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High-Performance Adaptive Attitude Control of Spacecraft With Sliding Mode Disturbance Observer

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ABSTRACT A new disturbance observer-based control method is presented in this paper to address the attitude tracking problem of rigid-body spacecraft in the presence of external disturbances and parameter uncertainties. Particularly, a sliding mode disturbance observer (SMDO) is designed. The most important feature of this SMDO is the relaxation of the assumption that external disturbances must be constants or changing at a slow rate, which is a typical assumption required in these classes of problems concerning disturbance observer (DO) design but hard to guarantee from the standpoint of practical engineering. In addition, a special adaptive integral sliding mode controller is combined with the SMDO to ensure system state convergence. The proposed control scheme's primary advantage is the enhanced robustness against system parameter uncertainties and external disturbances. Stringent closed-loop system stability analysis is performed using Lyapunov-based stability theory. Numerical simulations are carried out on nonlinear model of spacecraft to validate the proposed control scheme's efficiency compared to the existing methods in the literature.

INDEX TERMS Attitude control, adaptive control, disturbance observer, integral sliding mode.

I. INTRODUCTION

Over the last several decades, attitude control of spacecraft has gained much attention in the aerospace industry, since it has vital role in completion of many advanced space missions successfully [1], such as spacecraft rendezvous and docking [2]–[4], on-orbit servicing [5], [6], formation flying [7], [8]. In addition, many control schemes have been employed to solve attitude control problems, such as proportional-derivative control [9], [10], passivity-based control [11], adaptive control [12], [13] and sliding mode control (SMC) [3], [14]–[16]. However, the unpredictable space environment and the spacecraft model uncertainty render great difficulties for attitude controller design. To be specific, spacecraft always encounter unperceived disturbances and is subjected to parameter variations. Conventional control methods cannot provide sufficient robustness regarding these

issues, which may result in the deterioration of closed-loop system performance or even instability [17]–[19].

The SMC is an efficient control method used to attenuate disturbances and uncertainties successfully due to its high robustness [18]. It is applied to spacecraft attitude control problems due to ease in the implementation and ability to combine with other control methods [19]–[22]. Particularly, discontinuous terms are usually included in SMC laws to achieve the insensitivity to disturbances and uncertainties during the sliding phase. However, the terms also induce the chattering problem. This phenomena can be avoided using adaptive SMC [20], [23] or observer-based control schemes [15], [21]. The system states slide on sliding surface under the action of ISMC law by judiciously choosing control parameters. Thus, the reaching phase associated with the SMC is avoided, further enhancing the robustness of the control method [24]. The refs. [25], [26] used ISMC to control the system with unmatched and matched uncertainties due to its inherent benefits. The matched uncertainties were rejected

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unreservedly, while unmatched ones remained un-amplified. For the reasons, the ISMC has been applied to control non-linear systems such as spacecraft attitude control and robotic manipulator [27], [28]. However, control input chattering is still a crucial issue related to the control scheme. Control input obtained using ISMC still needs a discontinuous term which deals with the disturbance or uncertainty [25] which induce input chattering [29]. Adaptive methods are used in conjunction with ISMC to avoid the chattering to some extent in [30] and [31], but adaptive law design requires careful consideration due to possible over-adaptation or parameter drift.

Observer-based control is another effective method to avoid the chattering from the control input [32], [33] and improve the robustness of the control scheme [19], [34]. The presence of a DO in the control loop enhances the control algorithm robustness [35]. An NDO was employed with adaptive SMC to improve uncertainty rejection capabilities of spacecraft [36] while it was combined with SMC in [37] and back-stepping in [38] to obtain improved system performance. A unified output feedback control framework, using NDO and adaptive SMC, was developed in [39] to improve the robustness of the control scheme for attitude stabilization of spacecraft. However, the estimated disturbance was considered a constant, contrary to the practical spacecraft systems. The ESO was combined with inverse optimal feedback controller in [40] and fault-tolerant control law [41] for attitude control of spacecraft. Similarly, the ESO was integrated with the SMC for attitude control problem with delay in input [42]. Even though ESO can estimate variable disturbances, it has higher-order, and larger observer gains. SMDO is another observer with a simpler structure compared to the two discussed earlier. Few results using the SMDO have been presented. For instance, Ref. [43] used it to improve the disturbance rejection capabilities of the SMC law for the reusable launch vehicle. Furthermore, Ref. [44] applied the SMDO&SMC structure to locally Lipschitz systems, and a relevant result for flight control of a small quad-rotor vehicle was presented in [45]. Furthermore, a disturbance rejection compensator was proposed for disturbance attenuation in [46].

The use of observers for disturbance rejection makes the closed-loop system more robust against unknown external uncertainties when compared with the conventional control methods [33]. However, the DO in a closed-loop increases system complexity and associated nonlinearity. Consequently, the system stability analysis becomes a challenging task. Additionally, there is a lack of a unified observer-based control scheme, and it is hard to prove the convergence of DO estimation error and the system simultaneously. Unlike the disturbance observers discussed, the SMDO design is independent of the system's mathematical model, resulting in a simple structure. However, most of the existing SMDO design methods assume the disturbances as constants or slowly-changing variables and require the knowledge of their bounds [43], [45]. These

TABLE 1. List of acronym.

SMC	Sliding mode control
NDO	Nonlinear disturbance observer
ISMC	Integral sliding mode control
ESO	Extended state observer
HOSMC	Higher order sliding mode control
SMDO	Sliding mode disturbance observer
AISMIC	Adaptive integral sliding mode control

kinds of assumptions highly obstruct the applications of relevant results in practical systems. In fact, the disturbances are changing quietly from the standpoint of practical engineering.

In this paper, we address the attitude tracking problem of spacecraft in the presence of external disturbances and parameter uncertainties. An observer-based control technique employing the SMDO&AISMIC structure is presented. The key features of the proposed control method are as follows:

- A new SMDO is presented to estimate the unknown combined disturbance, which consists of time-dependent external disturbances and system parameter uncertainties. The proposed SMDO relaxes the strong assumption associated with disturbance boundedness, considerably enhancing the generality and application potential of the proposed method.
- A specially designed adaptive integral sliding mode control (AISMIC) law is combined with the proposed SMDO to achieve convergence of the system states. The designed controller is unique in the sense that SMDO states are used to formulate the AISMIC law enabling the convergence of SMDO error and system states simultaneously. The primary advantage of the proposed SMDO&ISMIC structure is enhanced robustness to external disturbance and system parameter uncertainties.
- Comparative simulations are carried out to investigate the credibility of the proposed control method. The developed controller gives higher control precision, faster system response, and anti-interference ability.

