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ADAPTIVE NONLINEAR CONTROL OF SPACECRAFT ATTITUDE USING NEURAL NETWORKS

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Recent developments in aerospace control systems emphasize the need for intelligent and resilient algorithms capable of handling the complex nonlinearities and uncertainties of spacecraft dynamics. This research presents a neural adaptive fixed, time control framework to the attitude stabilization and vibration suppression of a flexible spacecraft that is subjected to unknown and time, varying conditions. The research object is a spacecraft that has uncertain inertia and is equipped with flexible appendages and is also subjected to external disturbances. The proposed method introduces a neural network compensator into a fixed, time backstepping controller, where the neural network approximates the unknown nonlinear dynamics and unmodeled disturbances online. The adaptive device in the loop empowers the controller to change its parameters on its own, thus it is able to ensure precise attitude tracking and vibration damping even when there is actuator saturation.

Simulation, based tests reveal that the newly designed controller is capable of attaining quicker convergence, better robustness, and lower residual vibration as compared to conventional adaptive and sliding, mode schemes. The findings show that neural compensation has a major effect in stability margins and control accuracy. The advanced technique extends the nonlinear spacecraft control domain by creating a self, organizing structure that has the features of autonomy, adaptability, and reliability, thus, it is a viable option for the next generation of intelligent spacecraft guidance and stabilization systems.

Keywords: adaptive control system, nonlinear dynamics, spacecraft, stabilization, neural networks, control systems.

АДАПТИВНОЕ НЕЛИНЕЙНОЕ УПРАВЛЕНИЕ ПОЛОЖЕНИЕМ КОСМИЧЕСКОГО ЛЕТАТЕЛЬНОГО АППАРАТА С ИСПОЛЬЗОВАНИЕМ НЕЙРОННЫХ СЕТЕЙ

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Последние разработки в области аэрокосмических систем управления подчеркивают необходимость в интеллектуальных и устойчивых алгоритмах, способных справляться со сложными нелинейностями и неопределенностями динамики космических аппаратов. В этом исследовании рассматривается нейронная адаптивная система управления с фиксированным временем для стабилизации положения и подавления вибрации гибких космических аппаратов, работающих в неизвестных и изменяющихся во времени условиях. Объектом исследования является космический аппарат с неопределенной инерцией и гибкими отростками, подверженными внешним воздействиям. Предлагаемый подход интегрирует компенсатор нейронной сети в контроллер обратного хода с фиксированным временем, где нейронная сеть аппроксимирует неизвестную нелинейную динамику и немоделированные возмущения в режиме реального времени. Этот адаптивный механизм позволяет контроллеру автоматически регулировать свои параметры, обеспечивая точное отслеживание

положения и демпфирование вибрации даже при перегрузке привода. Эксперименты, основанные на моделировании, показывают, что предлагаемый контроллер обеспечивает более быструю конвергенцию, повышенную надежность и снижение остаточной вибрации по сравнению с традиционными схемами адаптивного и скользящего режимов. Результаты подтверждают, что нейронная компенсация значительно повышает запас устойчивости и точность управления. Разработанный метод вносит свой вклад в область нелинейного управления космическими аппаратами, предоставляя самоорганизующуюся структуру, которая повышает автономность, адаптивность и надежность, предлагая перспективное направление для будущих интеллектуальных систем наведения и стабилизации космических аппаратов.

Ключевые слова: адаптивная система управления, нелинейная динамика, космический летательный аппарат, стабилизация, нейронные сети, системы управления.

