (x_h^h, \gamma^h) \\
&= F^h_{\Phi} (x_h^h, \gamma^h) + \iota^h_{\Phi} \gamma^h,
\end{align*} \]

\[\begin{align*}
\dot{x}_h^V &= f^V_{\Phi} (x_V^h, \gamma^h) \\
&= F^V_{\Phi} (x_V^h, \gamma^h) + \iota^V_{\Phi} \gamma^h,
\end{align*} \]

**Control Objective:** Develop control laws for \( \Phi \) and \( \delta_\Phi \) under constraints (14) and (15) such that \([x_V, x_V^h, y_V, y_V^h, x_Q, y_Q]^T \in \mathbb{R}^5 \) track their reference commands \([x_V^d, x_V^h, y_V^d, y_V^h, x_Q^d, y_Q^d]^T \in \mathbb{R}^5,\) and furthermore the tracking errors \([e_V, e_V^h, e_V^h, e_Q, e_Q]^T = [x_V - x_V^d, x_V^h - x_V^h, y_V - y_V^d, y_V^h - y_V^h, x_Q - x_Q^d, y_Q - y_Q^d]^T \in \mathbb{R}^5 \) satisfy the prescribed behavior (10), i.e., tracking...
errors converge to steady-sates in finite-time \( T_{FT} \in \mathbb{R}_{>0} \) whose value can be set as needed, and moreover their steady-state values are within \((-p_{TFT}^e, p_{TFT}^e)\).

**Assumption 1** [16]. The reference commands \( x_V^d, x_h^d, x_h^v, x_h^d, x_h^Q^d \) and their time derivatives are bounded.

### 3 Controller design

#### 3.1 Velocity controller

In this subsection, we develop a constrained controller \( \Phi \in [\Phi_{\text{min}}, \Phi_{\text{max}}] \) to let \( x_V \rightarrow x_V^d \) in finite-time with readjusting prescribed performance.

The velocity tracking error \( e_V \) should satisfy the following readjusting prescribed performance

\[
p_{\text{lower}}^e(t) < e_V < p_{\text{upper}}^e(t),
\]

with performance functions \( p_{\text{lower}}^e(t) = -p_{\text{upper}}^e(t) \) and

\[
p_{\text{upper}}^e(t) = \begin{cases} 
\left( \frac{T_{FT}^e}{T_{FT}^e} - t \right) \left( p_0^e - p_{\text{upper}}^e \right), & \text{if } 0 < t \leq T_{FT}^e, \\
p_{\text{upper}}^e(t), & \text{if } t > T_{FT}^e,
\end{cases}
\]

where \( p_0^e \in \mathbb{R}_{>0} > p_{\text{upper}}^e \in \mathbb{R}_{>0} \) and \( l_{1e} \in \mathbb{R}_{>0} \) are design parameters, and \( T_{FT}^e \in \mathbb{R}_{>0} \) means the convergence time. \( p_{\text{upper}}^e(t) = \kappa_{\text{lower}, \text{1}} \tanh \left( \kappa_{\text{lower}, \text{2}} \arctan \left( \Phi - \Phi_0 \right) \right) \) is the readjusting term that correspondingly adjusts the funnels of \( p_{\text{lower}}^e(t) \) and \( p_{\text{upper}}^e(t) \) to avoid the singularity problem caused by actuator saturation. \( \kappa_{\text{lower}, \text{1}} \in \mathbb{R}_{>0} \) and \( \kappa_{\text{lower}, \text{2}} \in \mathbb{R}_{>0} \) are two design parameters.