The paper is organized as follows: Section II briefly explains the system model and spacecraft attitude tracking problem, and the objectives of the research paper are given with assumptions. In section III, details about system dynamics transformation are provided. In section IV, the SMDO structure and asymptotic stability proof are presented. In section V, an integral sliding surface is designed, and a control law is formulated. The closed-loop stability analysis is provided using Lyapunov theory. In section VI, numerical simulation results for the proposed SMDO&AISMIC structure are discussed. Finally, in section VII, the conclusion to the research note is provided using simulation results.

II. SPACECRAFT SYSTEM MODEL

This section gives attitude kinematic and dynamic models for rigid-body spacecraft. The relation between unit quaternion

Q, angle ϕ and Euler axis $\hat{e} = [\hat{e}_1 \ \hat{e}_2 \ \hat{e}_3]$ is written as,

$$Q = \begin{bmatrix} \hat{e} \sin(\phi/2) \\ \cos(\phi/2) \end{bmatrix} = \begin{bmatrix} q_v \\ q_4 \end{bmatrix} \quad (1)$$

Attitude kinematics using unit quaternions is modeled as in [47].

$$\dot{q}_v = \frac{1}{2}(q_4 I_3 + q_v^\times)\omega, \quad \dot{q}_4 = -\frac{1}{2}q_v^T \omega \quad (2)$$

where $q_v = [q_1 \ q_2 \ q_3]^T \in R^3$ and q_4 are the vector and scalar component of quaternion Q, respectively, with $q_v^T q_v + q_4^2 = 1$. The parameter $\omega = [\omega_1 \ \omega_2 \ \omega_3]^T \in R^3$ is the angular velocity, and matrix q_v^\times is defined by $q_v^\times = [0 \ -q_3 \ q_2; q_3 \ 0 \ -q_1; -q_2 \ q_1 \ 0] \in R^{3 \times 3}$. The rigid-body rotation dynamics under the effect of body-fixed devices can be written as [47],

$$J\dot{\omega} = -\omega^\times J\omega + u(t) + d(t), \quad (3)$$

where $J \in R^{3 \times 3}$ is an inertia matrix, $d(t) \in R^3$ is external disturbance and $u(t) \in R^3$ is control input vector.

A. PROBLEM FORMULATION

To address the spacecraft attitude tracking problem, consider

$Q_d = [q_d^T \ q_{4d}]^T = [q_{1d} \ q_{2d} \ q_{3d} \ q_{4d}]^T$ to be the desired quaternion. Then we can define the error quaternion $Q_e = [q_e^T \ q_{4e}]^T = [q_{1e} \ q_{2e} \ q_{3e} \ q_{4e}]^T$, which satisfies the relation as follows:

$$Q_e = \begin{bmatrix} q_{4d} - q_{4e}q_d - q_d^\times q_v \\ q_{4e}q_{4d} + q_v q_d \end{bmatrix}, \quad (4)$$

where Q_e represents the difference between Q and Q_d . Furthermore, the kinematic of Q_e satisfies the following equations [47]:

$$\dot{q}_e = \frac{1}{2}(q_{4e} I_3 + q_e^\times)\omega_e, \quad \dot{q}_{4e} = -\frac{1}{2}q_e^T \omega_e, \quad (5)$$

where $\omega_e = [\omega_{1e} \ \omega_{2e} \ \omega_{3e}]^T \in R^3$ is an error angular velocity, satisfying

$$\omega_e = \omega - [R(q_e)]\omega_d, \quad (6)$$

where $\omega_d = [\omega_{1d} \ \omega_{2d} \ \omega_{3d}]^T \in R^3$ is the desired angular velocity, while $R(q_e)$ denotes the direction cosine matrix, which can be written as

$$R(q_e) = (q_{4e}^2 - 2q_e^T q_e)I_3 + 2q_e q_e^T - 2q_{4e} q_{4e}^\times. \quad (7)$$

Note, the Eq. (7) satisfies $\|R(q_e)\| = 1$. In subsequent discussion in this paper, R will be used rather than of $R(q_e)$ for ease of expression.

Differentiating Eq. (6) renders

$$\dot{\omega}_e = \dot{\omega} - \dot{R}\omega_d - R\dot{\omega}_d. \quad (8)$$

Then, using the fact $\dot{R} = -\omega_e^\times R$, and multiplying both sides of Eq. (8) with inertia matrix J , one can get the attitude tracking dynamical equation as follows:

$$J\dot{\omega}_e = -\omega_e^\times J\omega + u(t) + d(t) + J(\omega_e^\times R\omega_d - R\dot{\omega}_d). \quad (9)$$

In the above mathematical formulations, parameter uncertainties are not considered. However, during the mission operation, fuel is consumed and appendages attached with the spacecraft move to perform various tasks causing the change in the inertia of the spacecraft. For instance, or-board solar panels rotate to adjust their alignment in the direction of the sun or movement of communication antennas. Following reasonable assumptions are employed to describe the inertial parameter uncertainties.

Assumption 1: The inertia of spacecraft is considered an unknown variable matrix. The inertia matrix is represented as $J = J_0 + \delta J$, where J_0 denotes the nominal and known matrix, while δJ is a time-varying uncertain part and a differentiable matrix.

Assumption 2: There exist positive constants $J_{kl,min}$ and $J_{kl,max}$, such that $J_{kl,min} \leq J_{kl} \leq J_{kl,max}$, $\forall k = 1, 2, 3, \dots, n$ and $l = 1, 2, 3, \dots, m$, where J_{kl} is the corresponding element of J . Furthermore, there exist $J_{kl}^d > 0$ such that $|\dot{J}_{kl}(\cdot)| \leq |J_{kl}^d|$.

Assumption 3: For time-dependent unknown external disturbance $d(t)$ acting on system, there exists a constant δ_d such that $\|\dot{d}(t)\| \leq \delta_d$.

