Reconfiguration Analysis Based on Single Function Module Fault for Satellite Sensor Subsystems

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***Abstract*—Reconfigurability evaluation in the design stage of satellite attitude control system is effective for building up the ability of disposing fault on orbit. This paper proposes an approach to evaluate and analyze the reconfigurability of the sensor subsystem under faulty conditions. The description of the reconfigurability in the presence of single function-module fault is formulated. An index is introduced to describe the reconfigurability of the system. The characteristic of the component and function-module is described by means of a parameter matrix, whose relation with the controllability Gramian of the attitude control system is given. Depth-first-search algorithm is proposed to calculate the reconfigurability parameter matrix. Simulation results on sensor subsystem illustrate the efficiency of the proposed approach, which provides an engineering method to evaluate the reconfigurability.**

Keywords-reconfigurability; sensor subsystems; function module; fault

I. INTRODUCTION

Due to the high requirement of safety and availability for satellite attitude control system, more attention has been paid on fault reconfiguration scheme including hardware backup and controller reconfiguration. Reconfiguration is the problem of replacing the faulty part by a normal one, so as to still stabilize the system and achieve the mission. In order to improve fault tolerant ability, it is of great importance to highlight system reconfiguration design for reasonable resource allocation[1].

Recent research on system evaluation mainly focuses on reconfigurable manufacturing systems[2-5]. There has been lots of theoretical results about comprehensive system evaluation in the manufacturing field, Only a few results are devoted to spacecraft reconfigurability[6,7]. Least Second-mode was brought out in [8,9] to describe the ability of system reconfiguration, which is deduced from the minimum singular value of product by the controllability Gramm matrix and observability Gramm matrix for a linear time-invariant system. Ref.[10] explored controllability and observability Gramm matrix to describe the reconfigurability of linear time-invariant systems. The controllability gramian of switching system was studied in [11], and the failure recoverability was introduced. But there are few research on reconfigurability.

Based on former work, this paper is devoted to provide an approach to evaluate and analyze the system reconfiguration ability in the presence of function module faults. The rest of this paper is organized as follows. In SectionⅡ reconfiguration index on single function module fault is introduced. Criterion of reconfigurability on satellite sensor subsystem is investigated in Section Ⅲ,. Section Ⅳ gives a relation on components and function-modules. Reconfigurability analysis in the present of single function-module fault is followed. Depth-First-Search method is developed to analyze and calculate the proposed index for sensor subsystem. Section Ⅴ provides some final conclusions and directions for further work.

II. RECONFIGURATION INDEX

Reconfigurable proportion is introduced as an index to describe the reconfigurability of the system, which is expressed as $R = n/m$. Define n as the number of reconfigurable cases with respect to single fault and R as single fault reconfigurable proportion, where m is the number of all single function module fault cases.

Single fault reconfigurable proportion is an index to describe the reconfigurability of the system with respect to single function module fault. Define n_1 as the number of reconfigurable cases with respect to single fault and R_1 as single fault reconfigurable proportion. Single fault reconfigurable proportion is expressed as $R_1 = n_1 / m_1$, where m_1 is number of all single function-module fault cases.

A linear satellite attitude control system is described as follows.

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{1}$$

where $x = [\varphi \quad \dot{\varphi} \quad \theta \quad \dot{\theta} \quad \psi \quad \dot{\psi}]$, φ, $\dot{\varphi}$, θ, $\dot{\theta}$, ψ, $\dot{\psi}$ are the angles and angle rates respectively. In (1),

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ M_{21} & 0 & 0 & 0 & 0 & M_{26} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ M_{41} & M_{42} & 0 & 0 & M_{45} & M_{46} \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & M_{62} & 0 & 0 & M_{65} & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ I_x^{-1} & I_x^{-1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & I_y^{-1} & I_y^{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_z^{-1} & I_z^{-1} \end{bmatrix}.D,$$