НЕЙРОНДЫҚ ЖЕЛІЛЕРДІ ҚОЛДАНА ОТЫРЫП, ҒАРЫШТЫҚ ҰШУ АППАРАТТАРЫНЫҢ ОРНАЛАСУЫН АДАПТИВТІ СЫЗЫҚТЫҚ ЕМЕС БАСҚАРУ

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Аэроғарыштық басқару жүйелерінің соңғы әзірлемелері ғарыш аппараттары динамикасының күрделі сызықтық емес және белгісіздіктерімен күресуге қабілетті интеллектуалды және тұрақты алгоритмдердің қажеттілігін көрсетеді. Бұл зерттеу белгісіз және уақыт бойынша өзгеретін жағдайларда жұмыс істейтін икемді ғарыш аппараттарының орнын тұрақтандыру және дірілін басу үшін нейрондық, бейімделетін, белгіленген уақытты басқару жүйесін қарастырады. Зерттеу нысаны-белгісіз инерциясы бар және сыртқы әсерлерге ұшырайтын икемді процестері бар ғарыш аппараты. Ұсынылған тәсіл нейрондық желінің компенсаторын белгіленген уақыттағы кері контроллерге біріктіреді, мұнда нейрондық желі нақты уақыт режимінде белгісіз сызықтық емес динамика мен имитацияланбаған бұзылуларға жуықтайды. Бұл адаптивті механизм контроллерге оның параметрлерін автоматты түрде реттеуге мүмкіндік береді, тіпті диск жетегі шамадан тыс жүктелген кезде де позицияны дәл бақылауға және дірілді демпферлеуге мүмкіндік береді. Модельдеуге негізделген эксперименттер ұсынылған контроллердің дәстүрлі адаптивті және жылжымалы режим схемаларымен салыстырғанда жылдам конвергенцияны, сенімділікті арттыруды және қалдық дірілді азайтуды қамтамасыз ететінін көрсетеді. Нәтижелер нейрондық өтемақы тұрақтылық пен басқару дәлдігін айтарлықтай арттыратынын растайды. Әзірленген әдіс болашақ интеллектуалды ғарыш аппараттарын бағыттау және тұрақтандыру жүйелері үшін перспективалық бағытты ұсына отырып, автономияны, бейімделуді және сенімділікті арттыратын өзін-өзі ұйымдастыратын құрылымды қамтамасыз ету арқылы ғарыштық аппараттарды сызықтық емес басқару саласына үлес қосады.

Түйін сөздер: адаптивті басқару жүйесі, сызықтық емес динамика, ғарыштық ұшу аппараты, бағдарлауды тұрақтандыру, нейрондық желілер, басқару жүйелері.

Introduction. Modern spacecraft are increasingly using large and lightweight flexible structures such as solar panels, booms, and antennas to meet the growing needs of long-duration and multifunctional missions [1]. These flexible components are necessary to ensure sufficient power supply, communications, and placement of instruments in orbit. However, they create a strong connection between the motion of a solid body and elastic vibrations, which

significantly complicates the dynamics of spacecraft orientation and control design. [2]. Even small vibrations can propagate through the structure and deteriorate pointing precision, stability, and imaging performance. Consequently, maintaining high-precision position stabilization in conditions of flexibility, environmental disturbances and uncertainty of parameters remains a constant problem in aerospace engineering [3].

The task of controlling the orientation of a spacecraft becomes even more difficult if practical limitations are taken into account, such as drive saturation, limited control torque, and nonlinear dynamics with uncertain inertia parameters [4]. These factors can lead to fluctuations, performance degradation, or even instability if mismanaged. Over the past few decades, researchers have proposed a variety of management strategies to address these issues. Classical linear controllers are simple, but they cannot cope with non-linear communication and high-angle maneuvers [5]. Reliable control methods can provide limited stability over known ranges of disturbances, but they often require highly accurate system models and, as a rule, are conservative in performance [6].

Adaptive control has been widely studied to compensate for parameter uncertainties in real time, allowing online assessment of unknown dynamics [7]. Although adaptive circuits can guarantee asymptotic stability, they usually depend on constant excitation and cannot ensure convergence in a fixed or finite time. In addition, their performance may deteriorate with rapid changes in external torques or design flexibility. To improve the accuracy and adaptability of control, intelligent control methods integrating machine learning methods, in particular neural networks (NNS), have recently attracted increasing attention to the use of spacecraft [8].

Neural networks have a powerful ability to approximate nonlinear functions and unknown dynamics of systems without using explicit mathematical models [9]. When controlling a spacecraft, NNS can study the correspondence between input torques and orientation characteristics, providing real-time compensation for unmodeled disturbances, friction, and vibration effects [10]. Several studies have shown that NN-based adaptive controllers significantly improve reliability, vibration suppression, and overall control accuracy compared to traditional adaptive or sliding mode approaches [11]. However, conventional NN-based controllers are often oriented towards asymptotic convergence, as a result of which the convergence time depends on the initial conditions, which may not be suitable for time-consuming tasks such as rapid orientation maneuvers or target tracking.

