Synthesis of a hybrid super-twisting and adaptive fractional-order sliding-mode control law for the gimbal seeker ensuring disturbance rejection and high accuracy

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ABSTRACT

This paper investigates the synthesis of an Adaptive Fractional-Order Super-Twisting Sliding Mode Control (AFOSTSMC) law to improve line-of-sight (LOS) stabilization performance for the two-axis gimbal drive system of an electro-optical seeker. The gimbal system has strongly nonlinear dynamics and is affected by angle-dependent varying moments of inertia, cross-coupling between the Yaw and Pitch channels, and uncertain disturbances. The proposed controller combines three techniques: (1) the Caputo fractional-order derivative, which accelerates convergence and smooths the error response; (2) the Super-Twisting Algorithm (STA), which suppresses chattering; and (3) an adaptive mechanism, which automatically tunes the controller gains online to compensate for disturbance components with unknown bounds. System stability is proven using Lyapunov theory and the Mittag-Leffler convergence criterion. Simulation results on a compact drive-system model demonstrate the advantages of the hybrid AFOSTSMC law over Super-Twisting Sliding Mode Control (STSMC) and Adaptive Fractional-Order Sliding Mode Control (AFOSMC) methods.

Keywords: Two-axis gimbal; Fractional-order sliding-mode control; Super-Twisting algorithm; IIR seeker; Chattering.

1. INTRODUCTION

Line-of-sight (LOS) stabilization systems for optical payloads are widely used in both military and civilian applications [1]. Depending on the configuration, three gimbal types are commonly employed: three-axis [2], two-axis Yaw–Pitch [3], and two-axis Roll–Swing [4]. Although the three-axis gimbal offers the best stabilization capability, its mechanical complexity limits its use to platforms with large installation space. Two-axis Yaw–Pitch gimbals are therefore preferred in mass- and volume-constrained applications such as missile infrared seeker heads [5], owing to their independent dual-channel control structure in a Cartesian frame [6, 7]. Precision control of such systems, however, is challenged by angle-dependent varying inertia, Yaw–Pitch cross-coupling, nonlinear LuGre friction, mass-unbalance torque, and carrier-induced disturbances.

Conventional linear controllers exhibit significant limitations under these uncertainties, and even intelligent self-tuning schemes such as fuzzy-PID, effective for vibration isolation in heavy machinery [16], degrade under strongly time-varying disturbances. Sliding Mode Control (SMC), pioneered by Utkin [8], offers strong robustness but suffers from chattering-high-frequency switching oscillations that cause mechanical wear and energy loss. The Super-Twisting Algorithm (STA) [11] addresses this by embedding the discontinuous term into the control derivative, producing a continuous output while preserving finite-time convergence [11–13]; however, its fixed gains limit tracking robustness when time-varying disturbances exceed the pre-defined bounds. Incorporating fractional-order derivatives into the sliding surface [14] further improves convergence speed and smoothness through their inherent memory property, while adaptive gain-tuning mechanisms eliminate the need for prior knowledge of disturbance bounds [9, 10].

Despite these advances, simultaneously suppressing cross-coupling, compensating for nonlinear friction, and achieving embedded-hardware compatibility remains an open problem. This paper proposes an Adaptive Fractional-Order Super-Twisting SMC (AFOSTSMC) for the two-axis gimbal of an electro-optical seeker, combining fractional-order memory, STA-based chattering suppression, and adaptive gain tuning to achieve high-accuracy LOS stabilization under strong disturbances. Two representative controllers, STSMC [11] and AFOSMC [14], are adopted as simulation benchmarks.

The remainder of this paper is organized as follows. Section 2 derives the gimbal dynamic model and the AFOSTSMC law with its stability proof. Section 3 presents comparative simulation results. Section 4 concludes the paper.

