Review on Attitude Determination and Control Methods for Satellite Emergency Recovery

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Abstract: Once a satellite experiences extreme abnormal conditions, it may face serious consequences such as structural damages, material low-temperature failures, propellant freezing, and even whole satellite failures if it is not rescued in time. Therefore, it is significantly important to study emergency recovery technologies for satellites. The research progress on attitude determination and control technologies during satellite emergency recovery is reviewed in detail. Moreover, the research achievements in the design and implementation of satellite emergency modes are summarized. By synthesizing and analyzing relevant literature, this paper aims to provide reference and guidance for emergency recovery technologies in response to extremely abnormal satellite states.

Key words: satellite emergency recovery; attitude determination; attitude control

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0 Introduction

With the development of space technologies, satellites have been widely used in various fields, such as communication, navigation, meteorological observation, scientific research, and military defense. They have become the most frequently launched and the most numerous spacecraft in orbit among human space activities[1-2]. Since satellites operate in a complex space environment, on-orbit failures are inevitable[3-4]. Among them, the number of failures in the attitude determination and control system (ADCS) is increasing. The statistical analysis of on-orbit failures in 28 remote sensing satellites from September 1988 to October 2014 is shown in Table 1. The ADCS was responsible for 58 failures, accounting for nearly 40% of all incidents, with a failure rate of 2.07 occurrences per satellite. Satellite systems are highly valuable and difficult to repair. If failures are not promptly and effectively addressed, they may lead to serious consequences, affecting mission success and even causing the satellite to disintegrate[5-6]. Therefore, to address these challenges, fault-tolerant control and emergency mode are often designed to enhance the reliability and safety of satellites[7-8].

Table 1 Statistics of satellite on-orbit failures

Fault location	Number	Percentage/%
ADCS	58	37.2
Payload	32	20.5
Power	8	5.1
Data	24	15.4
Telemetry	26	16.7
Data management	7	4.5
Thermal control	1	0.6
Total	156	100

In the design of satellite ADCS, fault-tolerant control and emergency mode are two important strategies for addressing failures. Fault-tolerant control primarily focuses on potential failures during the design phase, ensuring that even if some components fail, the overall system can still maintain its

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basic functions, or safely complete control missions with slightly reduced but acceptable performance metrics[9-10]. However, when the satellite encounters severe unexpected failures, the existing fault-tolerant control strategies of the ADCS are no longer sufficient to save the satellite. In such cases, the emergency mode becomes the final safeguard to ensure the satellite safety. In this mode, the available actuator and sensor resources on the satellite are utilized to implement specific emergency measures to ensure power supply and maintain basic functions, thereby rescuing the failing satellite[11].

Satellites that experience severe failures usually exhibit the following characteristics: (1) The satellite is typically in a high-spin state, with fluctuating illumination conditions and unstable power supplies; (2) the satellite's telemetry and control conditions are intermittent. As a key component of the satellite power system, the solar array is essential for the satellite's survival and reliable operation[12-13]. Once the satellite enters the emergency mode due to anomalies, the primary mission is to adjust the satellite attitude so that the solar array remains safely oriented towards the sun, thereby ensuring the satellite power supply. Subsequently, the telemetry and command channels are established to provide the necessary conditions for fault diagnosis. Once the fault is resolved, the satellite's operational attitude is restored.

The emergency mode primarily involves two key components: Emergency attitude determination and control. The structural of the satellite ADCS system in emergency mode is shown in Fig.1. Emergency attitude determination utilizes limited sensor resources and specially designed attitude determination algorithms to quickly and accurately obtain real-time attitude information of the satellite, which forms the basis for subsequent emergency control and recovery operations. Emergency attitude control adjusts the satellite attitude based on the determined attitude and the remaining actuators, such as reaction wheels or magnetorquers, to ensure the satellite power supply and restore stable attitude control. Based on the background that the emergency mode needs to be designed to rescue satellites after severe anomalies occur, this paper investigates and discusses the relevant research on emergency attitude estimation and control for satellites both domestically and internationally. The structure of satellite emergency recovery methods is shown in Fig.2.

