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ORIGINAL PAPER

The Study on Reconfigurability Condition of Spacecraft Control System

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Abstract

Reconfigurability refers to the ability of the system to overcome all faults or restore some of its performance by changing the structure or control algorithm under the condition of resource constraints and operating conditions within a certain period of time to ensure the security when the control system fails. The establishment of reconfigurability evaluation and design theoretical system is of great significance for improving the operational reliability and service life of the whole spacecraft. Research projects are being conducted worldwide regarding reconfiguration control technology. We summarize the performance factors that affect system reconfigurability based on several typical reconfiguration methods by analyzing the constraints that the system can satisfy through fault-tolerant approaches. Since the reconfigurability evaluation index reveals the limitations and potentials of reconfigurable ability of the system, we refine the quantitative reconfigurability evaluation method based on various influencing factors. We anticipate that this work will play a guiding role in the reconfiguration strategy and design of spacecraft in-orbit to achieve the fault forward.

Keywords Spacecraft control system · Reconfigurability · Evaluation method

1 Introduction

Spacecraft control systems, which are responsible for attitude control, orbit control, solar panel and antenna drive control, are the most important and complex systems in spacecraft. Due to the severity and complexity of the problems caused by control system failures and the urgent need to develop aerospace equipment with a long service life and high reliability, research on improving the reconfigurability of spacecraft control systems has garnered much attention. The concept of reconfiguration control was first proposed by NASA in 1982 [1, 2]. Specific research on reconfiguration control began with the design of the self-healing flight control (SRFC) system initiated by the U.S. government. The U.S. Air Force conducted a specific study on the design of SRFC systems in 1984 [3]. From 1989 to 1990, the USAF confirmed a reconfiguration control strategy based on the pseudo-inverse method on the F215 validator and achieved encouraging results. This result heralded the practical application of reconfiguration flight control technology [4].

The control system is of high importance in ensuring proper operation of a spacecraft, and consequences are severe in the event of a failure. Thirteen foreign spacecrafts suffered major faults in-orbit in 2010, of which 5 were spacecraft with faulty control systems, accounting for 38.5% of the total number of faults. Thus, the quality of the orbital operation of the control system is the key to the survival and reliability of the spacecraft. To ensure the safety and operational quality of the spacecraft control system in orbit, it is necessary to improve its in-orbit troubleshooting capabilities to ensure timely and effective measures to minimize the impact of failure after its occurrence. This method can effectively improve the operational reliability and life expectancy of the spacecraft control system.

Reconfigurability of the system is an important condition for the aerospace system to realize autonomous fault handling. Reconfigurability is defined as the ability of the system to overcome all faults or restore some of its performance by changing the structure or control algorithm under the condition of resource constraints and operating conditions within a certain period of time to ensure the security when the control system fail [5]. Research on reconfigurability is fundamental to improving spacecraft troubleshooting capabilities. At

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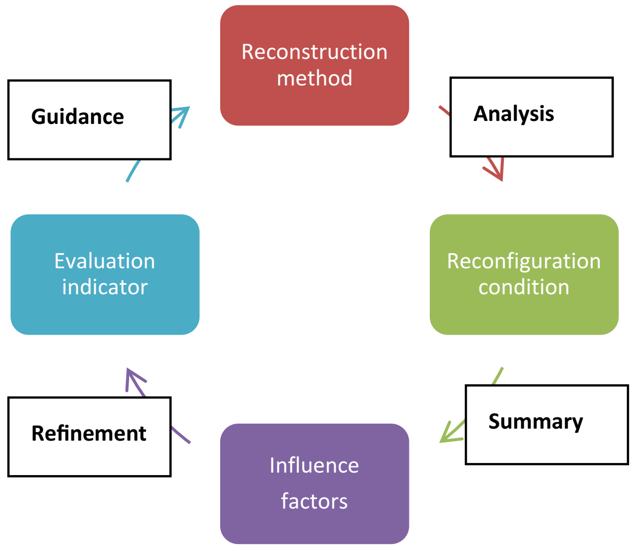

Fig. 1 Proposed concept

present, there are few specific requirements and evaluation methods for reconfigurability design in the development of spacecraft. Moreover, there is no specific quantified index or test method to determine whether the redundant configuration is reasonable or whether the handoff measures are effective. In view of this situation, by establishing a reconfigurability evaluation and design method system suitable for the control system, we can improve the reliability and service life of the entire spacecraft. This new approach to ensure maintainability of the system has high research value and engineering significance. Reference [5] presented details on the research studies of the reconfigurability of spacecraft control systems from both evaluation and design aspects. The focus of the present study is on the interrelationships between reconfigurability evaluation and reconfigurability methods.