Remark 1: Spacecraft inertia at a specific time instant is unknown. The unknown part δJ of inertia J is time-dependent due to variation in spacecraft inertia during mission operation in space. For instance, the time-dependent continuous functions governing the movement of installed appendages and fuel consumption cause change in inertia. Thus, it is reasonable to assume that total inertia as the sum of a constant and unknown variable matrix. Assumption 2 is acceptable as inertia is always positive definite during operation, and for operational justifications \dot{J} is taken as bounded.

Lemma 1: In [48], for spacecraft system in Eqs. (5) and (9) if sliding surface σ satisfy $\lim_{t \rightarrow 0} \omega_e(t) = 0$, it follows that $\lim_{t \rightarrow \infty} \omega_e(t) = 0$, $\lim_{t \rightarrow \infty} q_e(t) = 0$, and $\lim_{t \rightarrow \infty} q_{4e}(t) = 1$.

B. PROBLEM STATEMENT

The objective of the research note is to develop SMDO&ISMIC control law $u(t)$ that forces the error states q_e and ω_e to converge to zero, even in the presence of time-varying external disturbances and system parameter uncertainties, formalized as

$$\lim_{t \rightarrow \infty} \omega_e(t) = 0_3, \quad \lim_{t \rightarrow \infty} q_e(t) = 0_3, \quad \lim_{t \rightarrow \infty} q_{4e}(t) = 1. \quad (10)$$

III. SYSTEM TRANSFORMATION

In this section, the system dynamics transformation is presented for the ease of observer and controller design. The combined disturbance is also defined, which consists of external disturbances and parameter uncertainties. Using assumption 1, Eq. (9) can be written as

$$\begin{aligned} (J_0 + \delta J)\dot{\omega}_e &= -\omega_e^\times (J_0 + \delta J)\omega + u + d \\ &\quad + (J_0 + \delta J)(\omega_e^\times R\omega_d - R\dot{\omega}_d) \\ &= -\omega_e^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d) + u + d \\ &\quad - \omega_e^\times \delta J\omega + \delta J(\omega_e^\times R\omega_d - R\dot{\omega}_d). \end{aligned}$$

Rearranging the above equation and invoking equation (8), we obtain

$$\begin{aligned} J_0\dot{\omega}_e &= -\omega^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d) + u + d \\ &\quad - \omega^\times \delta J\omega + \delta J(\omega_e^\times R\omega_d - R\dot{\omega}_d) - \delta J\dot{\omega}_e \\ &= -\omega^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d) + u + d \\ &\quad - \omega^\times \delta J\omega + \delta J(\omega_e^\times R\omega_d - R\dot{\omega}_d) \\ &\quad - \delta J[\omega_e^\times R\omega_d - R\dot{\omega}_d] - \delta J\dot{\omega}. \end{aligned}$$

Simplifying and using equation (5), we get

$$\begin{aligned} J_0\dot{\omega}_e &= -\omega^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d) + u + d \\ &\quad - \omega^\times \delta J\omega - \delta J[J^{-1}(-\omega^\times J\omega + u + d)] \\ &= -\omega^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d) + u + d \\ &\quad - \omega^\times \delta J\omega + \delta JJ^{-1}\omega^\times J\omega - \delta JJ^{-1}u - \delta JJ^{-1}d \\ \dot{\omega}_e &= J_0^{-1}[-\omega^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d) + u - \omega^\times \delta J\omega \\ &\quad + \delta JJ^{-1}\omega^\times J\omega - \delta JJ^{-1}u + [I - \delta JJ^{-1}]d]. \quad (11) \end{aligned}$$

Considering $\zeta = J_0^{-1}\{-\omega_e^\times J_0\omega + J_0(\omega_e^\times R\omega_d - R\dot{\omega}_d)\}$, $D_\zeta = J_0^{-1}\{-\omega^\times \delta J\omega + \delta JJ^{-1}\omega^\times J\omega - \delta JJ^{-1}u\} + J_0^{-1}[I - \delta JJ^{-1}]d$ and $u_\zeta = J_0^{-1}u$, we can obtain a compact expression for $\dot{\omega}_e$ as follows,

$$\dot{\omega}_e = \zeta + D_\zeta + u_\zeta. \quad (12)$$

IV. SLIDING MODE OBSERVER DESIGN

In this section, a novel SMDO is formulated to estimate the unknown combined disturbance D_ζ . In Eq. (11), since ω , $u(t)$, $\dot{\omega}$ and $\dot{u}(t)$ are bounded for practical standpoint and from Assumption 1-2, it is fair to consider $|\dot{D}_\zeta| \leq \alpha$, where $\alpha > 0$.

Considering SMDO design as follows for uncertainty estimation

$$\beta_0 = \eta - \omega_e \quad (13)$$

$$\dot{\eta} = \zeta + \hat{D}_\zeta + u_\zeta \quad (14)$$

$$\beta_1 = \beta_0 + \Gamma\dot{\beta}_0 \quad (15)$$

$$\hat{D}_\zeta = -\Gamma^{-1}[\dot{\beta}_0 + a_1\beta_1 + a_2\text{sign}(\beta_1) + \hat{a}_3\text{sign}(\beta_1)], \quad (16)$$

where $\Gamma = \text{diag}[\gamma_i] \forall \gamma_i \geq 0$, $a_1 = a_1^T \geq 0$ and $a_2 = \text{diag}[a_{2i}] \forall a_{2i} \geq 0$. The observer convergence speed and output chattering is dependent on the design parameters a_2 and a_1 , respectively. The large values of parameters a_2 and a_1 result in higher chattering and lower convergence time. The selection of parameters is a tradeoff between chattering and convergence time. The signals \hat{D}_ζ and \hat{a}_3 estimate D_ζ and a_3 , respectively. The parameter \hat{a}_3 should be $a_3 \leq \Gamma\alpha$. The disturbance estimation error \tilde{D} is defined as $\tilde{D} = D_\zeta - \hat{D}_\zeta$. Furthermore, the function $\text{sign}(\beta_1) = [\text{sign}(\beta_{11}), \text{sign}(\beta_{12}), \text{sign}(\beta_{13})]^T$. The update law for \hat{a}_3 is given at later stage of the section.