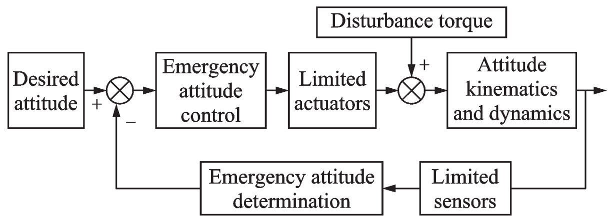

Fig.1 Structural of the satellite ADCS system in emergency mode

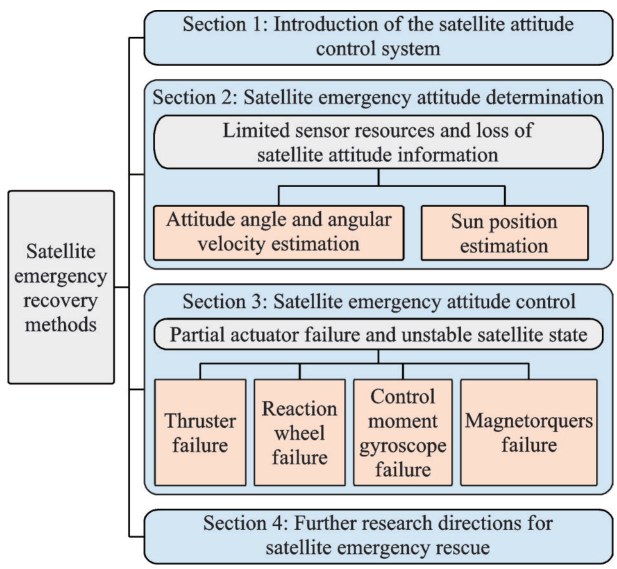

Fig.2 Structure of satellite emergency recovery methods

1 Satellite Attitude Control System

In the satellite emergency recovery processes, the specific recovery measures vary depending on the configuration of the satellite ADCS. With the continuous advancement of space technology and the improvement of product performance, the configuration of the satellite ADCS has also been upgraded. Satellites are equipped with sensors of varying performance specifications and actuators with different control capabilities according to the mission requirements. Figs.3—5 illustrate several typical satellite ADCS configurations.

