Analysis and Strategy Design for Quantitative Model-Based Fault Diagnosis

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Abstract. This paper studies and analyzes quantitative model-based fault diagnosis method, and then presents a design of quantitative model-based fault diagnosis structural strategy. It can isolate the faults of actuator and sensor with reduced quantitative models. The strategy is proposed based on the analysis of traditional quantitative model-based fault diagnosis method. By redefining the analytical model-based method, the process of fault isolation is studied with the conception of support component. The effectiveness of the proposed strategy is also analyzed in the paper. Finally, the proposed structural strategy is applied for fault diagnosis of satellite attitude control system.

Keywords: Fault diagnosis strategy · Quantitative model · Fault isolation analysis

1 Instruction

Model-based fault diagnosis methods have been developed in two distinct and parallel research domains in the past few decades [1–4]. One comes from the field of automatic control which is known as fault diagnosis method based on quantitative model or analytical model [5–7]; another one comes from the field of artificial intelligence which is called fault diagnosis method based on qualitative model or qualitative reasoning [8–10]. These two methods are collectively referred to as fault diagnosis methods based on deep knowledge, and they have the ability to make up the shortage of fault diagnosis method based on shallow knowledge [11–13]. However, these two kinds of diagnosis methods have been developed independently. Qualitative model-based methods describe the system diagnosed according to system structure and function. They focus on the studies of diagnosis solving process such as conflict identification and candidate generation. However, the research of qualitative model-based method has certain significance for fault diagnosis of quantitative model-based method.

This paper studies the traditional quantitative model-based method by combining system structure information, and then provides a new fault diagnosis strategy for model-based method. By this study the fault diagnosis based on quantitative model is extended

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from single structure system to multiple structure system. The designed strategy can isolate the faults of actuator and sensor with a reduced number of quantitative models working at the same time.

In summary, the main contributions of this paper are as follows: a) traditional quantitative method-based fault diagnosis method and the existing problems are analyzed; b) object systems and quantitative model-based methods are redefined, and diagnosis solving process is studied; c) quantitative model-based fault diagnosis structural strategy using redundancy of system structure is presented.

2 Quantitative Model-Based Fault Diagnosis Method and Its Difficulty

2.1 The Traditional Quantitative Model-Based Fault Diagnosis Method

The traditional quantitative model-based method commonly concerns certain dynamic system as their diagnosis object. This object system is usually described by a set of differential equations in state-space form. It composes of actuator, sensor and process. And three types of faults are generally distinguished, that is, actuator fault, sensor fault and process fault. An actuator fault is a malfunction on certain control input of the system; a sensor fault is an abnormal variation in output measurements; process faults are changes in the inner parameters of the system that can affect the system dynamic.

In these methods fault diagnosis is typically achieved by constructing quantitative or analytical models which contain fault information. These quantitative models are constructed based on the principle of dynamic systems. The essence of these methods is to detect the consistency between the computed output of the quantitative model and the real measurement output of the system.

There are two kinds of diagnosis approaches for quantitative model-based methods, using fault-free model or faulty model. The first approach declare the fault if the behaviors of system and the model is not consistent. The second approach declare the fault if the system behavior is consistent with the model behavior under a particular fault scenarios. The schematic for quantitative model-based method is shown in Fig. 1.

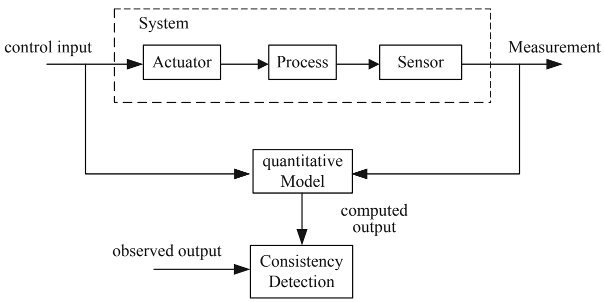

Fig. 1. The schematic for quantitative l model-based method

Faulty model-based approach need construct a particular pre-assigned fault model, and only the fault which can match the pre-assigned fault model can be detected. The drawback of this approach is all the likely fault should be taken into account, and the computational burden is large; however, the advantage is that the behavior of the fault can be estimated. Fault-free model-based approach uses nominal behavior of the system, and it can detect unknown fault. However, the behavior of fault cannot be further estimated by this approach.

