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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 11 (11): 1597-1604, 2012
ISSN 1812-5638 / DOI: 10.3923/itj.2012.1597.1604

Data-driven Health Evaluation of Multifunctional Self-validating Sensor Using Health Reliability Degree

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Abstracts: Aiming at the desired status self-validation of traditional multifunctional sensor, a novel multifunctional self-validating sensor functional model is proposed to improve the measurement reliability. Detailed self-validating functions are presented, especially the proposed health evaluation emphasized in this study. Being different from traditional fault diagnosis, it is improved from a quantitative perspective, in which a novel conception Health Reliability Degree (HRD) is defined to indicate the level. The HRD methodology is implemented by using the grey theory coupled with neural network-based multiple data fusion. The information entropy method is employed to obtain the weights distribution of each sensitive unit to indicate the distinct importance. A health evaluation experimental system of multifunctional self-validating sensor was designed to produce the actual samples and further verify the proposed methodology. Experimental results demonstrate that the proposed strategy could be used to indicate the health level quantitatively and provide a good solution to the health evaluation of multifunctional self-validating sensor.

Key words: Self-validating, health evaluation, health reliability degree, grey theory, multivariable fusion

INTRODUCTION

Multifunctional sensors are very important in modern production due to the advantages of detecting more measured components simultaneously. More sensitive units may cause more potential faults. In case failures come, the outputs with poor quality will brings negative influence on control and decision, even some major accident. To improve the reliability, the multifunctional sensor coupled with the advanced self-validating technology (Henry and Clarke, 1993; Henry, 2001) is proposed known as multifunctional self-validating sensor (Wang *et al*., 2010) and main contents are will recalled in following writing.

To avoid further performance degradation of multifunctional sensor, the research on health evaluation is extremely important. Based on some previous work (Feng *et al*., 2007; Feng and Wang, 2007; Feng *et al*., 2009; Shen and Wang, 2012; Shen *et al*., 2012; Wang and Zhao, 2011; Wang *et al*., 2012; Zhao *et al*., 2011), this study will centers on the health evaluation to help users comprehend the current health level as well as future performance degradation trend of multifunctional sensor. This novel self-validating function is also a supplement and extension of published self-validating sensor.

From a qualitative view, health state assessment could provide two or more health status (typically, health and fault) which is essentially a fault diagnosis. It is relatively simple, because many failure diagnosis methods have been proposed to solve this problem. However, more detailed health information could not be obtained in this way, especially from the global perspective of multifunctional sensor. Traditionally, some discrete Measurement Value Status (MVS) has been defined to indicate the working state of certain single-sensitive component. These states are defined based on expert experience; however, it is absence of a set of universal theory. Therefore, a quantitative health evaluation by applying reasonable health evaluation methodology may emerge as it can directly manifest the health degree.

From a quantitative view, however, the problem will become far more difficult. That is because the quantitative health level analysis of multifunctional self-validating sensor involves not only the health level of each sensitive unit itself, but relates to their distinct weight distribution. In general, this problem itself belongs to the complex multivariable data fusion (Mitchell, 2007). The multi-sensor data fusion method has been studied by many researchers. This study make such an improvement from qualitative health diagnosis to quantitative health level evaluation to develop the traditional self-validating function which would also provide more detailed health information for users.

One of the most important contents in this study does build a set of suitable methodology for quantitative health evaluation. The grey evaluation theory coupled

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with multivariable data fusion method can be adopted to implement this task. The grey theory has been applied commonly to qualitative scheme assessment (Tung and Lee, 2010). It is mainly used in incomplete information. The multifunctional sensor connotes a grey system due to certain known parameters such as the different measured objects and their corresponding outputs. However, there are still more parameters unknown because of their inner detailed or complex structure. Sometimes, the invisible changes of the structure are exactly the main reason why its health performance degrades. In addition, the quantitative health level evaluation itself is a grey estimation problem, because it is just an approximate evaluation, not a real performance level.

Although the reliability of sensor is studied by many scientist and some self-validating prototypes have been developed, there is little research about the quantitative health evaluation of multifunctional sensor to enrich self-validating function. Present study is supported by the National Natural Science Foundation of China (No. 60572010 and No. 60572010) and Specialized Research Fund for the Doctoral Program of Higher Education (No. 200802130020).