Taking derivative of β_0 in (13), we obtain

$$\dot{\beta}_0 = \dot{\eta} - \dot{\omega}_e.$$

Then, using equation (14) and equation (12), one can further get

$$\begin{aligned} \dot{\beta}_0 &= -\zeta - D_\zeta - u_\zeta + \zeta + \hat{D}_\zeta + u_\zeta, \\ \dot{\beta}_0 &= -D_\zeta + \hat{D}_\zeta, \\ \dot{\beta}_0 &= -\tilde{D}_\zeta. \end{aligned} \quad (17)$$

Furthermore, by taking derivative of (17), it is straightforward to obtain

$$\ddot{\beta}_0 = \dot{\hat{D}}_\zeta - \dot{D}_\zeta. \quad (18)$$

Taking derivative of β_1 in (15), we obtain

$$\dot{\beta}_1 = \dot{\beta}_0 + \Gamma\ddot{\beta}_0. \quad (19)$$

Using $\ddot{\beta}_0$ in (19), we get

$$\begin{aligned} \dot{\beta}_1 &= \dot{\beta}_0 + \Gamma(\dot{\hat{D}}_\zeta - \dot{D}_\zeta) \\ &= \dot{\beta}_0 - \Gamma\dot{D}_\zeta - \{\dot{\beta}_0 + a_1\beta_1 + a_2\text{sign}(\beta_1) + \hat{a}_3\text{sign}(\beta_1)\} \\ &= -\Gamma\dot{D}_\zeta - \{a_1\beta_1 + a_2\text{sign}(\beta_1) + \hat{a}_3\text{sign}(\beta_1)\} \\ &= -\Gamma\dot{D}_\zeta - a_1\beta_1 - a_2\text{sign}(\beta_1) - \hat{a}_3\text{sign}(\beta_1). \end{aligned} \quad (20)$$

We will use the signal $\dot{\beta}_1$ in the next theorem to prove the convergence of estimation error of combined disturbance \tilde{D}_ζ . The parameter update law for \hat{a}_3 is as follows,

$$\dot{\hat{a}}_3 = \gamma_0 \sum_{i=1}^3 |\beta_{1i}|. \quad (21)$$

The parameter approximation error \tilde{a}_3 , is given by $\tilde{a}_3 = a_3 - \hat{a}_3$, and $\gamma_0 > 0$ is a constant design parameter. Based on the discussions and analysis, one of the main contributions of this paper is organized in the following theorem.

Theorem 1: For the nonlinear uncertain system in (9), design the SMDO as in (13) – (16), then the compound disturbance observation error \tilde{D}_ζ asymptotically converges to zero.

Proof 1: For the stability analysis of the proposed SMDO design, we define the following Lyapunov function,

$$V_1 = \frac{1}{2}\beta_1^T\beta_1 + \frac{1}{2\gamma_0}\tilde{a}_3^2. \quad (22)$$

Differentiating (22) renders,

$$\begin{aligned} \dot{V}_1 &= \beta_1^T\dot{\beta}_1 - \frac{1}{\gamma_0}\tilde{a}_3\dot{\tilde{a}}_3 \\ &= \beta_1^T[-\Gamma\dot{D}_\zeta - a_1\beta_1 - a_2\text{sign}(\beta_1) - \hat{a}_3\text{sign}(\beta_1)] - \frac{\tilde{a}_3}{\gamma_0}\dot{\tilde{a}}_3 \\ &\leq -a_1\beta_1^T\beta_1 - \hat{a}_3\beta_1^T\text{sign}(\beta_1) - \frac{1}{\gamma_0}\tilde{a}_3\dot{\tilde{a}}_3 - a_2\beta_1^T\text{sign}(\beta_1) \\ &\quad + a_3\beta_1\text{sign}(\beta_1) \\ &\leq -a_1\beta_1^T\beta_1 - \hat{a}_3 \sum_{i=1}^3 |\beta_{1i}| - \tilde{a}_3 \sum_{i=1}^3 |\beta_{1i}| \\ &\quad + a_3 \sum_{i=1}^3 |\beta_{1i}| - a_2 \sum_{i=1}^3 |\beta_{1i}| \\ &\leq -a_1\|\beta_1\|^2 - a_2 \sum_{i=1}^3 |\beta_{1i}|. \end{aligned} \quad (23)$$

From Eq. (23), it could be concluded the proposed SMDO design is asymptotically convergent i.e. $\beta_1(t) \rightarrow 0$, and $\tilde{a}_3(t) \rightarrow 0$ as $t \rightarrow \infty$. In addition, according to (15) we have $\beta_0(t) \rightarrow 0$ and $\dot{\beta}_0(t) \rightarrow 0$, which indicates $\hat{D}_\zeta(t) \rightarrow D_\zeta(t)$ according to (17). The equation (23) along with proceeding analysis shows that \hat{D}_ζ converge to D_ζ asymptotically i.e. $\tilde{D}_\zeta(t) \rightarrow 0$.

Remark 2: In the proposed SMDO structure, the differential term $\dot{\beta}_0$ cannot be obtained directly. The derivative method can be used to obtain the derivative of β_0 . To obtain estimates of each element of differential term $\dot{\beta}_0$, we employ the higher-order sliding mode differentiator, which follow the following structure [49],

$$\begin{aligned} \dot{x}_0 &= b_0|x_0 - f(t)|^{\frac{1}{2}}\text{sign}(x_0 - f(t)) + x_1 \\ \dot{x}_1 &= b_1\text{sign}(x_1 - x_0), \end{aligned} \quad (24)$$

where $x_i \forall i = 0, 1$ are states of system (24), b_0 and b_1 are design parameters of differentiator, and $f(t) = \beta_0$ is known function. $x_0 = \hat{\beta}_0$ is the estimate of term $\dot{f}(t)$ of arbitrary accuracy if the term $x_0 - f(t_0)$ is bounded.

Remark 3: The SMDO is developed to estimate and tackle the compound disturbance of the system defined in the previous sections. The previous SMDO design in [43], [50], and [51], require information regarding upper bounds of unknown disturbance. While these bounds are used to get estimates from disturbance observers. For the SMDO proposed in (13) – (16), only upper bounds on derivative of compound disturbance \hat{D}_ζ are needed. Thus, the restrictive condition imposed on bounds is relaxed as compared to the existing literature.