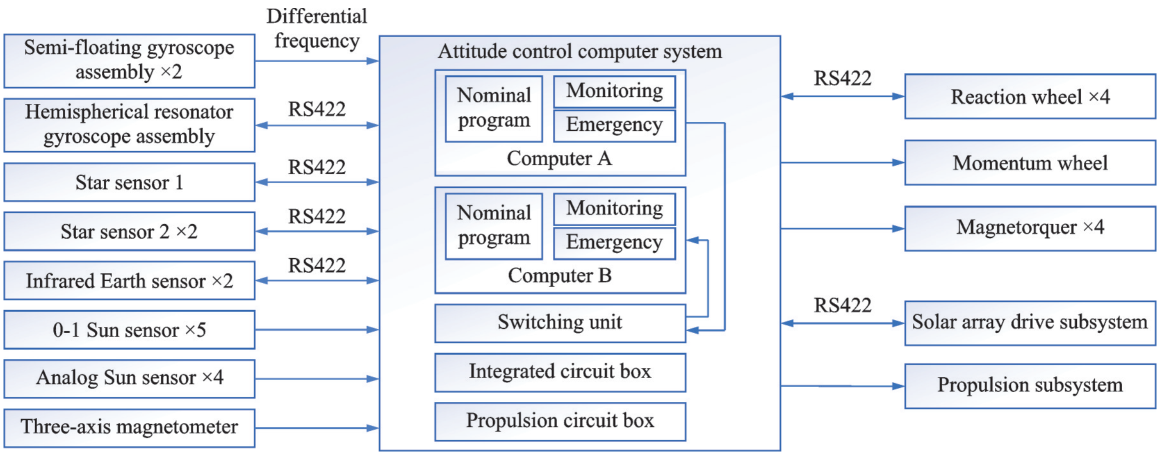

Fig.3 Composition of the Gaofen-5 Satellite ADCS

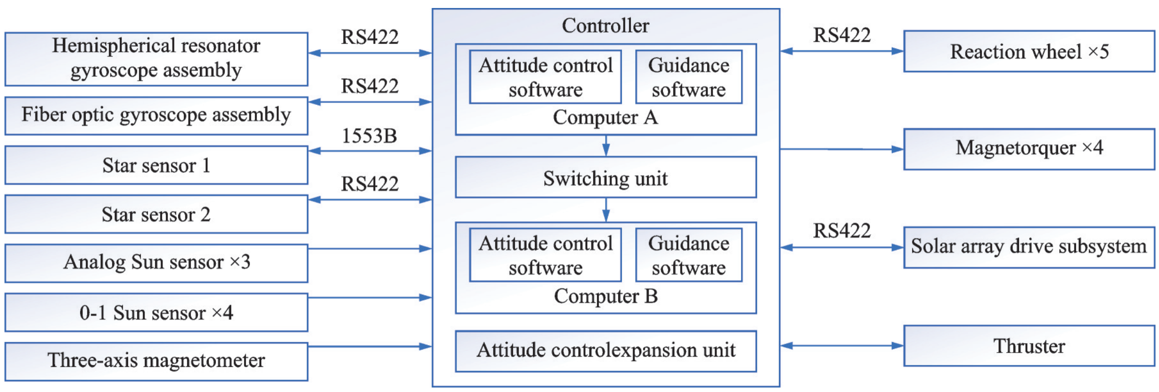

Fig.4 Composition of the Atmospheric Environment Monitoring Satellite ADCS

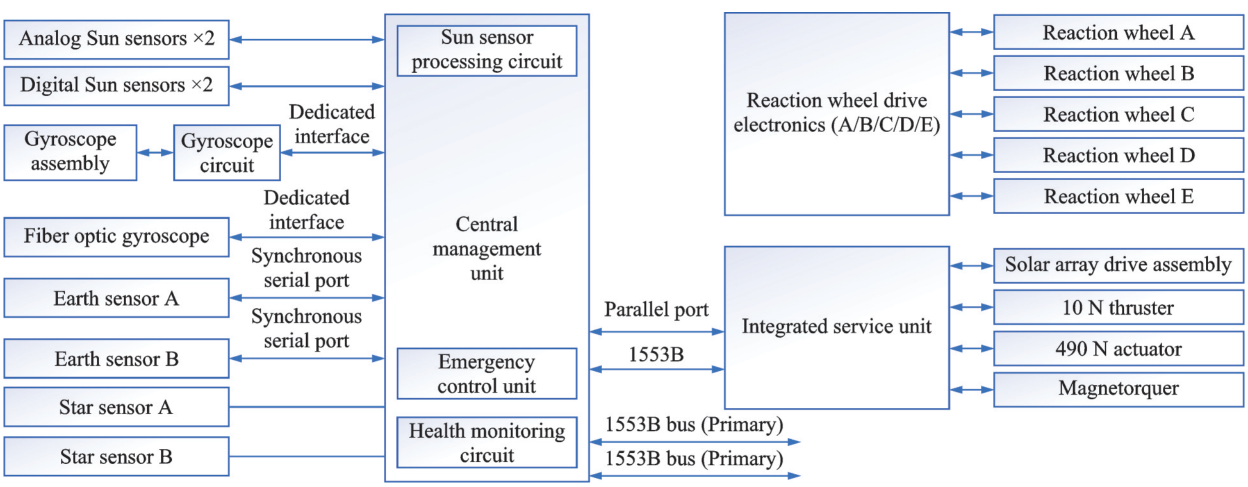

Fig.5 Composition of the Beidou-3 IGSO Satellite ADCS

The Gaofen-5 Satellite was successfully launched in May 2018. The satellite adopted the sun-synchronous retrograde orbit with a descending node local time of 13:30, an orbital altitude of 705 km, and an orbital inclination of 98.203°. The attitude sensors include star sensors, gyroscope assemblies (semi-liquid floating gyroscopes and fiber optic gyroscopes), Earth sensors (infrared horizon sensors), Sun sensors, and three-axis magnetometers. The actuators include flywheels (momentum wheels and reaction wheels), magnetorquers, solar array drive mechanism, and the propulsion subsystem. The controllers include the attitude and orbit control computer, integrated circuit box, and propulsion circuit box[14]. The composition of the Gaofen-5 Satellite ADCS is shown in Fig.3.

The Atmospheric Environment Monitoring Satellite was successfully launched in April 2022. The satellite is positioned in a Sun-synchronous retrograde orbit at an altitude of 705 km. The attitude sensors include star sensors, gyroscope assemblies (hemispherical resonator gyroscopes and fiber optic gyroscopes), Sun sensors (0-1 Sun sensors and analog Sun sensors), and three-axis magnetometer. The actuators include reaction wheels, magnetorquers, solar array drive mechanisms, and the propulsion system. The controllers include the attitude and orbit control computer and the attitude and orbit control expansion unit[15]. The composition of the Atmospheric Environment Monitoring Satellite ADCS is shown in Fig.4.

In April 2019, China launched its first Beidou-3 IGSO satellite. The attitude sensors include star sensors, gyroscope assemblies (gyro units and fiber optic gyroscopes), Sun sensors (analog and digital Sun sensors), and Earth sensors. The actuators include reaction wheels, solar array drive mechanisms, and the propulsion system. The controllers include the central control unit and the integrated service unit[16]. The composition of the Beidou-3 IGSO Satellite ADCS is shown in Fig.5.

2 Satellite Emergency Attitude Determination

During the satellite emergency recovery process, the most important control objective is to ensure that the solar array is accurately aligned with the Sun. Therefore, the satellite emergency attitude determination involves obtaining the Sun orientation relative to the satellite body, the satellite angular velocity, and the satellite pointing state. The commonly used sensors include gyroscopes, Earth sensors, star trackers, Sun sensors, and magnetometers. These devices allow for satellite attitude estimation through direct measurements or combined determination methods. However, when the satellite is in an emergency state with high-speed spin, it presents a series of challenges for attitude determination.

The drawback of gyroscopes is that their angular velocity measurement range is limited. When the measured angular velocity exceeds this range, the gyroscope can experience saturation, resulting in distorting of the output data. Since star sensors have weaker dynamic performance, they may struggle to quickly and accurately identify stars during rapid satellite maneuvers. Additionally, star sensors are susceptible to interference from factors such as Earth obstruction and sunlight. Due to field-of-view limitations, Earth sensors may fail to detect the Earth under certain situations, and thus cannot provide pointing information about the Earth. In view of the situation that the above-mentioned sensors cannot be used normally after the satellite enters the emergency mode, this section discusses how worldwide researchers determine the satellite attitude.

2.1 Attitude angle and angular velocity estimation

In general, the satellite attitude angle and angular velocity information are provided by star sensors and gyroscopes, respectively[17]. However, in emergency situations, only reliable vector sensors such as magnetometers and Sun sensors are available for use. In the case of severe shortage of attitude sensor measurement information, how to accurately obtain the satellite attitude information based on limited measurement information becomes an urgent challenge for satellite attitude anomalies.