(16) is equivalently expressed as

\[
e_V = S_e^e \left( e_V^e(t) \right) \left( p_{\text{upper}}^e(t) - p_{\text{lower}}^e(t) \right) + p_{\text{lower}}^e(t)
\]

with \( S_e^e \left( e_V^e(t) \right) = \frac{e_V^e(t)}{1 + e_V^e(t)} : \mathbb{R} \rightarrow (0, 1) \). The transformed error \( e_V^e(t) : \mathbb{R}_{>0} \rightarrow \mathbb{R} \) is derived from (18) as

\[
e_V^e(t) = \ln \left( \frac{e_V - p_{\text{lower}}^e(t)}{p_{\text{upper}}^e(t) - e_V} \right).
\]

To cope with the actuator saturation, a compensated system is devised as

\[
\dot{s}_V = -k_{sv} d_{sV} \arctan(s_V) + \iota_{\Phi}^V d_{\Phi_v} (\Phi - \Phi_d),
\]

with \( d_{sV} = \frac{p_{\text{upper}}^e(t) - p_{\text{lower}}^e(t)}{(p_{\text{upper}}^e(t) - e_V)(e_V - p_{\text{lower}}^e(t))} > 0, s_V \in \mathbb{R}, \) and \( k_{sv} \in \mathbb{R}_{>0} \).

The system state of (2) (i.e., \( s_V \in \mathbb{R} \)) is used to modify \( e_V^e(t) \).

\[
\dot{z}_V = e_V^e(t) - s_V.
\]

By employing (12), (18) and (20), the time derivative dynamics of (21) is given by

\[
\frac{\dot{z}_V}{d_{sV}} = F_V (x_V, \Phi) - \dot{x}_V + k_{sv} \arctan(s_V)
\]

with

\[
p_{\text{upper}}^e(t) := \frac{p_{\text{lower}}^e(t) - p_{\text{upper}}^e(t)}{p_{\text{upper}}^e(t) - p_{\text{lower}}^e(t)} S_e^e \left( e_V^e(t) \right) p_{\text{upper}}^e(t)
\]

\[
- \frac{p_{\text{lower}}^e(t) - p_{\text{upper}}^e(t)}{p_{\text{upper}}^e(t) - p_{\text{lower}}^e(t)} \dot{p}_{\text{upper}}^e(t) + \frac{\dot{p}_{\text{lower}}^e(t) - \dot{p}_{\text{upper}}^e(t)}{p_{\text{upper}}^e(t) - p_{\text{lower}}^e(t)} e_V
\]

\[
+ \frac{p_{\text{upper}}^e(t) \dot{p}_{\text{lower}}^e(t) - p_{\text{lower}}^e(t) \dot{p}_{\text{upper}}^e(t)}{p_{\text{upper}}^e(t) - p_{\text{lower}}^e(t)}
\]

where \( \sum_{\Phi} \dot{p} \) is bounded since its arguments are bounded.

The velocity controller is chosen as

\[
\Phi_d = - \frac{k_{\Phi}^V}{\iota_{V}} e_V^e - k_{sv} \arctan(s_V)
\]

with \( k_{\Phi}^V \in \mathbb{R}_{>0} \).
Substituting (23) into (22) and invoking (18), it leads to

$$\frac{d^2z^y}{d^2} \leq -k^y_{d} z^y - \dot{z}^d + \sum_{i}^{All} \bar{W}^d (S^y_v (e^y_i) (p^y_{upper} - p^y_{lower}) + p^y_{lower}, \Phi)$$

(24)

with

$$\sum_{i}^{All} := F^y_v (S^y_v (e^y_i) (p^y_{upper} - p^y_{lower}) + p^y_{lower}, \Phi)$$

Due to the boundedness of arguments, the continuous function \(\sum_{i}^{All}\) also is bounded, denoted by \(\text{abs} (\sum_{i}^{All}) \leq \sum_{i}^{All} \in \Re_{>0}\).