V. ISMC CONTROLLER DESIGN

In this section, an adaptive ISMC scheme is formulated for the rigid body spacecraft attitude model based on the proposed SMDO. The compound disturbance D_ζ is unknown, and it can not be used to formulate adaptive SMC directly. Thus, the proposed SMDO is used to estimate compound disturbance.

First, consider the following sliding surface,

$$\sigma = a_4 w_e + a_4 \beta_0 + a_5 k_s q_e + a_5 \int_0^t (\omega_e - k_s \dot{q}_e) dt, \quad (25)$$

where sliding surface $\sigma_i = [\sigma_1, \sigma_2, \sigma_3]^T$, $a_4 > 0$ and $a_5 > 0$ are design parameters and affect the dynamic behavior of sliding mode. The design parameters can be obtained using optimal methods, pole placement, Lyapunov function, or Routh-Hurwitz stability criterion. In this work, the parameters a_4 and a_5 are obtained using the Routh-Hurwitz stability criterion to keep the sliding mode stable. The system states need to be in sliding mode from the initial time instant in case of ISMC design, and there is no reaching phase, i.e., $\sigma_i(0) = 0$.

Taking derivative, invoking equation (12) and equation (17), results in

$$\begin{aligned} \dot{\sigma} &= a_4 \dot{w}_e + a_4 \dot{\beta}_0 + a_5 \omega_e \\ \dot{\sigma} &= a_4[\zeta + D_\zeta + u_\zeta] - a_4 \tilde{D}_\zeta + a_5 \omega_e \end{aligned} \quad (26)$$

According to the assumption and estimated disturbance or output of the proposed SMDO, the control law is formulated as

$$u(t) = \frac{-1}{a_4} [a_4 \zeta - a_4 \hat{D}_\zeta + a_5 \omega_e + K\sigma + W\text{sat}(\sigma)], \quad (27)$$

where $K = \text{diag}[k_i]$ and $W = \text{diag}[w_i]$ are design parameters such that $K_i, w_i > 0$ and the saturation function $\text{sat}(\sigma) = [\text{sat}(\sigma_1), \text{sat}(\sigma_2), \dots, \text{sat}(\sigma_n)]^T$, $\forall n \leq 3$ is defined on sliding surface σ as

$$\text{sat}(\sigma_i) = \begin{cases} \text{sign}(\sigma_i), & \text{if } |\sigma_i| > \epsilon_i \\ \frac{\sigma_i}{\epsilon_i}, & \text{if } |\sigma_i| \leq \epsilon_i. \end{cases} \quad (28)$$

Design constant $\epsilon_i > 0 \forall i = 1, 2, 3$ defines the thickness of boundary layer. Using equation (26) and (27), we get

$$\begin{aligned} \dot{\sigma} &= a_4 \left\{ \frac{-1}{a_4} [a_4(\zeta - \hat{D}_\zeta) + a_5 \omega_e + K\sigma + W\text{sat}(\sigma)] \right\} - a_4 \tilde{D}_\zeta \\ &\quad + a_5 \omega_e + a_4(\zeta + D_\zeta) \\ &= a_4(D_\zeta + \hat{D}_\zeta) - a_5 \omega_e - K\sigma - W\text{sat}(\sigma) - a_4 \tilde{D}_\zeta + a_5 \omega_e \\ \dot{\sigma} &= -(K\sigma + W\text{sat}(\sigma)) \end{aligned} \quad (29)$$

Therefore, from equation (29), it can be written as

$$\begin{aligned} \sigma^T \dot{\sigma} &= -\sigma^T (K\sigma + W\text{sat}(\sigma)) \\ \sigma^T \dot{\sigma} &\leq -K \|\sigma\|^2 - W \sum_{i=1}^3 |\sigma_i|. \end{aligned} \quad (30)$$

The adaptive ISMC controller design procedure for rigid-body spacecraft attitude tracking control is outlined in the following theorem.

Theorem 2: Consider the nonlinear system of a rigid body spacecraft in (5), (9) and also the sliding surface in (25). If structure of SMDO in (13) – (16) is used along with adaptive ISMC input control law in (30), then the attitude tracking errors converge to zero asymptotically.

Proof 2: We consider the following Lyapunov's function,

$$V = V_1 + \frac{1}{2} \sigma^T \sigma. \quad (31)$$

Taking derivative of V , invoking equation (23) and (30), we obtain

$$\begin{aligned} \dot{V} &= \dot{V}_1 + \sigma^T \dot{\sigma} \\ &\leq -a_1 |\beta_1|^2 - a_2 |\beta_1| - K |\sigma|^2 - W |\sigma|. \end{aligned} \quad (32)$$

From (32), it is concluded that the closed-loop system is asymptotically stable, i.e., The tracking error also converges to zero as $t \rightarrow \infty$. Thus the objective of the research note is achieved; this concludes the proof.

Remark 4: The major drawback of SMC is the chattering phenomena associated with it. One way to avoid the problem is to employ the saturation function instead of the sign(.). Thus, the saturation function is used in equation (27) to avoid chattering. The reaching condition of SMC is always satisfied according to equation (28).

Remark 5: The most challenging task in observer-based controller design is to prove convergence of the closed-loop

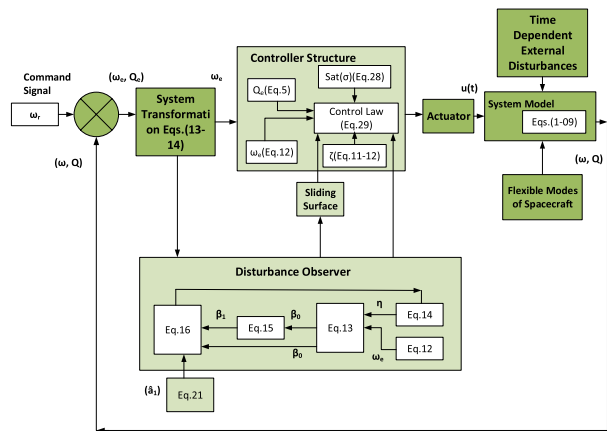
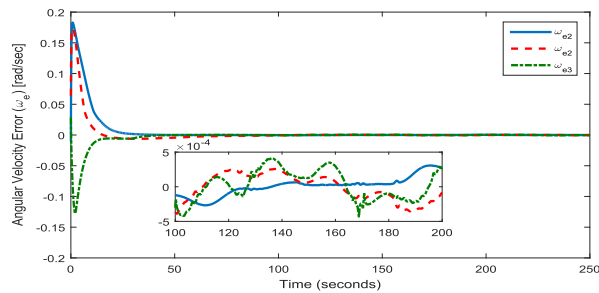
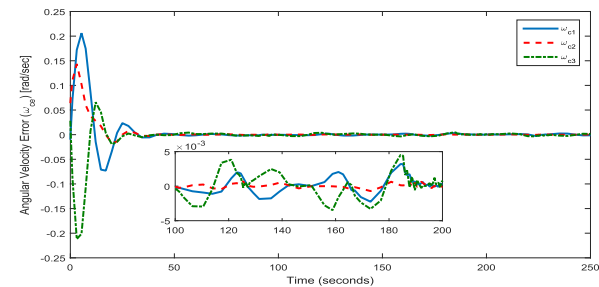


