Enhancing the Pointing Accuracy Using Adaptive Terminal Sliding Mode Control for Satellite With Single Gimbal VSCMG

Mayur Vijay Pawar
MIT Art, Design and Technology University, Pune
Khushi Jain
MIT Art, Design and Technology University, Pune
Abhinav Krishnan
Independent Researcher
Sunil V Dingare
MIT Art, Design and Technology University, Pune

ABSTRACT

The growing importance of Space Domain Awareness (SDA) has heightened the need for precise tracking of space objects, especially given the increasing number of small objects and their challenging detection with ground-based sensors. As a result, space-based observation has become crucial for accurate tracking, requiring highly accurate pointing systems. However, current systems face limitations in achieving the necessary precision, with steady-state errors around 0.1 degrees, leading to significant ambiguities in observations. This research aims to enhance the pointing accuracy of satellite tracking systems through an innovative control scheme utilising a Single Gimbal Variable Speed Control Moment Gyroscope (SGVSCMG) paired with an adaptive terminal sliding mode controller. This approach promises stability and synchronisation in the presence of external disturbances. The study focuses on satellite attitude control systems for space-based SDA, employing a Lagrange nonlinear system model and a terminal sliding mode surface to minimise attitude-tracking errors and counteract disturbances. Stability and synchronisation are ensured through the Lyapunov stability theory. Simulation results demonstrate the effectiveness of the proposed control scheme, achieving a pointing accuracy improvement to approximately 0.01 degrees. This research advances SDA capabilities by providing a robust control solution that meets the high precision demands of modern space missions, contributing to enhanced space safety and satellite operations.

1. INTRODUCTION

The development of satellite attitude control systems has evolved alongside the increasing demands and complexities of space missions as the need for greater precision and robustness in operations has grown. In the early stages of space exploration, simple methods such as spin stabilisation were adequate for basic satellite operations, as demonstrated by the launch of Sputnik in 1957. However, as space missions expanded in scope and sophistication during the 1960s and 1970s, more advanced active control systems, like reaction wheels and thrusters, were developed to meet the escalating demands for precise orientation. The requirement for accurate pointing systems became especially critical with the emergence of Earth observation and communication satellites, where precise orientation was essential for mission success. Despite advancements, conventional control methods such as Proportional-Integral-Derivative (PID) controllers had limitations in addressing the space environment's complex dynamics and external disturbances.

In the 1990s, the introduction of Sliding Mode Control (SMC) represented a significant advancement in the development of satellite attitude control systems. It offered enhanced robustness against system uncertainties and external disturbances. However, the chattering phenomenon in SMC prompted the development of Terminal Sliding Mode Control (TSMC), which provided finite-time convergence to a desired state, thereby improving pointing precision and responsiveness. Throughout the 2000s, further progress was made with integrating adaptive mechanisms, enabling control systems to adjust to changing conditions dynamically, thereby significantly enhancing accuracy and reliability. The advent of Single Gimbal Variable Speed Control Moment Gyroscopes (SGVSCMG) has since established new standards in pointing accuracy, particularly when coupled with adaptive TSMC. This study aims to build upon these developments by exploring the potential of state-of-the-art control techniques and hardware configurations to achieve unparalleled precision, which is essential for modern space missions and Space Domain Awareness (SDA).

The precision of space-based observation systems is crucial for accurately tracking and monitoring small space objects, which are often challenging to detect with ground-based sensors. To address the need for improved pointing accuracy in space, this research focuses on developing a novel control scheme that combines SGVSCMG with sliding mode control techniques. The goal is to minimise tracking errors, enhance satellite attitude control systems' stability and robustness against external disturbances, and set new standards in pointing accuracy for satellites used in Space Domain Awareness (SDA). This work aims to advance SDA capabilities and improve space operations' safety and efficiency.

The existing body of literature on Attitude Determination and Control Systems (ADCS) for spacecraft provides a comprehensive foundation for understanding various control strategies to enhance attitude stability and pointing accuracy. Studies such as those by Xiwang Xia et al. [1], which detail the ADCS of the TZ-1 satellite using sun sensors, magnetometers, magnetic torquers, and a momentum wheel, have demonstrated significant advancements in de-tumbling from high angular velocities and maintaining pointing accuracy within 20 degrees. Similarly, Zheng Zhu et al. [2] implemented a sliding mode control (SMC) scheme that ensures finite-time convergence for attitude stabilisation, addressing the chattering issues of conventional SMC methods and improving robustness by reducing actuator wear.

