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Research Article

Reconfigurability Analysis Method for Spacecraft Autonomous Control

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As a critical requirement for spacecraft autonomous control, reconfigurability should be considered in design stage of spacecrafts by involving effective reconfigurability analysis method in guiding system designs. In this paper, a novel reconfigurability analysis method is proposed for spacecraft design. First, some basic definitions regarding spacecraft reconfigurability are given. Then, based on function tree theory, a reconfigurability modeling approach is established to properly describe system's reconfigurability characteristics, and corresponding analysis procedure based on minimal cut set and minimal path set is further presented. In addition, indexes of fault reconfigurable degree and system reconfigurable rate for evaluating reconfigurability are defined, and the methodology for analyzing system's week links is also constructed. Finally, the method is verified by a spacecraft attitude measuring system, and the results show that the presented method cannot only implement the quantitative reconfigurability evaluations but also find the weak links, and therefore provides significant improvements for spacecraft reconfigurability design.

1. Introduction

Nowadays, autonomous control has become a key technology for increasing spacecraft survival capability. The reason is that autonomous control, regarding fault detection, identification, and reconfiguration, will be automatically activated to reduce the fault effect when faults emerge in a spacecraft. Therefore, how to increase the ability of fault processing has become a key issue for autonomous control of spacecraft. However, it can be concluded by many recent serious spacecraft incidents that certain deficiencies exist in their fault diagnosis and processing procedure. Further analysis reveals that these deficiencies are caused by reconfigurability lack of spacecraft. From this viewpoint, excellent reconfigurability has been becoming more and more critical for autonomous control to ensure the increasing requirements of spacecraft safety and reliability. In order to improve spacecraft autonomous control ability of tolerating faults, reconfigurability should be considered in design stage of spacecrafts and effective reconfigurability analysis method must be presented to guide the system design.

As far as the authors know, regarding reconfigurability design, mass research, aiming at enhancing flexibility about environment changes and function variations, has been conducted in computing and manufacturing fields [1, 2]. For spacecraft, although extensive attention to reconfigurability design has been devoted to controller designs after faults [3–9], or to system function changes [10] to satisfy other mission requirements, little improvement has been achieved regarding function recovery of faulty spacecraft by reconfigurability design. Meanwhile, some scholars have studied control reconfigurability from the intrinsic and performance-based perspectives. The intrinsic reconfigurability of LTI systems can be evaluated by the controllability and observability Gramians [11], or by the smallest second-order mode which is the smallest eigenvalue of the combination of controllability and observability Gramians [12]. The performance-based control reconfigurability is regarded as the ability of the considered system to keep/recover some admissible system performance when certain fault occurs. Staroswiecki discussed the reconfigurability under energy limitation constraints in [13]. However, all the studies mentioned above did not consider system's components and configuration, and thus they cannot settle reconfigurability analysis and design problems for complex systems such as spacecrafts. Consequently, the critical objective of this study is to construct an effective reconfigurability analysis method based on the function tree theory, which can synthesize components and reconfiguration strategies of spacecraft and estimate quantitative evaluation indexes.

The rest of this paper is organized as follows. Section 2 presents some basic definitions, and Section 3 constructs a reconfigurability modeling and analyzing method. In Sections 4 and 5, reconfigurability evaluation indexes and weak link analysis procedure for reconfiguration design are discussed, respectively. In Section 6, the proposed approach is illustrated by a practical application regarding spacecraft attitude measuring system. Some conclusions and relevant remarks are given in Section 7.

2. Basic Definitions

Siddiqi indicated that different definitions exist in different fields in [14]. By summing up a series of definitions, he defined reconfigurable system and reconfigurability as follows. Reconfigurable system is a system that can reversibly achieve distinct configurations (or states), through alteration of system form or function, in order to achieve a desired outcome within acceptable reconfiguration; while, reconfigurability is a system architectural property that defines the ease and extent to which a system is reconfigurable. Considering spacecraft, reconfiguration is the problem of replacing the faulty part of the system by a nonfaulty one, so as to still achieve control objectives, and reconfigurability is the ability of recovering all the functions or achieving degraded objectives by reconfiguration when faults appear.