In Ref.[11], Xu addressed the situation of the Fengyun-1B satellite losing control. The orientation of angular momentum H in inertial space was indirectly determined by the measurement information from the rolling infrared horizon sensor, which was used to calculate the angle between the angular momentum and the inertial coordinate system, thereby determining the attitude of the uncontrolled satellite. The rotational angular velocity of the uncontrolled satellite could be obtained through the variations in the output current of the solar array or the changes in signal strength received by ground control stations. When the rotational speed decreased, it could be directly measured using pitch gyroscopes. In Ref.[18], Peng et al. focused on the first Chinese Sun-synchronous orbit Earth observation remote sensing satellite, which entered a high-speed spin state due to an abnormal failure. The telemetry data from the satellite's solar array charging current and the azimuth information from the 0-1 type Sun sensor were used to determine the relationship between the solar vector and the plane of the solar array during one rotation cycle. The measurement data from the magnetometer was then used to establish the relationship between the directions of the geomagnetic field and the satellite magnetic field. Based on the geomagnetic vector and solar vector information, the cone intersection method[1] was used to determine the inertial direction of the rotation axis and the relationship between the spin axis and the solar position. Using over a month of data after the satellite failure, the rotation axis attitude of the satellite was successfully estimated by this method. In Ref.[19], Wang et al. proposed a method to estimate satellite attitude using only magnetometer measurement data, which was used to deal with the attitude anomaly problem when all attitude sensors except the magnetometer were ineffective. By establishing the geometric relationship between the magnetometer measurement vector and the satellite spin axis, the spin axis vector and spin angular velocity of the satellite in a spinning state were estimated. This identification method has been applied to attitude determination in the attitude anomaly and flip state of a certain meteorological satellite, yielding positive results and extending the satellite operational lifespan. In Ref.[20], Lei et al. proposed a method for determining satellite spin angular velocity based on measurements from Sun sensors, specifically for satellites experiencing on-orbit attitude anomalies. By analyzing the variation of the solar vector in the satellite body coordinate system during high-speed spin, the orientation and rotational speed of the satellite spin axis were calculated using the change in the solar vector sequence. Furthermore, the measurement accuracy of the spin angular velocity was analyzed by considering the measurement errors of the Sun sensor and its measurement principles. A strategy is provided to ensure the accuracy of determining different spin rates without altering the method of obtaining Sun sensor telemetry data.

In addition, many studies have been conducted on improving the accuracy and robustness of attitude estimation. Zhou et al.[21] studied a method that relied solely on magnetometer measurement data to obtain the satellite's three-axis attitude angles and angular velocity. By combining the Kalman filtering algorithm, the impact of measurement noise was reduced, and the estimation accuracy was improved. However, magnetometers could only instantaneously resolve the two-axis attitude of the spacecraft. Typically, magnetometers were used in combination with other sensors to fully resolve the three-axis attitude. In Ref.[22], Searcy et al. proposed a two-step extended Kalman filter to address this issue. In the first step, the magnetic field data was filtered to obtain the magnetic field derivative vector, which was then combined with the magnetic field vector in the second step to fully resolve the satellite three-axis attitude. The two-step extended Kalman filter method provided relatively accurate estimation and did not require the propagation of multiple state vectors or the additional states that would decrease covariance propagation efficiency. In Ref.[23], Li et al. proposed a method that combined three-axis magnetometer signals with solar array signals. Based on dual-vector attitude determination, the unscented Kalman filter estimation algorithm was used to achieve real-time continuous estimation of the three-axis attitude angles and angular velocity. Compared to the traditional extended Kalman filter estimation algorithm, the unscented Kalman filter algorithm made better use of the statistical characteristics of system noise, resulting in more accurate satellite attitude information. Considering that the inertial sensors are susceptible to performance degradation in the space environment, Chen et al.[24] proposed a scheme includes two-layer fault detection with isolation and two-layered recovery. The first layer of fault detection consisted of an adaptive unscented Kalman filter, the Quaternion estimator algorithm, and a residual generator, and the second layer of fault detection was composed of radial basis function neural networks and an adaptive complementary filter. These two layers were designed to isolate and identify faults while reducing false alarm rates. This scheme effectively addressed the problem of sensor outliers and provided higher accuracy. When one of the inertial sensors failed, the scheme could detect the fault and maintained high-precision attitude estimation through trained neural networks. Moreover, the secondary fault detection and isolation layer minimized false alarm rates, ensuring more reliable attitude information for satellites.

2.2 Sun position estimation

Before implementing Sun-pointing control on the satellite, it is necessary to determine the satellite's motion state, particularly the orientation of the solar array relative to the Sun and the satellite body. If this orientation is not correctly estimated, the normal direction of the solar array may deviate from the solar incident vector when adjusting the satellite attitude, which affects the illumination conditions of the solar array. If the battery cannot be normally used, the satellite abnormal state will spread further. A severe on-orbit anomaly occurs when the satellite battery power system fails before the solar array has established a stable power supply environment, which can suddenly cause the satellite to lose power and contact[25]. Under such circumstances, the satellite can only regain power when sunlight illuminates the solar array, allowing telemetry signals to be received again on the ground. Currently, solar arrays are typically driven by stepper motors, and the rotation angle is generally recorded using a step-counting method[26]. After the satellite power fails, it is impossible to determine the rotational angle of the solar array. Therefore, during the satellite emergency recovery process, it is necessary to determine the rotation angle of the solar array relative to the satellite body in order to achieve sun-pointing alignment of the solar array.