Despite these advancements, the application of adaptive terminal sliding mode control (ATSMC) for space-based observation satellites, mainly using single gimbal Variable Speed Control Moment Gyroscopes (VSCMG), still needs to be explored. The adaptive nature of ATSMC could offer enhanced pointing accuracy and robustness against disturbances and uncertainties, which is critical for observation missions. This unexplored avenue is particularly pertinent given the successful implementations of various control architectures for multi-spacecraft systems. For instance, Haibo Dua and Shihua Li [3] employed a distributed control approach that enhances robustness against communication delays and failures. At the same time, Horri and Palmer [4] developed singular controllers for underactuated systems, effectively managing external disturbances.

Incorporating these advanced control techniques into the ADCS of space-based observation satellites could further optimise their performance. The literature on decentralised adaptive sliding mode control, such as the work by Baolin Wu et al. [5]. These methods ensure precise attitude control, which is crucial for maintaining the stringent pointing requirements of observation satellites. Furthermore, other studies, including those by Ti Chen and Hao Wen [6] and Zhanjie Zhou and Zhihao [7], have explored distributed attitude-tracking controllers and adaptive strategies under various constraints. Moreover, methods addressing specific challenges such as input saturation [8], and actuator faults [9] further demonstrate the breadth of ongoing research to improve spacecraft attitude control under diverse operational conditions. Each of these studies contributes to a more robust and adaptive framework for future spacecraft missions, underscoring the importance of innovation in control systems to meet the demands of increasingly complex space missions. While these approaches provide a robust foundation for ADCS in diverse mission scenarios, they have yet to be explicitly adapted to enhance the pointing accuracy of space-based observation satellites utilising ATSMC and VSCMG. Therefore, integrating the innovative control strategies from existing literature with the unique requirements of space-based observation missions represents an untapped research opportunity. This novel application could leverage the strengths of ATSMC to improve the precision and reliability of ADCS systems in challenging environments, maintaining the standard processes while adapting to the specific needs of high-accuracy observation missions.

Control Moment Gyroscopes (CMGs) are crucial actuators that generate continuous torque by transferring angular momentum between the CMG and the spacecraft body. This constant torque generation, achieved by manipulating a gimballed flywheel's angular momentum vector, allows for highly precise attitude adjustments. Unlike conventional gas jets, which operate in a binary fashion and consume fuel, CMGs offer the significant advantage of propellant-free operation, thereby extending the operational lifespan of spacecraft. This feature makes CMG particularly suitable for large-scale space structures like space stations. It has led to their integration into notable missions, including Skylab, MIR, and the International Space Station (ISS).

CMGs are available in two main types: single gimbal CMGs (SGCMGs) and double gimbal CMGs (DGCMGs). SGCMGs are preferred for their more straightforward mechanical design and "torque amplification property," which enables substantial output torque with minimal input from the gimbal motor. However, they are prone to singular gimbal states, which pose a challenge in specific operational scenarios. This research focuses on SGCMGs and their variant, the Variable Speed Control Moment Gyroscope (VSCMG), which introduces the capability for variable wheel speed. The VSCMG functions as a hybrid actuator, combining the characteristics of both reaction wheels and conventional CMGs and offers additional applications in energy storage and advanced attitude control strategies. The primary goal of CMG and VSCMG systems is to provide torque for spacecraft attitude control. While existing studies have explored various methods for attitude stabilisation using these devices, this research introduces a novel model-based control approach for tracking RSO trajectories.

Adaptive Terminal Sliding Mode Control (ATSMC) is a robust technique for enhancing spacecraft attitude control, especially considering external disturbances and high-accuracy pointing. ATSMC combines the advantages of adaptive control — robustness to disturbances — with terminal sliding mode control (TSMC), which ensures finite-time convergence to the desired state, thereby providing precise control over spacecraft orientation. The adaptive nature of ATSMC allows for real-time adjustments to the control parameters, effectively responding to variations in spacecraft inertia and other dynamic conditions. Incorporating ATSMC in control systems for spacecraft, particularly those utilising Single Gimbal Variable Speed Control Moment Gyroscopes (SGVSCMGs), allows for enhanced performance in trajectory tracking. ATSMC maintains stability and synchronisation even in the presence of nonlinearities and uncertainties. This capability is especially vital for missions requiring high precision in attitude control, such as space domain awareness (SDA) and fine pointing for space-based observational satellites.