Model-based methods usually generate a set of residuals to fulfill the fault isolation task. Each residual is designed to be sensitive to some faults and insensitive to other faults. According to the insensitive and sensitive relationships between residuals and faults, there are two kinds of strategies for residuals generation, namely the dedicated residual set and the generalized residual set. For the dedicated residual set, each quantitative model is driven by only one control input (or sensor output) and thus sensitive to only one actuator fault (or one sensor fault). For the generalized residual set, each quantitative model is driven by all control inputs (or sensor output) but one and thus sensitive to all actuator faults (or sensor faults) except one. The schematic of structured residual set is showed in Fig. 2 and 3.

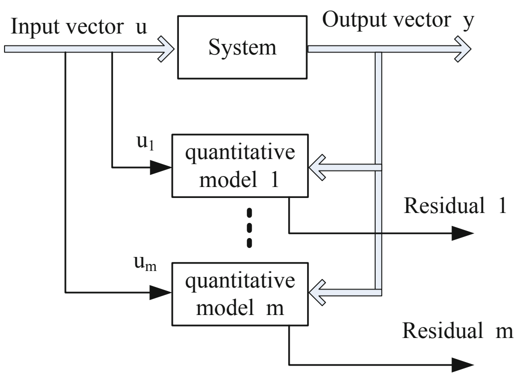

Fig. 2. The schematic of dedicated residual set

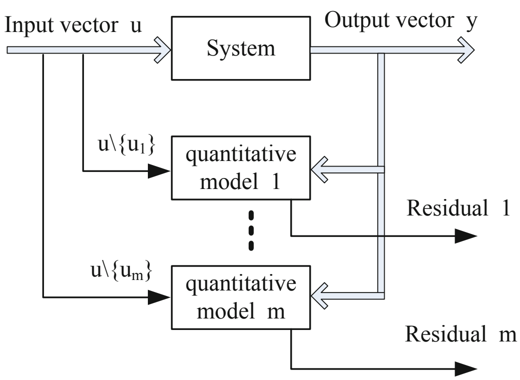

Fig. 3. The schematic of generalized residual set

In the dedicated residual set, simultaneous faults can be detected; however it needs more degrees of freedom to design such residual sets. In the generalized residual set, only a single fault can be detected, but it has more design degrees of freedom for achieving robustness against uncertainty of the system.

2.2 The Difficulty of the Quantitative Model-Based Fault Diagnosis Method

There are three difficult issues to be further study for quantitative model-based fault diagnosis methods:

1) Uncertainty processing: the accuracy of consistency detecting depends on the accuracy of the quantitative model. In quantitative model-based method, consistency detecting is achieved by residual which is a deviation between measurement of the real system and computed output of the model. In ideal case, the residual only reflects fault. However, the residual will be influenced by disturbance, noise and uncertainty of the system inevitably, which reduces the accuracy of fault detection. Thus, the study of robust model-based method is an important problem.
2) Faulty components determining: a system is constituted by three main parts: actuators, sensors and process (abstractly expressing the dynamic response between system inputs and outputs, which is determined by the objective laws of physics and may be affected by the system design parameter). These three components are all constituent parts of the system, and any component failure will cause the changes of the whole system behavior. Thus it is hard to judge the real faulty part that caused the fault characteristics.
3) Diagnosis strategy choosing: according to the above two diagnostic strategies, it can be seen that the fault-free quantitative model is simple, but only fault detection can be achieved, namely, determining the system is normal or not. Using faulty quantitative model-based method can achieve the determination of various faults by matching the pre-defined fault, but the pre-defined fault model must be constructed firstly which is usually complicated work. Thus effective combination of two diagnostic strategies is also worth discussing.