2. SYNTHESIS OF THE HYBRID SUPER-TWISTING AND ADAPTIVE FRACTIONAL ORDER SLIDING MODE CONTROLLER FOR THE TWO-AXIS GIMBAL

2.1. Modeling of the two-axis gimbal system

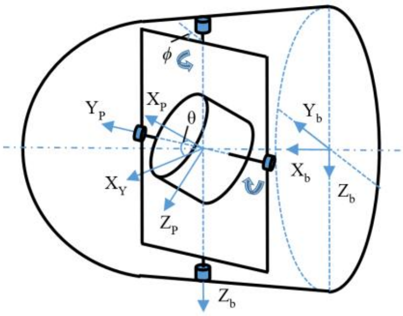


Figure 1. *Two-axis gimbal system.*

As shown in Figure 1, the single-joint two-axis gimbal system considered in this paper is analyzed. The system is described using three main reference frames: the carrier/body frame (B - $X_bY_bZ_b$), the outer frame (O – Yaw) ($X_YY_PZ_b$), and the inner frame (I - Pitch) ($X_PY_PZ_P$). The coordinate transformations from the carrier to the outer frame and from the outer frame to the inner frame are defined by the rotation matrices L_{OB} (with angle ϕ) and L_{IO} (with angle θ), respectively:

$$L_{OB} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}, L_{IO} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$

Let $\omega_B = [p,\ q,\ r]^T$ denote the angular velocity of the carrier platform. The inertial angular velocity of the inner frame $\omega_I = [p_i, q_i, r_i]^T$ is obtained by projecting the velocity components onto the corresponding axes and combining them with the body rotation rates $\dot{\phi}$ and $\dot{\theta}$:

Pitch axis (inner frame): $q_i = q_o + \dot{\theta}$; Yaw axis (outer frame): $r_o = r + \dot{\phi}$

The dynamic equation of the Pitch channel (inner frame) is described as follows [8]:

$$J_{iy}\ddot{\theta} = T_{iy} - T_{fric,i} - T_{unb,i} - T_{coupling,i} \tag{1}$$

where: J_{iy}: moment of inertia of the inner frame about the Y_I axis.

T_{iy}: control torque generated by the Pitch-channel motor.

$T_{coupling,i}$: cross-channel coupling torque component generated by the motion of the outer frame: $T_{coupling,i} = \frac{1}{2}r_o^2$

The Yaw-channel dynamic equation is written as follows:

$$J_s(\theta)\ddot{\phi} = T_{oz} - T_{fric,o} - T_{unb,o} - T_{coupling,o} \quad (2)$$

with $J_s(\theta)$ being the instantaneous moment of inertia:

$$J_s(\theta) = J_{oz} + J_{ix}\sin^2\theta + J_{iz}\cos^2\theta - D_{xz}\sin(2\theta) \quad (3)$$

The nonlinear friction torque T_{fric} is described by the LuGre model [15], which accurately captures frictional hysteresis, static friction variation, and low-velocity Stribeck behavior by modeling bearing contacts as elastic bristles.

To apply SMC and an observer, the system is transformed into the following nonlinear form:

$$\dot{x_1} = x_2 \quad (4)$$

$$\dot{x_2} = f(x) + g(x)u + d(t) \quad (5)$$

With $x = [\phi, \dot{\phi}, \theta, \dot{\theta}]^T$, the specific components for each channel are:

Pitch channel (θ): $x_{p1} = \theta, x_{p2} = \dot{\theta}$; system function $f(x) = -\frac{1}{J_{iy}}T_{coupling,i}$; input coefficient $g(x) = \frac{K_t}{J_{iy}R_a}$; lumped disturbance $d(t)$: includes friction, unbalance, and modeling error. Yaw channel (ϕ): $x_{y1} = \phi, x_{y2} = \dot{\phi}$; system function $f(x) = -\frac{1}{J_s(\theta)}$; input coefficient $g(x) = \frac{K_t}{J_s(\theta)R_a}$; lumped disturbance $d(t)$: includes friction, base motion, and modeling error. Since $g(x)$ depends on the state θ, the SMC controller requires a real-time equivalent control component u_{eq} to cancel the nonlinear terms $f(x)$.

2.2. Synthesis of the hybrid adaptive fractional-order super-twisting SMC law

This section derives the hybrid AFOSTSMC by integrating the STSMC [11] and AFOSMC [14] structures, as follows.