2. DYNAMICS

The satellite is modelled as a rigid body with six degrees of freedom (6-DOF) dynamics, incorporating four Single Gimbal Variable Speed Control Moment Gyroscopes (SGVSCMGs) as actuators. The satellite's altitude is represented using Euler angles (ϕ (roll), θ (pitch), ψ (yaw)), which provide a singularity-free parameterisation for rotational kinematics. The satellite's nonlinear dynamics are derived from Lagrange's equations, formulated to capture the coupled translational and rotational motions within the spacecraft's inertial reference frame.

The kinetic energy T of the satellite is due to its rotational motion:

$$T = \frac{1}{2}\omega^T I\omega$$

Where $\omega = [\omega_x, \omega_y, \omega_z]^T$ is the angular velocity vector in the body-fixed frame. I is the satellite's moment of inertia matrix in the body-fixed frame, which is a diagonal matrix for a symmetric satellite.

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$$

The Lagrange equations of motion for each generalised coordinate (in this case, the Euler angles ϕ, θ, ψ) are:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i$$

Where, q_i are the generalised coordinates (ϕ, θ, ψ). Q_i are the generalised forces or moments acting on the system. For rotational motion, Q_i represents the external torques τ_ϕ, τ_θ, and τ_ψ. Applying Lagrange's equations to each of the Euler angles:

$$\frac{d}{dt}\left(I_{xx}\dot{\phi} + (I_{yy} - I_{zz})\dot{\theta}\dot{\psi}\cos\theta\right) = \tau_\phi$$

$$\frac{d}{dt}\left(I_{yy}\dot{\theta} + (I_{zz} - I_{xx})\dot{\phi}\dot{\psi}\right) + (I_{zz} - I_{xx} - I_{yy})\dot{\phi}^2\sin\theta\cos\theta = \tau_\theta$$

$$\frac{d}{dt}\left(I_{zz}\dot{\psi} + (I_{xx} - I_{yy})\dot{\phi}\dot{\theta}\cos\theta\right) = \tau_\psi$$

The following equations characterise the satellite's rotational dynamics about its principal axes. Due to their nonlinear and coupled nature, these equations are well-suited for numerical simulation and can be linearised when necessary for control design.

$$\frac{d}{dt}\left(I_{xx}\dot{\phi} + (I_{yy} - I_{zz})\dot{\theta}\dot{\psi}\cos\theta\right) = \tau_\phi \quad \frac{d}{dt}\left(I_{yy}\dot{\theta} + (I_{zz} - I_{xx})\dot{\phi}\dot{\psi}\right) + (I_{zz} - I_{xx} - I_{yy})\dot{\phi}^2\sin\theta\cos\theta$$

$$= \tau_\theta \quad \frac{d}{dt}\left(I_{zz}\dot{\psi} + (I_{xx} - I_{yy})\dot{\phi}\dot{\theta}\cos\theta\right)$$

$$= \tau_\psi$$

This Lagrangian-based formulation yields a comprehensive nonlinear model of the satellite's attitude dynamics, resulting in a set of nonlinear ordinary differential equations (ODEs). These ODEs govern the evolution of the satellite's attitude over time in response to the applied torques.

The equations of motion for SGVSCMG are derived by taking the time derivative of the total angular momentum given as,[10]

$$\begin{aligned}&\left(A_t[\dot{\gamma}]^d(I_{\mathrm{cs}} - I_{\mathrm{ct}})A_s^T + A_s[\dot{\gamma}]^d(I_{\mathrm{cs}} - I_{\mathrm{ct}})A_t^T\right)\boldsymbol{\omega} + J\dot{\boldsymbol{\omega}}\\ &\quad + A_g I_{\mathrm{cg}}\ddot{\boldsymbol{\gamma}} + A_t I_{\mathrm{ws}}[\boldsymbol{\Omega}]^d\dot{\boldsymbol{\gamma}} + A_s I_{\mathrm{ws}}\dot{\boldsymbol{\Omega}} + \left[\boldsymbol{\omega}^\times\right]\left(J\boldsymbol{\omega} + A_g I_{\mathrm{cg}}\dot{\gamma} + A_s I_{\mathrm{ws}}\boldsymbol{\Omega}\right) = 0\end{aligned}$$