Regarding the issue of estimating the solar array's rotational angle, the simplest solution is to use a star sensor to determine the satellite attitude, and then combine the data from Sun sensors on the solar array to determine the orientation of the solar array relative to the satellite. However, star sensors cannot provide attitude information when the satellite is spinning at high speeds. In Ref.[27], He et al. proposed a method that used measurements from gyroscopes and Sun sensors to determine the solar array rotational angle. First, based on the transformation relationship between the satellite body frame and the solar array coordinate system, along with the kinematic equations of the satellite attitude, an analytical form for estimating the rotational angle of the solar array was derived. Second, given the low measurement accuracy of the Sun sensors, a Kalman filter based estimation method was proposed based on the analytical solution of the solar array rotation angle, which could suppress the influence of measurement noise and improve the accuracy of rotation angle estimation. In Ref.[28], He et al. also used measurements from gyroscopes and Sun sensors to determine the solar array rotational angle. First, based on the transformation relationship between the satellite body frame and the solar array coordinate system, as well as the rotation formula using Rodrigues parameters, an algorithm for indirectly measuring the solar array rotation angle was proposed. Second, considering the relatively low measurement accuracy of the Sun sensor, interval analysis techniques were used to provide interval-based rotation angle estimates and assess the impact of unknown noise. Based on the determined point measurements and interval analysis results, a zonotopic Kalman filtering method was further proposed to improve the accuracy of the measurements. This method only required simple mathematical operations and the Kalman filtering algorithm, resulting in low hardware requirements, low algorithm complexity, and easy applicability to engineering practice.

3 Satellite Emergency Attitude Control

3.1 Thruster failures

A thruster failure means that the satellite primary propulsion system cannot function properly or produce thrust under certain conditions. Such failures may occur due to a variety of reasons, including mechanical or electronic component faults in the propulsion system, fuel depletion, control system issues, effects of the space environment, power supply failures, and communication link interruptions. When a satellite experiences thruster failures, it loses the ability to adjust orbit, maintain positioning, or perform missions. Therefore, it is crucial to develop effective emergency control strategies to address thruster failure situations.

Xu[11] addressed the case of the Fengyun-1B meteorological satellite, which has lost control, leading to the depletion of onboard stored gas due to uncontrolled venting. Since the satellite had only three remaining star-mounted magnetorquers and a biased momentum wheel, a technical solution was designed to rescue the satellite by utilizing the external torques generated from the interaction between the Earth's magnetic field, the gravitational field, and the satellite magnetic moment and mass characteristics. In Ref.[18], Peng et al. addressed a situation where a remote sensing satellite experienced a failure, resulting in the depletion of fuel in the main storage tank and the exhaustion of the battery power, with the propulsion system's pipelines and tanks frozen due to the propellant freezing. At this point, the magnetorquer is the only available actuator during the satellite's recovery process. To reduce the overall load on the satellite, magnetic desaturation and magnetic precession control measures were implemented to enhance the power supply capability of the solar array, enabling continuous power supply to the satellite. Then, magnetic damping capture and magnetic control stabilization measures were adopted to maintain the satellite's motion state, thereby ensuring the power supply capability of the solar array. In Ref.[29], Li et al. proposed a safety control scheme based on magnetorquers and momentum wheels to address the satellite attitude control issue under the conditions of gyroscope and thruster failures. This scheme was capable of controlling the satellite Sun-pointing orientation under arbitrary initial attitude and initial angular velocity, with limited field of view from the Sun sensors, and utilized a control dead zone to eliminate the adverse effects of Earth's shadow. In Ref.[30], Li et al. derived a fault-tolerant control method based on the Lyapunov theory and genetic algorithms, which enabled the spacecraft to maintain attitude stability in the event of a thruster failure. In Ref.[31], Cai et al. conducted research on attitude fault-tolerant control of spacecraft equipped with thrusters as actuators. The uncertainty of the spacecraft moment of inertia was considered, and the upper bounds of all uncertainty factors affecting the spacecraft were estimated. The results showed that the adaptive control method could successfully complete the system designated tasks in the event of a thruster failure.

Patton et al.[32] proposed a robust fault detection and isolation scheme for the Mars Express Satellite system in response to thruster failure. This scheme took into account measurement errors, uncertainties, and disturbances. Additionally, by employing a combination of state estimation and unknown input decoupling methods, it achieved robust fault detection and isolation under dynamic uncertainties during the deployment of the main engine. In Ref.[33], Peng et al. proposed a novel reinforcement learning (RL) method to reorient the satellite antenna toward Earth and re-establish communication in scenarios where thrusters experienced sticking or minor explosions. In such emergencies, the RL controller learned through interaction with the environment and attempted to maximize returns based on a designed reward function. The results showed that the RL controller could develop a control strategy to maximize rewards, which in turn reoriented the antenna towards the Earth steadily or regularly, therefore at least an intermittent communication was possible.