MULTIFUNCTIONALSELF-VALIDATINGSENSOR

Multifunctional self-validating sensor inherits the merits of both multifunctional sensor and self-validating function which plays an important role in improving reliability of sensor itself and enhancing the safety in industrial production. The self-validating functions mainly include the Failure Detection, Isolation and Recovery (FDIR), validated uncertainty estimation, validated measurement value status indication, health evaluation and forecast. Detailed description of the functional models (Wang *et al*., 2010) is shown in Fig. 1 which is composed of multifunctional sensor, signal pretreatment, input interface involving auxiliary signal and known historical information and processor which are used to implement above self-validating functions and output interface.

FDIR: FDIR is a key part of multifunctional self-validating sensor. If faults appear, the incorrect measurements should be replaced with a best evaluating value of true value in order to ensure the normal working of the corresponding systems. The data recovery results are then as the inputs of signal reconstruction and the reconstructed outputs are also called as Validated Measurement Value (VMS). Once FDIR is accomplished, detailed fault information can be provided such as what type of, when and where faults occur.

Validated uncertainty (VU) evaluation: The uncertainty evaluation is used to reflect the accuracy of measurement value. Being different from the traditional static uncertainty evaluating method, the self-validating sensor is built on the online uncertainty evaluation and dynamic process. The different faults will bring different negative effects to VU, so, the FDIR results should be fully considered.

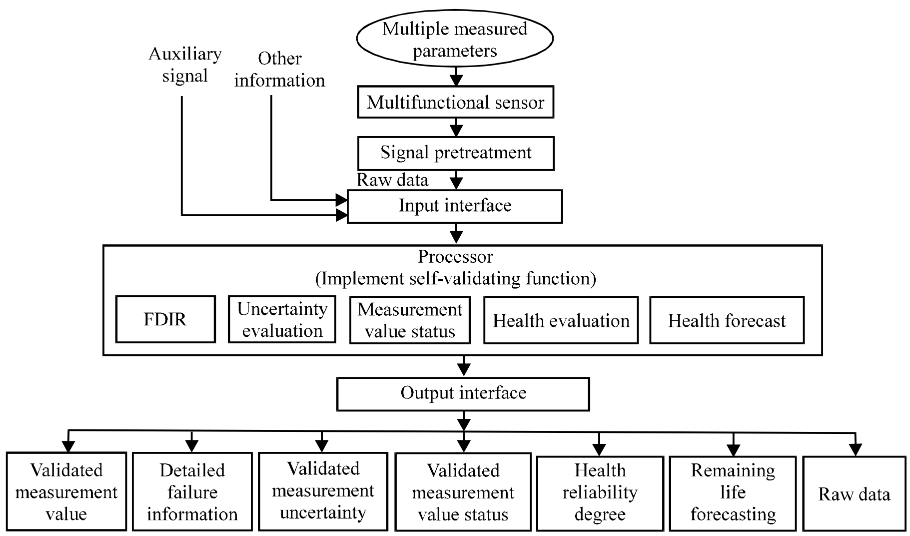

Fig. 1: Functional architecture of multifunctional self-validating sensor

Validated measurement value status: Professors from Oxford University present five qualitative MVSs to make users understand the current health state in 1993. The status is some discrete values which is subjective to definition of humans. The multifunctional self-validating sensor reserves above advantages and provides the MVS for every sensitive unit.

Health evaluation: The health evaluation of multifunctional self-validating sensor provides the device status from the overall perspective. More detailed health level information of overall multifunctional sensor itself should also be known by users. A new quantitative health evaluation emerges as it can manifest the detailed health level which is emphasized in this study. The health evaluation of multifunctional self-validating sensor is generalized as evaluating the reliability. Based on the idea of quantitative health level proposed by authors, the corresponding self-validating function will output health reliability degree.

Health forecast: Forecasting the future health level is necessary in order to remind users to take precautionary measures to improve its reliability. The self-validating function is also a supplement to the exiting self-validating sensor. From a detailed way, the health forecast issue can be summarized as the evaluation of the Remaining Useful Life (RUL). Once the health evaluation level at different time point is obtained, the change trend of performance can be forecasted though the time series analysis.

To sum up, the proposed multifunctional self-validating sensor centers on the reliability and aims at resolving some key issues, how to evaluate its health reliability degree, how to improve its health reliability level once it is faulty and how to forecast its health reliability level.