Based on several typical reconfiguration methods, we analyze the system reconfigurability constraints and summarize the factors that affect the system reconfigurability. Since reconfigurability indicators reveal the limit and potential of system's reconfigurable ability, we refine the reconfigurability indicators based on the above research results to quantitatively describe the system reconfigurability. We hope that this approach will serve as a guiding role in the choice of reconfiguration methods. The concept proposed in this study is schematically shown in Fig. 1.

2 Analysis of Reconfigurability Conditions

Great progress has been made in the study of control system reconfiguration techniques, with researchers having proposed multiple reconfiguration control schemes for spacecraft. The methods of reconfiguration control, such as robust control, pattern recognition, adaptive control, optimization method and intelligent control, form the foundation of the control system reconfiguration technology.

Existing refactoring control designs are generally based on the following methods: linear quadratic method, pseudo-inverse method, gain scheduling method, (model reference) adaptive control, feedback linearization, robust control, predictive control, sliding-mode control, generalized internal model control, self-healing control, the use of expert systems, the use of neural networks, the use of fuzzy logic, learning methods and intelligent control methods. Reconfiguration control methods were classified in Ref. [6] into (1) mathematical design tools, (2) design methods, (3) reconfiguration mechanisms, and (4) the types of systems to be addressed. Under various constraints, these methods have their own advantages and disadvantages. At present, there is no unified evaluation system to help designers choose the appropriate reconfiguration strategy in the process of reconfiguration control.

Here, we list several methods commonly used in the study of spacecraft reconfiguration control. These methods are developed based on typical reconfigurability schemes by analyzing the conditions of reconfigurability. The reconfigurability evaluation and reconfiguration control design methods are combined to reinforce the guiding role of reconfigurability evaluation in the design of reconfiguration control.

2.1 Reconfiguration Method Based on Self-Healing Control

Recently, the concept of self-healing control has been proposed, and fault diagnosis and fault-tolerant control methods have been integrated into a unified framework. The self-healing control method is defined as the method used to overcome the fault and maintain a certain system control performance [7]. The definition of reconfigurability implies that self-healing control is an effective method of reconfiguration control and is also an implementation of the reconfigurable capability of the system.

Self-healing control includes self-healing management, reference redesign, controller redesign and FDI [8]. The self-healing management module is used to detect whether the original reference can be implemented asymptotically. If not, then a new optimal reference is calculated using the reference redesign module. The feedback controller is used to maintain the stability of the system, while the feedforward controller monitors the performance. The function of the FDI module is to detect, isolate and identify the stuck failures.

In Ref. [4], a new self-healing control method for satellite attitude tracking based on synchronous fault estimation and control design was proposed. The proposed method integrates the fault estimation and reconfiguration control units in the dynamic system together; this method is not only more complex but also more reliable than separate design of the self-healing architecture. First, the model reference method is used to obtain the dynamic equation of tracking error. Subsequently, the enhancement error system is constructed using the fault as an auxiliary vector. Based on the enhanced error system, the fault estimator/controller is designed to achieve simultaneous robust reconfiguration control and robust fault estimation. The design condition of the fault estimator/controller proposed in the present study is transformed into a set of linear matrix inequalities that can easily solve the problem of reconfigurability solution.

The authors of Ref. [9] proposed that the satellite attitude control system must meet the following three conditions to design a self-healing controller. Given two scalars $\gamma_y > 0$, $\gamma_e > 0$, determine the matrix coefficient in the controller that satisfies the following conditions:

1. The error system is asymptotically stable and allows the output of the fault system to track the reference trajectory;
2. The tracking error of the controlled output Δy is robust to disturbance $\omega(k)$, i.e.,

$$\|\Delta \boldsymbol{y}\|_2 < \gamma_y \|\omega\|_2 \tag{1}$$

3. The error of the fault estimation $e_f(k)$ is robust to interference $\omega(k)$, that is,

$$\|e_f\|_2 < \gamma_e \|\omega\|_2 \tag{2}$$

where $e_f(k) = T_f(k) - \hat{T}_f(k)$ is the estimated error of the fault.