3 Quantitative Model-Based Method Redefinition

We define that the object system diagnosed by quantitative model fault diagnosis method is composed of a set of components and a set of measurements. The object system can achieve the specific function and realize the corresponding dynamic response from input to output. The three kinds of components that make up the object system are the input parts of the system called the actuator; the output part of the system called sensor; and the dynamic response relationship between input and output which is abstracted as a process component. Measurement refers to the direct value about the system operating conditions, including the control input and measurement outputs that the object system can observe. The task of fault diagnosis is defined as determining whether a fault occurs in the system, which parts are faulty, and what kind of fault occur.

An Analytical Redundancy Relation (ARR) is defined as a constraint deduced from system measurements, which is the basis for constructing analytical model. A residual is defined as the difference between outputs of real system and model corresponding to ARR. In order to further study the fault diagnosis process, the concept of ARR support is introduced. An ARR Support is defined as a set of components involved in the analytical redundancy relation, and the corresponding parts are called Support components for ARR. In traditional sense, ARR refers to the relationship between input and output of the system in normal situation. And the corresponding relationship between system input and output in a pre-defined fault condition is not included. The former is mainly used for FDI (fault detection and isolation), while the latter is used for the fault estimation. In the following, ARR in traditional sense and FDI based on the quantitative model are discussed first.

FDI based on quantitative models can be described in detail by the concept of ARR Support. Fault detection is defined as determining a certain subset of the support components set and one (corresponding to single fault situation) or some (corresponding to multiple faults situation) support components in this subset are faulty. Fault isolation is defined as determining a certain subset of the support components set, and all support components in this subset are faulty. The subset which has single component corresponds to single fault and which has multiple components corresponds to multiple faults. As fault diagnosis result comes from a subset of support components, the component set determines the maximum diagnostic granularity of FDI.

The fault symptom matrix (FSM) is defined as the binary relation matrix between the ARR support component and ARR, which can be deduced by the analytical redundancy relation. Assume that the total number of components in a system is m, and the number of analytical redundancy relation is n. thus, the FSM determines an n $\times$ m matrix denoted by d, which is a binary matrix composed with "0" and "1", the row of FSM corresponds to n ARR and the column of FSM corresponds to m components. If the i-th component is a support component of the j-th ARR, thus the element (j, i) in FSM is denoted by "1", otherwise it is denoted by "0". The i-th column of FSM is the fault feature vector of the i-th component, and two components can be isolated if and only if their fault feature vectors are different.

A multi-input and multi-output dynamic system S1 with three-input and three-output is showed in Fig. 4.

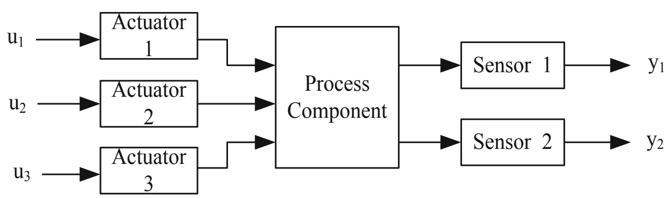

Fig. 4. Three-input and two-output system S1

In order to diagnose the actuator fault in S1, the strategies of dedicated residual set and generalized residual set are adopted, and the corresponding FSM is constructed in Table 1.

Table 1. Fault signature matrix for system S1

	Actuator 1	Actuator 2	Actuator 3	Process	Sensor 1	Sensor 2
ARR1	1	1	1	1	1	1
ARR2	0	1	1	1	1	1
ARR3	1	0	1	1	1	1
ARR4	1	1	0	1	1	1
ARR5	1	0	0	1	1	1
ARR6	0	1	0	1	1	1
ARR7	0	0	1	1	1	1

