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Attitude Tracking Control for Spacecraft With Fixed-Time Convergence ⋆

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Abstract: This work mainly discusses the attitude tracking issue of spacecraft which ensures fixed-time convergence property. To achieve this, the attitude tracking dynamics model is first established. Then a novel sliding manifold is constructed based on the presented sufficient condition of fixed-time stability. Moreover, a sliding mode controller is developed to ensure fixed-time convergence. Also, the closed-loop fixed-time stability of the whole system is proven to be guaranteed based on Lyapunov stability theory. Finally, the simulation results are provided to verify the superior performance of the designed controller.

Keywords: Attitude tracking, Spacecraft, Sliding mode, Fixed-time convergence, Lyapunov stability.

1. INTRODUCTION

The spacecraft attitude is vital for the space exploration activities, such as earth and planet imaging, communication, solar panel charging, etc.. Thus, the attitude control schemes for the current and forthcoming spacecraft are subject to specific performance requirements. Among these requirements, most of the spacecraft are always required to track the desired attitude trajectories with high accuracy. Therefore, plenty of works focus on the attitude tracking controller formulation. And various techniques have been applied to achieve satisfying control precision, which mainly include optimal control (Crassidis et al. (2000)), backstepping control (Kristiansen et al. (2009)), robust control (Jin and Sun (2009)), sliding mode control (Pukdeboon et al. (2010)), input-output linearization control (Tafazoli and Khorasani (2006)), nonlinear estimator-based approach (Xiao et al. (2017)), etc.. Note that these methods could achieve asymptotical convergence of the tracking errors, which may not be enough for some missions (such as imaging, agile maneuvering and so on) with specific settling time requirements (Karpenko et al. (2014); Marsh et al. (2018)).

To further improve the settling time property, finite time control technique is introduced to guarantee the stability of system within finite time (Bhat and Bernstein (2000); Yu et al. (2005)). Then terminal sliding mode control (TSMC) (Zhu et al. (2011)), time-varying sliding mode control (TVSMC) (Xiao et al. (2015)) , adding a power integrator (API) (Du et al. (2011); Li et al. (2009)) are utilized to construct finite time controllers. For the spacecraft attitude stabilization and tracking task, TSMC is adopted in (Zhu et al. (2011); Lu and Xia (2013)) to ensure finite time convergence property. And the potential singular issue of traditional TSMC is discussed and solved among the existing works (Lu and Xia (2013); Zou et al. (2011); Wu et al. (2011); Song et al. (2014)) by using modified fast TSMC method. Also, the chattering phenomenon of sliding mode control is avoided through boundary layer and neural network. However, the convergence time of finite time control schemes rely on the system initial conditions, which owns conservatives to some extent. Considering this situation, the fixed time control concept is extended by researchers, which makes the upper bound of settling time irrespective of any initial or instantaneous system conditions.

The fixed time stability is firstly presented by Polyakov in (Polyakov (2012))for the linear systems. And further discussions about the Lyapunov-based fixed time stabilization are provided in (Polyakov et al. (2015); Polyakov and Fridman (2014)). Zuo, et al. (Zuo (2015); Zuo et al. (2018a,b)) made efforts to apply the fixed-time consensus into the multi-agent networks with second-order and high-order dynamics. Recently, Basin, et al. (Basin et al. (2018)) designed a fixed-time controller for the mechatronic equipment. Gao, et al. (Gao and Cai (2015)) investigated the attitude tracking issue of spacecraft via terminal function to ensure fixed-time convergence. Jiang, et al. introduced the fixed time control technique into the spacecraft attitude stabilization (Jiang et al. (2016a)) and rendezvous missions (Jiang et al. (2016b)) respectively, which yielded satisfying time-related performance. In addition to the controller formulation, it is necessary to develop novel

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sufficient conditions of fixed time stability with less parameters and more compact form. This is also appreciating for the practical spacecraft attitude tracking controller design issue.