Where,

$$A_g = A_{g0}$$

$$A_s = A_{s0}[\cos\gamma]^d + A_{t0}[\sin\gamma]^d$$

$$A_t = A_{t0}[\cos\gamma]^d - A_{s0}[\sin\gamma]^d$$

3. CONTROL

The spacecraft's control system employs an Adaptive Terminal Sliding Mode Controller (ATSMC) to accurately manage the spacecraft's attitude, a critical aspect of successful space missions. This controller continually adapts its output to minimise the variance between the desired and actual attitudes, ensuring robust performance and rapid convergence. Control commands are transmitted to the Single-Gimbal Variable-Speed Control Moment Gyroscope (SGVSCMG) actuator. The combined effect of disturbance torques and external forces on the spacecraft is calculated alongside the control torques to determine the total torque acting on the spacecraft. The spacecraft's dynamics depict how its orientation changes in response to the applied torques. This system is depicted in Fig.1. These changes are fed back into the ATSMC. The sliding surface s_i for each angle is defined to achieve finite-time convergence:

$$s_i = \dot{e}_i + c_i e_i^{\alpha_i}$$

where s_i is the sliding surface for each Euler angle (e.g., s_ϕ, s_θ, s_ψ), $c_i > 0$ are positive constants that define the sliding surface, $0 < \alpha_i < 1$ and is the fractional power that ensures finite-time convergence. The control law aims to drive the sliding surface s_i to zero, providing the tracking error e_i converges to zero in a finite time.

The control input τ_i for each axis (e.g., τ_ϕ, τ_θ, τ_ψ) is designed as:

$$\tau_i = \tau_{eq,i} + \tau_{n,i}$$

Where, $\tau_{eq,i}$ is the equivalent control input derived from the dynamics to maintain the sliding surface. $\tau_{n,i}$ is the nonlinear switching term that enforces the sliding condition. For each axis, the equivalent control is given as,

$$\tau_{eq,i} = \frac{d}{dt}\left(I_i \dot{e}_i + (I_j - I_k)\dot{e}_j \dot{e}_k cos(e_\theta)\right)$$

This control input is designed to maintain the dynamics on the sliding surface, assuming ideal conditions without perturbations or uncertainties. A switching term is incorporated into the control law to ensure the system remains constrained to the sliding surface in the presence of disturbances or model uncertainties.

$$\tau_{n,i} = - k_i sign(s_i)|s_i|^{\beta_i}$$

Where, $k_i > 0$ is the gain associated with the sliding mode control. $0 < \beta_i < 1$ is a constant that ensures finite-time convergence. The complete control law for each axis becomes:

$$\tau_i = \frac{d}{dt}\left(I_i \dot{e}_i + (I_j - I_k)\dot{e}_j \dot{e}_k cos(e_\theta)\right) - k_i sign(s_i)|s_i|^{\beta_i}$$

The stability of Terminal Sliding Mode Control (TSMC) can be assessed using the Lyapunov theory. To facilitate this analysis, consider the Lyapunov function candidate for the system:

$$V_i = \frac{1}{2} s_i^2$$

Taking the time derivative:

$$\dot{V}_i = s_i \dot{s}_i$$

Substitute the expression for $\dot{s}_i$:

$$\dot{V}_i = s_i\left(\frac{d}{dt}\dot{e}_i + c_i \alpha_i e_i^{\alpha_i - 1} \dot{e}_i\right) + s_i\left(- k_i sign(s_i)|s_i|^{\beta_i}\right)$$

If the control gains k_i are chosen large enough, the first term will dominate, ensuring $\dot{V}_i < 0$ stability and convergence of s_i zero.