$$M_{21} = I_x^{-1}[(I_y - I_z)\omega_0^2 - \omega_0 h_y],\ M_{26} = I_x^{-1}[(I_y - I_z - I_x)\omega_0 - h_y],$$
$$M_{41} = I_y^{-1} h_x \omega_0,\ M_{42} = -I_y^{-1} h_z,\ M_{45} = I_y^{-1} h_z \omega_0,\ M_{46} = I_y^{-1} h_x,$$
$$M_{62} = I_z^{-1}[(I_y - I_z - I_x)\omega_0 - h_y],\ M_{65} = I_z^{-1}[(I_y - I_x)\omega_0^2 - \omega_0 h_y],$$
$$y = [\varphi \quad \dot{\varphi} \quad \theta \quad \dot{\theta} \quad \psi \quad \dot{\psi}],\ C = I_{6\times 6},\ I_x,\ I_y,\ I_z$$

are moments of inertia of corresponding axis, and $u = [u_1, u_2, \cdots, u_m]^T$ is the output torques of actuators. D is actuator installation matrix. ω_0 is orbit angular velocity. h_x, h_y, h_z are the momentums of the corresponding axis respectively. In the present of function module fault in a sensor subsystem, C is changed into C_f. According to the observability Gramm matrix of the linear system, if C_0 can be found from C_f to satisfy $rank(C_0, AC_0, \cdots, A^{n-1}C_0) = n$,the sensor subsystem can be observable. So it is reconfigurable.

III. COMPONENT ATTRIBUTE DESCRIPTION

There are gyros, earth sensors, sun sensors and star trackers on a satellite sensor subsystem. Earth sensors and sun sensors can only measure pitch and rolling angles. Star trackers can measure all three axis angles. Gyros can measure all three angular velocities.

Supposing there are m_1 sun sensors, m_2 earth sensors, m_3 star trackers and m_4 gyros. Vector S is defined as one sensor attribute matrix, $S_j = [s_{j1}, s_{j2}, s_{j3}, s_{j4}, s_{j5}, s_{j6}]$, where $j = 1, \cdots, (m_1 + m_2 + m_3 + m_4)$ is the serial number of sensors. Sun sensor is marked as S_{m1}, earth sensor, star tracker, gyros are marked as $S_{m_1+1} \sim S_{m_1+m_2}$, $S_{m_1+m_2+1} \sim S_{m_1+m_2+m_3}$, $S_{m_1+m_2+m_3+1} \sim S_{m_1+m_2+m_3+m_4}$ respectively.

s_{j2} is the kind of sensor, where 1 represents star sensors, and 2,3,4 represents infrared horizon sensors, sun sensors and gyros respectively.

s_{j3} is defined as state of the sensor. 1represents normal, and 0 represents fault.

s_{j4}, s_{j5}, s_{j6} is regular state of x y and z axis. 1 represents normal, and 0 represents fault. As for sun sensor and infrared horizon sensor, $s_{(1\sim m_2+1)6} = 0$,since earth sensors and sun sensors can only measure pitch and rolling angles.

Then a attribute matrix of a component m_s can be built as

$$S = \begin{bmatrix} s_{11} & \cdots & s_{16} \\ \vdots & \vdots & \vdots \\ s_{m_s 1} & \cdots & s_{m_s 6} \end{bmatrix}.$$

IV. SYSTEM RECONFIGURATION ANALYSIS BASED ON FUNCTION-MODULE

Sun sensor is composed by four kinds of function-modules named power unit, rolling measuring unit, pitch measuring unit and signal processing unit, which is numbered i = 1,2,3,4 in order. Followed by $i = 5 \sim 7$, which are the serial number of function-modules of infrared horizon sensor and star sensors. They are composed of three kinds of function-modules as power unit, measuring unit and circuit management unit. Gyro is composed of three kinds of function-modules as power unit, measuring unit and circuit management unit, which is numbered as $i = 8 \sim 10$.

Supposing that there are m_1 sun sensors, m_2 earth sensors, m_3 star sensors, m_4 gyros in one sensor subsystem, we can get $M_{1\sim4} = m_1$, $M_{5\sim7} = m_2 + m_3$, $M_8 = m_5$, $M_{9,10} = m_4$. Sensors and function modules are described in Fig.1,2,3.

