Reliability Evaluation of Welding Robot System Based on Grey System Theory

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Abstract: In this paper, the grey process method is applied to evaluate the reliability of welding robot system so as to find the system composition with relatively weak quality, and further the corresponding solutions. With combination of FMEA and Grey Process, the structure of the welding robot is decomposed to find out the common failure modes of each part, and then the corresponding reliability model and evaluation system are established. Finally, the basic failure modes are analysed and evaluated in terms of the probability and the severity of the failure.

1. Introduction

Since 1970s, the welding has begun to apply industrial robot and greatly improved the welding automation [1]. Welding robots can replace the workers in dangerous environment to complete the welding operations. However, its structure and function are very complex with great independence. At present, domestic and foreign scholars have carried out extensive researches on the reliability of welding robots. Wang et al. [2] applied the fault tree analysis (FTA) method to build the fault tree for the wire feeding mechanism of welding robot. Mariam et al. [3] studied the reliability and maintainability of welding robot by detecting the components of the robot's C-type torch welding system.

The reliability evaluation of welding robot parts has the characteristics of "small sample" and "poor information", so the grey evaluation method can be applied to the reliability evaluation of the welding robot system [4].

2. FMEA Analysis of Welding Robot

FMEA (Failure mode effect analysis), that is, failure mode impact analysis, refers to summarizing all failure modes of the system and its failure causes and effects at specific hierarchy by theoretical knowledge and practical experience [5].

2.1 System Definition

Since the joints of welding robot are driven-transmission-execution transmission forms, most of the components and components are basically coincident, and the failure modes are similar. Thus the system is divided according to the transmission relationship [6]. Taking the PR1400 welding robot as example, the robot system with any drive unit faulty cannot work normally, so the system can be simplified as a series model. Then each drive unit can be split further.

2.2 Failure Mode Analysis

The failure mode is defined as the manifestation of the fault. More precisely, the failure mode describes in a way the fault phenomena that can be observed or measured [7]. When analysing product failures, it basically starts from the phenomenon of product failure, and explores the causes and mechanisms according to the failure mode.

2.3 FMEA

Fill in the FMEA table with the main components information of PR1400 welding robot system, including the failure mode, cause, impact and its severity, detection method and compensation measures. Taking the flexible coupling as an example, its FMEA is shown in Table 1.

Table 1. FMEA table

Product name	Failure mode	Cause of failure	Fault impact			Severity	Fault detection method	Existing compensation measures
			Local influence	Impact on the previous level	Final impact			
Flexible coupling	Elastic ring wear	small axial clearance	Elastic ring damage	Coupling stops working.	System working improperly	III	Visual inspection	Adjust the gap.
	Elastic pin break	fatigue or excessive torque	Can't drive	The upper arm naturally hangs down.	Motion failure.	III	Visual inspection	Replace the pin.
	Pin hole pull	vibration and impact caused by axial movement	Coupling damage	Transmission fails.	System not working properly.	III	Visual inspection	Use elastomer with good shock absorption performance.

3. Grey Evaluation Method Based on Triangle Whitening Weight Function

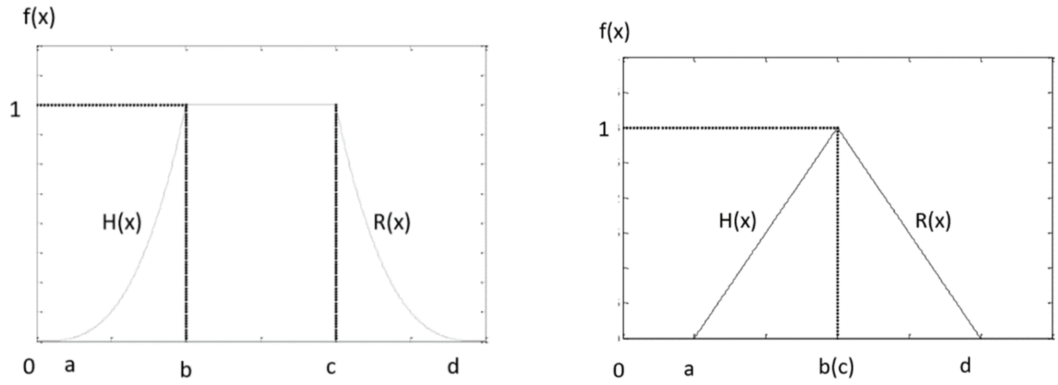
The Grey Process is derived from the theory of "grey system" proposed by Professor Deng Julong of Huazhong Institute of Technology in China [8]. The theory focuses on uncertainty such as “poor information” and “small sample” that cannot be solved by fuzzy mathematics, which is just the main problem in the current robot reliability data analysis.