System configuration is one of the basic factors that affect reconfigurability. Two relevant definitions, reconfiguration unit (RU) and minimal reconfiguration unit (MRU), should be explained here. RU is a combination of spacecraft components to achieve the anticipant function by reconfiguration itself or by switching to other RUs when the current RU fails. MRU is a combination of spacecraft components to achieve the anticipant function only by switching to other RUs when the current RU fails. It is the minimal unit in the reconfiguration analysis.

A novel reconfigurability model is established based on the function tree theory in this study. Function tree is a tree diagram whose vertex corresponds to the system function and whose branches are subfunctions decomposed from the system function, and its roots are the MRUs. Higher level functions and lower level functions in a function tree are connected by AND gates or OR gates. The relationship between function and MRUs can be clearly explained by the corresponding function tree. A typical function tree is illustrated in Figure 1.

In order to evaluate the reconfigurability quantitatively, definitions including cut set (CS), minimal cut set (MCS), path set (PS), and minimal path set (MPS) of a function tree are involved. A CS is a set of MRUs. When all MRUs in a CS are healthy, the system functions can be achieved. MCS is a special CS, and, if and only if all MRUs in MCS are in good condition, the system functions can be achieved. A PS is also a set of MRUs. When all MRUs in a PS fail, the system will lose its function. MPS is a special PS, and, if and only if failure appears in every MRU in MPS, the system function should have been lost. Furthermore, the MCS set or MPS set is called MCS family or MPS family.

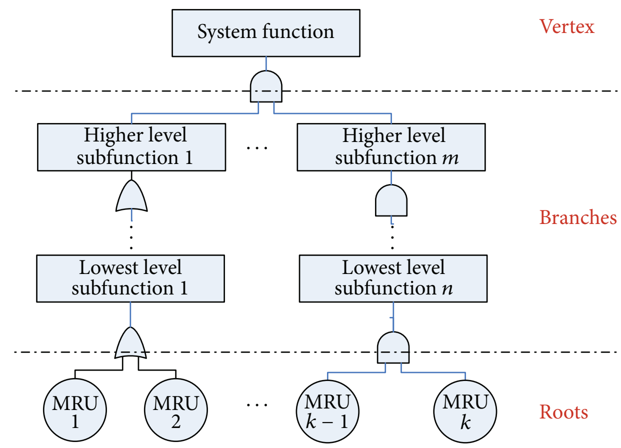


Figure 1: Function tree schematic diagram.

3. Reconfigurability Modeling

For reconfigurability evaluating and designing, one first needs to build an effective reconfigurability model and establish relationships between reconfigurability and MRUs. Then, evaluation indexes and weak links of the spacecraft reconfigurability can be analyzed.

We define a reconfigurability model from viewpoint of function tree, which is similar to theory of fault tree. The modeling processes are discussed as below.

Step 1. According to the system function, define the reconfiguration strategy based on the system observability and controllability.

For example, consider the LTI deterministic system

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t), \\ y(t) &= Cx(t). \end{aligned} \tag{1}$$

We adopt the observability criterion and controllability criterion

$$\begin{aligned} &\operatorname{rank}\left[C \;\; CA \;\; \cdots \;\; CA^{n-1}\right]' = n, \\ &\operatorname{rank}\left[B \;\; BA \;\; \cdots \;\; BA^{n-1}\right] = n \end{aligned} \tag{2}$$

to confirm the reconfiguration strategy by changing B or C in the system model and then obtain the component set C_{com}, each one of which can perform the system function.

Step 2. If any redundancy is involved in a system component, decompose it to the functional module. According to the redundancy relationship between the modules, determine the MRUs. Furthermore, according to the MRUs functions, the MRUs function set F_{MRU} can be obtained. And the elements in F_{MRU} are the lowest level function in the function tree.