When the faulty system satisfies the above conditions, the system is reconfigurable. It can recover all or part of its performance by means of self-healing control. As defined by the above three conditions, the method requires system stability, robustness and tracking performance. To some extent, each of these performance indices affects the system reconfigurability.

2.2 Reconfiguration Method Based on a Virtual Controller

The main idea of the virtual controller is described as follows [10]. The components of the fault and the system are represented as a system with a reconfiguration mechanism. When the reconfigurable system Σ_R has the same input and output performance, the fault is hidden in system Σ_C. With $(u(t), y(t))$ representing the nominal system input and output, respectively, if the nominal controller stabilizes the nominal system, then the reconfigured system is stabilized, and the solution to the problem of reconfigurability is independent of the nominal controller.

Virtual actuators were used in the linear time-invariant system in Ref. [11] and extended to various types of nonlinear systems in Refs. [12–14]. The references also give the sufficient conditions for the reconfigurability analysis based on the same parameter model of failure. To satisfy the reconfigurability of the system, we must meet the following conditions: stability and state trajectory recovery $(\forall t, x_f(t) = x(t))$.

Based on graph theory, the authors of Ref. [15] analyzed the controllability of the system by defining the directed graph, the structural matrix and the structural reconfigurability of the system [4, 15]. The controllability of the system was analyzed to study the system's reconfigurability. The report stated that reconfigurability depends mainly on the structural controllability of the system, i.e., the structure matrix satisfies (S_A, S_B) for $s - (S_A, S_B) = n$.

The above analysis of the condition of the reconfiguration method indicates that the reconfiguration method based on the virtual controller not only requires the stability of the system but also proposes the conditions for the controllability of the system structure.

2.3 Control Allocation Reconfiguration

Control allocation was first proposed for flight control system design and is now used in many engineering practices. The basic idea is to assign upper control instructions to redundant actuators based on a certain optimization goal and to ensure that actuator constraints are met. Research on control allocation algorithms has become increasingly complex, extending from static optimization to dynamic optimization and from single-objective optimization to multi-objective optimization.

Controlled distribution technology is an effective method for over-driving faulty actuators and considering the requirements of each flight task to achieve the coordinated assignment of control commands. Such technology is an important part of a reconfiguration control system. In recent years, scholars have studied a variety of multi-control surface reconfiguration control distribution schemes. In Ref. [16], a reconfiguration method for control allocation is proposed for the actuator failure and reconfiguration control is carried out in the case of environmental interference and failure.

Due to the limited fuel available for an in-orbit service spacecraft, to increase the service life of the spacecraft on-orbit, energy-optimal issues must be considered in the controller design process. In Ref. [17], a method of dynamic control distribution was designed and transformed into a quadratic programming problem as expressed by Eq. (3) as follows:

$$\min J = \left\{ \|R_0 W_0 v(t)\|^2 + \|R_1 W_1 [v(t) - v_s(t)]\|^2 + \|W_2 [v(t) - v(t-T)]\|^2 \right\}$$
$$\text{s.t. } Dv(t) = u(t) \tag{3}$$

where $u(t), v(t)$ represent the output torque and control input of the control assignment, respectively; matrix D is the control efficiency matrix; R_0, R_1 are the diagonal matrixes of the corresponding digits, and W_0, W_1, W_2 are the weight matrixes of the corresponding dimension. The physical meaning of the three parts of the constraint in (3) is as follows:

1. $\|W_0 v(t)\|^2$ is based on the principle of minimum energy; a higher weight matrix W_0 minimizes the energy consumption;
2. $\|W_1[v(t) - v_s(t)]\|^2$ is based on the principle of minimum error of control distribution; when W_1 is larger, the control torque is guaranteed to converge to the desired value faster;
3. $\|W_2[v(t) - v(t-T)]\|^2$ is based on the principle of minimizing the change speed of the control torque with respect to the sampling time; in the same manner, when the weight matrix W_2 is larger, the actuator movement is smoothed, and noise is suppressed.

The solution to this quadratic programming problem is equivalent to the solution to a dynamic allocation problem. According to the constraints in the quadratic programming problem, the reconfiguration method of controlling the distribution problem considers the energy consumption of the system and solves the problem of the optimal energy consumption.