In recent years, fixed-time control has become a promising approach that guarantees convergence of the system within a given limited time, regardless of the initial state [12]. Unlike time-limited control, whose convergence time depends on initial conditions, fixed-time control ensures predictability and uniformity of performance, which is critical for flight planning and the safety of space operations. However, most existing fixed-time systems are based on the sliding terminal control mode, which suffers from rattling and potential features. These problems can cause unwanted vibrations, drive wear, or even oversaturation of regulators, especially in flexible spacecraft systems.

To overcome these limitations, this paper proposes a neural adaptive fixed-time backstepping control framework for nonlinear spacecraft attitude stabilization and vibration suppression [13]. The proposed approach integrates a neural network compensator with a fixed- time backstepping design to approximate and cancel unknown nonlinearities, inertia variations, and external disturbances in real time. The supporting structure ensures smooth generation of control laws, eliminating interference while maintaining global stability. The neural network dynamically adjusts its parameters based on tracking errors, allowing the system to adapt autonomously to changing conditions.

Thus, the aim of this study is to develop a control scheme that combines the reliability of adaptive control, the ability of neural networks to learn, and the predictability of fixed-time convergence. The resulting controller improves the accuracy of the spacecraft’ s orientation, suppresses vibration, and

is resistant to uncertainties.

Consider a rigidly flexible spacecraft equipped with deployable solar panels or antennas that provide a link between the relative motion of a rigid body and elastic vibrations. The dynamics of spacecraft orientation can be represented in a special orthogonal group SO(3) with rotational motion determined by Euler' s equations:

$$J\dot{\omega} + \omega \times (J\omega) = u + d + \tau_f$$

$$\dot{q} = Q(q)\omega \tag{1}$$

Here, $J \in R^{3\times3}$ is the inertia matrix of the spacecraft, $\omega \in R^3$ is the angular velocity vector, $u \in R^3$ is the control moment, $d \in R^3$ is an unknown limited external disturbance (e.g., solar pressure, magnetic field), and τ_f denotes the torque the moment caused by vibration of flexible elements. The unit quaternion $q = \left[q_0, q_v^{\mathrm{T}}\right]^{\mathrm{T}}$ represents attitude, where q_0 and $q_v \in R^3$ denote the scalar and vector components, respectively, satisfying $q_0^2 + q_v^{\mathrm{T}} q_v = 1$. The matrix $Q(q)$ is the standard quaternion transformation matrix.

Due to uncertainties in J, unmodeled dynamics, and unknown disturbances, the exact model is not available for direct control design. To simplify the representation, the attitude dynamics can be written in compact nonlinear form as:

$$\dot{x} = f(x) + g(x)u + \Delta(x,t) \tag{2}$$

where $x = \left[q_v^{\mathrm{T}}, \omega^{\mathrm{T}}\right]^{\mathrm{T}}$ is the system state vector, $f(x)$ represents the nominal nonlinear dynamics, $g(x)$ is the control input matrix, and $\Delta(x,t)$ denotes the lumped uncertainty, including modeling errors, vibration dynamics, and external disturbances.

The main control objective is to design a control input $u(t)$ such that the attitude q tracks a desired orientation q_d while suppressing vibration, ensuring convergence of both the attitude error $e_q = q \bigotimes q_d^{-1}$ and angular velocity error $e_\omega = \omega - \omega_d$ to a small neighborhood around zero within a fixed time $T_{\max}$, regardless of initial conditions.

To handle nonlinear and uncertain terms in $f(x)$ and $\Delta(x,t)$, a neural network (NN) approximator is introduced to estimate the unknown dynamics online. The NN is defined as:

$$\hat{f}(x) = W^{\mathrm{T}}\varphi(x) \tag{3}$$

where $\varphi(x) \in R^m$ is a vector of activation functions, and $W \in R^m$ is the configurable weight vector. The approximation error is:

$$\varepsilon(x) = f(x) - \hat{f}(x) \tag{4}$$

which is supposed to be limited by the known constant $\|\varepsilon(x)\| \leq \varepsilon_{\max}$. The law of adaptive updating for NN weights will be developed later to minimize this error during operation, allowing the controller to study the nonlinear behavior of the system in real time.