The objective of this work is to provide a simple and novel fixed time control scheme for the spacecraft attitude tracking task. Then the main contributions of this paper are generalized as:1) a new sufficient condition of fixed time stability is proposed with a unified governing term, which yields less parameters to be chosen; 2) the designed sliding mode controller for the attitude tracking mission guarantees closed-loop stability in the sense of fixed time convergence, and the upper bound of the settling time owns a more concise expression than the existing ones.

The rest of this paper is organized as follows. Section 2 introduces the spacecraft attitude tracking dynamics model and the novel sufficient condition of fixed time stability. Sliding mode controller with fixed-time convergence is designed in Section 3. Section 4 provides numerical simulation results to demonstrate the effectiveness of the developed controller. General conclusions of this work are summarized in Section 5.

2. PROBLEM FORMULATION

Throughout this investigation, several key notations are defined as follows: Let $\|\cdot\|$ represent the Euclidean norm. For a given vector $x = [x_1, x_2, x_3]^T \in R^3$, $x^m = [x_1^m, x_2^m, x_3^m]^T \in R^3$, $sig^m(x) = [sig^m(x_1), sig^m(x_2), sig^m(x_3)]^T \in R^3$, where $m \in R$, $sig^m(x_i) = sign(x_i) \cdot |x_i|^m, (i = 1, 2, 3)$, $x/\tanh x = [x_1/\tanh x_1, x_2/\tanh x_2, x_3/\tanh x_3] \in R^3$, $x^\times$ is the skew-symmetric matrix which satisfies $x^\times y = x \times y, \forall x, y \in R^3$. I_3 denotes the 3×3 identity matrix.

2.1 Spacecraft Attitude Dynamics Model

To investigate the attitude dynamics issue, two coordinate frames should be introduced, namely inertial frame F_i and body-fixed frame F_b. The unit-quaternion is chosen as the attitude representation tool. Let $q = [q_v^T, q_4]^T = [q_1, q_2, q_3, q_4]^T \in R^3 \times R^1$ denote the attitude orientation of the frame F_b regarding to F_i expressed in frame F_b . The transformation matrix between frames F_i and F_b could be obtained as $R(q) = (q_4^2 - q_v^T q_v)I_3 + 2q_v q_v^T - 2q_4 q_v^\times$. Then the kinematics and dynamics model of a spacecraft with four reaction wheels is given as

$$\dot{q}_v = Q\omega, \dot{q}_4 = -0.5q_v^T\omega. \tag{1}$$

$$J\dot{\omega} = -\omega^\times J\omega + Du. \tag{2}$$

wherein $Q = 0.5(q_4 I_3 + q_v^\times)$, J is the inertia matrix of the spacecraft, $\omega = [\omega_1, \omega_2, \omega_3]^T$ represents the angular velocity of the spacecraft, D is the reaction wheel configuration matrix, $u = [u_1, u_2, u_3, u_4]^T$ denotes the control torque from the reaction wheels. The redundant configuration of four reaction wheels is presented in Fig. 1, which leads the detailed expressions of D:

$$D = \begin{bmatrix} 1 & 0 & 0 & \cos A \cdot \cos B \\ 0 & 1 & 0 & \cos A \cdot \sin B \\ 0 & 0 & 1 & \sin A \end{bmatrix}. \tag{3}$$

where A, B are the alignment angles of the reaction wheel 4 (namely, RW4).