Where, ARR1 is constructed based on the constraint relationship between u1, u2, u3 and y1, y2, and its support components are actuators 1, 2, 3, sensors 1, 2 and process components. ARR1 can only be used to achieve fault detection, namely, determining whether the system is normal. ARR2, ARR3, ARR4 are the analytical redundancy relations constructed by using the strategy of generalized residual set within analytic model method. ARR5, ARR6, ARR7 are the analytical redundancy relations constructed by using the strategy of dedicated residual set. According to FSM, choosing ARR2-4 or ARR5-7 alone makes actuator 1, 2 and 3 have different fault feature vectors, as shown in Table 2. Thus it is easy to isolate the actuators fault by using the strategy of dedicated residual set or generalized residual set. However the sensor 1, 2 and the process components have the same fault feature vector which means that additional information is required to achieve fault isolation.

Table 2. Fault feature vector for system S1

	Generalized residual strategy	Dedicated residual strategy
Actuator 1	0 1 1	1 0 0
Actuator 2	1 0 1	0 1 0
Actuator 3	1 1 0	0 0 1

It is often difficult to construct more ARR to complete fault isolation for all support components, because ARR construction will be influenced by constrained conditions, as well as the specific distribution matrix of actuators and sensors. In addition, more analytical redundancy relations means that more quantitative models should be built and run in parallel, which will increase the burden of computation.

4 Fault Isolation Analysis

The traditional quantitative model-based method for FDI has been widely researched in constructing precise quantitative model and reducing disturbance influence so as to improve the sensitivity of fault detection. However, structure knowledge of complex systems is less considered into research for ARR generation. In the following, the strategy of ARR generation for quantitative model-based method is studied from the perspective of system hierarchy and subsystem division. And the problem of fault isolation for support components is researched. Usually, the complex system is composed of some different function modules, and each module can be viewed as a subsystem. The function of any subsystem is described through its input and output. These independent subsystems constitute the complex system according to its structural relationship.

Consider the following system S2 as shown in Fig. 5:

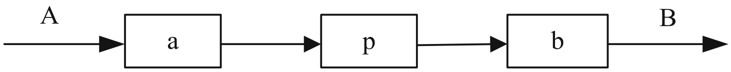

Fig. 5. The system S2 before the transformation

Where A is the control input of the system, B is the system output obtained by the sensor, *a* is the actuator, *p* the system process component, and *b* the sensor. If a new sensor *c* can be used to measure the intermediate process variables, the system can transform into a new form shown in Fig. 6. The process component *p* is abstracted as two process components *p*1 and *p*2 according to subsystem 1 and 2.

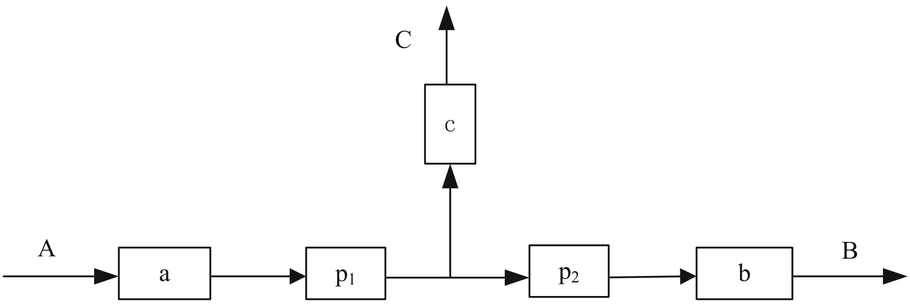

Fig. 6. The system S2 after the transformation

Through three measurements *A*, *B* and *C*, the original system can be divided into two subsystems, namely, the subsystem 1 with measurement *A* and *C*, and the subsystem 2 with measurement *C* and *B*. In subsystem 1, component *a* is the actuator of this subsystem, component *c* is the sensor of this subsystem, and *p*1 is the process component of subsystem 1. Since the input of *p*2 (i.e. the output of *p*1) is measured by the sensor *c*, the input information of subsystem 2 is obtained from measurement *C*. Thus, component *c* can be viewed as the actuator of subsystem 2, component *b* is the sensor of subsystem 2, and $p2$ is the process component of subsystem 2. After adding the new measurement C, the maximum diagnostic granularity is changed from the original components a, b, p to new components a, b, $p1$, $p2$, c, namely, an addition of measurement points is beneficial to obtaining more accurate diagnosis results.