FIGURE 1. System schematic under proposed control law.



(a) Proposed SMDO-AISM Law



(b) ASMC Law

FIGURE 3. Angular velocity error evolution: (a) SMDO-based ISMC law and (b) ASMC law.

TABLE 2. Attitude error under proposed SMDO-AISM and ASMC laws.

Time (s)		13	15	65	150
SMDO-AISM Law	q_{e1}	-0.0656	0.0412	0.001443	-0.00012
	q_{e2}	0.124	0.126	0.01812	0.00086
	q_{e3}	0.0744	0.0621	-0.00168	-0.0004
	q_{e4}	0.9865	0.988	0.9998	1
ASMC Law	q_{ce1}	0.1998	0.143	0.0086	-0.00976
	q_{ce2}	0.0178	0.0154	0.0003	0.00088
	q_{ce3}	-0.0689	-0.0152	0.0054	0.0117
	q_{ce4}	0.977	0.988	0.9995	0.999

schemes shows that the proposed SMDO-AISM law gives superior performance. System parameters for simulation purposes are taken from [47]. The nominal inertia of spacecraft is taken as

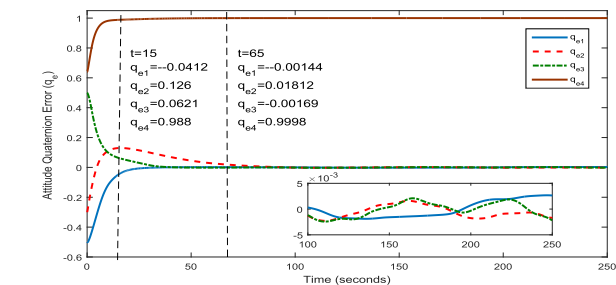
$$J_n = \begin{bmatrix} 20, & 1.2, & 0.9 \\ 1.2, & 17, & 1.4 \\ 0.9, & 1.4, & 15 \end{bmatrix} \text{ kg.m}^2.$$

Parameter uncertainty associated with spacecraft inertia matrix is considered as

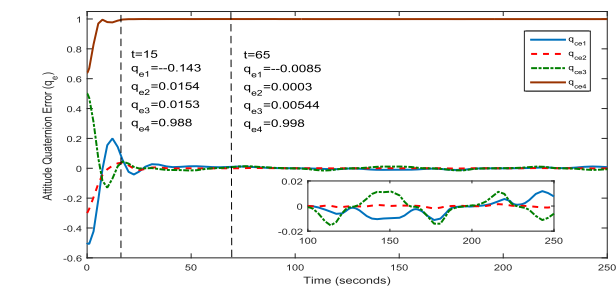
$$\delta J = \text{diag}([\sin(0.1t), 2\sin(0.2t), 3\sin(0.2t)]) \text{ kg.m}^2.$$

For simulation purposes, the desired angular velocity is given by

$$\omega_d = 0.05 \begin{bmatrix} \cos(\frac{\pi t}{100}) \\ \sin(\frac{2\pi t}{100}) \\ \cos(\frac{3\pi t}{100}) \end{bmatrix} \text{ rad/sec.}$$



(a) Proposed SMDO-AISM Law



(b) ASMC Law

FIGURE 2. Attitude quaternion error response: (a) SMDO-based ISMC law and (b) ASMC law.

system. In literature, observers are designed in such a way that they converge faster than the controllers. In the proposed control scheme, the term $a_4\beta_0$ is included in the sliding surface design to obtain the controller. This forces convergence of SMDO and ASIMC simultaneously, resulting in the overall stability of the system.

VI. SIMULATION RESULTS AND DISCUSSION

In this section, comparative numerical simulation results are presented to evaluate the performance and efficiency of the proposed SMDO based AISMC method for attitude tracking of spacecraft. The rigid-body spacecraft system schematic diagram of the proposed control law is shown in fig. 1. The simulation results demonstrate that the objectives are successfully achieved. Further, a comparison with other control

TABLE 3. Mean square error (MSE) comparison of states under proposed SMDO-AISM and ASMC laws.

MSE(q_e)	MSE(q_{ec})	MSE(ω_e)	MSE(ω_{ec})
2×10^{-3}	8×10^{-3}	1.8×10^{-4}	7×10^{-3}
1.2×10^{-3}	5.8×10^{-3}	1.4×10^{-4}	2×10^{-3}
2.4×10^{-3}	9.7×10^{-3}	6.5×10^{-5}	2.5×10^{-4}

The time-dependent external disturbance is selected as

$$d(t) = (|\omega|^2 + 0.05) \begin{bmatrix} \sin(\frac{2\pi t}{100}) \\ \cos(\frac{\pi t}{100}) \\ \cos(\frac{2\pi t}{100}) \end{bmatrix} \text{ N.m.}$$

In addition, simulations are carried out for the system subjected to the rapidly changing disturbance. The frequency of the periodic disturbance is selected as 10 rad/sec.

$$d_1(t) = (|\omega|^2 + 0.05) \begin{bmatrix} \sin(10\pi t) \\ \cos(10\pi t) \\ \cos(10\pi t) \end{bmatrix} \text{ N.m.}$$

The initial condition of spacecraft attitude quaternion and angular velocity is set as $q(0) = [-0.5, -0.3, 0.5, 0.6403]^T$ and $\omega = [0, 0, 0]^T$ rad/sec respectively.