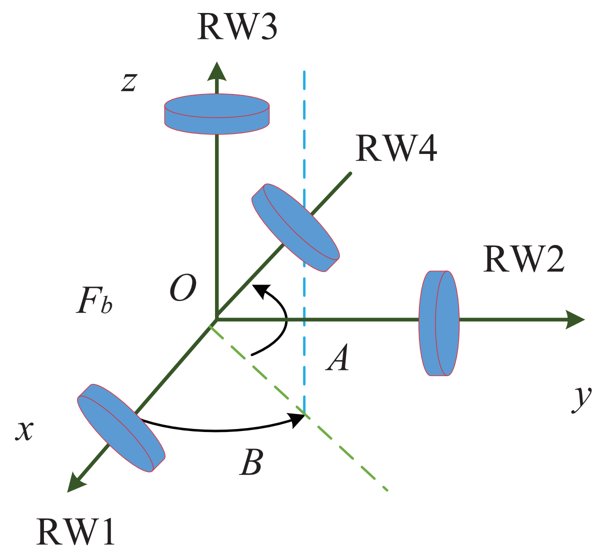

Fig. 1. Reaction wheel configuration

2.2 Attitude Tracking Dynamics Model

The spacecraft is always needed to track the desired attitude for some specified tasks. The desired attitude is represented by a desired frame F_d , and it is expressed by $q_d = [q_{dv}^T, q_{d4}]^T = [q_{d1}, q_{d2}, q_{d3}, q_{d4}]^T$ when referring to F_i. The governing law of desired attitude is $\dot{q}_{dv} = 0.5(q_{d4}I_3 + q_{dv}^\times)\omega_d$, $\dot{q}_{d4} = -0.5q_{dv}^T\omega_d$,where $\omega_d = [\omega_{d1}, \omega_{d2}, \omega_{d3}]^T$ is the desired angular rate. Then the dynamics model of the relative motion between the actual attitude and the desired one is described by

$$\dot{q}_{ev} = Q_e\omega_e, \dot{q}_{e4} = -0.5q_{ev}^T\omega_e. \tag{4}$$

$$J\dot{\omega}_e = -\omega^\times J\omega + J(\omega_e^\times R(q_e)\omega_d - R(q_e)\dot{\omega}_d) + Du. \tag{5}$$

wherein $Q_e = 0.5(q_{e4}I_3 + q_{ev}^\times)$, $q_e = [q_{ev}^T, q_{e4}]^T = [q_{e1}, q_{e2}, q_{e3}, q_{e4}]^T$ represents the attitude tracking error between the frames F_b and F_d , along with $q_{ev} = q_{d4}q_v - q_4 q_{dv} + q_v^\times q_{dv}$, $q_{e4} = q_{d4}q_4 + q_{dv}^T q_v$, the angular velocity tracking error is obtained as $\omega_e = \omega - R(q_e)\omega_d$, and the rotation matrix between frames F_b and F_d is $R(q_e) = (q_{e4}^2 - q_{ev}^T q_{ev})I_3 + 2q_{ev}q_{ev}^T - 2q_{e4}q_{ev}^\times$.

To establish a more compact form of (4)-(5), several tedious but straightforward algebraic manipulations lead to

$$M\ddot{q}_{ev} + C\dot{q}_{ev} + P^T H = P^T Du. \tag{6}$$

where $M = P^T JP$, $C = P^T J\dot{P} - P^T(JP\dot{q}_{ev})^\times P$, $P = {Q_e}^{-1}$, $H = (P\dot{q}_{ev})^\times J(R(q_e)\omega_d) + (R(q_e)\omega_d)^\times J(P\dot{q}_{ev} + R(q_e)\omega_d) - J(\omega_e^\times R(q_e)\omega_d - R(q_e)\dot{\omega}_d)$.

Remark 1. The invertible condition of Q_e is required to be ensured (Xiao et al. (2015)). This is a mild restriction for the quaternion-based attitude trajectory, which corresponds to $q_{e4} \neq 0$.

2.3 Definitions and Lemmas

Consider the system

$$\dot{x}(t) = f(x(t)), f(0) = 0, x(t) \in R^n. \tag{7}$$

where $f : U_0 \to R^n$ is continuous in the open set U_0 around the origin. The unique solution of (7) exists in forward time under all initial conditions.

Lemma 1. (Polyakov (2012)): For the system in (7), suppose there exists a continuous Lyapunov function $V(x(t))$ such that $\dot{V}(x(t)) \le -(g_1 \cdot V^m(x(t)) + g_2 \cdot V^n(x(t)))^K$ holds, where $g_1, g_2, m, n, K \in R^+$ and satisfies $mK < 1, nK > 1$. Then system (7) is fixed-time stable. The settling time upper bound, which does not rely on the initial states $x(0)$, yields

$$T(x(0)) \le 1/(g_1^K(1-mK)) + 1/(g_2^K(nK-1)). \quad (8)$$

Lemma 2. (Jiang et al. (2016a)): For any $n > 1, x, y \in R$, we can always have $|x+y|^n \le 2^{n-1}|x^n + y^n|$.