Define Lyapunov function

$$W^L_v = \frac{1}{2} (e^y_i)^2$$

(25)

Taking time derivative along (25) and employing (24), we get

$$\dot{W}^L_v = \dot{z}^y \frac{d^2z^y}{d^2}$$

$$\leq \frac{d^2}{d^2} \sum_{i}^{All} \text{abs} (\dot{z}^y_i) - k^y_{d} (\dot{z}^y)^2$$

$$= \frac{d^2}{d^2} \text{abs} (\dot{z}^y) \times \left( \sum_{i}^{All} - k^y_{d} \text{abs} (\dot{z}^y_i) \right)$$

(26)

If \(\text{abs} (\dot{z}^y) \geq \sum_{i}^{All} / k^y_{d}\), we have \(\dot{W}^L_v < 0\) and further obtain abs (\(\dot{z}^y\)) \(\leq \min \left\{ \text{abs} (\dot{z}^y (0)), \frac{\sum_{i}^{All}}{k^y_{d}} \right\}\).

Thereby, the boundedness of \(\Phi_d\) is guaranteed, and \(\Phi - \Phi_d\) also is bounded. The Lyapunov function is chosen as \(W^L_v = \frac{1}{2} s^y_v\). Then, by utilizing (20), we know

$$\dot{W}^L_v = \frac{s^y_v \dot{s}^y_v}{d^2}$$

$$= -k_s^y s^y \arctan (s^y) + \dot{V}^y_s (\Phi - \Phi_d)$$

$$\leq -\text{abs} (s^y) k_s^y \arctan (s^y) \text{abs} (\Phi - \Phi_d)$$

(27)

When \(k_s^y \frac{\pi}{2} > k_s^y \text{abs} (\arctan (s^y)) > \frac{\pi}{2} \text{abs} (\Phi - \Phi_d)\), i.e., \(k_s^y > \frac{\pi}{2} \text{abs} (\Phi - \Phi_d)\), we have \(\dot{W}^L_v < 0\). Thus, \(s^y_v\) is bounded. Noting that \(e^y_i = e^y_i (t) - s^y_v\), we conclude that the transformed error \(\dot{e}^y_i (t)\) also is bounded.

We choose the upper bound of \(\dot{e}^y_i (t)\) as \(\dot{e}^y_i \in \Re_{>0}\). On the basis of Theorem 1 presented in [16], it is derived from (19) that \(e^y_{upper} - P^y_{lower} = \frac{\exp (e^y_i (t))}{1 + \exp (e^y_i (t))}\) and

$$0 < \frac{\exp (e^y_i (t))}{1 + \exp (e^y_i (t))} \leq \exp (e^y_i (t)) \leq \exp (e^y_{upper} - P^y_{lower})$$

1. Finally, we obtain \(\dot{p}^y_{lower} > e^y > p^y_{upper}\). Thereby, the spurred prescribed performance can be guaranteed.

### 3.2 Altitude controller

In this subsection, we will exploit a constrained controller \(\delta e \in [\delta_{e_{min}}, \delta_{e_{max}}]\) to let \(x^h_h = x^h, x^y_h = x^y, x^h_d, x^y_d\) and \(x^Q\) in finite-time with readjusting prescribed performance being guaranteed for \(e^h, e^y, e^Q\), where \(x^h, x^y, x^Q\) are virtual controllers devised using back-stepping, while their time derivatives aren’t required for feedback control, effectively avoiding the problem of “explosion of terms”.

The tracking errors \(e^i = x^i - x^i_{lower}, i = h, y, \theta, Q\) should satisfy the following readjusting prescribed performance

$$p^e_{lower} (t) < e^i < p^e_{upper} (t), i = h, y, \theta, Q$$

(28)

with \(p^e_{lower} (t) = -p^e_{upper} (t)\) and

$$P^e_{upper} (t) = \left\{ \begin{array}{ll} \frac{T^e_{FF} T^e_{FF} - 1}{T^e_{FF}}, & 0 < t < T^e_{FF}, \\
\frac{T^e_{FF}}{T^e_{FF}} + \frac{p^e_{lower}, i}{T^e_{FF}}, & t > T^e_{FF}, \end{array} \right.$$  

(29)

where \(p^e_0 (\in \Re_{>0}) > p^e_{FF} (\in \Re_{>0})\) are design parameters with \(i = h, y, \theta, Q\) and \(T^e_{FF} \in \Re_{>0}\) are convergence times. \(p^e_{lower} (t) = \kappa^e_{i, 1, 1} \text{abs} (\delta e - \delta, d)\), \(i = h, y, \theta, Q\) are readjusting terms with \(\kappa^e_{i, 1, 1} \in \Re_{>0}\) and \(\kappa^e_{i, 2} \in \Re_{>0}\).