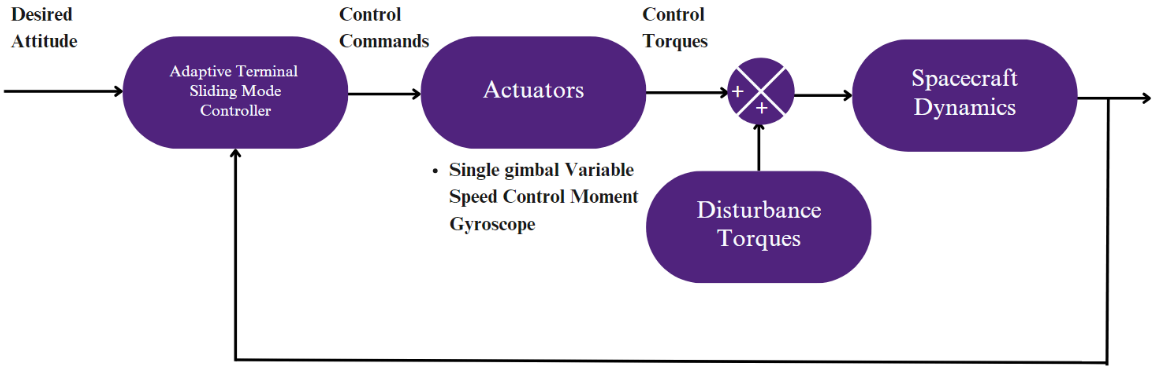


Fig. 1 Control System Architecture for Satellite

4. RESULTS AND DISCUSSIONS

To assess the performance of the ATSMC system in conjunction with an SGVSCMG, a testing scenario was developed, depicted in Figure 1. In this scenario, a space-based observational satellite must track a Resident Space Object (RSO) located just beyond its initial orientation. At the beginning of the simulation, the satellite and the RSO are in close proximity, separated by a distance of about 100 km, as illustrated in Figure 1. The RSO is positioned at the reference quaternion of [0, 0, 0, 1] in the satellite's body frame, indicating no initial rotation relative to the satellite's coordinate system.