Step 1: Design of the fractional-order sliding surface

The sliding surface incorporating the Caputo fractional derivative operator D^{μ} with $0 < \mu < 1$ is designed to improve the error dynamics:

$$s = \dot{e} + \lambda D^{\mu} e \quad (6)$$

where $e = q - q_d$ is the angular tracking error. Here, $\lambda > 0$ is the sliding-surface design coefficient. The Caputo operator D^{μ} provides faster convergence and reduces overshoot.

Step 2: Establishment of the sliding-surface dynamics

Taking the first-order derivative of s with respect to time:

$$\dot{s} = \ddot{e} + \lambda D^{\mu+1} e = (\ddot{q} - \ddot{q_d}) + \lambda D^{\mu+1} e \quad (7)$$

Substituting the gimbal dynamic model $\ddot{q} = f(x) + g(x)u + d(t)$ into the equation above:

$$\dot{s} = \ddot{e} + \lambda D^{\mu+1} e = (f(x) + g(x)u - \ddot{q_d}) + \lambda D^{\mu+1} e + d(t) \quad (8)$$

Here, $d(t)$ is the lumped disturbance (including LuGre friction, cross-channel coupling, and mass-unbalance disturbance) with a bounded derivative $|\dot{d}(t)| \le \delta$, but δ is unknown.

Step 3: Synthesis of the adaptive Super-Twisting reaching law

To suppress chattering and ensure robustness, the Super-Twisting structure is adopted with adaptive gains $\hat{k}_1(t)$ and $\hat{k}_2(t)$:

$$\dot{s}_{des} = -\hat{k}_1(t)|s|^{1/2}\mathrm{sgn}(s) + v \quad (9)$$

$$\dot{v} = -\hat{k}_2(t)\mathrm{sgn}(s) \quad (10)$$

The gain-update laws are designed to increase automatically when the error is large and decrease when the system has stabilized around the sliding surface:

$$\dot{\hat{k}}_1(t) = \gamma_1|s|, \quad \hat{k}_2(t) = \beta\hat{k}_1(t) \tag{11}$$

This mechanism allows the controller to operate without prior knowledge of the disturbance bound ($d(t)$) while still maintaining the ideal sliding mode.

Step 4: Synthesis of the hybrid AFOSTSMC control law

Combining the equivalent control component u_{eq} to cancel the known nonlinear terms with the Super-Twisting component to handle disturbances gives:

$$u = g(x)^{-1}\left[u_{eq} + u_{st}\right] \tag{12}$$

where: $u_{eq} = \ddot{q_d} - f(x) - \lambda D^{\mu+1}e$; $u_{st} = -\hat{k}_1(t)|s|^{1/2}\mathrm{sgn}(s) - \int_0^t \hat{k}_2(\tau)\mathrm{sgn}\big(s(\tau)\big)d$

The synthesized control signal is therefore:

$$u = g(x)^{-1}\left[\ddot{q_d} - f(x) - \lambda D^{\mu+1}e - \hat{k}_1(t)|s|^{1/2}\mathrm{sgn}(s) - \int_0^t \hat{k}_2(\tau)\mathrm{sgn}\big(s(\tau)\big)d\right] \tag{13}$$

The resulting law (13) thus combines a continuous control signal (Super-Twisting integral term), accelerated finite-time error convergence (fractional-order component D^{μ}), and automatic gain adjustment to actual disturbance levels, reducing actuator wear and control energy while maintaining LOS stability.

2.3. Stability proof of the AFOSTSMC controller

The stability of AFOSTSMC is established in two stages using Lyapunov theory for HOSM systems and fractional-order derivative properties: (1) finite-time convergence to the sliding surface under the adaptive Super-Twisting law, and (2) convergence of the tracking error to zero on the sliding surface via the Mittag-Leffler criterion. With the fractional sliding surface $s = \dot{e} + \lambda D^{\mu}e$ and the established control law, the derivative of the sliding surface takes the form:

$$\dot{s} = -\hat{k}_1(t)|s|^{1/2}\mathrm{sgn}(s) + v + \Delta(t) \tag{14}$$

$$\dot{v} = -\hat{k}_2(t)\mathrm{sgn}(s) + \dot{d}(t) \tag{15}$$

where $\Delta(t)$ is the model-estimation error and $\dot{d}(t)$ is the derivative of the lumped disturbance, assumed to be bounded by $\left|\dot{d}(t)\right| \leq \delta$. To prove the stability of the Super-Twisting algorithm with time-varying gains, the sliding-state vector is defined as:

$$\xi = [\xi_1, \xi_2]^T = \left[|s|^{1/2}\mathrm{sgn}(s), v\right]^T \tag{16}$$

The Lyapunov function V includes the quadratic sliding term and the adaptive-error terms:

$$V = \xi^T P\xi + \frac{1}{2\gamma_1}\left(\hat{k}_1 - k_1^*\right)^2 + \frac{1}{2\gamma_2}\left(\hat{k}_2 - k_2^*\right)^2 \tag{17}$$

where P is a symmetric positive-definite matrix:

$$P = \begin{bmatrix} \xi + 4\hat{k}_2 & -2\hat{k}_1 \\ -2\hat{k}_1 & 2 \end{bmatrix} \text{with } \zeta > 0 \tag{18}$$

Here, k_1^*, k_2^* are the ideal gain values large enough to dominate the disturbance δ.

Taking the time derivative of V: $$\dot{V} = -\frac{1}{|\xi_1|}\xi^T Q\xi + \frac{1}{\gamma_1}\widetilde{k_1}\dot{\hat{k}}_1 + \frac{1}{\gamma_2}\widetilde{k_2}\dot{\hat{k}}_2 \tag{19}$$

where Q is a positive-definite matrix whose coefficients $\hat{k}_1, \hat{k}_2$ satisfy the conditions $k_1 > 0$ and $k_2 > \delta + \text{const}$. When the adaptive laws $\dot{\hat{k}}_1 = \gamma_1|s|$ are substituted into the equation, the terms containing $\widetilde{k_\iota}$ combine with the terms in $\dot{V}_0$ to cancel the effects of disturbances with unknown bounds. The final result is:

$$\dot{V} \leq -\eta V^{1/2} \quad (\eta > 0) \tag{20}$$

This confirms that V converges to 0 within a finite time interval $T \leq \frac{2V(0)^{1/2}}{\eta}$. When $V \rightarrow 0$, it follows that $s \rightarrow 0$ and $\dot{s} \rightarrow 0$. Once the system lies on the sliding surface ($s = 0$), the error dynamics become:

$$\dot{e} = -\lambda D^{\mu} e \tag{21}$$

According to fractional-order stability theory, the solution of this equation has the Mittag-Leffler form $e(t) = e(0)\, E_{\mu,1}(-\lambda\, t^{\mu})$. Because $\lambda > 0$ and $0 < \mu < 1$, the tracking error $e(t)$ converges smoothly to 0 and reaches steady state. Thus, the proposed hybrid AFOSTSMC controller guarantees global asymptotic stability and finite-time convergence.

3. PERFORMANCE EVALUATION OF THE AFOSTSMC CONTROLLER FOR THE TWO-AXIS GIMBAL SYSTEM

The two-axis gimbal is a critical electromechanical component of a compact Imaging Infrared (IIR) seeker, subject to stringent size, weight, and LOS stabilization requirements.