A NOVEL HEALTH EVALUATION STRATEGY

Health is defined as an extent of degradation or deviation from certain expected state, so the health evaluation is built on the expected health levels. The proposed Health Reliable Degree (HRD) is a comprehensive variable as a quantitative index. Due to much existent sensitive units, the health evaluation of multifunctional sensor has been extended into the overall sensor. Therefore, the proposed quantitative health level idea is used to reflect sensor performance changes, in which information fusion of multiple sensitive units is essential to implement the novel HRD. By using historical HRDs, the further health forecast can be done as our next study which plays a more important role in industrial production.

Definition of health reliable degree: The range of HRD lies between 0 and 1, in which the state 0 indicates that the multifunction sensor is completely faulty, state 1 is extremely healthy and intermediate values represents different health levels. Therefore, more detailed health information can be acquired through HRD.

Four performance degradation stages of multifunctional sensor are defined as Health State (HS), Sub-Health State (SH), Marginal Failure State (MF) and Failure State (FS), respectively which can be regarded as evaluating criterions of grey theory. The corresponding relationship between HRD and health degradation stages is defined in Table 1.

The multifunctional sensor in HS is very healthy, each sensitive unit is also healthy and their measured data are nearly close to the true value. The following SH is an intermediate state between HS and MF, the outputs of certain sensitive unit may fluctuate around their true values within the normal ranges, so, it is reliable to some extent. Commonly, most situations are in HS or SH. The MF state is nearly a failure, some sensitive components are faulty and their measured data have deviated from their true values, but no deviation completely. The multifunctional sensor in FS is invalid, most sensitive units are faulty and the measurements have completely deviated from their true values, so, it is totally unreliable.

By using the proposed grey evaluating model, their corresponding attached parameters to above four evaluating criterions are not difficult to obtain which are called as the Belonging Relationship Degree (BRD). The comprehensive HRD can be further implemented by using the multi-variable data fusion of these parameters. From Table 1, the relationship between BRD and HRD is shown in Fig. 2. The multiple variables mapping is implemented by using Back-propagation Neural Network (BPNN). Four BRDs under four performance degradation stages of multifunctional sensor is taken as the inputs of BPNN model and the fused output is exactly the HRD. The number of the hidden layer of BPNN has selected as 10 and the Levenberg-Marquardt optimization procedure is selected as the training function because it is the fastest back-propagation algorithm in the toolbox. The above multivariable fusion process can be expressed as:

$$HRD = f\,(brd_{HS}, brd_{SH}, brd_{MF}, brd_{FS}) \tag{1}$$

Table 1: Relationship between HRD and health degradation stages

HRD: Health reliability degree	Health stages
(0.9, 1.0)	HS: Health state
(0.7, 0.9)	SH: Sub-health state
(0.2, 0.7)	MF: Marginal failure state
(0.0, 0.2)	FS: Failure state

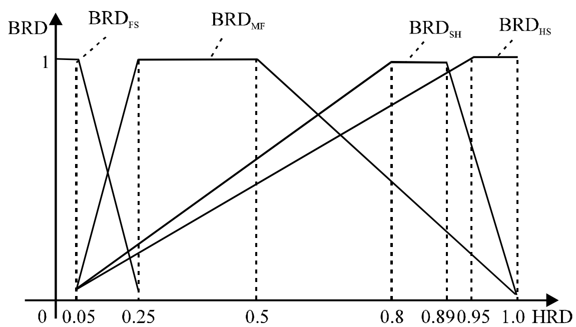

Fig. 2: Relationship between BRD and HRD

As an example, if the sensor is in HS and SH, it is fault free; the FDIR is needed once it is in MF and the sensor must be exchanged if it is in FS. The HRD itself is open or extensible. By using the proposed idea, the evaluating criterions can be extended from four into more classes if necessary and HRD results may be more concrete.

Computing feature parameters BRD: The feature parameters BRDs are acquired by using the proposed grey evaluation method. Coupled with above HRD computation, the novel strategy can be implemented by providing the quantitative health level. The correlation among multiple parameters has been fully considered for the weights distribution of different sensitive units which is different from the traditional evaluating methods. Detailed steps are as follows:

Establishing the grey evaluating criterions: To accurately distinguish the health hierarchy, four performance degradation stages (HS, SH, MF and FS) are treated as the grey evaluating criterion sets.