Moreover, based on the classical pseudo-inverse method, research studies have been performed to quantitatively deduce the influence of reconfiguration delay on the system reconfiguration performance for a linear stationary system with actuator failure [18]. The condition of reconfigurability time t_r needed to be satisfied by the system is given; in addition, the trade-off between the reconfigurability and the required control performance is ensured.

To quantitatively/qualitatively determine the reconfigurability of a faulty system, a threshold of performance index is required. This threshold represents the limit of performance degradation after a fault occurs [19, 20]. The performance metric considered is the distance between the nominal system and the faulty system. Let η be the threshold function of the indicator [21], let $u_{\min}$ and $u_{\max}$ be the upper and lower bounds of the control action, respectively, and let J_r be a function of the performance index considering the time constraint. t_d is the fault detection time, t_r is the fault reconfiguration time, and t_{mis} is the time of the mission. The indicator is given by the following:

$$\min_{t_r}(J_r)$$
$$\text{s.t.} \begin{cases} J_r < \eta \leq 0 \\ u_{\min} \leq u_f(t) \leq u_{\max} \\ t_d \leq t_r \leq t_{mis} \end{cases} \tag{4}$$

Equation (4) indicates that the indicator not only considers the problem of system energy limitation in the reconfiguration control but also quantitatively describes the reconfigurability of the system in terms of both the time limit and the performance index.

2.4 Sliding-Mode Reconfiguration Control

In recent years, reconfiguration methods based on sliding-mode observers have received wide attention for its capability of fault reconfigurable and fault estimation. By designing the required sliding surface and equivalent control law, this method can respond quickly to the input transformation without being sensitive to parameter transformation and disturbance. The method provides strong robustness. Sliding-mode variable structure control has gradually attracted the attention of scholars; its biggest advantages are the addition of the sliding mode to the system interference and the fully adaptive system perturbation. Moreover, once entering the sliding-mode motion, the system converges quickly to the control target; this method can effectively achieve a robust design of time-delay systems and uncertain systems. The structure of sliding-mode variable structure control is purposefully changed continuously in the dynamic process according to the current state of the system (such as deviation and its derivatives), forcing the system to move according to the state trajectory of the predetermined "sliding mode" [22]. The sliding-mode variable structure control features strong robustness against parameter deviation and external disturbance. Designing disturbance observers is an important application of sliding-mode control [23]; such control not only improves the control system's performance and engineering applicability but also eliminates the chattering caused by interference [24].

However, in the research of these reconfiguration control methods, the actual physical constraints of the actuator are not considered, that is, the constraint problem of controlling the limited saturation of torque is not explicitly considered. However, this nonlinear constraint with saturation severely affects the stability and reconfigurability of the system [25, 26].

In view of this issue, the authors of Ref. [27] proposed an adaptive robust attitude fault-tolerant control method based on the integral sliding-mode surface for spacecraft attitude control with simultaneous multiple actuator constraints, installation tolerances and limited control constraints. The designed controller ensures the stability of the system under the condition that the constraint of the actuator's control ability is limited. Furthermore, by introducing an online adaptive learning strategy of control parameters to improve the robustness to disturbance, both installation deviation and fault variation have little dependence on these parameters. The specific control is implemented as shown in (5):

$$\tau = D^{\mathrm{T}}(u_{\mathrm{nom}} + u_{\mathrm{l}}),$$
$$u_{\mathrm{l}} = \begin{cases} -\mu \frac{\sigma}{\|\sigma\|}, \ \sigma \neq 0 \\ 0, \ \sigma = 0 \end{cases}. \tag{5}$$

The parameter μ satisfies the following constraints:

$$\begin{cases} \frac{\gamma \tau_{\mathrm{m}} + \lambda_2 (k_{\mathrm{p}} + k_{\mathrm{d}}) + \bar{d}}{\lambda_1} < \mu \\ \mu < \frac{\tau_{\mathrm{m}} - (k_{\mathrm{p}} + k_{\mathrm{d}})}{\|D\|} \end{cases}$$
$$\lambda_1 = \lambda_{\min}(\mathrm{DED}^{\mathrm{T}}),$$
$$\lambda_2 = \lambda_{\max}(\mathrm{DED}^{\mathrm{T}} - I) \tag{6}$$