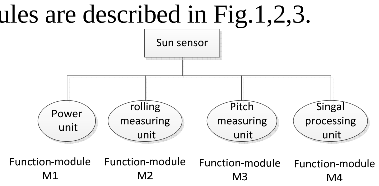

Figure1 function modules in sun sensor

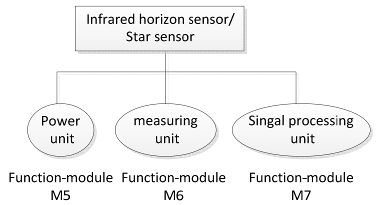

Figure 2 function modules in infrared horizon sensor and star sensor

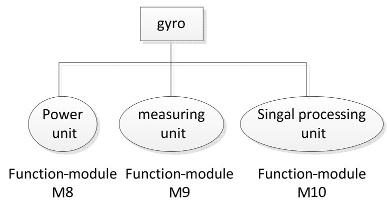

Figure 3 function modules in gyro

Depth-First-Search algorithm is adopted here to calculate single fault reconfigurable proportion for the sensor subsystem. The index calculation program is a process of going through each function-module. If the subsystem on one function module fault case is reconfigurable according to the observability Gramm matrix, n_{s1} will increase by one. Loop this process until all the function-modules have been gone through. The judge program on reconfiguration is given in Fig.4.

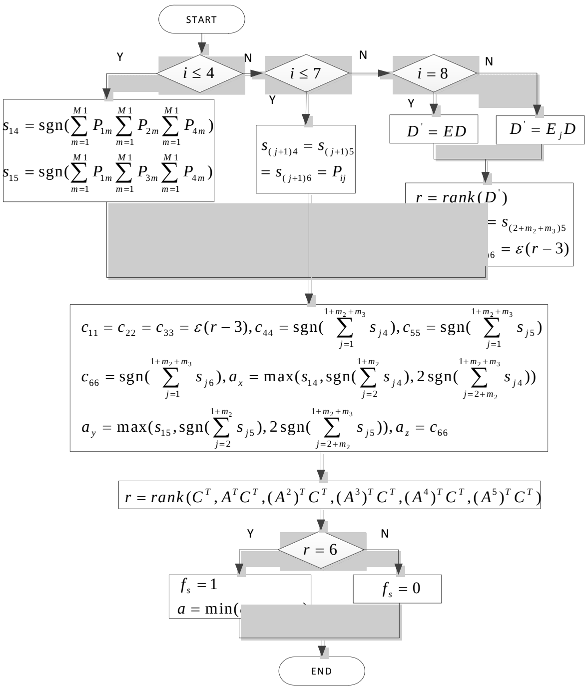

Figure.4 the judge program on reconfiguration

In Fig.4, D is the installation matrix of gyroes. E is a diagonal matrix, each element is $\sum_{j=1}^{m_5} P_{8j}$, such as $E = diag(\sum_{j=1}^{m} P_{8j}, \cdots, \sum_{j=1}^{m} P_{8j})$. EJ is a diagonal matrix expressed by $EJ = diag(1, \cdots, P_{ij}, \cdots, 1)$, jth element is P_{ij} and all other elements are 1. Here $rank(EJ) = rank(E)$. Define a as the grade of the reconfiguration. $a = 1$ represents low degree of accuracy for a sensor subsystem. On this cases, only sun sensor or earth sensor are working well. $a = 2$ represents high degree of accuracy. On this case, star tracking performances well.

It is assumed that the sensor system is deployed with four skewed gyros, two infrared horizon sensors, two sun sensors, and three star sensors. According to the analysis above, the number of each kind of function module is as follows: $m_1 = 2, m_2 = 2, m_3 = 3, m_4 = 4, m = 2$. Going through all the function-modules following the judge program, we can get $n_{s1} = 33$. Hence, configurability index can be calculated as follows $R_1 = \frac{n_{s1}}{4m_1 + 3m_2 + 3m_3 + m + 2m_4} = 1$. On this result, the set sensor subsystem can be reconfigurable in the present of one function module fault. So it is reliable against single fault.

Reconfigurability analysis for satellite systems provides an engineering guidance for reliability design. For high reliability, redundant designs are always adopted in other satellite subsystems. Based on this paper, two and more function module fault cases will be investigated for sensor subsystems and other subsystems in our further work.

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