The constant parameters for simulation of developed SMDO structure, are selected as follows, $a_1 = 0.02$, $a_2 = 0.01$ and $\Gamma = \text{diag}([0.5, 0.5, 0.5])$, while the parameters for integral sliding surface are selected as $a_4 = 100$, $a_5 = 0.008$ and $k_s = 0.5$.

Parameter for adaptive law is set as $\gamma_0 = 0.02$. Initial values for adaptive law are selected as $a_3(0) = 0.001$. The presented AISM control law design parameters are selected as $K = \text{diag}([10, 10, 10])$ and $W = \text{diag}([20, 20, 20])$. Additionally, an adaptive SMC controller in [15] is simulated for comparison purposes.

$$u_{ASMC} = -M - k\sigma - \frac{\sigma}{\|\sigma\|} \hat{D},$$

with

$$\hat{D} = \rho (\|\sigma\| - \mu \hat{D}),$$

where $M = \omega \times J_0 \omega + \frac{K_s}{2} (q_4 e I_3 + q_e^\times) \omega_e$, $\rho = 0.01$ and $\mu = 0.01$. The initial value of $\hat{D}(0) = 0.01$ is used in comparative simulation.

The attitude quaternion error evolution with time for spacecraft system under the effect of proposed SMDO-AISM law given in (27), is shown in fig. 2. Note that quaternion errors converge faster under the proposed controller and have better accuracy in steady-state fig. 2a, compared with ASMC law fig. 2b. Additionally, table 2 gives the comparison of system attitude error under both controllers. The simulation results around overshoot and steady-state are represented in table 2. The tracking error in the case of the proposed controller is small comparatively. The development of angular velocity error with reference to time is presented in fig. 3. It is easy

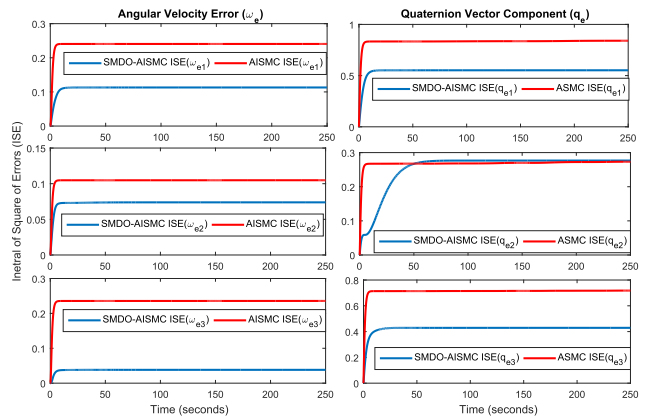
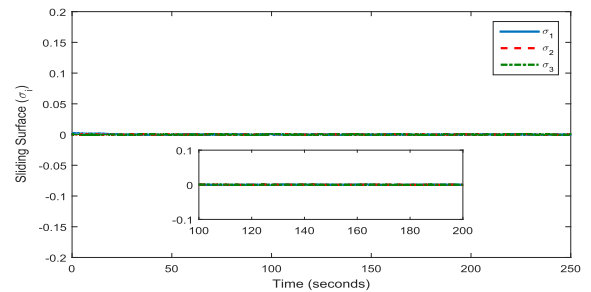
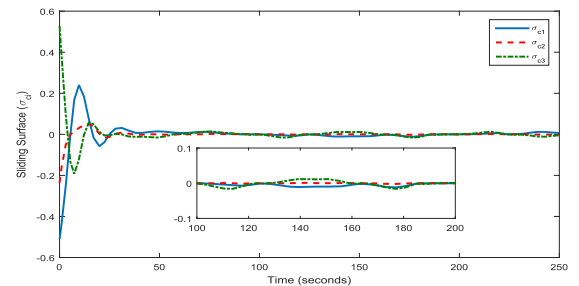


FIGURE 4. Integral absolute error (IAE) under the proposed SMDO-AISM and ASMC. (a) Angular velocity error ω_e . (b) Quaternion error (Q_e).



(a) Proposed SMDO-AISM Law



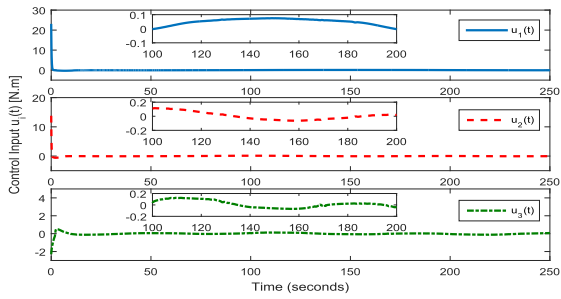
(b) ASMC Law

FIGURE 5. Sliding surface: (a) SMDO-based ISMC law and (b) ASMC law.

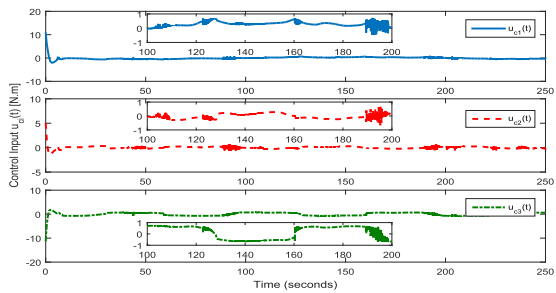
to follow that angular velocity error has less overshoot fig. 3a and has less steady-state error comparatively fig. 3b. The performance indexes, integral of absolute error (ISE) and means square error (MSE), are calculated to observe the overall system performance under both the controllers. The ISE of attitude quaternion error and angular velocity error are shown in the fig. 4 and the MSE are tabulated in table 3.

The system states reach to sliding surface initially and converge the equilibrium point along with the sliding surface. The fig. 5 shows the progress of the sliding surface with time. Note, there is no reaching phase for control law (27) as shown in fig. 5a, giving additional robustness to the proposed controller. The sliding surface for ASMC is shown in fig. 5b.

The control input torque, needed to force system states to track desired angular velocity and attitude quaternion, is depicted in fig. 6. The torque input generated by the



(a) Proposed SMDO-AISM Law



(b) ASMC Law

FIGURE 6. Control input torque: (a) SMDO based ISMC law and (b) ASMC law.