where τ is the actual input control torque of the four-reaction flywheel, D is the nominal mounting matrix, and u_{nom} is the control law of the spacecraft's dynamic nominal system. We define the spacecraft dynamics system of the spacecraft dynamics nominal system as neglecting external disturbances and other factors. For the design of u_{nom}, the current method of proportional–integral–differential of aerospace engineering is adopted, where k_{p}, k_{d} are the PID control parameters. Assuming each flywheel has the same characteristics, its maximum output torque is τ_{m}, and the torque meets the amplitude-limited requirements of $\tau(t) \leq \tau_{\mathrm{m}}$, where $\bar{d}$ is the unknown interference norm upper bound. Here, E is defined as $E = \mathrm{diag}(e_1, \ldots, e_4)$, where e_i is the ith reaction flywheel effective factor. σ describes the synovial surface.

In the process of parameter selection of the control law, the range of amplitude is limited, that is, the control torque saturation is considered in the process of controller design.

3 Reconfigurability quantitative assessment

Sections 2.1–2.4 are based on four typical reconfiguration control methods from the perspective of the reconfigurability of control law and the analysis of the reconfigurability conditions. We summarize the factors that influence reconfigurability: stability, controllability, energy limitation, time limitation and input saturation, as shown in Table 1.

Table 1 The summary of reconfigurability factors

Method	Factors
Self-healing control	Stability
Virtual controller	Stability and controllability
Control allocation	Energy and time
Sliding-mode	Input saturation

Among these factors, stability is the precondition to ensure the control and safe operation of spacecraft control system. Further, control reconfigurability essentially measures the remaining controllability of the controlled process under unfavorable conditions; thus, the controllability of the system must be considered. In fact, the control inputs of the system are all physically restrained. However, little consideration has been given to the actual physical constraints of the actuator in the current research studies on the reconfiguration control methods, i.e., the constraint problem of controlling the saturation of torque has not been explicitly considered. This strong nonlinear saturation constraint severely affects the stability and reconfigurability of the system. Due to resource limitations, the actual reconfiguration capability of the spacecraft control system is affected by a variety of constraint constraints spanning time and space, such as time, energy, and control input.

Each existing control system reconfigurability design has its own advantages and limitations. At present, no unified framework exists to evaluate and guide the attitude control of spacecraft with strong reconfigurability. In the design of the reconfigurability system, it is necessary to know what fault conditions or which component failures have reconfigurability to achieve fault tolerance. Therefore, it is necessary to analyze the control reconfigurability of the system.

In view of the system reconfigurability conditions, rich control system reconfigurability analysis theory research and the actual reconfigurability system design provide an important theoretical basis. We summarize the factors that influence system reconfigurability. How do these factors affect the reconfigurability of the system? How can the quantitative/qualitative indicators be used to indicate the degree of influence and further guide the system's reconfigurability design? This problem bears research significance.

3.1 Reconfigurability Assessment for Stability

1. Reconfigurability goals based on stability

Stability is a prerequisite for the control and safe operation of spacecraft control systems. When the system fails, we must first ensure that the system is stable; otherwise, we should maintain system stable by reconfiguration method.

Stability is one of the major requirements of any control system and can be divided into three periods of system operation: the trouble-free period, the transition period during reconfiguration control, and the steady-state period after reconfigurable control. In the recent development of stability analysis, several important works have been reported. For example, theoretical studies on the stochastic stability of noise, modeling uncertainty, fault detection delay, decision error and actuator saturation have been performed [28–30]. In the linear matrix inequality (LMI) framework [31], the stability analysis based on gain estimation was solved. In Ref. [32], a method based on combinatorial analysis and simulation was introduced for the stability analysis of reconfigurability systems with actuator saturation. By applying LMI optimization techniques to multi-model structures, a stability-guaranteed FTCS was developed to prevent actuator failure [33]. In Ref. [34], the stability of the entire reconfiguration control system in the multi-model based on flight control scheme was verified using the multi-Lyapunov function. However, the stability analysis and stability robustness of real-time reconfiguration control system in real environment require further study.

In the current research, we provide the following: (1) a fixed controller, fault system maximum reconfigurability boundary ε and (2) a concrete calculation procedure that allows the robust controller to achieve the maximum boundary $\varepsilon_{\max}$ of the fault model when the original system and the faulty system can be stabilized simultaneously for the case that the controller is unknown.

