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Performance-guaranteed adaptive fault-tolerant tracking control of six-DOF spacecraft

Kewei XIA[1] & Yao ZOU[2,3*]

[1] *Yonsei University Observatory, Yonsei University, Seoul 03722, Korea;*
[2] *School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China;*
[3] *Institute of Artificial Intelligence, University of Science and Technology Beijing, Beijing 100083, China*

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Dear editor,

In recent decades, the six-DOF (degree-of-freedom) spacecraft (i.e., motions of the attitude and the orbit) control has received considerable attention owing to its broad applications in aerospace missions like space station construction [1, 2]. In practice, the actuator fault is ubiquitous in space arising from component degradation and aging phenomenon after long service duration which is likely to result in performance demotion or even stability deterioration [3, 4]. Although many fault-tolerant control strategies have been reported [5–7], the undesirable transient performance, such as sharp overshoot and long duration, may be induced without the performance maintenance mechanism [8].

This study focuses on the solution to the six-DOF spacecraft tracking issue with guaranteed transient performance, where the inertia uncertainty, spatial disturbance, and actuator fault are simultaneously considered. To describe the preassigned transient and convergence performance, a novel performance function in possession of the specific setting time is proposed, in contrast to [8]. Based on the backstepping framework, a passive fault-tolerant control strategy with a norm-based adaptive mechanism is developed. Compared with [5, 6], this not only largely relieves the computation complexity, but also avoids the fault detection and diagnose algorithm of each thruster or momentum wheel. It is shown that the six-DOF closed-loop error system is asymptotically stable with guaranteed transient performance.

Integrated six-DOF dynamics. According to [1, 2, 5], the six-DOF tracking error dynamics of a rigid spacecraft can be derived as

$$\dot{\boldsymbol{x}} = \boldsymbol{\Gamma}\boldsymbol{z}, \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{z}} = \boldsymbol{\varsigma} + \boldsymbol{A}\boldsymbol{\Upsilon}\boldsymbol{p} + \boldsymbol{d}, \tag{2}$$

where $\boldsymbol{x} \in \mathbb{R}^6$ and $\boldsymbol{z} \in \mathbb{R}^6$ are the tracking errors, $\boldsymbol{M} \in \mathbb{R}^{6\times 6}$ is the inertial parameter matrix, $\boldsymbol{\Gamma} \in \mathbb{R}^{6\times 6}$ and $\boldsymbol{\varsigma} \in \mathbb{R}^6$ are nonlinear terms, $\boldsymbol{A} \in \mathbb{R}^{6\times(M+N)}$ represents the distribution of actuators, $\boldsymbol{\Upsilon} \in \mathbb{R}^{(M+N)\times(M+N)}$ is the fault coefficient, $\boldsymbol{p} \in \mathbb{R}^{M+N}$ is the control command, and $\boldsymbol{d} \in \mathbb{R}^6$ is the lumped disturbance. See Appendix A for details.

Assumption 1. The desired angular velocity and trajectory as well as their derivatives are bounded. The inertia parameters are slowly-changing but bounded. Moreover, the lumped disturbance is bounded.

Assumption 2. The distribution matrix $\boldsymbol{A}_i$ and fault coefficient matrix $\boldsymbol{\Upsilon}_i$ satisfy $\mathrm{rank}(\boldsymbol{A}_i\boldsymbol{\Upsilon}_i\boldsymbol{A}_i^{\mathrm{T}}) = 3$. In addition, owing to the semi-positive definiteness of $\boldsymbol{\Upsilon}_i$, there exists a positive constant η_i such that [7]

$$0 < \eta_i \leqslant \lambda_i \triangleq \inf\{\lambda_{\min}(\boldsymbol{A}_i\boldsymbol{\Upsilon}_i\boldsymbol{A}_i^{\mathrm{T}})\},\ i = r, t. \tag{3}$$

Novel performance function. To accommodate the quick and steady maneuver response in space, we put forward a new performance function herein with the advantage of possessing flexibly adjustable settling time. In particular, a switching function is first defined as follows:

$$\hbar_{t_s}(t) = \begin{cases} 1 - \cos^n\left(\dfrac{\pi}{2}\sin^n\left(\dfrac{\pi}{2t_s}t\right)\right), & \text{if } t < t_s, \\ 1, & \text{if } t \geqslant t_s, \end{cases} \tag{4}$$

where n is a positive integer and $t_s > 0$. By introducing such a switching function, the proposed performance function is in the following form:

$$k(t) = (1 - \hbar_{t_s}(t))k_0\mathrm{e}^{-bt} + k_\infty, \tag{5}$$

where k_0, k_∞ and b are positive constants. It is trivial to show that $k(t) \equiv k_\infty$ for $t \geqslant t_s$. Therefore, t_s explicitly determines the settling time. This provides flexibility in modulating the performance constraint. To maintain the transient performance of the tracking error, we assign