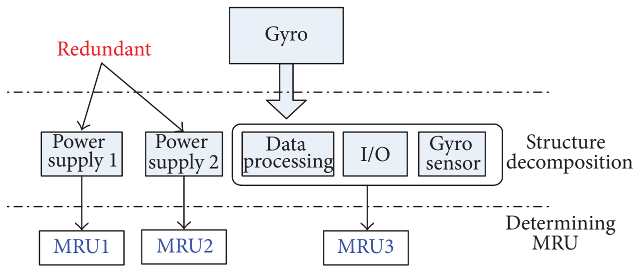


FIGURE 2: Structure decomposition of gyro.

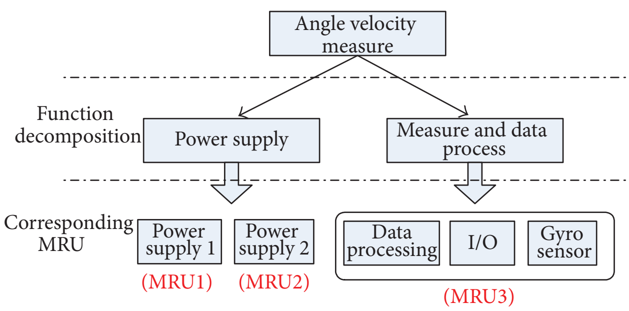


FIGURE 3: Function decomposition of gyro.

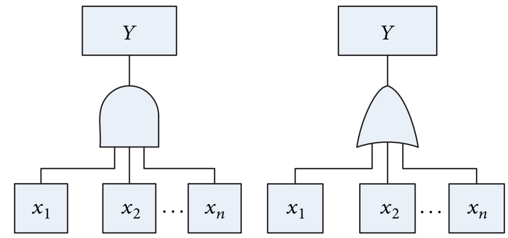
To get a better understanding, a gyro system is utilized as an example to illustrate this procedure. A gyro can be decomposed to several modules, such as power supply module, data processing module, I/O module, and gyro sensor module. If the power supply module is redundant, while others are not, any single power supply module can be considered as MRU, and the rest can be treated as MRU. Consequently, F_{MRU} of a gyro is {*power supply*, *measure and data process*}. Figure 2 shows the decomposition structure.

Step 3. From the system function, decompose higher level functions into lower level functions (or subfunctions) until the functions are contained in F_{MRU}.

Return to the example of gyro. "*Angle velocity measure*" is the function of a gyro. It can be decomposed into two subfunctions, "*power supply*" and "*measure and data process*". Then the decomposition process can be terminated, because "*power supply*" and "*measure and data process*" belong to F_{MRU}. The decomposition process is illustrated in Figure 3.

Step 4. Build a function tree by AND gate and OR gate. The vertex of this function tree is the system function, the branches are the subfunctions, and the roots are the MRUs. AND gate and OR gate connect the higher layers and the lower layers according to the relationship between the subfunctions.

AND gate and OR gate in function trees are depicted in Figure 4. The AND gate in Figure 4(a) shows that the upper level function Y can only be achieved when all the subfunctions x_i have been realized, $i = 1, 2, \ldots, n$, while for OR gate in Figure 4(b), it can be concluded that the upper level function Y can be realized when any single or multiple or all subfunctions x_i are achieved, $i = 1, 2, \ldots, n$.



(a) AND gate (b) OR gate

FIGURE 4: AND gate and OR gate.

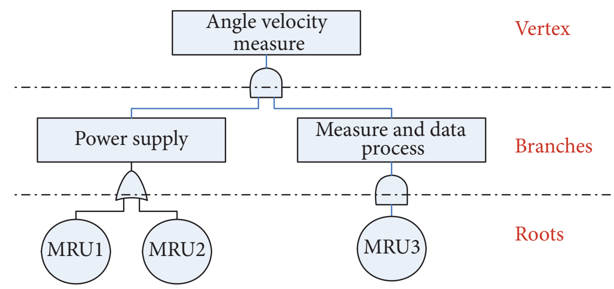


FIGURE 5: Function tree of gyro.

