Research and Realization of Sensor Fault-tolerance of Fusion Diagnosis System Using Evidence Redistribution

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Abstract – Abnormal sensor signals may cause missed diagnosis in the fusion fault diagnosis system based on evidence theory. To diagnose the fault in time with abnormal sensor signals, fault-tolerance is required. An evidence redistribution method is proposed for the sensor fault-tolerance of fusion diagnosis system. The evidences directly calculated from sensor characteristic parameters are updated by an evidence redistribution function. Fusion experiments are done on the hardware experimental platform for vibration isolation. The diagnosed fault is vibration divergence. The fusion diagnosis results on the situations of misconnection, disconnection, multichannel abnormity and normal sensor signals are analysed and compared. Experimental results show that the evidence redistribution method can solve the sensor fault-tolerance problem effectively.

Keywords: evidence theory, fusion diagnosis, sensor fault-tolerance, evidence redistribution, vibration isolation.

1 Introduction

Sensor signals may go wrong during the process of information fusion. Abnormal sensor signals can cause the fused information fault. On the other hand, high accuracy and real-time are required in the fusion processes, which need accurate judgment of the fusion object before finding the problem of information source. This puts forward the requirement of fault-tolerance of information fusion.

There have been some researches about fault-tolerance of information fusion. Clouqueur, Saluja and Ramanathan [1] researched the collaborative sensor network for target detection and proposed two algorithms, value fusion and decision fusion. The algorithms make the decision superior. Sun and Deng [2] designed a general multisensor optimal information fusion decentralized Kalman filter with two-layer fusion structure, which has fault tolerance and robustness properties when some sensors are faulty. An on-line adaptive weighted fusion algorithm based on fault-tolerance for the sensitive skin structure of intelligent robot was developed by Cao, Fu, Wang et al. [3]. Chen and Wang [4] proposed another fault-tolerant algorithm using neural network in integrated navigation system. A genetic optimization procedure was proposed to research the fault-tolerant schedules using genetic algorithms by Mok, Kwong and Wong [5]. In 2008 the fault-tolerance research was detailedly reviewed by Zhang and Jiang [6]. Li, Li and Chu [7] presented a fault-tolerant fusion method determining the weighted value based on correlation function, with no need of prior knowledge. The condition of uncorrelated noises is the limitation of this method.

In the theoretical research of fault-tolerance using evidence theory, Li, Zhu and Li [8] proposed a fault-tolerant interval integration method on the basis of Marzullo method. The method can guarantee a smaller output interval and satisfies local Lipschitz condition, providing the output interval reliability.

Evidence theory is an uncertainty theory. It does not require prior knowledge and can deal with the uncertainty caused by indeterminacy and unknowness. These make evidence theory an effective method of information fusion and often used in fault diagnosis process.

Recently fault diagnosis based on evidence theory has been wildly used to many engineering objects, such as gearbox [9], induction monitor [10], sensor network [11], engines [12, 13] and highway bridge [14].

However, the fault-tolerance in fault diagnosis system based on evidence theory has been rarely researched.

Fault-tolerance of fusion diagnosis process based on evidence theory is researched in this paper. We have realized the real-time diagnosis for the vibration divergence fault. Using evidence theory, the diagnosis system fuses the vibration signals from the multisensors. On this basis, an evidence redistribution method in the form of variance index is designed for the sensor fault-tolerance of fusion system. The method is also verified on the hardware experimental platform for vibration isolation.

The rest of the paper is organized as follows. Theoretical basis of fault diagnosis based on evidence theory is briefly presented in section 2. Section 3 introduces the vibration divergence fault. Section 4 presents the process of fault diagnosis. The method for the sensor fault-tolerance problem is designed in section 5. Section 6 illustrates the sensor fault-tolerance experimental results and the paper concludes with section 7.

2 Theoretical basis

2.1 Evidence theory

The mathematical theory of evidence was introduced by Dempster in 1967 and extended by Shafer in 1976 [15]. Let finite set Θ be the frame of discernment. The set consisting of all the subsets of Θ is called the power set of Θ, denoted by $\Omega(\Theta)$. Basic Probability Assignment (BPA) function is defined as $m:\Omega(\Theta)\rightarrow[0,1]$, such that: ① $m(A)\geq 0,\forall A\in\Omega$ ② $m(\phi)=0$ ③ $\sum_{A\subseteq\Omega}m(A)=1$. $m(A)$ expresses how strongly the evidence supports the set A.