(28) is equivalently expressed as

$$e^i = S^i_h \left( e^i \right) \left( p^e_{upper} (t) - p^e_{lower} (t) \right)$$
+ p_{lower}^{e,i}(t), i = h, γ, θ, Q, \quad (30)

with \( e^{e,i}_h \in \mathbb{R} \) and \( S^{e,i}_h \left( e^{e,i}_h \right) = \frac{e^{e,i}_h}{1 + e^{e,i}_h} : \mathbb{R} \rightarrow (0,1) \), where \( i = h, γ, θ, Q \).

From (30), we further get the formulation of transformed errors \( e^{e,i}_h \), \( i = h, γ, θ, Q \)

\[
e^{e,i}_h = \ln \left( \frac{p_{upper}^{e,i}(t) - e^{e,i}_h}{p_{lower}^{e,i}(t) - e^{e,i}_h} \right), \quad i = h, γ, θ, Q \quad (31)
\]

Invoking (13) and (30), \( \dot{e}^{e,i}_h, i = h, γ, θ, Q \) are given by

\[
\begin{align*}
\frac{\dot{e}^{e,h}_h}{d_{e,h,h}} &= F^h_γ + h^h_γ x^h_γ - \dot{x}^{h,d}_h + \sum_{h} P^{p,\dot{p}}_h, \\
\frac{\dot{e}^{e,γ}_h}{d_{e,h,γ}} &= F^h_γ + h^h_γ x^h_γ - \dot{x}^{h,d}_h + \sum_{h} P^{p,\dot{p}}_h, \\
\frac{\dot{e}^{e,θ}_h}{d_{e,h,θ}} &= F^h_θ + h^h_θ x^h_θ - \dot{x}^{h,d}_h + \sum_{h} P^{p,\dot{p}}_h, \\
\frac{\dot{e}^{e,Q}_h}{d_{e,h,Q}} &= F^h_θ + h^h_θ x^h_θ - \dot{x}^{h,d}_h + \sum_{h} P^{p,\dot{p}}_h,
\end{align*}
\]

with

\[
d_{e,h,i} = \frac{1}{1 - S^{e,i}_h} \left( \frac{P^{p,\dot{p}}_h}{S^{e,i}_h \left( e^{e,i}_h \right)} - p^{p,\dot{p}}_h \right),
\]

\[
\begin{align*}
> 0, \quad i = h, γ, θ, Q, \\
\sum_{h,i}^{p,\dot{p}} : &= \frac{p^{e,i}_h(t) - p^{e,i}_h(t)}{p^{e,i}_h(t) - p^{e,i}_h(t)} S^{e,i}_h \left( e^{e,i}_h \right) P^{e,i}_h(t) \\
&- \frac{p^{e,i}_h(t) - p^{e,i}_h(t)}{p^{e,i}_h(t) - p^{e,i}_h(t)} S^{e,i}_h \left( e^{e,i}_h \right) P^{e,i}_h(t) \\
&+ \frac{p^{e,i}_h(t) - p^{e,i}_h(t)}{p^{e,i}_h(t) - p^{e,i}_h(t)} P^{e,i}_h(t) \\
&+ \frac{p^{e,i}_h(t) - p^{e,i}_h(t)}{p^{e,i}_h(t) - p^{e,i}_h(t)} P^{e,i}_h(t),
\end{align*}
\]

\[
i = h, γ, θ, Q.
\]

Due to the boundedness of arguments, \( \sum_{h,i}^{p,\dot{p}} : i = h, γ, θ, Q \) are also bounded. Based on the backstepping procedure, we design the following virtual control laws

\[
x^{γ,d}_h = - \frac{k^{γ}_h e^{e,γ}_h}{h^{γ}_h e^{e,γ}_h},
\]

\[
x^{θ,d}_h = - \frac{k^{θ}_h e^{e,θ}_h}{h^{θ}_h e^{e,θ}_h},
\]

\[
x^{Q,d}_h = - \frac{k^{Q}_h e^{e,Q}_h}{h^{Q}_h e^{e,Q}_h},
\]

with \( k^{i}_h \in \mathbb{R}_{>0}, i = h, γ, θ \).