According to the steps mentioned above, the function tree of a gyro can be formed, which is shown in Figure 5.

In order to analyze the reconfigurability quantitatively, the MCS and MPS of function tree should be obtained firstly.

Let $\mathbf{C}_i(x_j)$ denote the ith MCS for the jth level function x_j, and let $\mathbb{C}(Y)$ denote the CS family for the upper level function Y. For AND gate,

$$\begin{aligned}\mathbb{C}(Y) &= \left\{\mathbf{C}_i(x_1) \cup \mathbf{C}_j(x_2) \cup \cdots \cup \mathbf{C}_k(x_n)\right\}, \\ & i \in \left(1, 2, \ldots, \left|\mathbb{C}(x_1)\right|\right), \\ & j \in \left(1, 2, \cdots, \left|\mathbb{C}(x_2)\right|\right), \\ & k \in \left(1, 2, \cdots, \left|\mathbb{C}(x_n)\right|\right).\end{aligned} \tag{3}$$

For OR gate,

$$\mathbb{C}(Y) = \mathbb{C}(x_1) \cup \mathbb{C}(x_2) \cup \cdots \cup \mathbb{C}(x_n), \tag{4}$$

where $|\mathbb{C}(x_i)|$, $i = 1, 2, \ldots, n$, is the cardinal number of $\mathbb{C}(x_i)$, which indicates MCS number in the MCS family for the subfunction x_i.

Let $\mathbf{R}_i(x_j)$ be the ith MPS for the jth level function x_j, and let $\mathbb{R}(Y)$ be the PS family of the upper level function Y. For AND gate,

$$\mathbb{R}(Y) = \mathbb{R}(x_1) \cup \mathbb{R}(x_2) \cup \cdots \cup \mathbb{R}(x_n). \tag{5}$$

For OR gate,

$$\begin{aligned}\mathbb{R}(Y) &= \left\{\mathbf{R}_i(x_1) \cup \mathbf{R}_j(x_2) \cup \cdots \cup \mathbf{R}_k(x_n)\right\}, \\ & i \in \left(1, 2, \ldots, \left|\mathbb{R}(x_1)\right|\right), \\ & j \in \left(1, 2, \ldots, \left|\mathbb{R}(x_2)\right|\right), \\ & k \in \left(1, 2, \ldots, \left|\mathbb{R}(x_n)\right|\right),\end{aligned} \tag{6}$$

where$|\mathbb{R}(x_i)|$, $i = 1, 2, \ldots, n$, is the cardinal number of $\mathbb{R}(x_i)$, which corresponds to the MPS number of the MPS family for the subfunction x_i.

Although $\mathbb{C}(Y)$ or $\mathbb{R}(Y)$ derived by (3) to (6) may not be MCS family or MPS family, the MCS and MPS are needed in the upper level function analysis according to (3) to (6). Consequently, the MCS and MPS of function Y can be calculated by the following steps.

Step 1. Initialize $\mathbb{C}_{\min}(Y)$ or $\mathbb{R}_{\min}(Y)$ to be a null set.

Step 2. Choose $\mathbf{C}_{\min}(Y)$ or $\mathbf{R}_{\min}(Y)$ with a minimum cardinal number in all sets in $\mathbb{C}(Y)$ or $\mathbb{R}(Y)$ and transform it into $\mathbb{C}_{\min}(Y)$ or $\mathbb{R}_{\min}(Y)$.

Step 3. Check all remaining sets in $\mathbb{C}(Y)$ or $\mathbb{R}(Y)$. If there is a set containing all the MRUs in $\mathbf{C}_{\min}(Y)$ or $\mathbf{R}_{\min}(Y)$, delete it from $\mathbb{C}(Y)$ or $\mathbb{R}(Y)$ and go back to Step 2 otherwise.

Step 4. Execute Steps 2 and 3 repeatedly until $\mathbb{C}(Y)$ or $\mathbb{R}(Y)$ turns to a null set. Then elements $\mathbf{C}_i(Y)$ or $\mathbf{R}_i(Y)$ in $\mathbb{C}_{\min}(Y)$ or $\mathbb{R}_{\min}(Y)$ are the expected MCS or MPS.