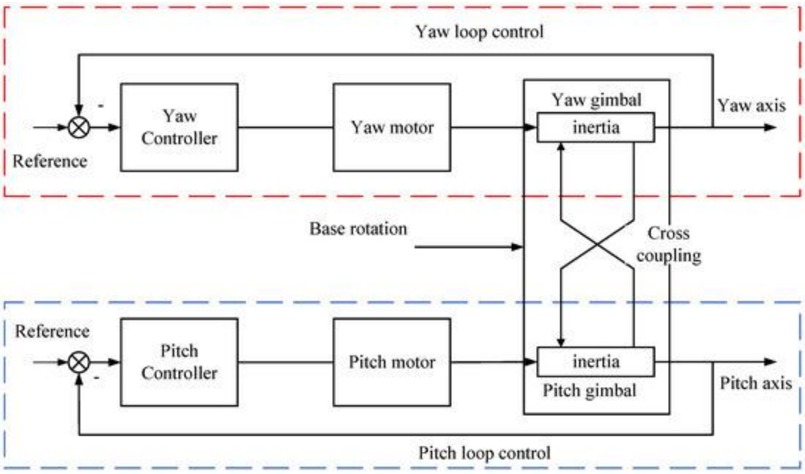


Figure 2. *Control model of the two-axis gimbal system.*

This section evaluates the tracking and disturbance rejection capabilities of the proposed AFOSTSMC via a MATLAB/Simulink simulation scenario of a compact IIR seeker under strong cross-coupling and LuGre friction. The physical and electrical parameters of the gimbal system, adopted from verified empirical models are summarized in Table 1 and below [8, 15].

Table 1. *Friction-model parameters of the gimbal seeker.*

No.	Parameter	Symbol	Expected value
1	Bristle stiffness	σ_0	$300 - 450$
2	Damping coefficient	σ_1	$2.0 - 4.5$
3	Viscous friction coefficient	σ_2	$0.05 - 0.08$
4	Static friction torque	T_s	$0.06 - 0.10\ Nm$
5	Coulomb torque	T_c	$0.03 - 0.05\ Nm$
6	Stribeck velocity	v_s	$0.01 - 0.05\ rad/s$

The gimbal parameters are: $J_o = 0.025$, $J_i = 0.008$, $J_{ix} = J_{iz} = 0.005$, $D_{xz} = 0.0001$ kg·m²; the direct-drive BLDC torque motor has $K_t = 0.284$ Nm/A, $R_a = 16.5\ \Omega$, $L = 6.3$ mH. The specific parameters of the controllers are selected as follows. STSMC controller: $\lambda = 25$; $k_{1yaw} = 5.5$; $k_{2yaw} = 3.0$; $k_{1p} = 5.0$; $k_{2p} = 2.5$; AFOSMC controller: $\alpha = 0.6$; $\lambda_1 = 12$; $\lambda_2 = 20$; $\gamma = 8.5$; $\phi = 0.05$; AFOSTSMC controller: $\mu = 0.05$; $\lambda = 35$; $\gamma = 3.5$; $\beta = 0.1$

The simulation results are as follows:

In the Yaw channel, AFOSTSMC achieves the fastest tracking, converging within 0.8 s with near-zero steady-state error and none of the overshoot or ripple oscillations observed with STSMC and AFOSMC. In the Pitch channel, which is strongly affected by Yaw cross-coupling and low-velocity LuGre friction, STSMC exhibits large-amplitude oscillations (0.2 rad), confirming that fixed gains are insufficient under strongly varying disturbances; AFOSMC requires the longest settling time (>1.5 s, with an initial peak error of −0.6 rad), while AFOSTSMC converges fastest (<0.7 s) and maintains accuracy under disturbance effects.

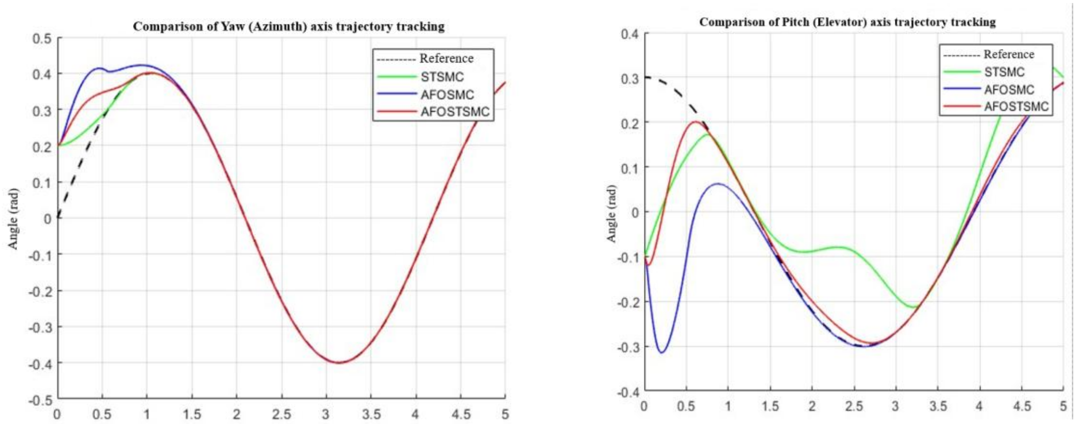
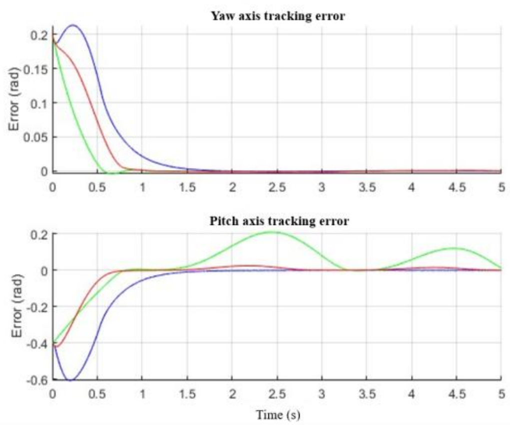