Substituting (33) into (32) and using (30), we obtain

\[
\begin{align*}
\frac{\dot{e}^{e,h}_h}{d_{e,h,h}} &= F^h_γ + h^h_γ \left( e^{e,h}_h + x^{γ,d}_h \right) - \dot{x}^{h,d}_h + \sum_{h,h} P^{p,\dot{p}}_h, \\
\frac{\dot{e}^{e,γ}_h}{d_{e,h,γ}} &= F^h_γ + h^h_γ \left( e^{e,γ}_h + x^{θ,d}_h \right) - \dot{x}^{h,d}_h + \sum_{h,γ} P^{p,\dot{p}}_h, \\
\frac{\dot{e}^{e,θ}_h}{d_{e,h,θ}} &= F^h_θ + h^h_θ \left( e^{e,θ}_h + x^{Q,d}_h \right) - \dot{x}^{h,d}_h + \sum_{h,θ} P^{p,\dot{p}}_h,
\end{align*}
\]

with

\[
\sum_{h,i}^{p,\dot{p}} : = F^h_γ + h^h_γ \left( e^{e,h}_h + x^{γ,d}_h \right) - \dot{x}^{h,d}_h + \sum_{h,h} P^{p,\dot{p}}_h, \\
\sum_{h,i}^{p,\dot{p}} : = F^h_θ + h^h_θ \left( e^{e,θ}_h + x^{Q,d}_h \right) - \dot{x}^{h,d}_h + \sum_{h,θ} P^{p,\dot{p}}_h.
\]

We easily conclude that \( \sum_{h,i}^{p,\dot{p}} : i = h, γ, θ \) are bounded since their arguments are bounded, that is, there exist constants \( \sum_{h,i}^{p,\dot{p}} : i = h, γ, θ \) such that \( \sum_{h,i}^{p,\dot{p}} : i = h, γ, θ \).

Define Lyapunov function

\[
W^{e,e,i}_h = \frac{1}{2} \left( e^{e,i}_h \right)^2, \quad i = h, γ, θ
\]
Taking time derivative of (35) and utilizing (34), we know

\[ \dot{W}_h^{e,e,i} = d_{e,h,i} \left[ e_h^{e,i} \sum_{\bar{i}} k_{i}^h \left( e_h^{e,i} \right)^2 \right] - k_{i}^h \left( e_h^{e,i} \right)^2, \]

where \( k_{i}^h \), \( \bar{i} \), \( h \), and \( e \) are used to modify virtual control laws, which eliminates the problem of virtual control laws. Substituting (40) into (39) leads to

\[ \dot{\delta}_{ed} = -k_{\delta_{e}} \arctan(s_{\theta}) - \frac{k_{\delta_{e}}}{\ell_{\theta}^h} \arctan(s_{\theta}) \]

with \( k_{\delta_{e}} \in \mathbb{R}_{>0} \).

Substituting (40) into (39) leads to

\[ \dot{z}_h^{e,Q} = -k_{\delta_{e}} d_{e,h,Q} x_h^{Q,d} + d_{e,h,Q} \sum_{\bar{i}} k_{i}^h \left( e_h^{e,i} \right)^2 \]

where \( \Sigma_{\delta_{e}}^{All,h} := F_{\delta_{e}}^{h} - \dot{x}_h^{Q,d} \sum_{\bar{i}} k_{i}^h \left( e_h^{e,i} \right)^2 \) is bounded since