4. Reconfigurability Evaluation Indexes

Based on the reconfigurability model constructed in the preceding section, reconfigurability evaluation indexes for spacecrafts are given as follows.

4.1. Fault Reconfigurable Degree (FRD). FRD describes whether the system has available resources and methods for reconfigurations after certain faults as

$$\gamma = \begin{cases} 1 & \text{fault is reconfigurable} \\ 0 & \text{fault is unreconfigurable.} \end{cases} \tag{7}$$

When certain faults emerge, the MCS family should be activated by deleting all the MCSs including the fault reconfigurable units. Consider $\gamma = 0$ if the MCS family is empty; consider $\gamma = 1$ otherwise.

4.2. System Reconfigurable Rate (SRR). SRR indicates the rate of reconfigurable faults with respect to all faults in the system

$$r = \frac{\sum_{i=1}^{m} w_i \gamma_i}{\sum_{i=1}^{m} w_i}, \tag{8}$$

where γ_i is the FRD of the ith fault f_i, m is the number of all the system fault modes, and w_i is the weight of fault f_i according to its severity and occurrence probability. The major fault has a bigger weight than a minor one; and the fault with high occurrence probability has a bigger weight than the one with low occurrence probability. If the fault severity can be defined as four levels, as listed in Table 1, and the occurrence probability can be divided into five levels, as listed in Table 2, then w_i can be determined from Table 3. S denotes the fault severity level and P indicates the fault occurrence probability in Table 3.

Table 1: Fault severity level definition.

Level	Definition
I	System function is lost or service life is shortened seriously.
II	System function is degraded seriously or service life is reduced by 1/4 to 1/2.
III	System function is degraded partially or service life is reduced below 1/4.
IV	There is little affection in system function and service life.

Table 2: Fault occurrence probability definition.

Level	Definition
A	MRU fault probability ≥ 20% × total fault probability
B	20% × total fault probability > MRU fault probability ≥ 10% × total fault probability
C	10% × total fault probability > MRU fault probability ≥ 1% × total fault probability
D	1% × total fault probability > MRU fault probability ≥ 0.1% × total fault probability
E	MRU fault probability < 0.1% × total fault probability

Table 3: w_i matrix.

P	S			
	I	II	III	IV
A	1	1/3	1/7	1/13
B	1/2	1/5	1/9	1/16
C	1/4	1/6	1/11	1/18
D	1/8	1/10	1/14	1/19
E	1/12	1/15	1/17	1/20

5. Weak Link Analysis in Reconfigurability Design

For better reconfigurability, the reconfiguration weak links should be improved in the design phase of a spacecraft. Based on the established configurability model, the following two indexes are proposed to determine weak links in reconfiguration.

5.1. Importance Degree of MRU (IDMRU). IDMRU denotes the rate of the number of MCSs that includes the MRU with respect to the number of all MCSs as

$$I_M = \frac{N_M}{N_T}, \tag{9}$$

where I_M is the IDMRU of MRU M, N_M is the number of MCSs that comprise the MRU, and N_T is the number of all MCSs.

For any system, the MRU with maximal IDMRU contributes most in system function realization. Consequently, necessary redundancy or special reliability design should be considered for this MRU.

5.2. System Fault Tolerance Degree (SFTD). SFTD represents the maximal number of failure MRUs that the system can tolerate without loss of system functions. SFTD reflects the system reconfigurability as

$$T = \min\left(\left|\mathbf{R}_i\right|\right) - 1 \quad \left|\mathbf{R}_i\right| \in \mathbb{R},\ i = 1, 2, \ldots, |\mathbb{R}|, \tag{10}$$

where T denotes SFTD, $\mathbf{R}_i$ is the ith minimal path set of the function tree, $|\mathbf{R}_i|$ is the cardinal number of $\mathbf{R}_i$.