In evidence theory, the process of fusion is realized by combining multisource evidences. Let m_1 and m_2 be the two BPAs of one frame of discernment. The degree of evidence conflict is defined as

$$K=\sum_{A\cap B=\phi}m_1(A)m_2(B) \tag{1}$$

Dempster's rule of combination is the most basic and widely used rule of evidence combination:

$$m_D(C)=\begin{cases}\frac{1}{1-K}\sum_{A\cap B=C}m_1(A)m_2(B) & \forall C\subseteq\Omega, C\neq\phi\\ 0 & C=\phi\end{cases} \tag{2}$$

2.2 Fault diagnosis based on evidence theory

Fault diagnosis based on evidence theory needs to extract characteristic parameters, form the frame of discernment and BPAs, calculate fused BPA using combination rule, and diagnose faults according to the fusion result. BPAs, the input of fault diagnosis process, can be given by experts or calculated directly.

This paper uses a calculation method based on information source to get the objective evaluation of BPAs. Most of the frame of fault discernment is formed referring to Basir's method [13]. However, the Minkowski distance between S_k and X_j is reconstructed as:

$$d_{kj}=\begin{cases}\left[\sum_{i=1}^{m_k}\left(\frac{s_{ki}-x_{ji}}{x_{ji}}\right)^{\alpha}\right]^{1/\alpha} & k=1\\ \left[\sum_{i=1}^{m_k}\left(\frac{s_{ki}-x_{j\left(i+\sum_{l=1}^{k-1}m_l\right)}}{x_{j\left(i+\sum_{l=1}^{k-1}m_l\right)}}\right)^{\alpha}\right]^{1/\alpha} & k=2,3,\cdots,M\end{cases} \tag{3}$$

The meaning of the symbols in formula (3) is similar to those in reference [13]. Formula (3) is different from the distance defined in Basir's method. This form of distance has clear ordinals of features. The normalization form shows the process of calculating BPAs from characteristic parameters directly.

3 Vibration divergence fault

Vibration divergence is a common fault in vibration systems. It can be caused by the faults from mechanical structures, control law, external disturbance and so on. In this paper, a typical vibration mechanical system — vibration isolation is studied to research the sensor fault-tolerance of the fusion diagnosis of vibration divergence fault.

3.1 Structure of vibration isolation

The hardware experimental vibration isolation system is composed of vibration exciter, load, vibration isolator, base and elastic foundation [16]. The structure diagram is illustrated in fig. 1. The object of the system is to reduce the vibration transferred from the load to the base.

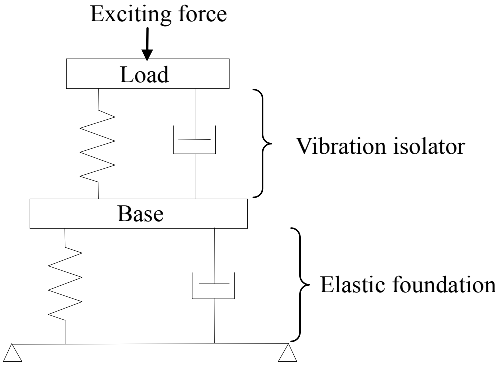

Fig. 1 Structure diagram of vibration isolation

Multisensor data measured during the system operation is adopted. Acceleration of the load is measured by the impedance head. Acceleration of the base is acquired from the acceleration sensor while the displacement sensor outputs the relative displacement of the load and base. The frequencies of the three sensors are all 1000Hz.

3.2 Fault symptom

During the experiment, the vibration exciter gives the sinusoidal exciting force to the load, making the load vibrate. In the normal operation, the electromagnetic actuator in the isolator generates force to reduce the vibration transferred to the base. If the vibration increases continuously, it means the vibration isolation system has divergence fault. The fault symptoms are the increments of the sensor signals' amplitudes. Fig. 2 shows a typical divergence fault in an experiment with the vibration frequency at 7Hz. The pulse at about the 4th second in the base acceleration curve is caused by the start of the vibration isolation control process.