Determining the whitening function of the grey model: The actual outputs of each sensitive unit have a mapping to the above four evaluating criterion sets. If certain sensitive unit is not in FS, the measured outputs are closer to the true values, the grey BRD will become higher and so will be the corresponding health level. The BRD is 1 if the measurement value is in the allowed fluctuating range while BRD is assumed to be decreased linearly if the measurement is out of above range.

Computing grey sample evaluating (GSE) matrix: By using the established whitening functions under different evaluating criterions, the GSE matrix can be obtained. The GSE matrix of multiple sensitive unit at single time point can be expressed as $GSE_j = (ges_{nk})_{m\times n}$ (i = 1, 2,..., m; k = 1, 2,..., n) shown in Eq. 2.

$$GSE_j = \begin{array}{c} \\ S_1 \\ S_2 \\ \vdots \\ S_m \end{array} \begin{array}{c} \begin{array}{cccc} I_1 & I_2 & \cdots & I_n \end{array} \\ \begin{bmatrix} a_{1j1} & a_{1j2} & \cdots & a_{1jn} \\ a_{2j1} & a_{2j2} & \cdots & a_{2jn} \\ \vdots & \vdots & & \vdots \\ a_{mj1} & a_{mj2} & \cdots & a_{mjn} \end{bmatrix} \end{array} \quad (2)$$

where, j represents the time point, S_i (i = 1, 2,..., m) indicates all the sensitive units of multifunctional sensor and I_k (k = 1, 2,..., n) is still the evaluating criterion.

Deciding weights by using information entropy: As for HRD computation of overall multifunctional self-validating sensor, the health evaluation assignment is implemented at single time point. It only needs objective weight of each sensitive unit to indicate its information importance which can be well expressed by using the information entropy method (Yi and Zhu, 2010). The objective weight of each sensitive unit is obtained as follows:

Firstly, construct grey evaluating matrix GSE = $(GSE_{ik})_{m\times n}$ as shown in Eq. 2.

Secondly, compute the kth assessment criterion's probabilistic proportion P_{ik} of ith sensitive unit by using Eq. 3:

$$P_{ik} = \frac{gse_{ik}}{\sum_{k=1}^{n} gse_{ik}} \quad (i = 1, 2, \cdots, m;\ k = 1, 2, \cdots, n) \quad (3)$$

Thirdly, compute the information entropy E_i of the ith sensitive unit using Eq. 4:

$$E_i = -\frac{1}{\ln n}\sum_{k=1}^{n} P_{ik} \ln P_{ik} \quad (i = 1, 2, \cdots, m)$$
$$\text{subject to } P_{ik} \ln P_{ik} = 0 \quad \text{if } P_{ik} = 0 \quad (4)$$

Fourthly, compute the deviation G_i by using Eq. 5. The greater the output G_i is, the more important the sensitive unit is:

$$G_i = 1\text{-}E^i \quad (i = 1, 2, \cdots, m) \quad (5)$$

Lastly, compute the objective weight w_{ij} of the ith sensitive unit at the time point j by using equation 6 and then the weight vector $W_j = (w_{1j}, w_{2j}, \ldots, w_{ij}, \ldots, w_{mj})$ is determined correspondingly:

$$w_{ij} = \frac{G_i}{\sum_{i=1}^{m} G_i} \quad (i = 1, 2, \cdots, m) \quad (6)$$

Calculate the comprehensive grey assessment values under evaluating criterion sets: The weights W_j of multifunctional self-validating sensor at time point j have been obtained, then the comprehensive grey assessment values (CGAV) are computed by using Eq. 7. The CGAV represents the current health distribution under the above four grey health evaluating criterion sets and they are exactly the feature attached parameters in Eq. 1:

$$CGAV = W \times GSE \quad (7)$$

Computing HRD: The proposed health evaluation strategy can provide the qualitative assessment result as usual. The health state belongs to the health evaluating criterion which has the maximum of CGAVs. From the local and global way, the HRD is then calculated to describe the detailed health information by using Eq. 1.

EXPERIMENT AND RESULTS

To verify the effectiveness of the proposed methodology, the multifunctional self-validating sensor experimental system was designed to temperature, humidity and gas concentration. The experiment was conducted in the laboratory environment.