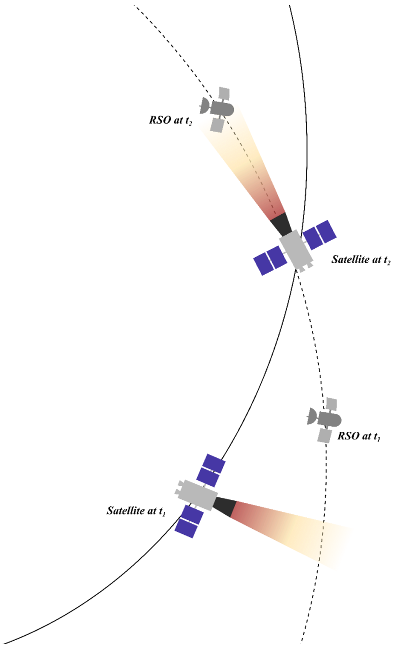


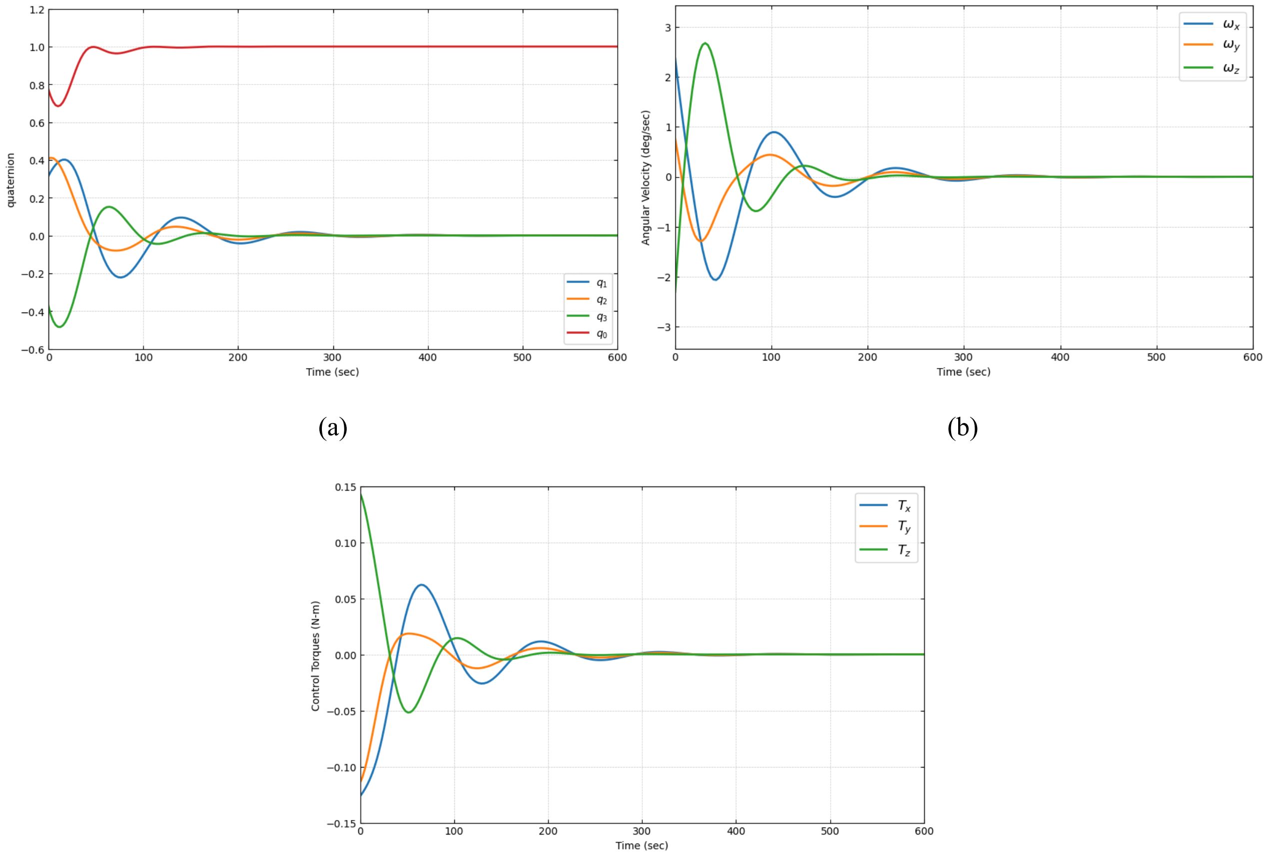
Fig.2 Testing scenario where satellite performs attitude manoeuvre to track RSO.

The satellite's initial attitude, represented in quaternion form, deviates from this reference and necessitates an attitude manoeuvre to align the satellite's sensors with the RSO's position. The pointing vector required for realignment is generated by calculating the relative vector from the satellite to the RSO in the satellite's body frame, which determines the direction the satellite must face to keep the RSO within its sensor's field of view. Table 1 presents the initial quaternion values, highlighting the satellite's starting orientation that requires correction. The objective of the manoeuvre is to adjust the satellite's orientation to achieve precise alignment with the RSO, thereby ensuring continuous observation as the object progresses along its orbit. As depicted in Figures 1-4, the outcomes highlight the system's capability to meet and sustain the necessary accuracy for RSO tracking.

Table 1. Initial attitude of satellite in Quaternions

Quaternion Component	**Value**
q_0	0.8325
q_1	0.3147
q_2	0.4058
q_3	0.3730

In Figure 3a, we can observe the evolution of quaternions over time. The quaternion components representing the satellite's orientation converge to near-zero values within approximately 500 seconds while the satellite stabilises at unity. This convergence indicates that the satellite successfully aligns itself with the desired attitude for RSO tracking. The initial oscillations observed in the first 200 seconds reflect the controller's proactive corrective actions to orient the satellite, followed by precise adjustments to maintain the desired attitude.



(a) (b)

(c)

Fig. 3 (a) Satellite quaternion evolution over time, (b) Angular velocity of the satellite, (c) Control torque provided by SGVSCMG.

The angular velocity components (ωx, ωy, ωz) depicted in Figure 3b showcase the satellite's rotational stabilisation. Initially, the peaks reach nearly ±3 deg/sec and then gradually taper off, with all components stabilising to approximately zero by 400 seconds. This behaviour highlights ATSMC's ability to stop unwanted rotations and uphold a steady pointing direction, which is essential for continuous RSO observation. The graph in Figure 3c illustrates the control torques (Tx, Ty, Tz) exerted by the SGVSCMGs. Initially, high-magnitude torques reach around ±0.15 N·m, related to the rapid reorientation phase. As the satellite nears the desired attitude, the control inputs decrease significantly, necessitating only minor adjustments after 300 seconds. This efficient control effort minimises energy consumption and reduces wear on the actuators, which is crucial for prolonged mission durations.