The former judges whether the system can restore the stability of the system by reconfigurability design when the system fails. The latter evaluates whether the system reconfigurability index of the faulty system is greater than ε, that is, whether the system stability can be restored by the control law K' after the system is unstable; moreover, there is also a demand for clear objectives of the optimal robust controller. The two stability-based refactoring indicators not only analyze and evaluate the stability-based reconfigurability of the system but also play a guiding role in the reconfigurability design. The specific calculation method is as follows.

After the controller is fixed, the maximum reconfigurability boundary of the control system fault can be expressed as follows:

$$\left\| \begin{bmatrix} V \\ U \end{bmatrix} + \begin{bmatrix} -N \\ M \end{bmatrix} \right\|_{\infty} \leq \varepsilon^{-1}. \tag{7}$$

In other words, when the faulty system meets the following conditions, the system has reconfigurability:

$$\left\| \begin{matrix} \Delta_M \\ \Delta_N \end{matrix} \right\|_{\infty} = \left\| \begin{matrix} M_\Delta - M \\ N_\Delta - N \end{matrix} \right\|_{\infty} < \varepsilon \tag{8}$$

where U, V, M, N, are the corresponding coprime factorization of the controller and the nominal system. $K = UV^{-1}, G = NM^{-1}$ and M_Δ, N_Δ are the corresponding coprime breakdown forms of the faulty system, and $G_\Delta = N_\Delta M_\Delta^{-1}$.

In this manner, the following types of problems are solved: when the controller is fixed, if the controlled object fails, then the maximum fault boundary ε of the known controller can be obtained according to the controller K and the controlled object θ, and if the fault model can be stabilized by the controller, then the fault boundary must be less than ε.

Alternatively, if the system reconfigurability index is greater than the maximum reconfigurability boundary ε after system failure, then it is necessary to determine whether the system can be stabilized by refactoring the controller, that is, the maximum boundary problem that the robust controller can tolerate is the fault model when the original system and the faulty system can be stabilized simultaneously with the controller being unknown. The determination of this boundary $\varepsilon_{\max}$ allows the optimal robust controller to have a clear design goal. The specific expression is as follows:

$$\begin{aligned} \varepsilon_{\max}^{-1} &= \frac{1}{\sqrt{1 - \lambda_{\max}(YQ)}} \\ &= \left(1 - \| \tilde{N} \ \tilde{M} \|_H^2\right)^{-\frac{1}{2}} \end{aligned} \tag{9}$$

where $Y \geq 0$ is the steady-state solution of the following equation:

$$AY + YA^* - YC^*CY + BB^* = 0. \tag{10}$$

Q is the solution of the Lyapunov equation as follows:

$$Q(A - YC^*C) + (A - YC^*C)Q^* + C^*C = 0 \tag{11}$$

In this manner, we can obtain the maximum boundary of the fault model that the robust controller can tolerate when the original system and the faulty system can be stabilized simultaneously in the case that the controller is unknown.

3.2 Reconfigurability Assessment for Controllability

Control reconfigurability essentially measures the remaining controllability of the controlled process under unfavorable conditions. Therefore, it is necessary to study the relationship between the reconfigurability of the faulty system and the residual controllability. In the current research, most of the literature quantitatively describes the system reconfigurability based on the standard Gram matrix [35]. However, the standard Gram matrix algorithm is only applicable to stable systems with eigenvalues and non-zero non-stationary systems, and the standard Gram matrix is no longer suitable

Table 2 Comparison of the advantages and disadvantages of three reconfigurability evaluation methods based on system controlled gram matrices

Method	Standard gram matrix	Empirical Gram matrix	Refined integral
Characteristics	Usable only for linear stabilization systems	1. Breaks through the limitations of the system constraints, can be used for unstable, nonlinear systems 2. Large amount of computation and low efficiency	1. Can be used for singular systems 2. Small amount of calculation and high efficiency 3. High accuracy

when unstable systems contain two eigenvalues of zero. In view of this issue, the authors of Ref. [36] broke through the limitation of the properties of linearity and stability of the system by introducing the empirical Gram matrix. Because the empirical Gram matrix does not require the specific form of the system matrix, the controllability calculation is performed only through the corresponding data, thus compensating for the deficiency of the existing method that the spacecraft control system cannot control the Gram matrix. To simplify the calculation and improve the computational efficiency, the authors of Ref. [37] proposed the method of using the refined integral to calculate the system's Gram matrix. The specific advantages and disadvantages of the method are shown in Table 2.