Experimental setup: Figure 3 shows the setup for multifunctional self-validating sensor experimental system. The system consisted of multifunctional sensor, data acquisition device, PC processor, power supply, gas chamber and gas sample. One temperature sensitive unit, one humidity sensitive unit and four gas sensitive units were included in the multifunctional sensor. The data acquisition assignment was done by using PCI-data acquisition board PCI-6014 made by National Instrument Corporation which included 16 analog inputs maximum up to 200 kHz sampling rate and supported 16 bits sampling accuracy. The gas chamber was sealed and made by the organic glass material, whose capacity was 50×20×10 cm. The above multifunctional sensor is fixed in this chamber. The power was provided by the dual-channel direct current supply DH1718E-5. The following health evaluation algorithm was implemented in PC with 2.4 GHz and 2 G RAM. The hydrogen was chosen as the gas sample whose concentration levels are 500~5000 ppm and it was injected into the chamber by a syringe. There was a fan which assured the uniform distribution of the gas in chamber.

This multifunctional self-validating system which is used to measure the hydrogen concentration, temperature and humidity components, can give their validated components even under some faults, provide the corresponding validated uncertainty to reflect the accuracy of validated measured components and present the validated measurements status to indicate the working state of every sensitive unit. Above self-validating functions has been studied in our previous achievements and the novel health evaluation is illustrated and verified here.

HRD analysis of multifunctional self-validating sensor: The HRD of multifunctional self-validating sensor means that the health evaluation is implemented from a global way, so it is related to all the sensitive units. In this section, three situations that represent different health levels would be introduced to verify the proposed strategy.

Situation 1

All the sensitive units are fault free: When the hydrogen concentration is 1000 ppm, the temperature is about 23.7°C and humidity is near 34.6% RH, the sensitive components are all fault free. Commonly, the health state should be in HS or SH and the validity of the proposed HRD methodology is then evaluated.

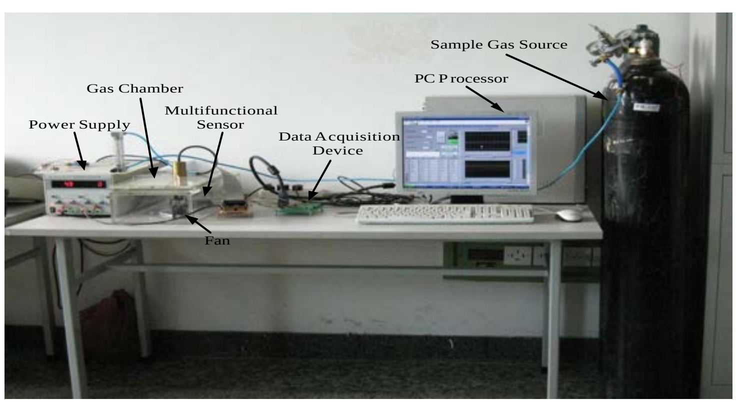

Fig. 3: Setup of multifunctional self-validating sensor experimental system

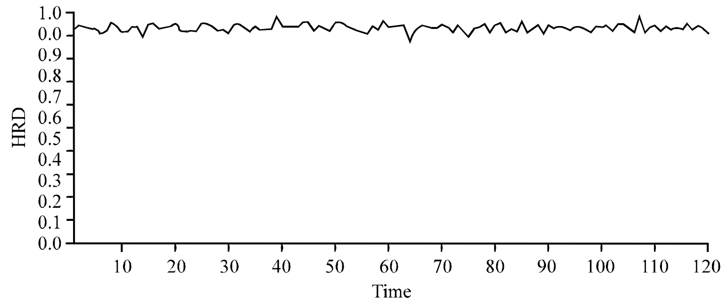

Fig. 4: HRDs of multifunctional self-validating sensor when it works normally

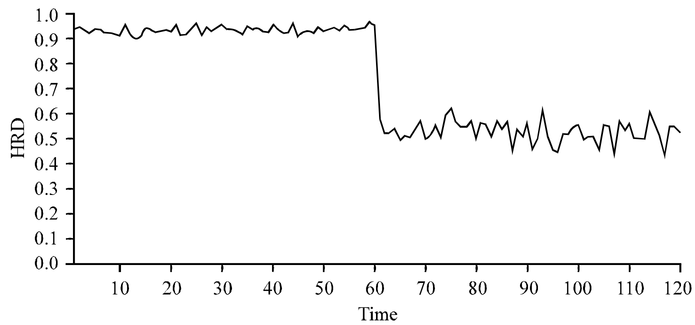

Fig. 5: HRDs when gas sensitive unit 3 is faulty

The HRDs of all the time points are computed as shown in Fig. 4. The fluctuation of HRD curve is mainly caused by the measurement noise. In Fig. 4, all the HRDs are greater than 0.90 excluding the 64th time point (its HRD equals to 0.8703) which implies that the multifunctional self-validating sensor is either HS or SHS. The experimental results are consistent with the normal operational condition which validates the proposed method. The HRD of the 64th time point is lower than 0.9, therefore, further research is needed. It discovers that the output of temperature sensitive unit has deviated 1.9 centigrade from the 23.7°C which has exactly caused the health level degradation of the whole multifunctional self-validating sensor.