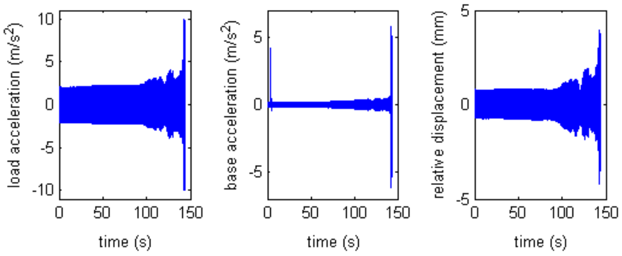

Fig. 2 Sample data of sensors when vibration isolation system had vibration divergence fault

From fig. 2 it can be seen that the amplitudes of load acceleration, base acceleration and relative displacement began to increase quickly at about the 100th second. Divergence fault symptoms appeared. The severe vibration caused collision and abnormal voice of the equipments. The experimenters found the divergence fault by their experiences in time and shut off the instruments at the 143rd second.

4 Fault diagnosis

4.1 Fault characteristic parameter

A suitable fault characteristic parameter can make the diagnosis result accurate and effective. Through several experiments, the forward quotient of the variances, defined in formula (4) is chosen as the characteristic parameter x of the vibration divergence fault.

$$x = \frac{CurVar}{OriVar} \tag{4}$$

$CurVar$ and $OriVar$ denote the variance of the latest 1000 samples in each second and the variance of the 1000 samples one second ago respectively.

4.2 Forming the discernment frame

There are three sensors in the vibration isolation system. Each sensor offers one measured value. Normal running without fault and the vibration divergence fault are the two states.

The forward quotient of the variances is chosen as the characteristic parameter. Let $\alpha = 2$ in eq. (3) and the distance converges to the Euclidean distance.

Suitable state parameters are selected after analyzing the effect of fault diagnosis and the BPA matrix can be got using the method in section 2.

4.3 Fusion diagnosis

According to Dempster's rule of combination, each row vector of the BPA matrix P should be fused. The calculation result BPA represents the evidence of the fault supported by the three sensors' fusion. The threshold value is set 0.5. If the BPA is higher than 0.5, it means the vibration divergence fault occurs. Otherwise, the vibration isolation system is in normal state.

We have programmed to realize the real-time fusion and monitoring process above. The monitoring interface of the fault in fig. 2 is shown in fig. 3.

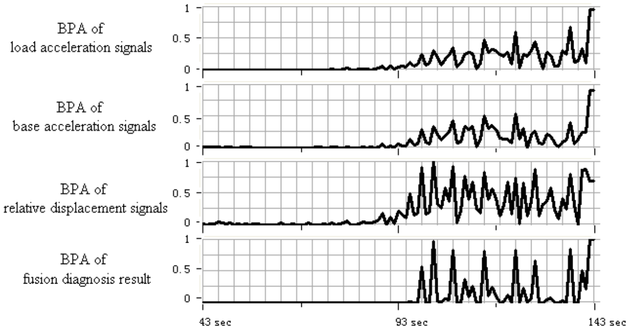

Fig. 3 Monitoring interface of vibration divergence fault in vibration isolation system

There are four monitor windows on the interface. The above three ones display the BPAs curves calculated from load acceleration, base acceleration and relative displacement respectively. The monitor window at the bottom of the interface shows the fusion BPAs curve. The lateral axis is time axis. The BPAs update at each second and the monitoring curves move forward over time. This program can also replay the monitoring process.

5 Sensor fault-tolerance of diagnosis system

The fusion diagnosis method can operate normally and give reasonable results depending on correct sensor signals. However, when there are some sensor signals faults, such as misconnection and disconnection, the fusion outcome may also be incorrect.

5.1 Sensor fault-tolerance problem

We have misconnected other signals to the fused signals. There also have been disconnections in the hardware, leaving only noises in the sensor signal channels. When these occurred, the fusion result may be wrong.

Fig. 4 shows the monitoring interface of one existing misconnection. The reference signal (fig. 5), a signal in vibration isolation control system, is misconnected to the base acceleration channel. To make comparison with the original fusion method, the divergence fault in fig. 2 is chosen.