Further expands the system discussed above into a multi-input and multi-output system S3, such as two-input and two-output system shown in Fig. 7.

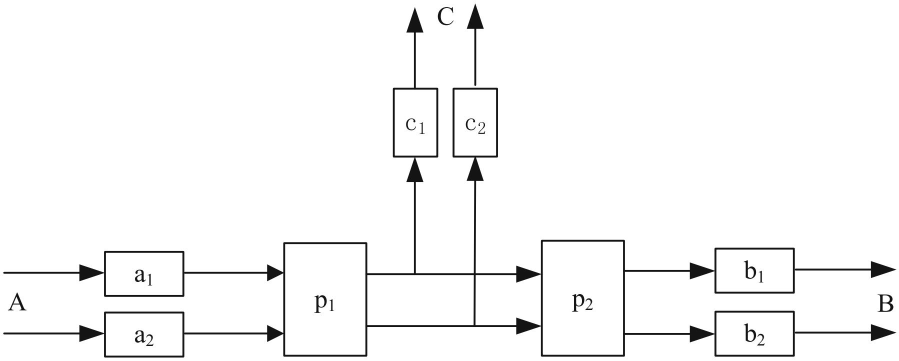

Fig. 7. The structure diagram of two-input and two-output system S3

It can be seen from Fig. 7 that in the two subsystems, support components for subsystem 1 are $a1, a2, p1, c1, c2$ and support components for subsystem 2 are $c1, c2, p2, b1, b2$. Fault detection and isolation for S3 is to determine the fault components from all support components $a1$, $a2$, $b1$, $b2$, $c1$, $c2$, $p1$, $p2$. Thus quantitative model should be constructed according to ARR of this system.

Two independent ways for generating analytical redundancy relation are provided based on subsystem 1 and 2. Six ARRs can be constructed, and the corresponding FSM is showed in Table 3.

Table 3. Fault signature matrix for system S3

	a1	a2	p1	c1	c2	p2	b1	b2
ARR1	1	1	1	1	1			
ARR2				1	1	1	1	1
ARR3	1	0	1	1	1			
ARR4	0	1	1	1	1			
ARR5				1	0	1	1	1
ARR6				0	1	1	1	1

In Table 3, ARR1 is a analytical redundancy relation constructed according to all of six components in subsystem 1; ARR2 is a analytical redundancy relation constructed according to all of six components in subsystem 2; ARR3 and ARR4 are analytical redundancy relations constructed according to subsystem 1 by the strategies of dedicated residual set or generalized residual set, and the corresponding support components are $a1, p1, c1, c2$ and $a2, p1, c1, c2$; ARR5 and ARR6 are analytical redundancy relations constructed according to subsystem 2, and the corresponding support components are $c1, p2, b1, b2$ and $c2, p2, b1, b2$.

According to the above FSM, the corresponding fault feature vectors can be easily obtained, and they are showed in Table 4:

Table 4. Fault feature vector for system S3

Component	Fault feature vector	Component	Fault feature vector
a1	1 0 1 0 0 0	p2	0 1 0 0 1 1
a2	1 0 0 1 0 0	b1	0 1 0 0 1 1
p1	1 0 1 1 0 0	b2	0 1 0 0 1 1
c1	1 1 1 1 1 0	c2	1 1 1 1 0 1

The fault components can be determined according to the differences of fault feature vectors. Due to components $p2, b1, b2$ have the same fault feature vector, the fault in $p2, b1, b2$ cannot be isolated in the current case, which means that some new analytical redundancy relations are required to solve this problem. Thus the final fault diagnosis result is {a1}, {a2}, {p1}, {c1}, {c2}, {p2, b1, b2}.

