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Research on health evaluation system of liquid-propellant rocket engine ground-testing bed based on fuzzy theory

Zhigang Feng*, Qi Wang

Department of Automatic Measurement and Control, Harbin Institute of Technology, P.O. Box 351, 92 Xidazhi Street, Harbin 150001, China

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Abstract

In this paper, the theory based on multi-sensor information fusion is studied, which is used to evaluate the health condition of liquid-propellant rocket engine ground-testing bed. The concept of health degree is defined. It is used as a quantitative index for evaluating the health condition of the ground-testing bed. In order to evaluate the health condition of the ground-testing bed on different levels, health degrees of a single parameter, of a sub-system and of a system are defined. They accordingly measure the health conditions of single parameter, sub-system and system of the ground-testing bed. The method of fuzzy data fusion is used to calculate the health degree. In this method the weight of each monitoring sensor is calculated by analytic hierarchy process (AHP), then, the multi-sensor data are fused by the fuzzy comprehensive evaluation method, next, the sequence data are fused by two-grade index evaluation method, finally, the health degree is calculated by defuzzification method. Based on these, the health condition evaluation system of ground-testing bed is set up, which can evaluate the health condition of the ground-testing bed properly and quantitatively. At last, the application of the health evaluation system in fault detection and health evaluation of the ground-testing bed are discussed.

Keywords: Ground-testing bed; Health evaluation system; Data fusion; Fuzzy comprehensive evaluation; Health degree

1. Introduction

Liquid-propellant rocket engines (LRE) are the heart of space vehicles and space transporting systems [1]. After a rocket engine is produced, in order to check out whether the rocket engine fulfills the design requirements, it should be tested on the ground-testing bed. For example, the space shuttle main engine (SSME) is periodically acceptance tested by firing it on the ground using test bed located at NASA Stennis Space Center. The test bed provides a structure strong enough to hold a rocket engine in place as it is fired, and a fuel feed system to provide fuel and oxidizer to the engine. Usually, the fuel is liquid hydrogen and the oxidizer is liquid oxygen. In the ground-testing process, it is clear that if there are any faults in the test bed, it will provide fuel and oxidizer for the rocket engine improperly. The rocket engine will work abnormally or even will be destroyed. So it is very necessary and important to detect anomalies of the ground-testing bed so as to decrease the bad effects of its faults to the rocket engine.

The current approach to detecting anomalies in ground-testing bed sensor data is to use large numbers of human experts. Test controllers watch the data in near-real time during each test. Engineers study the

* Corresponding author. Tel.: +86 0451 8641 5440x16; fax: +86 0451 8641 3621x12.
E-mail addresses: fzg1023@yeah.net, fengzhigang@hit.edu.cn (Z. Feng).

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data after each test. These experts are aided by limit checks that signal when a particular variable goes outside of a predetermined range. The current approach is very labor intensive. Also, humans may not be able to recognize faults that involve the relationships among large numbers of variables. Further, some potential faults could happen too quickly for humans to detect them and react before they become catastrophic.

In order to realize the automating anomaly detection of test bed, the researchers of NASA Ames Research Center explore a particular data-driven approach, which is based on anomaly detection algorithms from the machine learning community. They give the initial results of applying two machine-learning-based unsupervised anomaly detection algorithms, Orca and GritBot, to data from two rocket propulsion test beds [2].

In order to fulfill the requirements for a next-generation rocket test facility, John Schmalzel and his colleagues implement elements of a prototype intelligent rocket test facility. The initial results establish a basis for future advanced development and validation using the rocket test stand facilities at Stennis Space Center (SSC) [3].

In this paper, we extend the anomaly detection of ground-testing bed to health condition evaluation of ground-testing bed by using fuzzy data fusion method. It can not only be used to anomaly detection, but also for health evaluation of the ground-testing bed. Firstly, we define the concept of health degree. It is used as a quantitative index for the health condition evaluation of the ground-testing bed. In order to evaluate the health condition of the ground-testing bed accurately and on different levels, health degrees of a single parameter, of a sub-system and of a system are defined. Next, we propose the calculating method of the health degree and set up the health condition evaluation system of the ground-testing bed. Finally, we apply the health evaluation system in fault detection and health evaluation of the ground-testing bed.

2. Definition of health degree

Health degree is a quantitative index. It is used to measure the health condition of the ground-testing bed quantitatively. Health degree of a single parameter measures the health condition of a single monitoring parameter on the ground-testing bed, such as the health degree of Pohr. Health degree of a sub-system measures the health condition of a sub-system on the ground-testing bed, such as health degree of the liquid hydrogen supercharging system. Health degree of a system measures the health condition of the whole ground-testing bed.

Suppose there are p monitoring parameters on the ground-testing bed, and the measured data of the ith parameter are $X_i = (x_{i1}, x_{i2}, \ldots, x_{in})$, where n is the total number of data collected in one testing, then the health degree of the ith parameter is defined generally as [4]

$$\mathrm{HD}_i = f(X_i) = f(x_{i1}, x_{i2}, \ldots, x_{in}). \tag{1}$$

Suppose there are m $(m < p)$ monitoring parameters on the ith sub-system of the ground-testing bed, and the measured data of one testing are $X_1, X_2, \ldots, X_m$, where $X_i = (x_{i1}, x_{i2}, \ldots, x_{in})$, then the health degree of this sub-system is defined generally as

$$\mathrm{HD}_{\mathrm{sub}i} = F(X_1, X_2, \ldots, X_m). \tag{2}$$

Suppose there are k sub-systems of the ground-testing bed, and the health degree of the ith sub-system is $\mathrm{HD}_{\mathrm{sub}i}$. The health degree of system is defined generally as

$$\mathrm{HD}_{\mathrm{sys}} = g(\mathrm{HD}_{\mathrm{sub1}}, \mathrm{HD}_{\mathrm{sub2}}, \ldots, \mathrm{HD}_{\mathrm{sub}k}), \tag{3}$$

where HD_i is the health degree of the ith parameter. $\mathrm{HD}_{\mathrm{sub}i}$ is the health degree of the ith sub-system of the ground-testing bed. $\mathrm{HD}_{\mathrm{sys}}$ is the health degree of the ground-testing bed. The values of these three health degrees are all between 0 and 1. When the value is 0, the accordingly parameter, sub-system or the ground-testing bed is in severe fault state, otherwise, when the value is 1, accordingly the parameter, sub-system or the ground-testing bed is in complete healthy state. The more the value is nearer to 1, the healthier the system is.

Fig. 1 shows the health degree levels of the ground-testing bed. Health degrees of Pohr and Tohr are two examples of health degrees of a single parameter. They are calculated by fusing the sequence measured data of the parameter using two-grade index evaluation method. The health degree of liquid hydrogen providing system is an example of health degree of sub-system. It is calculated by fusing the measured data of the all parameters which affect the health condition of this sub-system. The health degree of ground test-bed is the health degree of system, which is calculated by fusing the health degrees of all the sub-systems.

3. Principles and calculating method of health degree

3.1. Principles of health degree

Because the concept of health is a fuzzy concept, and the set of health does not have certain extensions, it is