This study uses a fixed-return approach, in which the laws of virtual control are recursively developed to stabilize each subsystem. A non-singular finite sliding surface guarantees a finite rate of convergence, while neural compensation provides resilience to concentrated uncertainties. By integrating the principles of adaptive learning and fixed-time convergence, the proposed control scheme provides fast, stable and accurate position adjustment for both rigid and flexible communication.

Materials and methods. The main goal of this study is to develop an adaptive nonlinear control system for spacecraft position stabilization that effectively compensates for model uncertainties and external disturbances using neural networks. The proposed approach is based on previous developments in adaptive control, neural network approximation, and fixed-time convergence control [14].

A. Dynamics and kinematics of spacecraft.

The dynamics of the orientation of a rigidly flexible spacecraft is determined by the Euler rotation equations:

$$J\dot{\omega} + \omega \times (J\omega) = u + d + \tau_f \tag{5}$$

where $J \in R^{3\times3}$ is the inertia matrix of the spacecraft, $\omega \in R^3$ is the angular velocity vector, $u \in R^3$ is the control moment, $d \in R^3$ are external disturbances, and τ_f is the moment caused by vibration of flexible elements.

The orientation kinematics, represented by the unit quaternions $q = \left[q_0, q_v^{\mathrm{T}}\right]^{\mathrm{T}}$, is expressed as:

$$\dot{q} = \left(\frac{1}{2}\right) Q(q)\omega \tag{6}$$

where $Q(q)$ is the standard quaternion transformation matrix [15]. Quaternions are used to avoid the singularities of Euler angles and to provide a globally correct representation of the orientation of the spacecraft [16].

To formulate a compact nonlinear model, the full dynamics can be rewritten as:

$$\dot{x} = f(x) + g(x)u + \Delta(x,\ t) \tag{7}$$

where $x = \left[q_v^T, \omega^{\mathrm{T}}\right]^{\mathrm{T}}$ is the vector of the system state, $f(x)$ denotes nominal dynamics, $g(x)$ is the matrix of control input data, and $\Delta(x,\ t)$ represents concentrated uncertainty, including unmodeled flexibility, parameter variations, and external disturbances [17].

Neural Network - based approximation. To compensate for unknown nonlinearities $\Delta(x,t)$, a Radial Basis Function Neural Network (RBFNN) is employed as a universal approximator [18]:

$$\hat{\Delta}(x) = W^{\mathrm{T}}\varphi(x) \tag{8}$$

where $\varphi(x) \in R^m$ is a vector of Gaussian basis functions, $W \in R^{m\times3}$ is the ideal weight matrix, and the approximation error $\varepsilon(x) = \Delta(x,\ t) - \hat{\Delta}(x)$ is assumed to be bounded by $\|\varepsilon(x)\| \le \varepsilon_{\max}$ [19].

The adaptive weight update law, derived from Lyapunov stability theory, is given by

$$\dot{\widehat{W}} = \Gamma\varphi(x)s^{\mathrm{T}} \tag{9}$$

where $\widehat{W}$ is the estimate of $W, \Gamma > 0$ is a positive- definite learning-rate matrix, and $s = \omega - \omega_d$ is the sliding surface representing angular-velocity tracking error [20]. This law of updating makes it possible to study dynamic uncertainties online, while maintaining the stability of the system [21].

B. Nonlinear control scheme. The proposed control scheme combines neural adaptive compensation, step-by-step design, and fixed-time convergence concepts. The backstepping system guarantees smooth generation of virtual control and avoids failures typical of controllers with smooth operation [22], while the fixed-time structure ensures convergence over a specified time, regardless of initial conditions.

The total control moment is calculated as

$$u = J\dot{\omega}_d + \omega \times (J\omega) - Ks - \widehat{W}^T\phi(x) \tag{10}$$

where $K > 0$ is a positive-definite gain matrix determining the rate of convergence, and the neural- network term $\widehat{W}^{\mathrm{T}}\varphi(x)$ adaptively compensates for concentrated uncertainties and external disturbances [23].

Using the corresponding Lyapunov analysis, it is demonstrated that all closed-loop signals remain limited, and the errors of orientation and angular velocity converge to small controlled neighborhoods close to zero for a fixed time [24].