3.2 Reaction wheel failures

Reaction wheels, commonly used as the main attitude control actuators for satellites, are prone to fail after a long-term operation. If these failures are not detected and addressed in a timely manner, it may lead to loss of satellite attitude control. To address attitude control issues in the event of reaction wheel failures, a hardware redundancy backup scheme is commonly adopted, such as the widely used 3+1 reaction wheel configuration, which can still complete the satellite three-axis attitude control mission in the event of a single reaction wheel failure. However, due to strict limitations on volume, power, and weight of spacecraft, reaction wheel failures cannot be simply addressed by adding more reaction wheels. To meet constraints on power consumption, mass, and cost, small satellite attitude control systems only implement hardware redundancy in a few critical components. Therefore, exploring effective attitude control methods in the event of reaction wheel failures has become an important topic in the design of modern small satellite attitude control systems. Currently, there are two main approaches for handling attitude control problems related to satellite reaction wheel failures: (1) Fault-tolerant control algorithms are designed to manage reaction wheel failures; (2) combined control using magnetorquers and the remaining reaction wheels, or solely using magnetorquers, is employed to address reaction wheel failures.

3.2.1 Fault-tolerant control for reaction wheel failures

Jin et al.[34] designed an attitude tracking fault-tolerant controller based on a time-delay method to address reaction wheel failure. Hu et al.[35] proposed a fault diagnosis method based on the Kernel Fuzzy C-Means algorithm for reaction wheel faults. Ma et al.[36] considered reaction wheel failures and designed a spacecraft attitude compensation controller using an adaptive control method. Cao et al.[37] proposed a fault-tolerant attitude control strategy based on the nonsingular terminal sliding mode control method, which could address the reaction wheel failure problem in small satellites. Jin et al.[38] established an accurate open-loop system model for the reaction wheel and designed a second-order nonlinear continuous extended state observer. This method treated the reaction wheel failure as an external disturbance and performed fault detection and recovery for the satellite reaction wheel system. Huo et al.[39] proposed an attitude stability control method for rigid body satellites based on the sliding mode control theory, which achieved fault-tolerant control for partial reaction wheel failures and compensatory control for mounting deviations. Zhang et al.[40] proposed a fault-tolerant attitude control method based on an iterative learning observer to address issues such as installation deviations, failures, and external disturbances of the reaction wheels on the satellite.

Baldi et al.[41] designed a fault diagnosis algorithm for satellite reaction wheel failures using a disturbance decoupling method. Based on the diagnostic information, the attitude controller was reconstructed through parameter adjustment to achieve high-precision stable attitude control. In Ref.[42], Petersen et al. proposed a method to restore the linear controllability of underactuated spacecraft by considering the effects of solar radiation pressure. This method established a solar radiation pressure torque model related to the spacecraft's attitude and provided the necessary and sufficient conditions for restoring linear controllability when the solar radiation pressure torque was included in the spacecraft's attitude model. Once linear controllability was restored, conventional controllers could be designed for the underactuated spacecraft. In Ref.[43], Kumar et al. studied two configuration structures of reaction wheel assemblies: The traditional four-wheel setup and the pyramid-shaped four-wheel setup. In addition, an adaptive fault-tolerant nonlinear control scheme based on a linear sliding surface was proposed. This algorithm provided precise three-axis attitude control without requiring explicit fault detection and isolation mechanisms, even when reaction wheels in either configuration experienced failures.

3.2.2 Combined control of magnetorquers and remaining reaction wheels

Chen et al.[44] and Duan et al.[45] proposed a fault-handling scheme for attitude control in the event of reaction wheel failures, which utilized a combined control of magnetic torquers and reaction wheels. This approach introduced a control allocation layer between the control algorithm and the actuators. Additionally, based on this, a control allocation strategy and a magnetic unloading algorithm under fault conditions were derived. Xiang et al.[46] addressed the problem of three-axis attitude control in the case of micro-momentum wheel failures and proposed a method to achieve attitude recovery using only magnetorquers. This method included the design of two magnetic control strategies: Proportional-derivative (PD) control and constant-coefficient linear quadratic regular (LQR) control, which could achieve attitude reorientation to Earth after the reaction wheel failures. Zhang et al.[47] developed an attitude magnetic control scheme for small satellites that used only magnetometers for attitude determination and magnetic torquers as the active control components. The scheme featured an improved PD control law for the pitch channel, with the introduction of a low-pass filter to enhance the controller's ability to suppress system noise.