Figure 3. *Comparison of trajectory tracking capability along the two gimbal axes.*



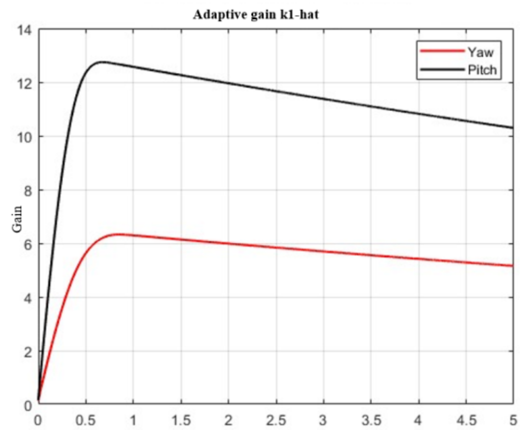
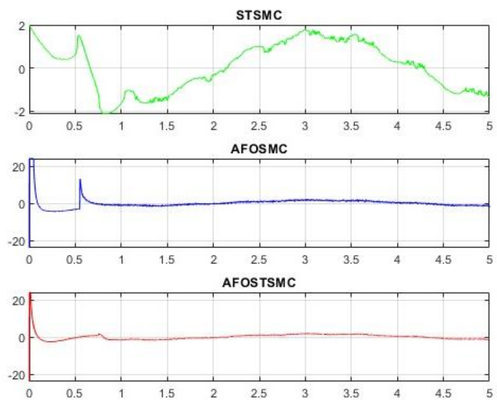


Figure 4. *Tracking error along the two gimbal axes.* ***Figure 5.*** *Adaptive gains of AFOSTSMC.*



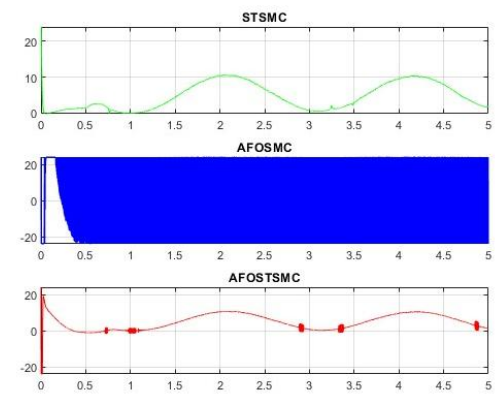


Figure 6. *Yaw-channel control signal.* ***Figure 7.*** *Pitch-channel control signal.*

The adaptive gains respond dynamically to system demands: during the reaching phase, both gains increase rapidly within the first 0.7 s, with the Pitch-channel gain peaking at 12.8 - approximately twice the Yaw-channel value of 6.4 - reflecting the more complex dynamics of the Pitch axis. Once the error converges to the sliding-surface neighborhood, the gains decrease gradually, reducing unnecessary motor energy consumption.