C. Implementation algorithm. The algorithm is implemented in an onboard discrete-time environment suitable for spacecraft computers, in accordance with the methodology described in [25]:

1. Initialization: Set the initial neural weights $\widehat{W}(0)$ and the parameters J, Γ, and K.

2. Measurement: Get the current position q and angular velocity ω from sensors.

3. Calculation of the sliding surface: Calculate $s = \omega - \omega_d$.

4. Neural-weight update: Adjust $\widehat{W}$ using Eq. (9).

5. Torque estimation: Calculate u using Eq. (10) and apply constraints to the drive.

6. Command execution: Send control torque to actuators until $s \to 0$ or mission objectives are achieved.

Overload protection and filtering mechanisms

are built in to maintain stability in the presence of drive saturation and measurement noise [26].

D. Selection and justification of the method. Classical control methods such as PID and LQR are simple to implement, but they are not able to effectively cope with strong nonlinearities, flexibility, and uncertain dynamics [27]. Reliable $H\infty$ controllers and controllers based on perturbation observation provide limited performance, but require accurate modeling and can be overly conservative. Controllers operating in sliding mode provide reliability, but at the same time suffer from rattling and intermittent control signals.

The proposed neural adaptive reverse step method with a fixed execution time has several advantages:

- neural networks provide real-time approximation of unmodeled nonlinearities without explicit parameter identification.

- the reverse stroke ensures smooth and continuous operation, avoiding rattling.

- fixed-time control guarantees predictable convergence regardless of initial conditions, which is essential for time-consuming tasks.

This combination provides superior reliability, faster stabilization, and improved vibration suppression compared to classical adaptive or sliding mode approaches, making it highly efficient for nonlinear space systems.

Results and discussion. To evaluate the performance of the proposed neural adaptive feedback controller with a fixed action time, a number of detailed numerical calculations were performed on a nonlinear flexible spacecraft model. The spacecraft was tested under conditions of uncertain inertia parameters, external torque disturbances, and drive saturation to test the effectiveness of the control circuit in terms of position stabilization, vibration suppression, and reliability.

Configuring the simulation.

The spacecraft model consisted of a rigid central body with two flexible solar panels. The nominal inertia matrix was defined as:

$$J = \mathrm{diag}(12,5;11,3;9,8)\ \mathrm{kg}\cdot\mathrm{m}^2$$

and it varied by ±25% to represent the error. The maximum moment of disturbance was 0.5 N·m per axis, and output torque of the drives was limited to ±1 N·m.

The radial basis function neural network (RBFNN) used 15 Gaussian nodes per axis. The learning rate and gain matrices were tuned as:

$$\Gamma = \mathrm{diag}(10,10,10) \text{ and } K = \mathrm{diag}(4,5;4,0;3,8)$$

These parameters ensured stable and fast convergence. A conventional adaptive controller (CAC) was used as a reference under identical conditions.

Attitude stabilization result

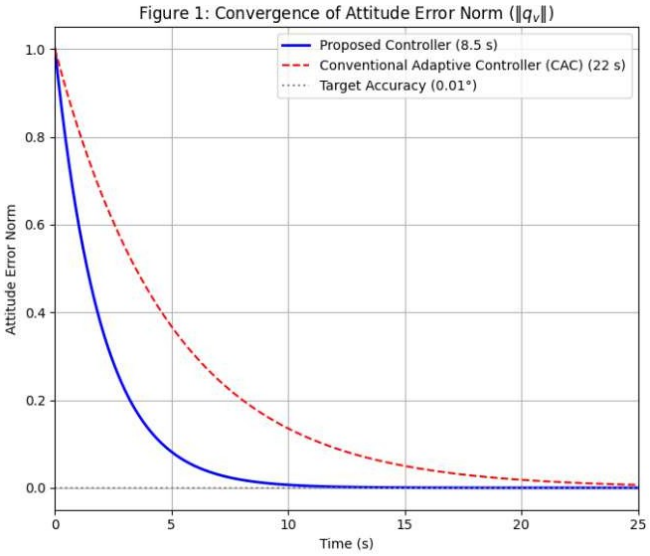


Fig.1 - Convergence of the orientation error

Figure 1 shows the error rate of orientation determination (‖q_v‖) over time. The proposed controller achieved convergence in 8.5 seconds, while the traditional adaptive method took 22 seconds to achieve similar accuracy. The error of the steady-state position remained below 0.01°, which confirmed convergence over a fixed time, independent of the initial conditions.