Roberts et al.[48] proposed a combined control strategy of reaction wheels and magnetic torquers for the FUSE satellite, where two of its four reaction wheels had failed. This strategy utilized the existing magnetic torquers to substitute for the reaction wheels, restoring three-axis control. Ousaloo[49] investigated the attitude control problem for three-axis satellites and studied a hybrid control strategy combining magnetorquers and reaction wheels. The magnetorquers were used for momentum unloading of the reaction wheels and for rate damping of the satellite, while the reaction wheels were used to control the satellite's attitude. Two reaction wheels were installed on the spacecraft in three different configurations. This control algorithm ensured global and asymptotic stability of the spacecraft's attitude, and the method was not limited by the zero angular momentum assumption used in most existing two-wheel control techniques.

3.3 Control moment gyroscope failure

Control moment gyroscopes (CMGs) enable continuous high-torque output to meet angular momentum requirements, and are regarded as ideal actuators for satellites requiring rapid attitude maneuvers. Based on their structure and working principles, CMGs are primarily divided into single-gimbal CMG (SGCMG) with a fixed rotor speed, double-gimbal CMG (DGCMG), and variable-speed CMG (VSCMG). SGCMGs offer advantages such as high torque amplification, simple structure, and high reliability, and are suitable for applications requiring large control torques. However, it is a critical challenge to address singularity avoidance. DGCMGs are structurally complex and have low torque amplification capability. They are typically used in scenarios where both momentum exchange and output torque requirements are low. VSCMGs combine the characteristics of SGCMGs with constant rotor speeds and reaction wheels with variable rotor speeds, achieving singularity avoidance by introducing an additional degree of freedom through rotor speed variation.

Considering the dual requirements of three-axis attitude control and singularity avoidance for spacecraft, most satellite systems are designed with configurations using no fewer than four CMGs. When only two CMGs remain operational during a failure, the system degrades into an underactuated configuration. A significant amount of research literature has addressed the issue of underactuated control for satellite motion.

Lei et al.[50] studied the attitude control problem of a three-axis stabilized Earth-pointing satellite, where only two SGCMGs remained operational after a failure. Then, a hybrid control strategy that combined the two SGCMGs with magnetorquers was proposed. By decomposing the three-dimensional control torque command space into two orthogonal subspaces, each was executed by the control moment gyroscopes and magnetorquers. Control decoupling for these two types of actuators with significantly different torque output characteristics was achieved, thereby overcoming the robustness issues in underactuated control.

Kasai et al.[51] studied the problem of attitude maneuvering using two SGCMGs. Although two control moment gyroscopes can generate torque around all satellite axes, they cannot independently generate torque around each axis. Therefore, satellite control methods designed for two reaction wheels cannot be directly applied to the three-axis attitude maneuvering problem of satellites equipped with two SGCMGs. To simplify the problem, maneuvers around the x-axis and z-axis were first considered, followed by maneuvers around the y-axis induced by the angular effects of maneuvers around the x-axis or z-axis. By constructing a new operation sequence, large-angle attitude maneuvers were achieved using only two SGCMGs. Sasaki et al.[52] proposed two control modes using DGCMD as actuators: The parallel DGCMD mode and the single double-gimbal variable-speed CMD (DGVSCMD) mode. Both modes achieved system stability and control performance simultaneously by constructing an LPV model. When one of the gyroscopes failed, the system switched from the parallel DGCMD mode to the single DGVSCMD mode to realize three-axis attitude control of the spacecraft. Choi et al.[53] proposed a method based on fuzzy logic and Q-learning for fault detection and isolation in satellites equipped with small CMGs. Fuzzy logic was used to handle the nonlinear characteristics of the CMG system and detected faults through residual analysis, while Q-learning optimized the rules of the fuzzy inference system to enhance fault detection performance. This approach overcomed the optimization issues of traditional fuzzy logic, providing a reliable fault detection solution for satellite systems with limited redundancy.

3.4 Magnetorquers failure

In the complex environment of satellite attitude control, magnetorquers have become an important component in the design of satellite safe mode systems due to their advantages of being lightweight, low-power, cost-effective, simple in hardware, and highly reliable. When reaction wheels and thrusters are unable to function properly, emergency control schemes using magnetorquers as the sole actuators can ensure that the satellite maintains its expected orbit and attitude. However, even though magnetorquers consider the ultimate fallback solution, they are not entirely immune to failures.

Failures in satellite magnetorquers can be caused by various factors, including electronic component malfunctions, magnetic field sensing issues, or coil damage. When a magnetorquer fails, the satellite may lose all primary means of attitude control, resulting in an unstable or uncontrolled state. To address magnetorquer failures, it is crucial to fault-tolerant control strategies that can minimize the impact of such failures and ensure the reliability and success of satellite missions.