Lemma 3. For the system in (7), suppose there is continuous Lyapunov function $V(x(t))$ accounting that $\dot{V}(x(t)) \le -kV^{(g+2)/2}(x(t))/\tanh V^{1/2}(x(t))$, where $k \in R^+$ and $0 < g < 1$. Then the origin of system (7) is fixed-time stable. The convergence time is upper bounded by a user-determined function, which does not depend on system initial conditions. That is

$$T(x(0)) \le 2/[kg(1-g)]. \quad (9)$$

Proof. As $\dot{V}(x(t)) \le -kV^{(g+2)/2}(x(t))/\tanh V^{1/2}(x(t))$, we could easily obtain $\dot{V}(x(t)) < -kV^{(g+2)/2}(x(t))$ for $V(x(t)) > 1$ and $\dot{V}(x(t)) \le -kV^{(g+1)/2}(x(t))$ for $V(x(t)) \le 1$. Therefore, the dominant term ensures $V(x(t)) \le 1$ when $t \ge T_1 = 2/(kg)$ for any initial conditions such that $V(x(0)) > 1$. Correspondingly, the governing term guarantees that $V(x(t)) = 0$ at $t \ge t_0 + T_2 = t_0 + 2/[k(1-g)]$ for any conditions satisfying that $V(x(t_0)) \le 1$. Hence, the system convergence is ensured within fixed-time $T \le T_1 + T_2 = 2/[kg(1-g)]$ for any initial conditions. The proof is thus completed.

Remark 2. The advantages of our proposed *Lemma 3* mainly lie in its unified governing term, which could guarantee the convergence property in both far and near neighborhoods of the origin. This term differs from the traditional one in *Lemma 1* with less parameters and more compact form. Besides, the upper bound function of the settling time is more concise than the existing ones.

3. NOVEL FIXED-TIME SLIDING MANIFOLD CONTROLLER

In this part, a novel sliding manifold is formulated based on the proposed sufficient condition of fixed-time stability. Then, a fixed-time controller is constructed in the framework of sliding mode control technique. Furthermore, the closed-loop stability in the sense of fixed-time convergence is guaranteed via Lyapunov stability theory.

3.1 Novel Sliding Manifold Formulation

Consider the relative motion model (6) and the presented *Lemma 3*, a novel fixed-time convergent sliding mode surface is established as

$$S = \dot{q}_{ev} + k_1 S_{nft}. \quad (10)$$

wherein $S_{nft} = [S_{nft1}, S_{nft2}, S_{nft3}]^T$,$0 < p < 1$,$S_{nfti} = \begin{cases} sig^p(q_{ei}) \cdot q_{ei}/\tanh q_{ei}, if\ \bar{S}_i = 0\ or\ \bar{S}_i \neq 0, |q_{ei}| > \varepsilon \\ aq_{ei} + bsig^2(q_{ei}), if\ \bar{S}_i \neq 0, |q_{ei}| \le \varepsilon \end{cases}$, $k_1 = diag[k_{11}, k_{12}, k_{13}] > 0$, $\bar{S} = [\bar{S}_1, \bar{S}_2, \bar{S}_3]^T$, $\bar{S}_i = \dot{q}_{ei} + sig^p(q_{ei}) \cdot q_{ei}/\tanh q_{ei}$, $a = (1-p) \cdot \varepsilon^p/\tanh \varepsilon + \varepsilon^{p+1}/\tanh^2\varepsilon - \varepsilon^{p+1}$, $b = p \cdot \varepsilon^{p-1}/\tanh \varepsilon - \varepsilon^p/\tanh^2\varepsilon + \varepsilon^p$, ε is a positive scalar to be chosen.

Theorem 1. If the developed sliding manifold (10) satisfies that $S = \bar{S} = 0_{3\times1}$, then the relative tracking error q_{ev} could converge to zero within fixed time. The upper bound of the convergence time is expressed by

$$T(q_{ev}) \le 1/[k_{1\min} p(1-p)]. \quad (11)$$

where $k_{1\min} = \min\{k_{11}, k_{12}, k_{13}\}$.