Situation 2

One sensitive unit is faulty: This experiment was done in the same gas chamber on the same day and the heating voltage of gas sensitive unit 3 was removed to simulate that the heater strip is broken at the 61th time point. After about 7 sec, its output tends towards steady again. The hydrogen concentration is still 1000 ppm and the outputs of multifunctional self-validating sensor are shown in Fig. 5. By using the proposed HRD strategy, the HRDs of all the time points under single fault can be obtained as shown in Fig. 5.

In Fig. 5, all the HRDs are lower than 0.70 starting from the 61th time point which implies that the multifunctional self-validating sensor is in MF. The experimental results are consistent with the proposed extended meaning of HRD.

Situation 3

More sensitive units are faulty: This experiment has also been done in the same gas chamber on the same day and the heating voltage of gas sensitive unit 3 and gas sensitive unit 4 would be both removed to simulate that both of heater strips are broken. The moment when faults occur is at the about 51th time point. After about 8.5 sec, their outputs tend towards steady again. The hydrogen concentration is still kept as 1000 ppm. To simulate more faults, the power supply of temperature and humidity sensitive unit was also removed at the 91th time point and most sensitive units are faulty.

By using the proposed HRD strategy, the HRDs of all the time points under multiple faults are shown in Fig. 6. In Fig. 6, the HRDs have decreased to nearby 0.3 starting at the 51th time point which is caused by the two faulty sensitive units. According to the definition of HRD, the current health state is still in MF which agrees with the experimental situation. The measured results of gas sensitive unit 3 and gas sensitive unit 4 are both unbelievable and the overall health level has become very low and it has degraded further than the above situation 2.

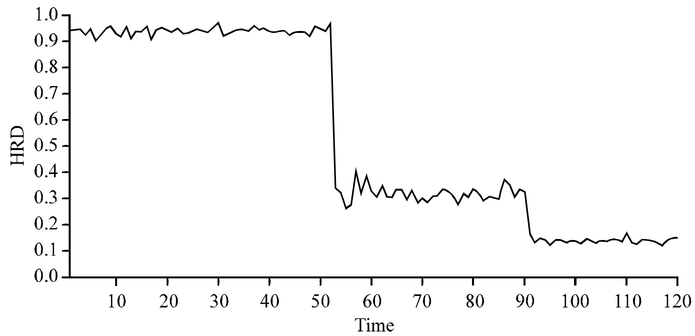

Fig. 6: HRDs when more sensor units are faulty

With more faulty sensitive units, the HRD is bound to be lower and the measured output would also be more suspected. In the latter part of Fig. 6 starting from about 91th point, four sensitive units have been faulty. The corresponding HRDs have further decreased to nearby 0.1 as shown in Fig. 6. The current health state is in FS, the multifunctional self-validating sensor should be exchanged because most of sensitive units have suffered failures.

CONCLUSION

In this study, a novel functional model of multifunctional self-validating sensor has been presented. It gives detailed introduction of its self-validating functions, especially the thought of global health evaluation in a quantitative way and health forecast of remaining useful life. It is very meaningful in its actual industrial production; meanwhile, it is also the enrichment and development of the given self-validating sensor.

Aiming at one of most important self-validating functions, the health evaluation is deeply studied, in which a new concept of HRD is proposed to describe the health level in a quantitative way in this study. As the emphasis of this article, the HRD methodology is implemented by using the multi-variable data fusion technology coupled with grey evaluation algorithm. To get the weights distribution of all sensitive units, the information entropy way is used, in which the correlation of multiple parameters has fully considered.

The experimental system of the multifunctional self-validating sensor was designed in the laboratory. The HRDs under different health situations is analyzed thoroughly and experimental results conclude that the HRD could be used to indicate the quantitative health level. As one of the most important self-validating functions, the health evaluation is rather meaningful for the following health forecast by using the available HRD.

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