\[ \dot{z}_h^{e,Q} = -k_{\delta_{e}} d_{e,h,Q} x_h^{Q,d} - \frac{k_{\delta_{e}}}{\ell_{\theta}^h} \left( F_{\delta_{e}}^{h} - \dot{x}_h^{Q,d} \sum_{\bar{i}} k_{i}^h \left( e_h^{e,i} \right)^2 \right) \]

bounded, that is, there is a constant \( \Sigma_{\delta_{e}}^{All,h} \in \mathbb{R}_{>0} \) such that

\[ \left| \Sigma_{\delta_{e}}^{All,h} \right| \leq \Sigma_{\delta_{e}}^{All,h} \]

Define Lyapunov function

\[ W_h^{e,e,Q} = \frac{1}{2} \left( z_h^{e,Q} \right)^2. \]  

(42)

Taking time derivative along (42) and employing (41), we obtain

\[ \dot{W}_h^{e,e,Q} = -k_{\delta_{e}} \left( e_h^{e,i} \right)^2 \]

(43)

It can be seen that \( \dot{W}_h^{e,e,Q} \) will be negative if

\[ \left| e_h^{e,i} \right| > \frac{k_{\delta_{e}}}{\ell_{\theta}^h}, \]

thereby, we conclude that

\[ \dot{W}_h^{e,e,Q} < 0, i = h, \gamma, \theta. \]

Finally, we obtain

\[ \dot{W}_h = s_h \dot{\delta}_{ed} \]

(44)

Let \( k_{\delta_{e}} > k_{\delta_{e}} \arctan(s_{\theta}) \) (i.e., \( k_{\delta_{e}} > 2 \ell_{e}^h \arctan(s_{\theta}) / \pi \)). We obtain \( \dot{W}_h < 0 \).

It is further concluded that \( s_h \) and \( z_h^{e,Q} := e_h^{e,Q} - s_h \) are bounded.

The above discussions prove the boundedness of \( e_h^{e,i}, i = h, \gamma, \theta, Q \), given by \( \left| e_h^{e,i} \right| \leq \frac{k_{\delta_{e}}}{\ell_{\theta}^h} \) in \( \mathbb{R}_{>0} \), \( i = h, \gamma, \theta, Q \). Based on Theorem 1 of [16], we conclude from (31) that

\[ \frac{\exp(-e_{h}^{e,i})}{p_{upper}(t) - p_{lower}(t)} \]

(45)

\[ i = h, \gamma, \theta, Q and 0 < \frac{\exp(-e_{h}^{e,i})}{1 + \exp(e_{h}^{e,i})} \leq \frac{\exp(e_{h}^{e,i})}{1 + \exp(-e_{h}^{e,i})} \]

\[ \frac{\exp(e_{h}^{e,i})}{1 + \exp(-e_{h}^{e,i})} < 1, i = h, \gamma, \theta, Q . \]

Finally, we obtain

\[ p_{lower}(t) < e_{h}^{e,i} < p_{upper}(t), i = h, \gamma, \theta, Q \].

Thereby, the spurred prescribed performance can be guaranteed for \( e_{h}^{e,i} = h, \gamma, \theta, Q \).

Remark 3 Controllers (33) and (40), developed utilizing back-stepping, don’t contain the time derivatives of virtual control laws, which eliminates the problem of
Remark 4 From [5, 16], we know that \( L^V \), \( t^h_\Phi \), \( t^h_\phi \), \( t^h_Q \) and \( t^h_{\delta e} \) satisfy: 

\[
\begin{align*}
L^V & > \frac{1}{2} \frac{\partial f^h_{\delta e}(x^h, \Phi)}{\partial \Phi}, \quad t^h_\Phi > \frac{1}{2} \frac{\partial f^h_{\delta e}(x^h, \Phi)}{\partial \Phi}, \\
& > \frac{1}{2} \frac{\partial f^h_{\delta e}(x^h, \Phi)}{\partial \Phi}.
\end{align*}
\]

\( \delta e \) is the initial value of the performance function, and its value can be chosen as a constant that satisfies \( p^V_0 > 0 \) and \( p^V_0 \in \mathbb{R}_{>0} \). The proposed method via compared simulation. The actual simulation performance, we choose the following values for the design parameters: 

\( \delta e > 1.5 \). Moreover, there is no need of any fuzzy/neural approximation for (33) and (40). Hence, the computational complexity is avoided.