Proof. Due to $S = \bar{S} = 0_{3\times1}$, it follows that $\dot{q}_{ei} = -sig^p(q_{ei}) \cdot q_{ei}/\tanh q_{ei}$. The Lyapunov function is established as $V_{ei} = q_{ei}^2, (i = 1, 2, 3)$, and its derivative yields $\dot{V}_{ei} = -2k_{1i}V_{ei}^{(p+2)/2}/\tanh V_{ei}^{1/2}$. Based on *Lemma 3*, it can be readily obtained that the upper bound of settling time for q_{ei} is $T_{ei} \le 1/[k_{1i}p(1-p)]$. Therefore, the relative tracking error would be fixed-time stable with $T(q_{ev}) \le 1/[k_{1\min}p(1-p)]$. This completes the proof procedure.

3.2 Fixed-Time Controller Design

To achieve the fixed-time attitude tracking, a novel controller based on *Lemma 3* is designed as

$$\begin{aligned} u = D^+[&-Q^T M \cdot k_2 \cdot diag(sig^{p_*}(S)) \cdot (S/\tanh S) \\ &- Q^T M \cdot k_1 \dot{S}_{nft} + Q^T C\dot{q}_{ev} + H] \end{aligned}. \quad (12)$$

wherein $k_2 = diag[k_{21}, k_{22}, k_{23}] > 0$,$D^+ = D^T(DD^T)^{-1}$, $diag(sig^{p_*}(S)) = diag[sig^{p_*}(S_1), sig^{p_*}(S_2), sig^{p_*}(S_3)]$,$0 < p_* < 1$.

Theorem 2. Consider the relative attitude motion dynamics model (6) while utilizing control law (12) with the sliding manifold (10), it could be concluded that the fixed-time convergence stability of the closed-loop system is guaranteed, and the upper bound yields that

$$T_F(q_{ev}) \le 2^{p_*}/[k_{2\min}p_*(1-p_*)] + 1/[k_{1\min}p(1-p)]. \quad (13)$$

where $k_{2\min} = \min\{k_{21}, k_{22}, k_{23}\}$.

Proof. As a stepping stone, a positive definitive Lyapunov function is defined as

$$V_S = S^T S. \quad (14)$$

Then the derivative of V_S with respect to time is obtained by substituting control scheme (12) as

$$\begin{aligned} \dot{V}_S &= 2S^T\dot{S} \\ &= 2S^T[M^{-1}(-C\dot{q}_{ev} - P^T H + P^T Du) + k_1\dot{S}_{nft}] \\ &= -2S^T k_2 \cdot diag(sig^{p_*}(S)) \cdot (S/\tanh S) \\ &= -2\sum_{i=1}^{3}(k_{2i}|S_i|^{p_*+2}/\tanh|S_i|) \\ &\le -2k_{2\min}\sum_{i=1}^{3}[|S_i|^{p_*+2}/\tanh V_S^{1/2}] \\ &\le -2^{1-p_*} \cdot k_{2\min} \cdot V_S^{(p_*+2)/2}/\tanh V_S^{1/2} \end{aligned}. \quad (15)$$

According to *Lemma 3*, it can be readily obtained that the reaching phase is completed within fixed time. The corresponding time upper bound is $T_S \leq 2^{p_*}/[k_{2\min} p_*(1-p_*)]$. Combing *Theorem 1*, the closed-loop system is fixed time stable, and the settling time is bounded by

$$T_F(q_{ev}) \leq 2^{p_*}/[k_{2\min} p_*(1-p_*)] + 1/[k_{1\min} p(1-p)]. \quad (16)$$

Remark 3. The presented sliding mode control strategy achieves fixed-time convergence for the attitude tracking task of the spacecraft from a new viewpoint. Although this work mainly addresses the spacecraft attitude tracking control issue, such method could also easily extend to other second-order systems which aims to achieve similar fixed convergence time property.