Six quantitative models (observers) should be constructed corresponding to the above six ARRs. If these six quantitative models run in parallel, the calculation amount of the fault diagnosis system will be large. Therefore, it is necessary to study the reasonable diagnosis strategy for diagnosis system to reduce the number of quantitative models in parallel.

5 Quantitative Model-Based Fault Diagnosis Structural Strategy

The fault isolation structural strategy based on quantitative model is proposed below, which achieve the fault diagnosis task in two stages. In the first stage, the fault is detected preliminarily; and in the second phase, the fault is isolated.

In the first stage, the quantitative model is designed respectively for each subsystem. This quantitative model is a fault-free model designed based on normal system, and its analytical redundancy relation contains all support components in the subsystem which corresponds to the above ARR1 and ARR2. According to fault symptom matrix determined by ARR1 and ARR2, $a1, a2, p1$ have the same fault feature vector [0, 1], $c1, c2$ have the same fault feature vector [1, 1], $p2, b1, b2$ have the same fault feature vector [0, 1]. Therefore, according to the quantitative model constructed by ARR1 and ARR2, the diagnosis results obtained are {a1, a2, p1}, {c1, c2}, {p2, b1, b2}.

In the second stage, a set of quantitative model is designed respectively for each subsystem. These analytical redundancy relations contain different support components from each other, which can be achieved by the strategies of dedicated residual set or generalized residual set. Analytical redundancy relations constructed based on subsystem 1 and 2 are ARR3,4 and ARR5,6 respectively. According to ARR3,4, the diagnosis result {a1}, {a2}, {p1, c1, c2} can be obtained; according to ARR5,6, diagnosis results {c1}, {c2}, {p2, b1, b2} can be obtained. Through the above analysis, fault diagnosis strategy is established in the following, which is showed in Fig. 8.