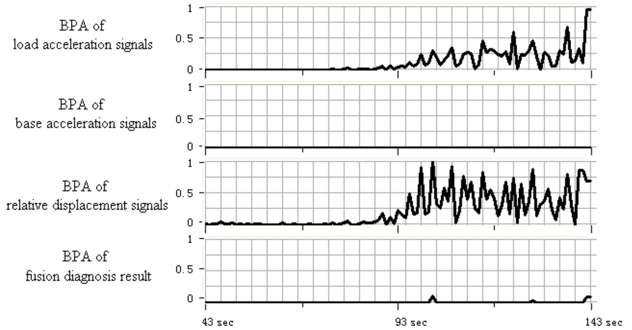

Fig. 4 Monitoring interface of misconnection

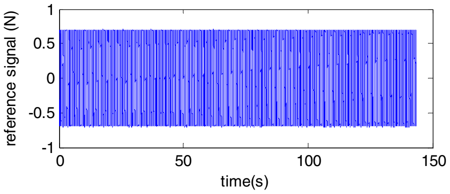

Fig. 5 Reference signal

It can be seen that the BPAs calculated from the "base acceleration" are close to 0, meaning there is no fault throughout the monitoring process, although the vibration divergence fault has appeared at the late stage. As a result, the fusion BPA is also close to 0, causing missed diagnosis.

Although the sensor signals are abnormal, the operation of vibration isolation system still needs to be monitored and the vibration divergence fault should be diagnosed in time. These make sensor fault-tolerance a supportable attribute.

In this paper, the sensor signals' faults are constrained as follows:

(1) Sensor signals' faults exist in the fusion diagnosis system, such as misconnection and disconnection.

(2) There is one normal channel at least.

(3) It is unknown that which sensor's signal is abnormal.

5.2 Evidence redistribution

On this basis, it can be found that the existing hardware sensor signals' faults have a common feature: the amplitude of abnormal signals is obviously lower than normal signals. This makes variance a good choice for describing the information and distinguishing the normal and abnormal signals. Then the evidences, calculated from the sensors separately, can be redistributed based on the variance and fused in order to get reasonable diagnosis result.

According to the fault diagnosis system of the vibration isolation, the principles of evidence redistribution are formulated as follows:

(1) The importance degree of information source should be positive correlated to the variance of the signals.

(2) Information source with lower degree of importance, which means sensor signals' faults occur, has a BPA representing almost ignorance. In this paper, the state number is 2, so the ignorance BPA is 0.5.

(3) Information source with higher degree of importance means the signals are normal, so the BPA should change little.

(4) The "nearly abnormal" BPAs should be close to 0.5, while the "nearly normal" BPAs should be close to the BPAs before redistribution.

In the fault diagnosis realization, the mean value of sensor signals is set equal to the zero value. However, sometimes offsets may affect the calculation. To avoid the undesirable effect, we define a redistribution transition coefficient $t_i, i=1,2,3$:

$$t_i^* = \frac{\sqrt{Var_i}}{AbsMean_i} \tag{5}$$

$$t_i = \frac{t_i^*}{\sum_i t_i^*} \tag{6}$$

where Var_i represents the variance of the i-th sensor's signals and $AbsMean_i$ is the mean value of the absolute value of all the i-th sensor's signals.

The redistribution transition coefficient t_i reflects the relative reliability of the i-th fused signal, $i=1,2,3$.

According to the redistribution transition coefficient, the redistribution power function is formed:

$$m_i^* = \frac{1}{2}\left(2m_i\right)^t \tag{7}$$

where

$$t = \sqrt[n]{t_i} \tag{8}$$

and n is an adjustable parameter.

In the vibration isolation system mentioned above there are three signal channels, so the BPAs should change little when $t_i > 1/3$, and sharply down close to 0 along with $t_i < 1/3$ and t_i close to 0. Through experiments and analysis, $n=4$ is appropriate.

6 Experiments of sensor fault-tolerance

Experiments are done to verify the effectiveness of the sensor fault-tolerance evidence redistribution method. In order to make comparisons, the fusion process of a typical vibration divergence fault, as shown in fig. 2, is studied and the following sensor fault-tolerance experiments are all carried out on it.

6.1 Misconnection

Misconnection is an occasional mistake in multisensor systems. However, its negative influence is significant, especially when the timeliness is needed.

We study one occurred misconnection, fusing reference signals in the control system as the base acceleration signals by mistake, as referred in section 5.1. The monitoring interface with un-redistributed evidence is shown as fig. 4.

Fig. 6 shows the monitoring interface with evidence redistribution. To show the redistribution process, the three windows above show the redistributed BPAs rather than un-redistributed ones.

The effectiveness of evidence redistribution is clearly. The fusion BPAs show the correct diagnosis results in time.