Das et al.[54] proposed a novel method for reconfiguring Earth-pointing satellite attitude control based on magnetic dipole moment modulation. When one magnetorquer failed, this method could reconfigure the magnetic dipole moment to maintain the control capability of the satellite system. This approach was independent of the control law design, allowing it to be combined with any control law for a stable system. De Ruiter[55] proposed a spin-stabilized fault-tolerant control algorithm using only magnetorquers, specifically for actuator failures in the JC2Sat-FF spacecraft. Under reasonable assumptions about the Earth's magnetic field, the control law could remain asymptotically stable even when only two magnetorquers were operational for an axially symmetric spacecraft. Giri et al.[56] conducted research on fault-tolerant attitude control for purely magnetically controlled satellite systems in the event of a single magnetorquer failure. This method used a PD controller to calculate the required control torque and focused on analyzing the controllability and stability issues of satellites with partially failed magnetorquers. Giri et al.[57] also considered a novel nonlinear sliding mode surface and proposed a fast terminal sliding mode control algorithm for magnetically driven satellite systems. Additionally, the applicability of the algorithm to scenarios involving single magnetorquer faults was verified. Prabhat et al.[58] proposed an improved super-twisting terminal sliding mode control algorithm for satellite attitude control using only magnetorquers. This algorithm could achieve fast convergence and reduced chattering even in the presence of disturbance torques, ensuring system stability even if one of the magnetorquers failed.

4 Conclusions

When a satellite fails and enters emergency mode, immediate recovery actions are required to rescue the satellite. However, at this stage, only a limited set of sensors and actuators are available. This paper focuses on the satellite emergency recovery under extreme anomaly conditions, and provides a detailed review of the research progress in satellite emergency attitude estimation and control techniques. Emergency estimation needs to use the remaining available sensor data to estimate the current satellite attitude and Sun-pointing direction, which forms the foundation for subsequent emergency control and recovery operations. Emergency control focuses on making effective attitude adjustments with the limited actuators to ensure the satellite stability and maintain energy supply. The scenarios involving failures of various actuators are discussed, including thrusters, reaction wheels, CMGs, and magnetometers.

Over the past few decades, significant progress has been made in the research and application of satellite emergency attitude determination and control technologies. However, there remains a certain gap between the current state of these technologies and the intelligent autonomous emergency control capabilities required for deep space exploration missions. Based on the current research status in both domestic and international contexts, the following issues require further in-depth investigation.

(1) Diagnosability and maintainability analysis during the design phase

Although the current emergency mode design process emphasizes reliability, the diagnosability and maintainability of the attitude determination and control system are equally critical to the safety of the satellite. Integrating diagnosability and maintainability concepts into the design, manufacturing, and testing phases can provide feedback that helps refine design and testing processes, rather than devising countermeasures only after system design is completed. Neglecting the analysis and design of diagnosability and maintainability in the early stages may lead to unforeseen costs and workloads during system integration. Although modern spacecraft systems are increasingly complex, early-stage design for fault management remains underdeveloped and requires further exploration.

(2) Intelligent autonomous fault diagnosis and fault-tolerant control for satellites

Satellites operate in harsh space environments, where environmental changes may trigger unforeseen faults. For example, space radiation can cause single-event effects, leading to failures in critical electronic components. Additionally, during the mission, the satellite internal parameters may change due to fuel consumption, liquid sloshing, and rapid maneuvers, which pose significant challenges to emergency attitude determination and control. Given the limited capability for ground intervention, these internal and external changes can complicate fault diagnosis and fault-tolerant control. Therefore, it is essential for satellite emergency mode to possess high levels of intelligent autonomy, enabling real-time adjustments and diagnostics. Enhancing the intelligent autonomous capabilities of fault diagnosis and fault-tolerant control systems using artificial intelligence and automation technologies is an important future research direction.

(3) Comprehensive emergency control approaches for engineering applications

Current research on satellite emergency mode often focuses on a single approach. Whether based on model-driven, data-driven, or knowledge-based techniques, each approach has its own limitations. For instance, model-based methods require accurate mathematical models of the system, data-driven methods need extensive historical data, and knowledge-based approaches face challenges in knowledge acquisition. Satellites are complex systems, and relying on a single approach to handle emergency attitude control is often insufficient. Hence, developing integrated solutions that combine multiple methods to enhance the accuracy of fault diagnosis, improve fault tolerance, and broaden the applicability of fault-tolerant control is a critical area of future research.

(4) Ground verification of emergency control technologies

Unlike typical industrial systems, satellites are highly customized systems, which adds complexity to the research and verification of emergency attitude control technologies. Currently, most research in this field remains theoretical, with a considerable gap between theory and practical engineering applications. Ground verification is a vital step in translating these technologies into practical use. Developing efficient and streamlined methods for performance evaluation of fault diagnosis techniques is an area that requires more attention. However, there is currently a lack of a systematic theoretical framework and practical, feasible rapid validation methods, which requires further research.

In conclusion, further research on these key issues is essential to enhance the practical application of satellite emergency attitude determination and control technologies. Through the development of more intelligent, efficient, and reliable control systems, the success and safety of satellite missions can be better ensured.

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卫星应急恢复状态下的姿态确定与控制方法

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摘要:当卫星遭遇极端异常状态时,可能会造成结构损伤、低温失效、推进剂冻结,甚至整星失效等严重后果。因此,研究卫星应急恢复技术至关重要。本文综述了在卫星应急恢复过程中姿态确定和控制技术的研究进展,总结了国内外学者在设计和实施卫星应急模式方面的成就。通过综合分析相关文献,本文旨在为极端异常状态下的卫星恢复技术提供参考和指导。

关键词:卫星应急恢复;姿态确定;姿态控制