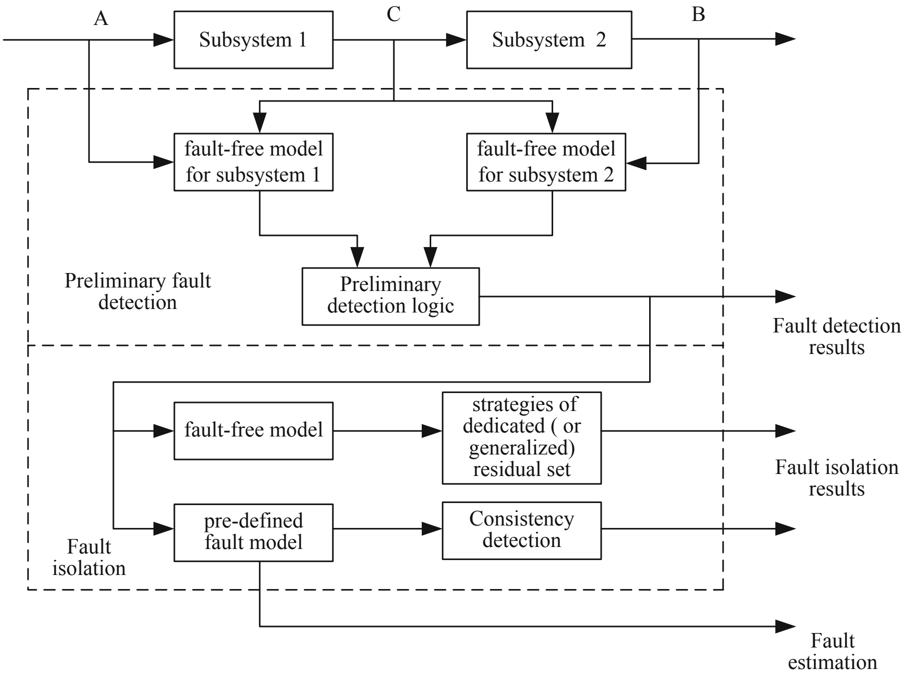

Fig. 8. The scheme of the fault diagnosis strategy

First of all, the two quantitative models designed in the first stage run in parallel. When there is a fault in the system, we will get diagnosis result {a1, a2, p1}, {c1, c2}, {p2, b1, b2}. Thus, preliminary fault detection can be achieved, and a subset which contains possible fault components can be obtained. According to the above detection result, fault isolation in the second stage is started. If the fault detection result is {a1, a2, p1}, the quantitative models corresponding to ARR3,4 are activated. As the result of {a1, a2, p1} ∩ {{a1}, {a2}, {p1, c1, c2}} is {a1}, {a2}, {p1}, the fault components $a1$, $a2$, $p1$ can be isolated. If the fault detection result is {c1, c2}, the quantitative models corresponding to ARR5,6 are activated. As the result of {c1, c2}∩{{c1}, {c2}, {p2, b1, b2}} is {c1}, {c2}, the fault components $c1$, $c2$ can be isolated.

It can be seen that by adopting the above diagnosis strategy, the final diagnosis result is the same as the six quantitative models run in parallel. However, due to adopting the hierarchical strategy, the detection and isolation of fault component is achieved step-by-step. Compared with no hierarchical diagnosis, the numbers of the quantitative model running in parallel at the same time is reduced, and the burden of computation is also reduced.

Remark. We limit the discussion of quantitative model-based FDI to fault-free model in the beginning. However, the diagnosis strategy proposed above is also suitable for pre-defined fault model. For ARR corresponding to pre-defined fault model, its support components is all of the components involved in ARR except the pre-defined fault components. In the research process for fault diagnosis by using FSM, ARR corresponding to pre-defined fault model is equal to the strategy of generalized residual set. All the components except the pre-defined fault components are all denoted by "1" in corresponding element of FSM. Using the method of pre-defined fault model may achieve deeper diagnosis for the fault component, such as application of adaptive technique which can estimate the time-varying characteristics of the fault.

6 Application of Fault Diagnosis Structural Strategy for Satellite Attitude Control System

A satellite attitude control system includes actuators, inertial sensors and direction sensors. Faults may occur in any one of these components, thus the primary task of satellite attitude control system fault diagnosis is to determine whether a fault occurs and the fault comes from which components. Although there are many researches on fault diagnosis for satellite attitude control system, they usually focus on particular part of components, such as actuators or sensors. Researches considering fault diagnosis for all parts of satellite attitude control system are few. In this section, Fault diagnosis structural strategy is used to discuss this problem.

The typical structure of the satellite attitude control system is shown in Fig. 9. The dynamics subsystem expresses the relationship between control torques and angular velocity, including the supporting component actuator 1, 2, 3, dynamics process, and gyro 1, 2, 3. Kinematics subsystem expresses the relationship between satellite angle and angular velocity, including supporting components gyro 1, 2, 3, kinematics process, and the star sensor. We consider that the attitude dynamics and kinematics of rigid-body satellites as laws of physics, thus process faults are ignored. However, both actuators and sensors faults can occur, and the diagnostic tasks are to isolate faults of actuator 1, 2, 3, gyro 1, 2, and the star sensor.

According to the proposed Structural isolation strategy, in the first stage, a fault-free model is designed according to the fault-free dynamics subsystem, which is referred to as the fault detection observer 1 (FDO1), and it is sensitive to all actuator and gyro faults. And another fault-free model is designed according to the fault-free Kinematics subsystem, which is referred to as the fault detection observer 2 (FDO2), and it is sensitive to all gyro and star sensor faults.

In the second stage, a bank of fault-free models based on the generalized residual set is designed according to the fault-free dynamics subsystem, which is referred to as the fault isolated observer group 1 (FDI1), it is insensitive to the specific actuator fault. And a bank of pre-defined fault models is designed according to the Kinematics subsystem