Moreover, based on the theory of graph theory, Ref. [38] gives the influence of faults on the controllability of the system through the connected graph and the bipartite graph and obtains the reconfigurability quantitative index based on the controllability. This method provides an expression that depends on the controllability of the actuator and the satisfaction of defining the condition of controllability. Next, the probability measurement of the system's ability to save these attributes is deduced from this expression and the reliability of each actuator involved is given to obtain the controllable reconfigurability quantitative index of the entire system.

3.3 Reconfigurability Assessment for energy

Control reconfigurability refers to the ability of the system to allow performance restoration under constraints of energy consumption after a system failure. Considering that the system satisfies considerable conditions, from the viewpoint of system controllability, refactoring is understood to have the following two meanings: (1) the system is still controllable after the fault occurs, and (2) there is at least one permissible solution to the reconfiguration control problem under the constraint of energy consumption; otherwise, even if the system is controllable and the reconfiguration time requires more energy than the constraints, reconfigurability cannot be achieved. Due to the limited on-board resources of the spacecraft, the power generation capability of solar panels and the carrying capacity of propellants are severely limited. Therefore, the energy consumption constraint is a key factor that affects the reconfigurability of the control system.

Reconfigurability metrics based on system energy constraints are given in [39]. The goal of the system of meeting the energy constraints can be transformed into an optimal control problem that minimizes the energy function $Q(\mu, \gamma) = \int_0^\infty \|u(t)\|^2 \mathrm{d}t$. According to optimal control theory, the standard optimal solution is given by (12)

$$Q(I) = \tilde{\gamma} W_c^{-1} \gamma \tag{12}$$

Among the variables, W_c is the controllability of the system Gram matrix, and I is the system fault set. The reconfigurability index based on the system energy limit can be expressed as follows:

$$\tau(\gamma) = \frac{\sigma(\gamma)}{\tilde{\gamma} W_\mathrm{c}^{-1}(I)\gamma} \tag{13}$$

where $\sigma(\gamma)$ is a given function. The actual physical meaning of the four special choices for $\sigma(\gamma)$ can be interpreted as follows:

1. $\sigma(\gamma) = \infty, \forall \gamma \in R^n$

In this case, fault tolerance is only related to the existence of the optimal solution, regardless of its cost, that is, the actual energy consumption constraint of the system is not considered.

2. $\sigma(\gamma) = \sigma < \infty, \forall \gamma \in R^n, \|\gamma\| \le 1$

Regardless of the initial state in the unit sphere, $\|\gamma\| \le 1$ defines a uniform limit to the energy consumption of the faulty system.

3. $\sigma(\gamma) = \tau \cdot \tilde{\gamma} W_\mathrm{c}^{-1}(I)\gamma, \ \forall \gamma \in R^n$

Regardless of the control objectives, a unified efficiency loss limit is set for systems that control failures, regardless of the control objectives.

4. $\sigma(\gamma) = \tau \cdot \tilde{\gamma} W_\mathrm{c}^{-1}(I)\gamma + \Delta\sigma$

$\Delta\sigma$ for a given constant can be understood as a unified boundary of excessive cost of controlling a faulty system regardless of the control target.

3.4 Reconfigurability Assessment for Time Limits

In general, real-time systems should accomplish a given task in a fixed amount of time, and time is an important issue for all control applications. Control methods based on time optimization have drawn much attention. When moving from control system design to active fault-tolerant control system design, little consideration has been given to the time factor. However, recent studies have shown that failure detection and reconfiguration delays in active fault-tolerant control methods can severely affect the quality of reconfiguration control. As a result, analysis of the time limit after the fault is an important indicator of whether the fault must be adjusted in time, that is, the reconfigurability of the system is affected to some extent. Thus, finite time analysis is of strong guiding significance to the comprehensive design of reconfiguration control. The time-based reconfigurability index can be directly given by the control condition of (4).