4. SIMULATION TESTS AND ANALYSES

In this section, related parameters and system conditions are offered to illustrate the effectiveness of the presented control strategy through simulation experiments. The initial conditions for the spacecraft rotation motion are chosen to be $[q_v^T(0), q_4(0)]^T = [-0.1, 0.5, -0.2, \sqrt{0.7}]^T$, $\omega(0) = [-0.01, 0.02, 0.01]$rad/s. Assume the initial value for the desired rotation motion is $[q_{dv}^T(0), q_{d4}(0)]^T = [0, 0, 0, 1]^T$ with the angular rate $\omega_d = [0.03\sin(0.01t), 0.02\sin(0.01t), 0.01\sin(0.01t)]$rad/s .The spacecraft is set with the inertia matrix as follows

$$J = \begin{bmatrix} 20 & 1.2 & 0.9 \\ 1.2 & 17 & 1.4 \\ 0.9 & 1.4 & 15 \end{bmatrix} \mathrm{kg \cdot m^2}. \quad (17)$$

For the redundant reaction wheel, its alignment angles are chosen to be $A = \arcsin(\sqrt{3}/3)$, $B = \pi/4$ .The maximum magnitude of the control torque for a single reaction wheel is 1Nm. To further present the superior performance of the designed controller, the quaternion-based backstepping control scheme in (Kristiansen et al. (2009)) is selected as the comparison method. The control parameters for the developed strategy in this work are set as $k_1 = diag[0.15, 0.15, 0.15]$, $k_2 = diag[0.09, 0.09, 0.09]$, $\varepsilon = 0.0003$, $p = p_* = 0.6$. The relevant parameters for the comparative scheme are chosen as $k_1 = diag[3, 3, 3]$ and $k_2 = diag[3, 3, 3]$.

The simulation results of the quaternion tracking errors under the preceding two controllers are shown in Fig. 2 respectively. It is obvious that the presented controller achieves faster convergence rate than the comparative one. To make this more straightforward, the history of the Euler angle tracking errors is illustrated in Fig. 3. Besides, Fig. 4 shows the angular rate tracking errors of the two methods. And it can be concluded that the designed controller is superior to the other one with shorter convergence time and less overshot in Fig. 4. Furthermore, the corresponding control torque responses for each reaction wheel are provided in Fig. 5. It is apparent that the developed controller does not lead to too much control torque saturation situation as the comparison method, especially at the initial stages of attitude tracking operation. In addition, an index defined as $E = \int_0^T \|u\|^2 dt$ is introduced to evaluate the energy consumption of reaction wheels. Then the energy indexes in Fig. 6 show that the proposed controller consumes much less energy than the rest one. Overall, the presented method in this work owns excellent performance, guaranteeing fixed-time convergence, while achieving high-accuracy attitude tracking motion.