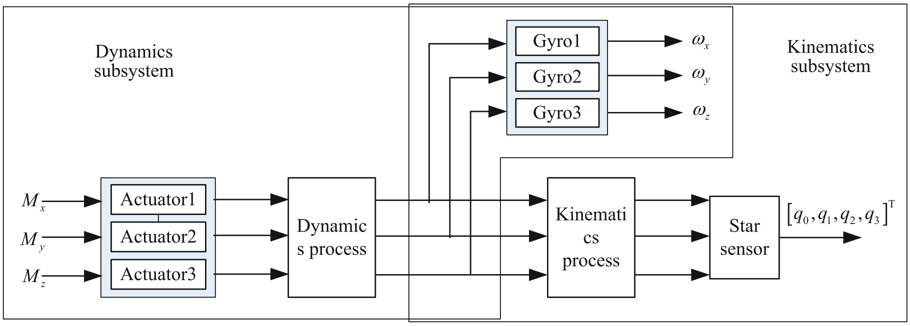

Fig. 9. The structure of the satellite attitude control system

with gyro faults, which is referred to as the fault isolation observer group 2 (FDI2), and it is insensitive to the specific gyro fault.

Thus the complete fault isolation logic is as follows:

Firstly, FDO1 and FDO2 run in parallel to detect whether there is a fault in the satellite attitude control system, and determine which part (actuator, gyro mechanism, star sensor) the fault comes from. It is assumed that r_{FDO1} is the residual evaluation function of FDO1 and $\overline{\varepsilon}_1$ is the corresponding fault detection threshold; r_{FDO2} is the residual evaluation function of FDO2 and $\overline{\varepsilon}_2$ is the corresponding fault detection threshold. The initial fault detection logic is as follows:

$$\begin{cases} r_{FDO1} \le \overline{\varepsilon}_1, r_{FDO2} \le \overline{\varepsilon}_2 \Rightarrow no\ \ fault \\ r_{FDO1} > \overline{\varepsilon}_1, r_{FDO2} \le \overline{\varepsilon}_2 \Rightarrow actuator\ fault \\ r_{FDO1} > \overline{\varepsilon}_1, r_{FDO2} > \overline{\varepsilon}_2 \Rightarrow gyro\ fault \\ r_{FDO1} \le \overline{\varepsilon}_1, r_{FDO2} > \overline{\varepsilon}_2 \Rightarrow star\ sensor\ fault \end{cases}$$

When the detection result is that the actuator has a fault, FIO1 is activated, which includes three fault isolation observers and $r_{FIO1-i}, i = 1, 2, 3$ is the residual evaluation function of the isolation observer designed to diagnoses the i-axis actuator fault, and $\overline{\varepsilon}_{1i}, i = 1, 2, 3$ is the corresponding threshold value, then

$$\left.\begin{array}{l} r_{FIO1-i} \le \overline{\varepsilon}_{1i} \\ r_{FIO1-j} > \overline{\varepsilon}_{1j}, \forall j \ne i \end{array}\right\} \Rightarrow \text{the i - axis actuator fault}, j,\ i = 1, 2, 3$$

When the detection result is that the gyro has a fault, FIO2 is activated, which also includes three fault isolation observers and $r_{FIO2-i}, i = 1, 2, 3$ is the residual evaluation function of the isolation observer designed to diagnoses the ith gyro fault, and $\overline{\varepsilon}_{2i}, i = 1, 2, 3$ is the corresponding threshold value, then

$$\left.\begin{array}{l} r_{FIO2-i} \le \overline{\varepsilon}_{2i} \\ r_{FIO2-j} > \overline{\varepsilon}_{2j}, \forall j \ne i \end{array}\right\} \Rightarrow \text{the ith gyro fault}, j,\ i = 1, 2, 3$$

Thus, the key components of the satellite attitude control system, including actuators, gyros and the star sensor, can be detected and isolated with the reasonable observer design.

7 Conclusions

In this paper, the traditional quantitative method-based fault diagnosis method is summarized and the difficulty of this method is analyzed. Furthermore, quantitative model-based fault diagnosis methods are redefined, and diagnosis solving process is studied. Finally, quantitative model-based fault diagnosis structural strategy which can isolate the faults of actuator and sensor with reduced analytical models is proposed and the corresponding analysis for diagnosis result is also presented.

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