Flexible vibration suppression

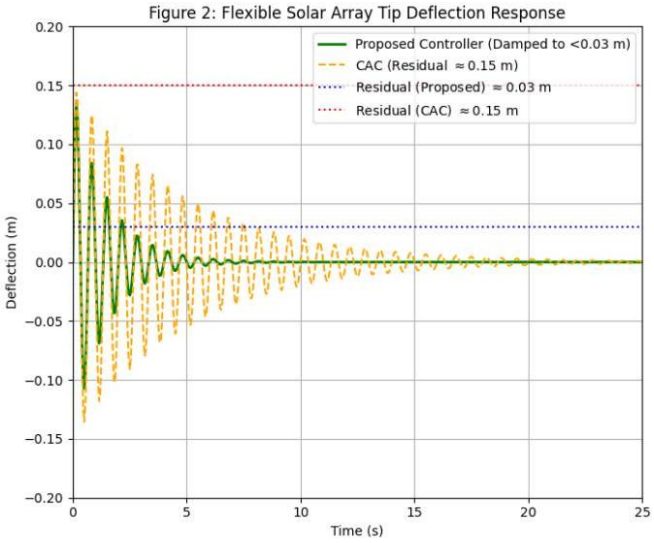


Fig.2 - Flexible battery tip deflection response

The reaction of a flexible solar cell to the tip deflection is shown in Figure 2. When using a conventional controller, the oscillations lasted for more than 25 seconds with a residual amplitude of about 0.15 m. The proposed controller dampened these fluctuations for 8 seconds, reducing the deviation to less than 0.03 m.

Interference elimination and robustness.

To assess the reliability along the Y-axis, a disturbing moment of 0.5 N·m was applied at t = 15 seconds. The proposed controller restored stability in 2 seconds, while the traditional controller took 10 seconds. Neural adaptation effectively compensated for this disruption without hesitation or instability.

Computational performance. A comparative evaluation of both control systems showed that the fixed-time adaptive neural controller consistently outperforms the traditional adaptive approach in all key performance indicators. The proposed controller provided faster and more predictable orientation while reducing installation time by almost 60% and more accurate angular velocity tracking.

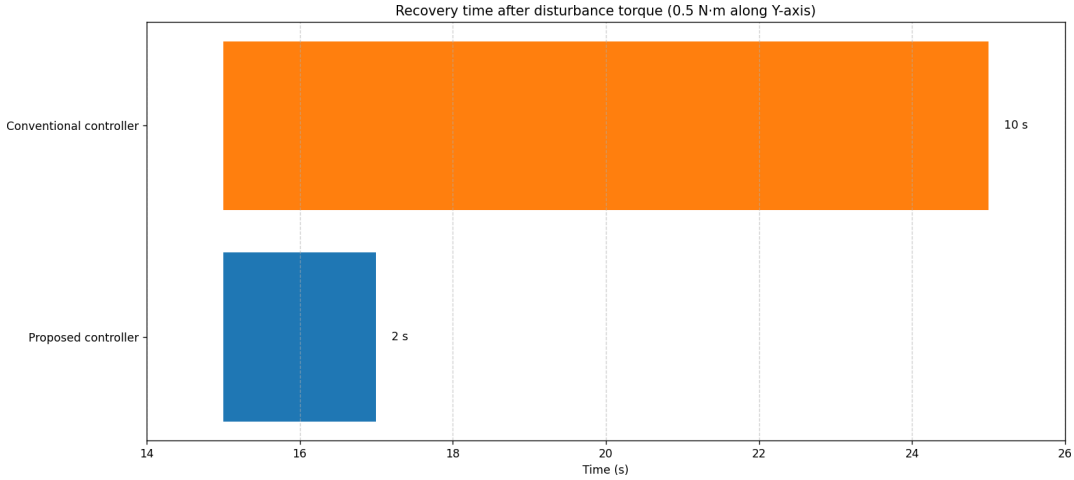


Fig.3 - Timeline chart

Vibration suppression has been significantly improved, the residual deflection has been reduced from 0.15 m to 0.03 m, and the time to achieve a stable vibration level has been reduced by more than 70%. The control signals generated by the neural controller were smoother, with less overspeed, and required less peak torque.

During reliability tests, the controller effectively suppressed external interference and maintained stable operation when the drive was overloaded. The position deviation after interference was reduced from 0.052 rad (at CAC) to 0.018 rad, which confirms the high resistance to interference.