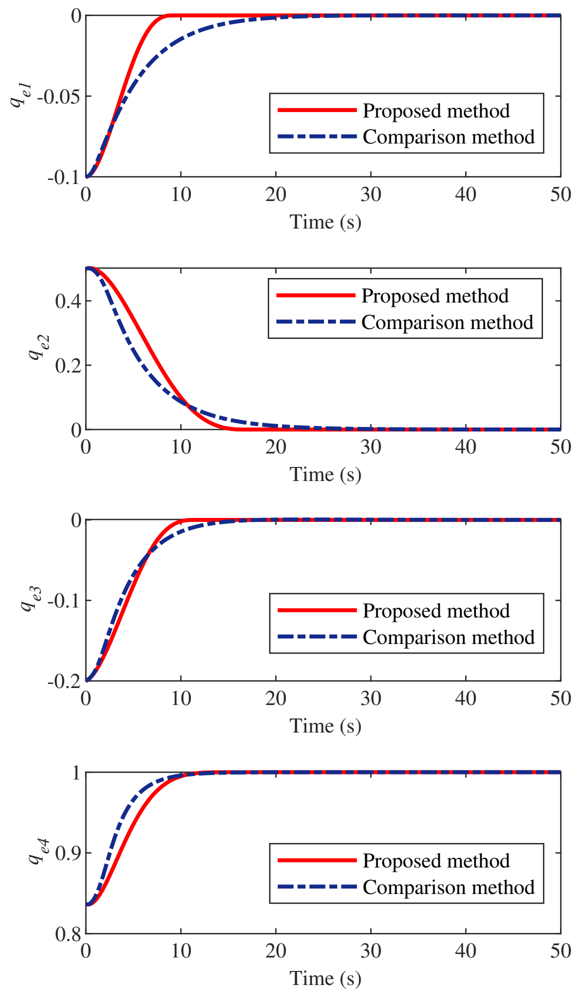

Fig. 2. Quaternion errors

5. CONCLUSION

In this work, we have presented a fixed-time control strategy for the attitude tracking mission of spacecraft. The developed controller is built in the sliding mode control framework, which is based on the novel sufficient conditions of fixed time stability. In contrast to the existing fixed-time control schemes, the proposed controller owns a unified dominant term, which ensures faster convergence and higher accuracy in both large and small scales of tracking errors. The simulation results further show that the designed fixed time controller achieves rapid convergence and high precision in the attitude tracking task. The future work would focus on handling the saturation and failure issues of the reaction wheels while designing the fixed-time controller.

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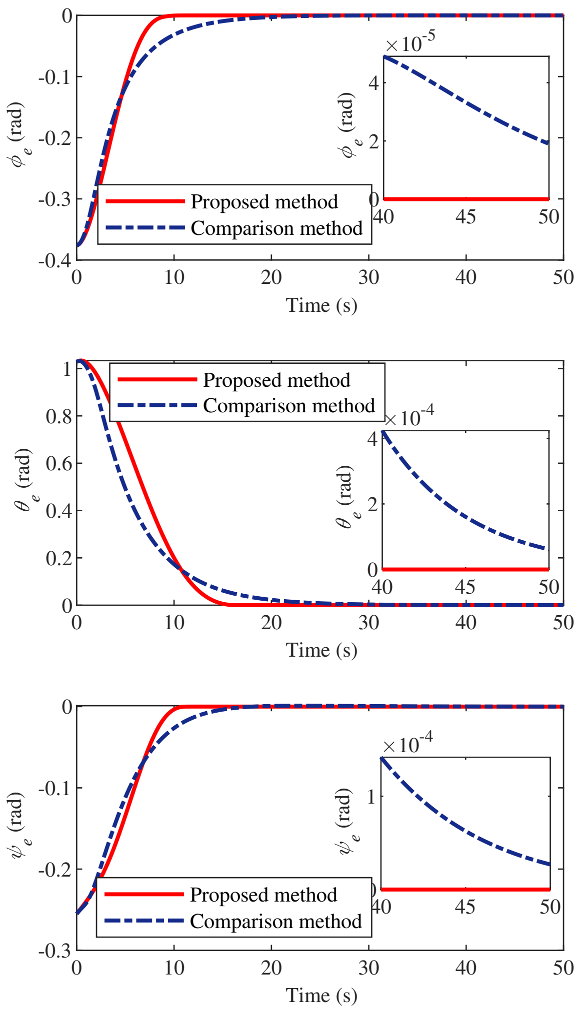