The purpose of this section is to validate the effect of the proposed method via compared simulation. The addressed controllers (23), (33), and (40) with compensated systems (20) and (37) are tested in the MATLAB/Simulink environment by utilizing the fourth-order Runge–Kutta algorithm with a fixed-step of 0.01 s. Based on the discussions presented in Remark 3 and the actual simulation performance, we choose the following values for the design parameters: 

- \( \delta e = 1.3 \),
Fig. 6  Velocity tracking performance of the proposed method

Fig. 7  Altitude tracking performance of the proposed method

Fig. 8  Velocity tracking error of the proposed method

\[ \begin{align*}
\theta &= 1.3, \\
\phi &= 1.3, \\
\psi &= 1.3, \\
\delta_E &= 1.3, \\
P_0^e &= 6, \\
P_{T_F}^e &= 2, \\
P_{Q}^e &= 3, \\
T_F^e &= 6, \\
\kappa_{\Phi,1} &= 1.5, \\
\kappa_{\Phi,2} &= 20, \\
k_{\psi} &= 1.5, \\
\kappa_{\psi} &= 0.6, \\
P_0^{e,h} &= 1.6, \\
P_{T_F}^{e,h} &= 0.4, \\
\epsilon_e &= 3, \\
T_F^{e,h} &= 8, \\
P_0^{e,y} &= 0.08, \\
P_{T_F}^{e,y} &= 0.017, \\
\end{align*} \]

Fig. 9  Altitude tracking error of the proposed method

Fig. 10  Flight-path angle tracking error of the proposed method

Fig. 11  Pitch angle tracking error of the proposed method

\[ \begin{align*}
l_{\epsilon,y} &= 3, \\
T_F^{e,y} &= 8, \\
P_0^{e,y} &= 0.12, \\
P_{T_F}^{e,y} &= 0.025, \\
l_{\epsilon,\theta} &= 3, \\
T_F^{e,\theta} &= 8, \\
P_0^{e,\theta} &= 0.3, \\
P_{T_F}^{e,\theta} &= 0.05, \\
l_{\epsilon,Q} &= 3, \\
T_F^{e,Q} &= 8, \\
P_0^{e,Q} &= 1.2, \\
P_{T_F}^{e,Q} &= 0.5 (i = h, \gamma, \theta, Q), \\
\kappa_{\phi,1} &= 1.2 \pi, \\
\kappa_{\phi,2} &= 0.5 (i = h, \gamma, \theta, Q), \\
k_{\phi} &= 0.05, \\
k_{\phi} &= 0.06, \\
k_{\phi} &= 0.13, \\
k_{\phi} &= 0.9, \\
k_{\phi} &= 0.5. \\
\end{align*} \]

We assume that the control inputs are constrained.
The proposed readjusting prescribed performance controller is compared with the traditional PPC [17–19]. Moreover, to test the robust performance, we consider parameter uncertainty up to 45

\begin{equation}
C = \begin{cases} 
C_0, & 0s \leq t < 50s \\
C_0 [1 + 0.4 \sin(0.01\pi t)], & 50s \leq t < 80s 
\end{cases}
\end{equation}

where \( C \) denotes the value of uncertain coefficient and \( C_0 \) means the nominal value of \( C \).