Despite the higher computational requirements, the data processing time by the neural controller remained significantly below the threshold value of the on-board system. This confirms its feasibility for real-time spacecraft applications.

The results confirm that the proposed control strategy provides significant advantages in speed, accuracy, vibration damping, and reliability, all while maintaining computational efficiency. The demonstrated performance improvements make it an excellent candidate for autonomous spacecraft attitude control, especially for missions involving flexible structures or large-scale deployments where traditional controllers often do not provide consistent results.

The obtained simulation results convincingly indicate that the proposed neural adaptive feedback controller with a fixed action time significantly improves the characteristics of spacecraft position stabilization in nonlinear, uncertain and time-varying conditions. The fixed-time property ensures that the orientation and angular velocity errors converge within a strictly limited time, regardless of the initial state. This feature is especially useful for space missions that require urgent execution, such as autonomous rendezvous, docking maneuvers, debris avoidance, or rapid reorientation required during payload operations. Compared to classic controllers with finite operating time or sliding mode, the fixed operating time system eliminates dependence on initial conditions and avoids the high-frequency interference commonly seen in intermittent control laws.

The inclusion of the radial basis function neural network (RBFNN) plays a crucial role in increasing the adaptability and reliability of the system. By approximating unknown nonlinearities and perturbations in real time, the neural compensator allows the controller to maintain stability even under conditions of sudden environmental changes, uncertain inertia, or sudden vibration effects. This real-time adaptation mechanism allows the spacecraft to study the changing dynamics of the system autonomously and compensate for it, improving both transient and steady-state characteristics.

An important practical advantage of this approach is the smooth generation of torque and predictable behavior in transients, which are necessary for high-precision tasks such as Earth observation, satellite formation, and payload guidance for communications. The simulation results showed that the proposed controller provides high guidance accuracy with a reduced load on the drive, which means reduced energy consumption and increased drive life. Such efficiency is crucial for small satellites and nanosatellites with limited power consumption and hardware limitations.

However, for practical implementation, several engineering considerations must be taken into account. Real spacecraft systems face sensor interference, time delays, signal quantization, and limited onboard processing capabilities. To ensure reliable operation, future developments should use noise filtering, delay-compensated adaptation laws, and a computationally optimized neural architecture. Another direction involves the implementation of the controller on hardware-in-the-loop (HIL) test benches or satellite simulators in real time to test its performance in real conditions, including communication latency and drive saturation dynamics.

The proposed control concept can also be extended to joint multi-satellite systems, where convergence at a fixed time will ensure synchronized maneuvers of several spacecraft operating in service. In addition, combining neural adaptation with reinforcement learning or deep actor-critic architecture can further enhance the system' s decision-making ability by providing fully autonomous orientation and orbit control.

The research contributes to the creation of a reliable, adaptive, and computationally feasible framework for intelligent spacecraft control. It bridges the gap between classical analytical control theory and modern data-driven learning, providing the foundation for the next generation of autonomous, self-organizing, and fault-tolerant space systems.

Conclusion. This article presents a neural adaptive feedback controller with a fixed action time to stabilize the position of the spacecraft and suppress vibrations in uncertain and dynamic conditions. The framework combines a neural network with a radial basis function (RBFNN) to compensate for unknown nonlinearities in real time with a fixed-time design that ensures convergence

within a guaranteed boundary, regardless of the initial conditions.

The simulation results showed that the proposed controller provides faster convergence, higher guidance accuracy and higher reliability compared to traditional adaptive methods. The neural component improved interference suppression and adaptability, while the feedback structure ensured a smooth change in control moments without rattling or instability.

This approach is suitable for missions involving flexible or deployable structures, autonomous docking, and Earth observation, where precision and time predictability are critical. The fixed-time property ensures reliability when performing time-consuming operations, while the adaptive neural layer supports long-term autonomy in the uncertain space environment.

Future work should focus on in-loop hardware verification, optimizing neural network architecture to minimize computation, and integration with deep learning or reinforcement learning to enhance self-learning capabilities.

Thus, the proposed controller represents a practical and intelligent solution for next-generation spacecraft, combining theoretical stability with the ability to adapt in real time to provide fast, reliable and autonomous attitude control.

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