Fig. 3. Euler angle tracking errors

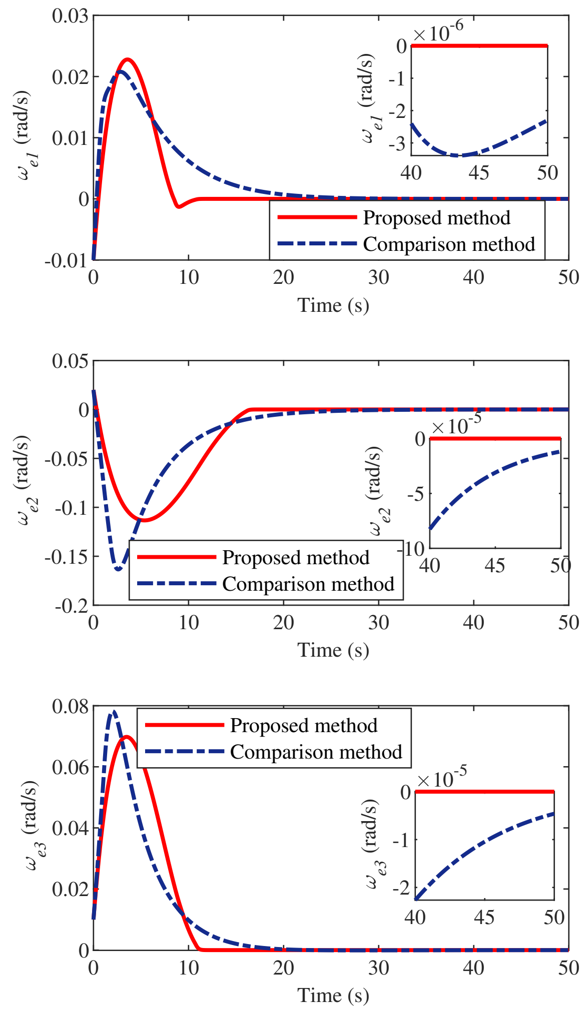

Fig. 4. Angular rate tracking errors

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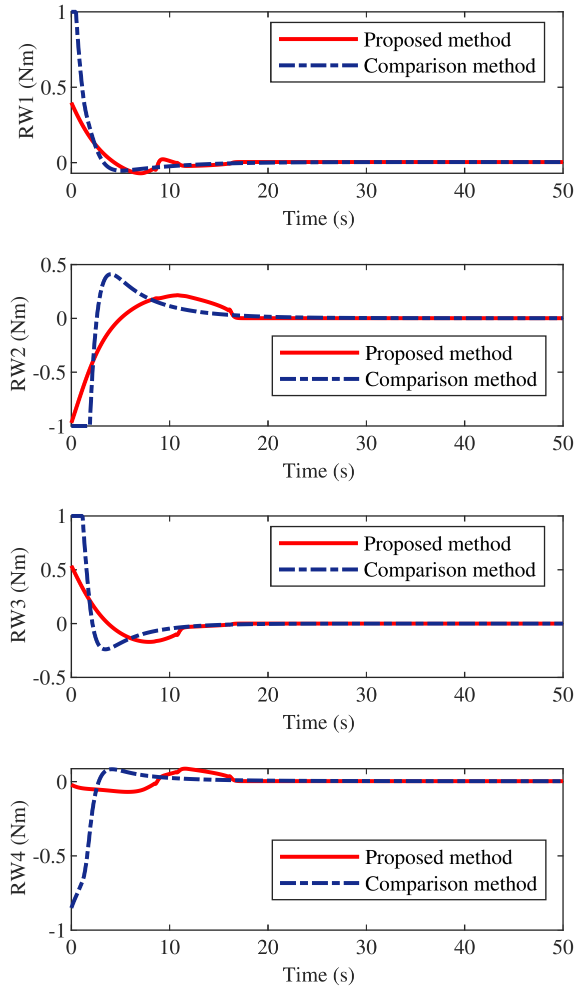

Fig. 5. Control torques from reaction wheels

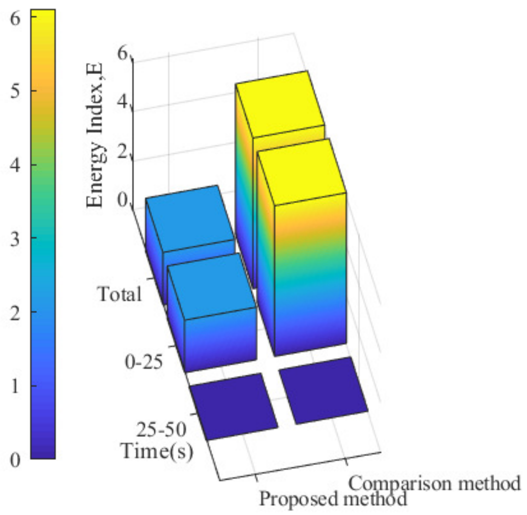

Fig. 6. Energy consumption index

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