The obtained simulation results are depicted in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16. Figures 3, 4, and 5 clearly infer that the traditional PPC [17–19] exhibits fragility to the actuator saturation. If the actuator is saturated (See Fig. 3), the tracking error \( e_V \) increases gradually so that \( e_V \) reaches the traditional prescribed funnel [17–19] (See Fig. 4). As a result, the transformed errors tend to diverge (See Fig. 5). Thereby, as to the traditional PPC [17–19], the actuator saturation will result in the singular problem. As a contrast, the proposed method can effectively guarantee tracking errors with desired prescribed performance in the presence of actuator saturation, as shown in Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16. The velocity tracking performance and the altitude tracking performance are presented in Figs. 6 and 7. Figs. 8, 9, 10, 11, 12, 13 and 14 indicate that the addressed method is capable of adaptively readjusting the prescribed funnels (See Figs. 8, 9, 10, 11 and 12) when actuators are saturated (See Figs. 13 and 14), while avoiding the fragile problem associated with traditional PPC [17–19]. Besides, the developed compensated system can provide timely
compensations when actuators are saturated (See Fig. 15). Finally, Fig 16 shows the boundedness of transformed errors.

5 Conclusions

The non-fragile tracking control methodology is exploited for WVs subject to actuator saturation. A new type of PPC with readjusting prescribed performance is proposed to handle the fragile problem. Moreover, the improved back-stepping is used to devise velocity controller and altitude controller, while the problem of “explosion of terms” is avoided. Besides, compensated systems are developed to provide effective compensations for actuator saturations. Finally, the presented simulation results prove the effectiveness and superiority of the proposed design. In our future work, we will try to handle the actuator saturation utilizing the Bessel function.

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Data availability The experimental data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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Appendix: Nomenclature

| Symbol | Description |
|--------|-------------|
| $S$    | reference area |
| $h$    | altitude     |
| $V$    | velocity     |
| $\gamma$ | flight-path angle |
| $\theta$ | pitch angle |
| $\alpha$ | angle of attack ($\alpha = \theta - \gamma$) |
| $Q$    | pitch rate   |
| $T$    | thrust       |
| $D$    | drag         |
| $L$    | lift         |
| $M$    | pitching moment |
| $I_{yy}$ | moment of inertia |
| $\bar{c}$ | aerodynamic chord |
| $z_T$  | thrust moment arm |
| $\Phi$ | fuel equivalence ratio |
| $\delta_e$ | elevator angular deflection |
| $N_i$  | $i$th generalized force |
| $N_i^{\alpha}$ | $j$th-order contribution of $\alpha$ to $N_i$ |
| $N_i^0$ | constant term in $N_i$ |
| $N_i^{\delta_e}$ | contribution of $\delta_e$ to $N_2$ |
| $\beta_i(h, \bar{q})$ | $i$th trust fit parameter |
| $\eta_i$ | $i$th generalized elastic coordinate |
| $\varsigma_i$ | damping ratio for elastic mode $\eta_i$ |
| $\omega_i$ | natural frequency for elastic mode $\eta_i$ |
| $C_D^{\delta_e}$ | $i$th-order coefficient of $\delta_e$ in $D$ |
| $C_D^0$ | constant coefficient in $D$ |
| $C_L^{\delta_e}$ | $i$th-order coefficient of $\delta_e$ in $L$ |
| $C_L^0$ | constant coefficient in $L$ |
| $C_{M,\alpha}^{\delta_e}$ | $i$th-order coefficient of $\alpha$ in $M$ |
| $C_{M,\alpha}^0$ | constant coefficient in $M$ |
| $C_T^{\delta_e}$ | $i$th-order coefficient of $\delta_e$ in $T$ |
| $C_T^0$ | constant coefficient in $T$ |
| $h_0$ | nominal altitude for air density approximation |
| $\tilde{\rho}_0$ | air density at the altitude $h_0$ |
| $\tilde{\psi}_i$ | constrained beam coupling constant for $\eta_i$ |
| $c_e$ | coefficient of $\delta_e$ in $M$ |
| $1/h_s$ | air density decay rate |
| $\Re_{>0}$ | the set of all real-positive numbers |
| $\Re$ | the set of all real numbers |
| $\Re_{\geq0}$ | $\Re_{>0} \cup \{0\}$ |
:=  \quad \text{define as} \\
\varepsilon  \quad \text{belong to} \\

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