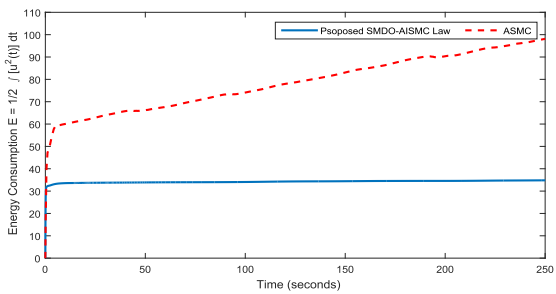


FIGURE 7. Control input energy.

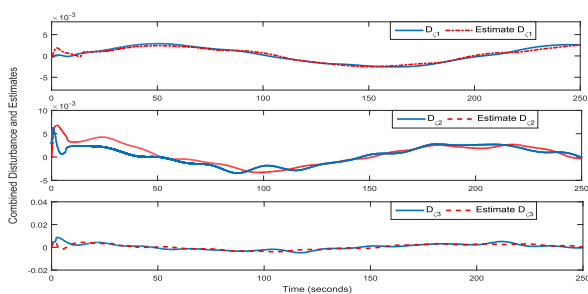


FIGURE 8. Combined disturbance and estimates.

proposed controller is smooth and chattering free, and steady-state control input torque is comparatively lesser.

Total energy consumption of system actuators are shown in fig. 7. The energy is calculated using following expression $E = \frac{1}{2} \int_0^t (|u_i(t)|) dt$. It can be noted that the energy consumption for the proposed controller is less than ASMC, indicating better efficiency. The combined system disturbances and their estimates obtained using SMDO are presented in fig. 8. It is clear from the figure that observer estimates are good enough. The Disturbance estimation errors are given

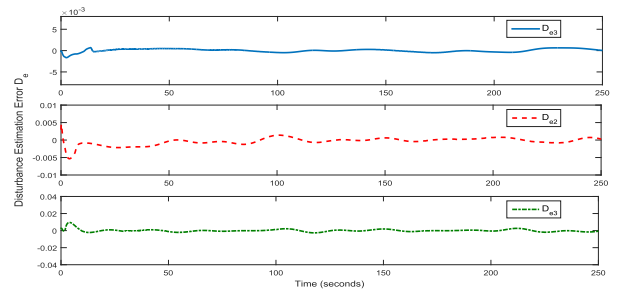


FIGURE 9. Combined disturbance estimation error.

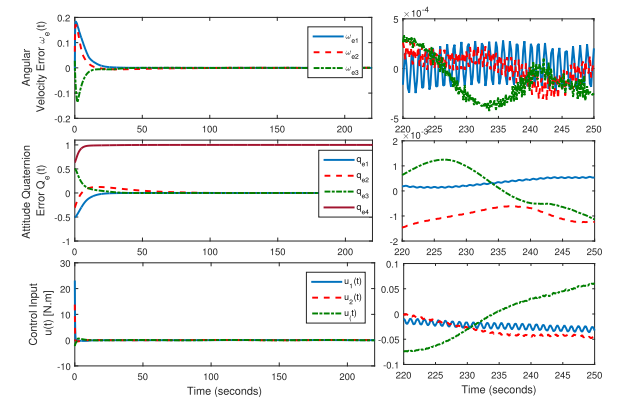


FIGURE 10. Angular velocity error, attitude quaternion error, and control input for system subjected to rapidly changing disturbances.

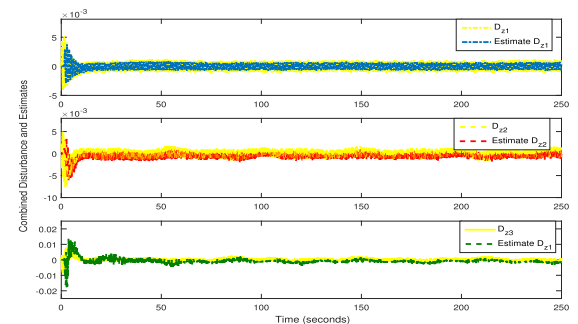


FIGURE 11. Combined disturbance and estimates for system subjected to rapidly changing disturbances.

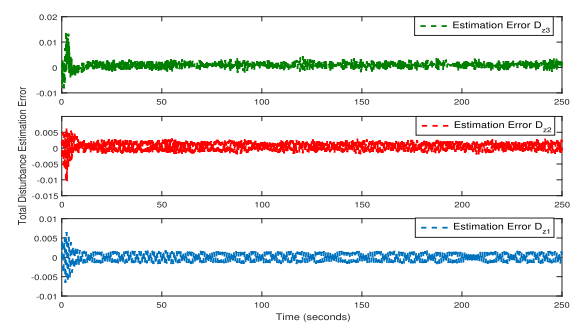


FIGURE 12. Combined disturbance estimation error for system subjected to rapidly changing disturbances.

in fig. 9. In addition, simulations are carried out subjected to rapid changing disturbance $d_1(t)$. Figure 10 shows the angular velocity error, attitude quaternion error, and control

input evolution of spacecraft. The combined system disturbance and estimates from SMDO are shown in fig. 11, and estimation error is presented in fig. 12. The proposed SMDO gives combined disturbance estimates successfully online with acceptable accuracy.

VII. CONCLUSION

In this paper, a new observer-based attitude tracking control of spacecraft under the effect of time-dependent external disturbance and system parameter uncertainties has been developed successfully. Particularly a novel SMDO is proposed and incorporated with adaptive ISMC for spacecraft attitude control. Initially, SMDO estimates the combined disturbance composed of external disturbance and system parameter uncertainties. The key feature of the proposed SMDO is that it does not need an assumption on disturbance being constant or varying at slow rates. The estimates obtained from the SMDO have been used to formulate adaptive law for time-dependent variable gain and ISMC controller for spacecraft attitude tracking control. A rigorous stability analysis for the proposed SMDO estimation error has been provided to show asymptotic convergence. In addition, the closed-loop stability analysis of the system under consideration is performed using Lyapunov's theory. Numerical simulations are carried out to show that the proposed control scheme gives a satisfactory performance with smooth and chattering free signals.

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