3.1 Quantification of Evaluation Indicators and Determination of Gradation

The basis of reliability system evaluation is the quantification of evaluation indicators. We use the scale method to quantify, that is, using the “0-10” scale, where 0 represents the lowest value and 10 represents the highest.

3.2 Establish the Grey Triangle Whitening Weight Function

The whitening weight function refers to the degree to which a grey number is "liked" to different values within its range. For most grey systems, the grey number whitening process is not s equal [9]. For the convenience of calculation, H(x) and R(x) are usually reduced to a straight line, and when the points b, c of the H(x) and R(x) functions coincide, they become the triangular whitening weight function f(x)(Figure 1).



a) Typical whitening weight function b) Triangular whitening weight function

Figure 1. The Evolution of whitening weight function to triangular whitening weight function

3.3 Calculate the Weight of the Indicator

The "Calibration cluster weight" is calculated as formula 1:

$$\eta_k^{(j)} = \frac{\lambda_k^{(j)}}{\sum_1^s \lambda_k^{(j)}} \tag{1}$$

Where $\eta_k^{(j)}$ is the calibration clustering weight of the index j belonging to the kth grey class, i.e. $\eta_k^{(1)}, \eta_k^{(2)}, \eta_k^{(3)}, \ldots, \eta_k^{(p)}$ constitute the weights of p indicators for a certain k grey class.

Obviously, $\eta_1^{(j)}+\eta_2^{(j)}+\ldots\eta_s^{(j)}=1$. $\lambda_k^{(j)}$ is a threshold value, indicating the x value corresponding to the whitening weight function of the kth gray class of the jth index (ie, the vertex), which is theoretically a critical value in the gray number of each gray type. There are two cases at this time: when the whitening weight function image is pointed (as shown in Fig 2b), the $\lambda_k^{(j)}$ of each gray class of each indicator is unique; but when the image is flat top (such as Figure 1a), the upper limit value of the flat top region is usually taken as $\lambda_k^{(j)}$. In the multi-index comprehensive evaluation, $x_k^{(j)}$ needs to be converted into the same metric according to the selected homogenization method, and then the "calibration weight" is calculated [10].

3.4 Determine the Object Membership Grey Class

According to $y_k^{(j)} = \sum_{p=1}^{m} f_k^{(j)}(x_p^j)$, calculate the clustering coefficient of each indicator for grey class k, and p is the number of scores. Then calculate the comprehensive clustering coefficient $\sigma_k = \sum_j y_k^{(j)} \eta_k^{(j)}$ of all indicators for grey class k, and finally determine the grey class where k is the grey class according to $\max_{1<k<s}\{\sigma_k\}$ [11].

4. Application Example of Grey Evaluation Method in Reliability Evaluation of Robot System

The limited data of product operation and the uncertainty of human cognition indicate that the reliability evaluation of robots is a grey problem with incomplete information. Therefore, the grey evaluation method can be used to evaluate the reliability of the robot system.

4.1 Establishment of Reliability Evaluation Index System

According to the FMEA analysis model in Section 1 and collected key failure mode and faults of PR1400 welding robot, the reliability evaluation index system are established, as shown in Figure 2.