3.5 Reconfigurability Assessment for Control Input Saturation

Input saturation is another common constraint of control systems due to the physical limitations of the actuator. Most research studies on system reconfigurability do not consider the system input limitation. In fact, the system control inputs are subject to physical constraints [40, 41]. In Ref. [42], the reconfigurability of systems based on system controllability and its calculation method were studied with the system inputs symmetrically constrained. In practice, system inputs are often subject to asymmetric or even positive constraints. This situation requires a higher system degree, requiring not only full rank of the system controllability matrix but also other conditions of full rank [43–46]. The exact formulation of the state norm reconfigurability given in Ref. [47] can be applied to input systems that receive arbitrary constraints but requires two optimizations to obtain the result, and the final result depends on the recovery time T. On the basis of the reconfigurability discrete-time estimation method of the state norm [48], Ref. [49] expanded the discretization method of controllable degree from $U = [-1, 1]^m$ to $U = [a, b]^m$, $a \in R$, $b \in R$ and outlined the discrete estimation method of the reconfigurability index. These reconfigurability calculations depend on the recovery time. In practice, there is often a need for reconfigurability metrics that are independent of recovery time T and that can be applied to any input constraint.

Results from the literature have been used to analyze the reconfigurability of the spacecraft during a momentum wheel failure using the above necessary and sufficient conditions of controllability. The results show that the controllability matrix Q_c is full rank, but the spacecraft is still uncontrollable, that is, the reconfigurability is weak because, after a momentum wheel failure, the system suffers from a positive constraint Ω (i.e., the system can provide only a positive yaw moment or negative yaw moment). To obtain the reconfigurability of the system when the system does not depend on the time T or satisfy the constraint set Ω, Ref. [50] presented a reconfigurability index of the constraint set Ω based on the control torque: the minimum distance of U from Ω's boundary of $\partial\Omega$. In other words, the input-constrained system, based on the system controllability of the reconfigurability index, is defined as follows:

$$\rho(X, \partial\Omega) \triangleq \begin{cases} \min\{\|X - U\| : X \in \Omega, U \in \partial\Omega\} \\ -\min\{\|X - U\| : X \in \Omega^c, U \in \partial\Omega\} \end{cases}, \tag{14}$$

where Ω^c is the complement of Ω, $\partial\Omega$ is the boundary of Ω, and X is the n-dimensional state space. The controllability-based reconfigurability index $\rho(X, \partial\Omega)$ of the system reflects to some extent the degree of reconfigurability of the control system of the aircraft and can be easily extended to a general system, such as $\dot{x} = Ax(t) + Bu(t)$.

4 Prospects

Reconfigurability of the control system, after more than two decades of development, remains in the design, simulation and test flight stages; as a result, such a system is far from practical. Despite the emphasis on reconfiguration control research in aerospace activities in terms of improving flight safety and reliability, the following issues still require further study.

1. Reconfigurability comprehensive evaluation problem

In this study, reconfiguration control methods based on the constraints are summarized and refined based on system stability, controllability, energy constraints, reliability constraints, control input saturation and time constraints of the reconfigurability evaluation index. Because the complexity of a satellite attitude control system determines the system reconfigurability design, we must consider the system energy, performance and other constraints. Therefore, the comprehensive evaluation of control system reconfigurability can be an optimal decision-making scheme for the comprehensive design of control system reconfigurability and thus is of important engineering significance.

2. Reconfigurability of the reconfigurability strategy guidance

The operational quality of spacecraft control system is reflected mainly in three aspects: the in-orbit fault diagnosis and processing level, the product inherent reliability design level and system diagnostic, and the reconfigurability design level. The in-orbit fault diagnosis and processing level is the acquired factor of the system fault diagnosis and processing capability. Although this capability can remedy certain faults, it is also strictly restricted and limited by the system design. Improving the inherent reliability of the product design level can reduce the number of on. However, due to the design limitations, processing level and quality of components, in-orbit operation failure still inevitably occurs. In addition, at the system diagnostic reconfigurability design level, as a congenital factor of system fault diagnosis and processing capability, the operational quality of spacecraft control system must be improved from the design point of view.

5 Conclusion

We have summarized the primary factors that influence the scalability of the system according to the limitations of several typical reconfiguration methods. We provide quantitative metrics for different influencing factors and evaluated the reconfigurability of the system; these results provide guidance in the reconfigurability of the design. As stated in the prospects section, despite the existing research studies on reconfigurability indicators and reconfigurability designs, the guiding role of system reconfigurability indicators must be further studied. In other words, when refactoring indicators are obtained, in addition to assessing the refactoring capabilities of the system, determining how to better guide the refactoring design is of certain research value for improving system reconfigurability.

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