$$-\underline{k}_j(t) < x_j(t) < \bar{k}_j(t),\quad \forall t \geqslant 0,\quad j = 1, 2, \ldots, 6, \tag{6}$$

where $\underline{k}_j(t) = \gamma_j\iota_j k_j(t) + (1-\gamma_j)k_j(t)$, $\bar{k}_j(t) = (1-\gamma_j)\iota_j k_j(t) + \gamma_j k_j(t)$,

$$\gamma_j = \begin{cases} 1, & x_j(0) \geqslant 0, \\ 0, & x_j(0) < 0, \end{cases}$$

* Corresponding author (email: zouyao@ustb.edu.cn)

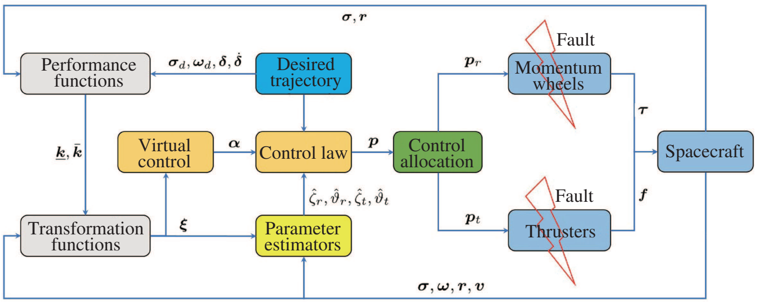

Figure 1 (Color online) Control block diagram.

$\iota_j \in [0, 1]$ is a performance scalar constant, and $k_j(t)$ is defined according to (5) with appropriate parameters. Note from (6) that the upper and lower performance constraints associated with each tracking error can be asymmetric.

Control law development. To maintain the tracking errors within the prescribed performance constraint, motivated by [9], we first introduce a transformation variable as

$$\xi_j = \xi_j(x_j) \triangleq \frac{x_j}{(\underline{k}_j + x_j)(\bar{k}_j - x_j)}, \quad j = 1, 2, \ldots, 6. \tag{7}$$

Given $x_j(0) \in (-\underline{k}_j, \bar{k}_j)$, $\xi_j(x_j) \in \mathcal{L}_\infty$ is sufficient for $x_j(t) \in (-\underline{k}_j, \bar{k}_j), \forall t \geqslant 0$. Also, it is trivial to show that $\xi_j(x_j) = 0$ implies $x_j = 0$. Let $\boldsymbol{s} = [\boldsymbol{s}_r^{\mathrm{T}}, \boldsymbol{s}_t^{\mathrm{T}}]^{\mathrm{T}} = \boldsymbol{z} - \boldsymbol{\alpha}$ with $\boldsymbol{\alpha} = [\boldsymbol{\alpha}_r^{\mathrm{T}}, \boldsymbol{\alpha}_t^{\mathrm{T}}]^{\mathrm{T}}$ being a virtual control given by

$$\boldsymbol{\alpha} = -\boldsymbol{\Gamma}^{-1}\boldsymbol{\Lambda}(\boldsymbol{K}_1 + \boldsymbol{\Pi})\boldsymbol{x}, \tag{8}$$

where $\boldsymbol{K}_1 = \mathrm{diag}(\kappa_1 \boldsymbol{I}_3, \kappa_2 \boldsymbol{I}_3)$ with $\kappa_1 > 0$ and $\kappa_2 > 0$, $\boldsymbol{\Lambda} = \mathrm{diag}(\lambda_1, \lambda_2, \ldots, \lambda_6)$ with $\lambda_j = (\underline{k}_j + x_j)(\bar{k}_j - x_j) / (\underline{k}_j \bar{k}_j + x_j^2)$, $\boldsymbol{\Pi} = \mathrm{diag}(\varrho_1, \varrho_2, \ldots, \varrho_6)$, and $\varrho_j = -\dot{\bar{k}}_j / (\underline{k}_j + x_j) - \dot{\underline{k}}_j / (\bar{k}_j - x_j)$.