It should be explained that, although the redistributed BPAs is different from original ones, they are just transition values.

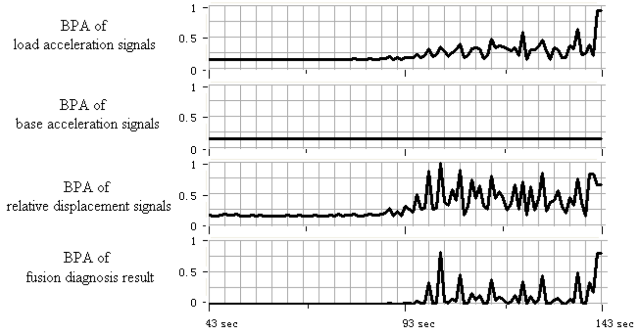

Fig. 6 Monitoring interface of misconnection with evidence redistribution

The following interface's windows arrangement is same as this evidence redistribution experiment.

6.2 Disconnection

Disconnection is another common mistake in multisensor systems. When some channels are imperceptibly disconnected, the leaving signals are noises. This causes the divergence fault signals' amplitudes small in the disconnection channels while they should be large. Therefore, the disconnection signals' variances are small and change little even if the divergence fault occurs. This leads the sensors' BPAs and the fusion BPAs all close to 0. The vibration divergence fault is missed diagnosed.

To show the general status, the disconnection channel signal is simulated using white Gaussian noise, as shown in fig. 7.

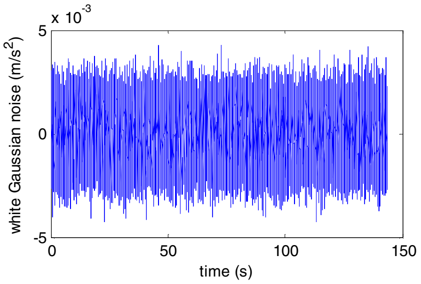

Fig. 7 White Gaussian noise

To make comparisons, the base acceleration channel is also chosen as the disconnection channel. Monitoring interfaces with un-redistributed evidence and redistributed evidence are shown in fig. 8 and fig. 9 respectively.

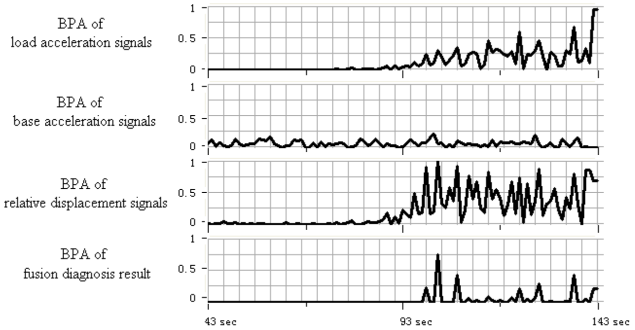

Fig. 8 Monitoring interface of disconnection with evidence un-redistribution

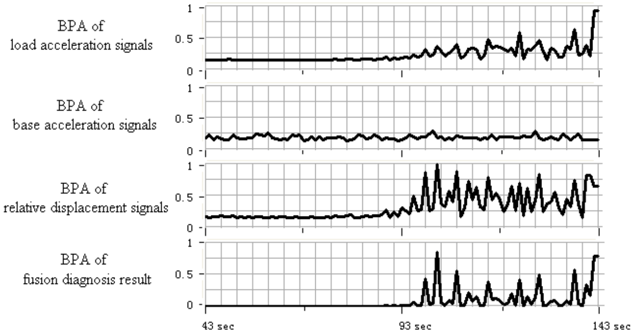

Fig. 9 Monitoring interface of disconnection with evidence redistribution

The advantage of evidence redistribution in sensor fault-tolerance is same as in the misconnection.

6.3 Multichannel abnormity

Sensor fault-tolerance of multichannel abnormal is also verified. The signals of load acceleration and base acceleration are replaced by the reference signal (fig. 5) and noise signal (fig. 7) respectively. Fig. 10 shows the monitoring interface.