In a system, the path set with the minimum number of MPSs is the weakest link. And for this part, necessary redundancy or special reliability design should be considered according to the subfunctions of MRUs in the MPS.

The four indexes proposed above are closely connected to each other. Let f_i be a fault whose corresponding reconfigurable degree is equal to zero, $\gamma_i = 0$; namely, the corresponding MRU cannot be reconfigured; then the importance degree I_M of the MRU will be equal to one and the system fault tolerance degree T will become zero. Otherwise, if all fault reconfigurable degrees are one, namely, all the MRU can be reconfigured, then we can conclude that all the importance degrees will be less than one, the system fault tolerance degree will be not less than one, and the system reconfigurable rate will be equal to 100%.

6. Empirical Results

In this section, we focus on the practical performance of the proposed method. Our experiment is presented for the reconfigurability analysis of an attitude measuring system in a spacecraft. The dynamic functions regarding momentum devices are shown in (11). The spacecraft is considered as rigid body systems, and the body coordinate system coincides with the principle axes of inertia as

$$\begin{aligned}
&I_x\dot{\omega}_x - \left(I_y - I_z\right)\omega_y\omega_z - h_y\omega_z + h_z\omega_y = -\dot{h}_x + T_x,\\
&I_y\dot{\omega}_y - \left(I_z - I_x\right)\omega_z\omega_x - h_z\omega_x + h_x\omega_z = -\dot{h}_y + T_y,\\
&I_z\dot{\omega}_z - \left(I_x - I_y\right)\omega_x\omega_y - h_x\omega_y + h_y\omega_x = -\dot{h}_z + T_z,
\end{aligned} \tag{11}$$

where I_x, I_y and I_z are moments of inertia along axes Ox, Oy and Oz, respectively; $\boldsymbol{\omega} = [\omega_x, \omega_y, \omega_z]^T$ is the angular velocity vector; $\mathbf{h} = [h_x, h_y, h_z]^T$ is the synthesizing angular momentum vector of all the momentum devices; $\mathbf{T} = [T_x, T_y, T_z]^T$ is the control torque vector applied on the spacecraft except for the torque from the momentum devices. Therefore, the control torque vector $\mathbf{T} = [T_x, T_y, T_z]^T$ in (11) includes torques from thrusters, other space torques, and disturbing torques.

If all attitudes vary in a small scale, the dynamic functions can be simplified as

$$\begin{aligned}
\omega_x &= \dot{\varphi} - \omega_0\psi,\\
\omega_y &= \dot{\theta} - \omega_0,\\
\omega_z &= \dot{\psi} + \omega_0\varphi,
\end{aligned} \tag{12}$$

where φ, θ and ψ are Euler angles; ω_0 denotes the orbit angular velocity with which the spacecraft circles around the center body.

Then, the linearization form of the attitude dynamic function can be derived based on (11) and (12) as

$$\begin{aligned}
&I_x\ddot{\varphi} + \left[\left(I_y - I_z\right)\omega_0^2 - \omega_0 h_y\right]\varphi\\
&\quad + \left[\left(I_y - I_z - I_x\right)\omega_0 - h_y\right]\dot{\psi}\\
&\quad = -\dot{h}_x + \omega_0 h_z + T_x,\\
&I_y\ddot{\theta} + h_x\left(\dot{\psi} + \omega_0\varphi\right) - h_z\left(\dot{\varphi} - \omega_0\psi\right) = -\dot{h}_y + T_y,\\
&I_x\ddot{\psi} + \left[\left(I_y - I_x\right)\omega_0^2 - \omega_0 h_y\right]\psi\\
&\quad - \left[\left(I_y - I_z - I_x\right)\omega_0 - h_y\right]\dot{\varphi}\\
&\quad = -\dot{h}_z - \omega_0 h_x + T_z.
\end{aligned} \tag{13}$$