Let $\boldsymbol{\xi}_r = [\xi_1, \xi_2, \xi_3]^{\mathrm{T}}$, $\boldsymbol{\xi}_t = [\xi_4, \xi_5, \xi_6]^{\mathrm{T}}$, $\boldsymbol{\Theta}_r = \mathrm{diag}(\theta_1, \theta_2, \theta_3)^{\mathrm{T}}$, and $\boldsymbol{\Theta}_t = \mathrm{diag}(\theta_4, \theta_5, \theta_6)^{\mathrm{T}}$, where $\theta_j = (\underline{k}_j \bar{k}_j + x_j^2) / ((\underline{k}_j + x_j)(\bar{k}_j - x_j))^2$, $j = 1, 2, \ldots, 6$. Let $\boldsymbol{\psi}_r = [\|\tilde{\boldsymbol{\omega}}\|^2, \|\tilde{\boldsymbol{\omega}}\|, \|\boldsymbol{\Theta}_r\| \|\boldsymbol{\xi}_r\|, \|\boldsymbol{\alpha}_r\|, \|\dot{\boldsymbol{\alpha}}_r\|, 1]^{\mathrm{T}}$ and $\boldsymbol{\psi}_t = [\|\boldsymbol{n}_t\|, \|\tilde{\boldsymbol{v}}\|, \|\boldsymbol{\Theta}_t\| \|\boldsymbol{\xi}_t\|, \|\boldsymbol{\alpha}_t\|, \|\dot{\boldsymbol{\alpha}}_t\|, 1]^{\mathrm{T}}$. The proposed control law is

$$\boldsymbol{p} = -\boldsymbol{K}_2 \boldsymbol{A}^{\mathrm{T}} \boldsymbol{s}, \tag{9}$$

where $\boldsymbol{K}_2 = \mathrm{diag}((\kappa_r + \chi_r)\hat{\vartheta}_r \boldsymbol{I}_N, (\kappa_t + \chi_t)\hat{\vartheta}_t \boldsymbol{I}_M)$ with $\kappa_r > 0$ and $\kappa_t > 0$, $\chi_i = \hat{\zeta}_i \|\boldsymbol{\psi}_i\|^2 / \sqrt{\|\boldsymbol{\psi}_i\|^2 \|\boldsymbol{s}_i\|^2 + \varepsilon_i(t)^2}$, $i = r, t$, $\varepsilon_i(t) > 0$ is an integrable function satisfying $\int_0^t \varepsilon_i(\tau)\mathrm{d}\tau \leqslant \bar{\varepsilon}_i < \infty, \forall t > 0$, $\hat{\zeta}_i$ and $\hat{\vartheta}_i$ are the estimates of ζ_i and $\vartheta_i = \eta_i^{-1}$. Moreover, the adaptation laws for $\hat{\zeta}_i$ and $\hat{\vartheta}_i$ are designed as

$$\begin{aligned} \dot{\hat{\zeta}}_i &= \beta_{i1}\left(\frac{\|\boldsymbol{\psi}_i\|^2 \|\boldsymbol{s}_i\|^2}{\sqrt{\|\boldsymbol{\psi}_i\|^2 \|\boldsymbol{s}_i\|^2 + \varepsilon_i(t)^2}} - \varphi_{i1}(t)(\hat{\zeta}_i - \zeta_{i0})\right), \\ \dot{\hat{\vartheta}}_i &= \beta_{i2}((\kappa_i + \chi_i)\|\boldsymbol{s}_i\|^2 - \varphi_{i2}(t)(\hat{\vartheta}_i - \vartheta_{i0})), \end{aligned} \tag{10}$$

where β_{i1} and β_{i2} are positive constants, $\varphi_{i1}(t) > 0$ and $\varphi_{i2}(t) > 0$ are integrable functions satisfying $\int_0^t \varphi_{i1}(\tau)\mathrm{d}\tau \leqslant \bar{\varphi}_{i1} < \infty$ and $\int_0^t \varphi_{i2}(\tau)\mathrm{d}\tau \leqslant \bar{\varphi}_{i2} < \infty, \forall t > 0$, $\zeta_{i0} > 0$ and $\vartheta_{i0} > 0$ are the initial values of $\hat{\zeta}_i$ and $\hat{\vartheta}_i$, respectively. A control block diagram is drawn in Figure 1 to show a better understanding of the proposed strategy. In terms of the above argument, the following theorem establishes the stability result of the six-DOF closed-loop system.

Theorem 1. Suppose that the six-DOF error dynamics (1) and (2) satisfy Assumptions 1 and 2. If the initial condition $-\underline{k}_j(0) < x_j(0) < \bar{k}_j(0)$ for $j = 1, 2, \ldots, 6$ holds, then the asymptotical tracking with preassigned transient and steady state performance can be achieved by the proposed control law (9) with adaptation laws (10).

Conclusion. A performance-guaranteed adaptive fault-tolerant control strategy is proposed for the six-DOF spacecraft tracking. The main contributions include the novel performance function with the explicit settling time, the nonlinear variable transformation, and the norm-based robust adaptive algorithm. In the future work, cooperative formation control of multiple six-DOF spacecraft with guaranteed transient performance would be an interesting topic.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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