Regarding control-signal quality, AFOSMC produces the severest chattering (index 181373.95 in Table 2), which can cause mechanical wear and infrared-image disturbance. STSMC yields the lowest chattering index (194.87) owing to its continuous output, yet its fixed gains result in the poorest tracking, with an Integral of Time-weighted Absolute Error (ITAE) nearly seven times that of the hybrid law. AFOSTSMC balances control authority and smoothness, suppressing more than 99% of the AFOSMC oscillation (1417.28): transient sawtooth pulses appear only at reversal points or during disturbance spikes and are rapidly attenuated by the memory property of the fractional-order sliding surface.

Table 2. *Performance comparison of the control laws.*

Method	IAE	ITAE	RMSE	Chattering
STSMC	0.5129	1.0046	0.1318	194.87
AFOSMC	0.4869	0.1970	0.1856	181373.95
AFOSTSMC	0.2521	0.1457	0.1030	1417.28

In terms of tracking accuracy, AFOSTSMC attains the lowest indices in Table 2: its Integral of Absolute Error (IAE) (0.2521) is nearly 50% below those of STSMC and AFOSMC, and its ITAE (0.1457) and Root Mean Square Error (RMSE) (0.1030) are also the smallest, confirming the effectiveness of combining a fractional-order sliding surface with an adaptive mechanism.

4. CONCLUSIONS

This paper has proposed and evaluated an AFOSTSMC for the two-axis gimbal of an electro-optical seeker, combining the fractional-order derivative D^{μ}, the Super-Twisting algorithm, and an adaptive gain-tuning mechanism to simultaneously achieve fast convergence, chattering suppression, and robustness against unknown disturbance bounds. Simulation results under time-varying disturbances and LuGre friction confirm the superiority of AFOSTSMC: the IAE is reduced by 50% relative to STSMC and AFOSMC; the RMSE is 0.1030 rad; and the chattering index is suppressed by 99% compared with AFOSMC. The adaptive law automatically adjusts k_1 and k_2 to compensate for cross-coupling and mass-unbalance torques, ensuring LOS stability during aggressive carrier maneuvers. The proposed control law thus bridges the gap between high-precision LOS stabilization and mechanical safety for hardware implementation, establishing a foundation for advanced nonlinear control in next-generation precision-guided systems operating under complex disturbance environments.

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TÓM TẮT

Tổng hợp luật điều khiển trượt lai Super-Twisting và thích nghi bậc phân số cho hệ truyền động đầu tự dẫn đảm bảo khả năng chống nhiễu và độ chính xác cao

Bài báo nghiên cứu tổng hợp luật điều khiển trượt lai Super-Twisting thích nghi bậc phân số (Adaptive Fractional-Order Super-Twisting Sliding Mode Control - AFOSTSMC) nhằm nâng cao hiệu suất ổn định đường ngắm (LOS) cho hệ truyền động gimbal hai trục của đầu tự dẫn quang điện tử. Hệ thống gimbal có động lực học phi tuyến mạnh, chịu ảnh hưởng bởi mô-men quán tính biến thiên theo góc quay, hiện tượng ảnh hưởng chéo giữa hai kênh Yaw-Pitch và các nhiễu loạn bất định. Luật điều khiển đề xuất là sự kết hợp giữa ba kỹ thuật: (1) Đạo hàm bậc phân số Caputo giúp tăng tốc độ hội tụ và độ mượt của đáp ứng sai số; (2) Thuật toán Super-Twisting (STA) giúp triệt tiêu hiện tượng chattering; và (3) cơ chế thích nghi giúp tự động hiệu chỉnh hệ số của bộ điều khiển trực tuyến để bù các thành phần nhiễu chưa biết biên. Tính ổn định của hệ thống được chứng minh thông qua lý thuyết Lyapunov và tiêu chuẩn hội tụ Mittag-Leffler. Kết quả khảo sát trên mô hình hệ truyền động kích thước nhỏ cho thấy ưu điểm của luật lai AFOSTSMC so với các phương pháp STSMC và AFOSMC.

Keywords: Gimbal hai trục; Điều khiển trượt bậc phân số; Thuật toán Super-Twisting; IIR Seeker; Chattering.