Accordingly, the dynamic function of the spacecraft can be expressed by a state space form, as shown in (1), with the following notations:

$$\begin{aligned}
x &= \left[\varphi\ \ \dot{\varphi}\ \ \theta\ \ \dot{\theta}\ \ \psi\ \ \dot{\psi}\right]^T,\\
A &= \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0\\
M_{21} & 0 & 0 & 0 & 0 & M_{26}\\
0 & 0 & 0 & 1 & 0 & 0\\
M_{41} & M_{42} & 0 & 0 & M_{45} & M_{46}\\
0 & 0 & 0 & 0 & 0 & 1\\
0 & M_{62} & 0 & 0 & M_{65} & 0
\end{bmatrix},\\
M_{21} &= I_x^{-1}\left[\left(I_y - I_z\right)\omega_0^2 - \omega_0 h_y\right],\\
M_{26} &= I_x^{-1}\left[\left(I_y - I_z - I_x\right)\omega_0 - h_y\right],\\
M_{41} &= I_y^{-1} h_x\omega_0,\\
M_{42} &= -I_y^{-1} h_z,\\
M_{45} &= I_y^{-1} h_z\omega_0,\\
M_{46} &= I_y^{-1} h_x,\\
M_{62} &= -I_z^{-1}\left[\left(I_y - I_z - I_x\right)\omega_0 - h_y\right],\\
M_{65} &= I_z^{-1}\left[\left(I_y - I_x\right)\omega_0^2 - \omega_0 h_y\right].
\end{aligned} \tag{14}$$

Matrixes B and C in (1) can be determined according to the detailed configuration of the system. For example, a system, with two infrared earth sensors, three orthogonal gyros, and one main backup thruster, can be described as

$$\begin{aligned}
u(t) &= \left[T_{x1}\ \ T_{x2}\ \ T_{y1}\ \ T_{y2}\ \ T_{z1}\ \ T_{z2}\right]^T,\\
y(t) &= \left[\varphi_{h1}\ \ \theta_{h1}\ \ \varphi_{h2}\ \ \theta_{h2}\ \ g_x\ \ g_y\ \ g_z\right]^T,
\end{aligned}$$

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ I_x^{-1} & I_x^{-1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & I_y^{-1} & I_y^{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_z^{-1} & I_z^{-1} \end{bmatrix},$$

$$C=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -\omega_0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \omega_0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (15)$$

Considering a spacecraft system described by (1), when faults appear, the premise of achieving system reconfigurability is that the remaining of the system is observable and controllable. The corresponding criterion is given by (2). According to engineering experience, one can assume that $I_x \neq I_y \neq I_z$ and $\omega_0 \neq 0$. Consider the following.

(1) Only one infrared earth sensor is employed for attitude determination as

$$C_1=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}, \qquad \operatorname{rank}\begin{bmatrix} C_1 \\ C_1A \\ \vdots \\ C_1A^5 \end{bmatrix}=6. \quad (16)$$

(2) Three gyros are employed for attitude determination as

$$C_2=\begin{bmatrix} 0 & 1 & 0 & 0 & -\omega_0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \omega_0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \qquad \operatorname{rank}\begin{bmatrix} C_2 \\ C_2A \\ \vdots \\ C_2A^5 \end{bmatrix}=5. \quad (17)$$

(3) One infrared earth sensor and three gyros are employed for attitude determination as

$$C_3=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -\omega_0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \omega_0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \qquad \operatorname{rank}\begin{bmatrix} C_3 \\ C_3A \\ \vdots \\ C_3A^5 \end{bmatrix}=6. \quad (18)$$

From (16) to (18), the attitude can be measured in the following two ways:

M1: by infrared earth sensors;

M2: by infrared earth sensors and gyros.

In addition, it is assumed that two infrared earth sensors share one power supply and three gyros share another power supply; then Table 4 lists the MRUs and their corresponding subfunctions.

Table 4: MRUs and their corresponding functions.

MRU	Functions
Infrared earth sensor power (ESP)	Power supply for infrared earth sensor (PS for ES)
Infrared earth sensor 1 (ES1)	φ and θ measure
Infrared earth sensor 2 (ES2)	φ and θ measure
Gyro power (GPower)	Power supply for gyros (PS for gyro)
Gyro $x(G_x)$	measure ω_x
Gyro y (G_y)	measure ω_y
Gyro z (G_z)	measure ω_z

Table 5: Results of reconfigurability analysis.