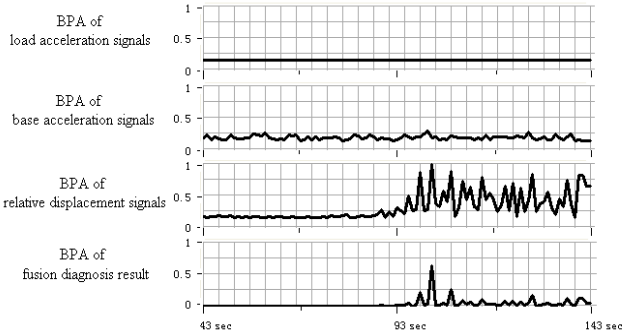

Fig. 10 Monitoring interface of mulichannel abnormity with evidence redistribution

Although the fusion result does not determinately diagnose the vibration divergence fault, the advantages in sensor fault-tolerance can also be found. Compared with the un-redistribution fusion results shown in fig. 11, the change of the fusion BPA curve in fig. 10 after the 100th second indicates some fault may exist and shows the sensor fault-tolerance attribute.

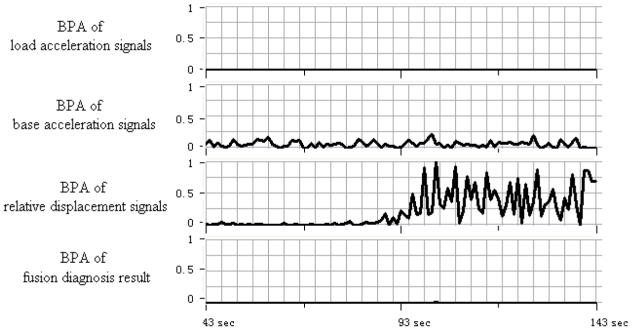

Fig. 11 Monitoring interface of mulichannel abnormity with evidence un-redistribution

Other experiments of multichannel abnormity cases are also done. The results are similar with those in fig. 10 and fig. 11.

6.4 Normal signals

The performance of the evidence redistribution method in sensor signals normal transportation also need considering. The experiment signals, as shown in fig. 2, are fused with the evidence redistribution method. Comparing the monitoring interface (fig. 12) with the traditional one (fig. 3), it can be seen that the evidence redistribution does not affect the fault diagnosis result.

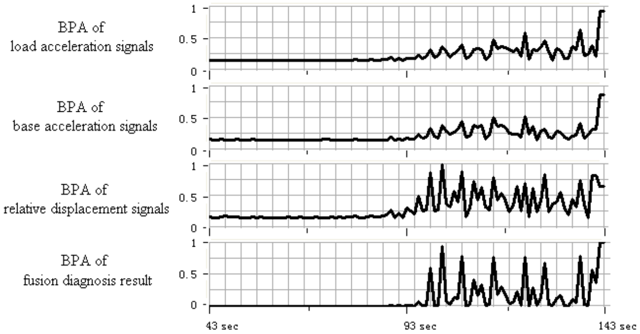

Fig. 12 Monitoring interface of the three normal signals with evidence redistribution

6.5 Summary

The sensor fault-tolerance fusion diagnosis system's performances in the case of misconnection, disconnection and multichannel abnormity are presented in this section. To make comparison, the experiment in the sensor normal status has also been done. The results show that:

(1) The evidence redistribution method can deal with the mentioned sensor fault-tolerance problems effectively.

(2) The method has no adverse effect on the sensor signals normal status.

This summary is also suitable for the similar vibration divergence faults as fig. 2 shows. Due to the space limitations, other experiment results are not listed.

7 Conclusion

Sensor fault-tolerance is needed in the fusion diagnosis system for the vibration divergence fault. To solve this problem, an evidence redistribution method is proposed. A redistribution transition coefficient is calculated to reflect the relative reliability of the fused signals. The redistribution function is formed to recalculate the fused BPAs, using the evolution of the redistribution transition coefficient as the index. Experiments are carried out on the hardware experimental platform for vibration isolation. The conditions of sensor misconnection, sensor disconnection, multichannel abnormity and normal sensor signals are considered. From the monitoring interfaces, it can be concluded that the evidence redistribution method can solve the sensor fault-tolerance problem efficiently with no adverse effect on normal sensor signals. The evidence redistribution method to the fusion process can avoid the missed monitoring, increasing the fault-tolerance and robustness of the fusion diagnosis system. Although this method is tested for the vibration divergence fault, it can be extended to other fusion areas based on evidence theory.

In the future research, we will use this evidence redistribution idea to other fault diagnosis process. Proposing a universal fault diagnosis method with fault-tolerance in multisensor fusion is our aim.

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