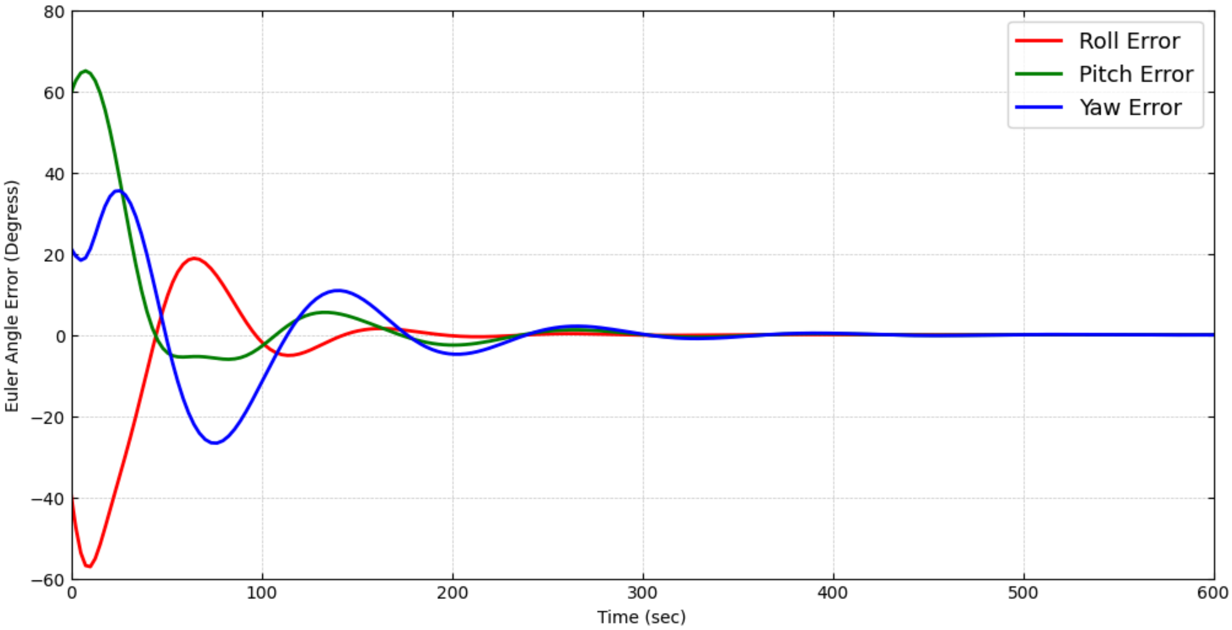


Fig. 4 Satellite attitude error evolution is represented in Euler angles from initial to desired state.

The Euler angle errors in Figure 4 demonstrate the ATSMC's ability to minimise attitude deviations. Initially, pitch errors of up to 65 degrees and roll errors of -60 degrees are effectively reduced. Within 500 seconds, all three angle errors (roll, pitch, yaw) converge to within ±0.01 degree of the target orientation. This high precision is maintained throughout the simulation, showcasing the controller's robustness in handling potential disturbances and model uncertainties. With a pointing accuracy of 0.01 degrees, this control scheme, combined with SGVSCMG, meets the required specifications for RSO tracking.

5. CONCLUSION

The ATSMC algorithm has showcased its ability to accurately track Resident Space Objects (RSOs) in satellite missions. Key performance metrics indicate that the system consistently achieves and maintains the desired attitude within a settling time of 300-400 seconds, which is suitable for most Low Earth Orbit (LEO) observation scenarios. The steady-state accuracy, evidenced by Euler angle errors remaining below 0.01 degrees post-convergence, meets the stringent requirements for space-based optical payloads. Additionally, the control efficiency is demonstrated by the smooth reduction of control torques, indicating an optimal balance between rapid manoeuvrability and long-term stability facilitated by the SGVSCMGs. The robustness of the controller is highlighted by its ability to handle significant initial attitude errors and maintain precision in the presence of potential disturbances, showcasing its adaptability to real-world space environments. These findings confirm the effectiveness of the ATSMC approach for high-precision attitude control in satellite RSO tracking missions, suggesting that the controller can consistently keep the RSO within the satellite's sensor field of view, enabling continuous observation and data collection.

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