MRU	γ	I
ESPower	0	1
ES1	1	0.5
ES2	1	0.5
GPower	1	0
G_x	1	0
G_y	1	0
G_z	1	0

Figure 6 illustrates the function tree constructed by the reconfigurability modeling process. The MCS family and the MPS family could be derived by analyzing the function tree in Figure 6 as

$$\begin{gathered} \mathbb{C}=\{\{\mathrm{ESP},\mathrm{ES1}\},\{\mathrm{ESP},\mathrm{ES2}\}\}, \\ \mathbb{R}=\{\{\mathrm{ESP}\},\{\mathrm{ES1},\mathrm{ES2}\}\}. \end{gathered} \quad (19)$$

Thus, reconfigurability indexes can be calculated by (7) to (10). Table 5 lists the FRD and IDMEU of all the MRUs. Furthermore, suppose that the severity and occurrence possibility for all MRUs are the same; then $w_i = 1$, $r = 6/7$, and $T = 0$.

According to the analysis results of IDMRU and SFTD of all MRUs, the weakest link of this system is the power of infrared earth sensors. Consequently, it is better to store a backup in this link.

7. Conclusion

To involve reconfigurability in spacecraft design phase for potential faults, a novel reconfigurability analysis method is investigated in this paper. First, on the basis of observability and controllability, the reconfigurability criterion is given for spacecraft that is considered as a rigid body system. Then, the function tree is built for modeling reconfigurability, and evaluation indexes are proposed. After that, according to minimal cut set and minimal path set of the function tree, a quantitative evaluation method for reconfigurability indexes and an approach for determining system weak links

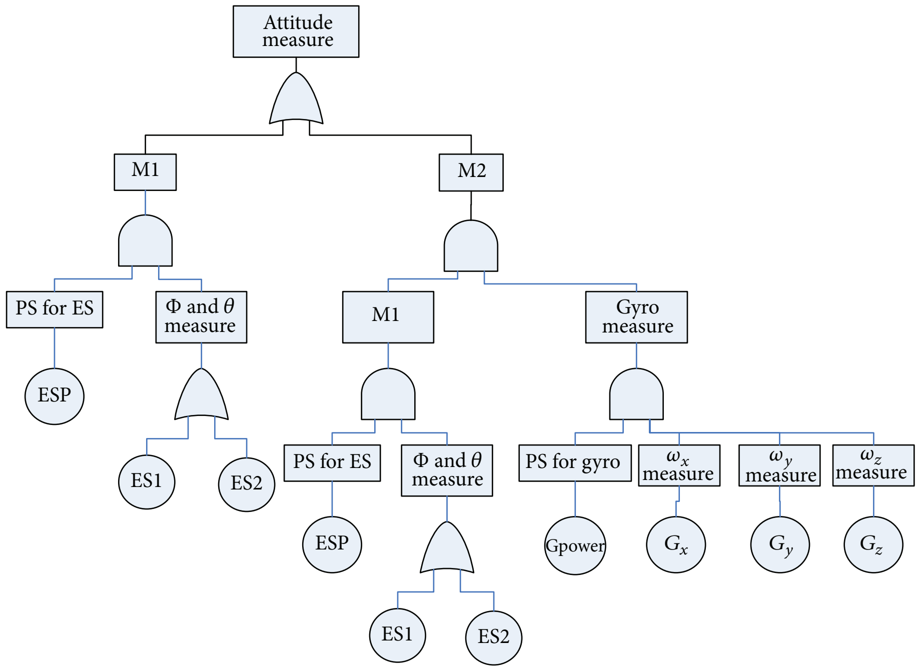


FIGURE 6: Function tree for attitude determinations.

are summarized. Theoretical research and empirical study both illustrate the benefit of the constructed methodology for spacecraft reconfigurability design on reliability criterions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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