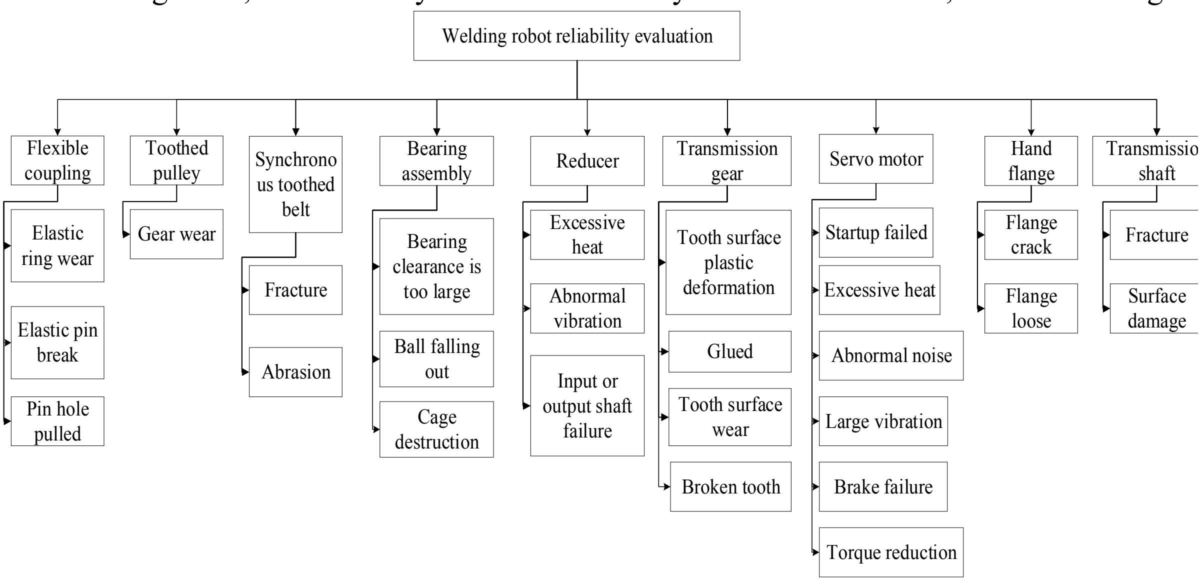


Figure 2. Robot reliability evaluation index system

It can be seen from Fig. 3 that the first-level evaluation index has nine parts, namely: elastic coupling, toothed pulley, synchronous toothed belt, bearing assembly, reducer, transmission gear, servo motor, hand flange and the drive shaft. The secondary evaluation index has a common failure mode of each part, for a total of 26.

4.2 Evaluation Index Quantification and Grey Scale

The effect of each factor involved is graded. The evaluation indicators will be divided into five categories according to the possibility of failure, the severity of failure impact and detection difficulty of. The specific rules are shown in Table 2:

Table 2. Grey table

Grey class	Division range	Possibility of occurrence	The severity of the impact	Detecting difficulty
1	[0,2]	Rare	Slight	Very low
2	[2,4]	Low	Low	Low
3	[4,6]	Medium	Medium	Medium
4	[6,8]	High	High	High
5	[8,10]	Very high	Very high	Unable to check out

It can be seen from Table 4 that in this proposed evaluation model, k has the values of 1, 2, 3, 4, and 5. And s=5, a1=0, a2=2, a3=4, a4=6, a5=8, a6=10.

4.3 Expert Scoring and Calculation

The five experts who have relevant experiences in robot reliability have scored the second-level indicators of the robot in terms of occurrence probability, influence degree and detection difficulty, namely M=[m1, m2, m3, m4 , m5]. Taking the first evaluation index “elastic coupling elastic ring wear” as an example, the expert score is

$$M = \begin{bmatrix} 7.2 & 7.6 & 8 & 7 & 7.6 \\ 7.0 & 7.5 & 6.5 & 5.4 & 6.0 \\ 6.0 & 4.2 & 6.4 & 4.7 & 5.6 \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} \tag{2}$$

For gray class 1, λ=(0+2)/2=1, and the triangular whitening weight function is the lower limit measure; for grey class 2, λ=(2+4)/2=3; for grey class 3, λ=(4+6)/2=5; for grey level 4, λ=(6+8)/2=7; for grey class 5, λ=(8+10)=9, and its triangle whitening weight function is the upper limit measure. The five triangular whitening weight functions (Figure 3) are as follows:

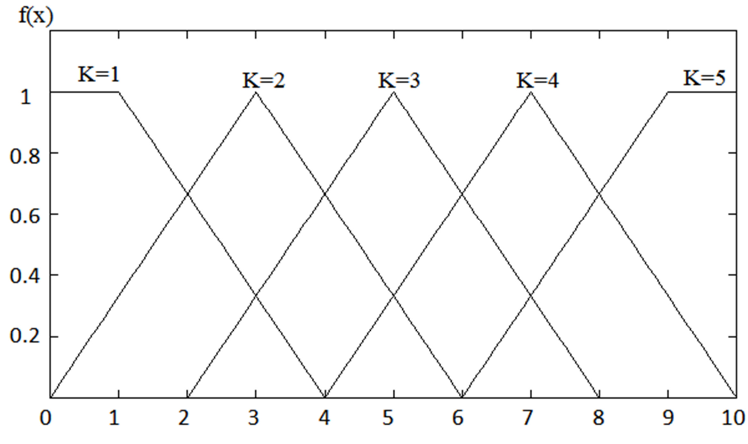


Figure 3. Grey triangle whitening weight function image

Next, according to the expert scoring value of the "elastic coupling elastic ring wear" index , whitening function value can be obtained in five different greys in terms of failure probability , fault severity and detection difficulty. Then, substitute the whitening function value into formula $y_k^{(j)} = \sum_{p=1}^{m} f_k^{(j)}(x_p^{(j)})$.

According to the comparison result of each evaluation angle, it can be judged that the occurrence probability of "elastic coupling elastic ring wear" is 4, failure severity of is 4, and the detection difficulty is 3. Similarly, the grey values of the rest indicators are calculated as shown in Table 3 below:

Table 3. Secondary indicator grey value

Evaluating indicator	Evaluation angle	Possibility of occurrence	The severity of the impact	Detecting difficulty
Flexible coupling	Elastic ring wear	4	4	3
	Elastic pin break	4	5	3
	Pin hole pulled	3	4	3
Toothed pulley	Gear wear	2	3	1
Synchronous toothed belt	Fracture	4	5	1
	Wear	3	1	3
Bearing assembly	Bearing clearance is too large	3	1	4
	Ball falling out	2	5	1
	Cage destruction	1	5	1
Reducer	Excessive heat	4	2	1
	Abnormal vibration	2	4	4
	Input or output shaft does not rotate	2	5	1
Transmission gear	Tooth surface plastic deformation	4	2	4
	Glued	1	1	5
	Tooth surface wear	5	5	2
	Broken tooth	1	5	1
Servo motor	Cannot start	4	2	1
	Excessive heat	4	3	2
	Abnormal noise	2	4	3
	Large vibration	3	4	4
	Brake failure	2	4	5
	Torque reduction	4	1	4
Hand flange	Flange crack	1	1	2
	Flange loose	1	1	3
Transmission shaft	Fracture	2	5	1
	Surface damage	5	1	3

Finally, the comprehensive clustering coefficient of the first-level index for the grey level k is calculated. The grey levels of the rest parts are calculated, as shown in Table 4:

Table 4. Primary indicator grey value

Evaluation index / Evaluation angle	Possibility of occurrence	The severity of the impact	Detecting difficulty
Flexible coupling	4	4	3
Toothed pulley	2	3	1
Synchronous toothed belt	4	3	2
Bearing assembly	2	4	2
Reducer	3	4	3
Transmission gear	5	5	3
Servo motor	3	3	4
Hand flange	1	1	2
Transmission shaft	4	2	2

5. Conclusion

In this paper, the qualitative analysis of the welding robot system is carried out with the establishment of the reliability evaluation system and the evaluation standard. Firstly, the FMEA model of the robot is established. The main components of the welding robot and its failure mode are summarized, which provides the basis for the establishment of the evaluation system. Then the principle and steps of the grey evaluation method based on the triangle whitening weight function are introduced. Finally, the reliability evaluation system of the welding robot is established and the grey evaluation method is used to quantify the evaluation index, determine the grey level and the specific operation process.

The next steps are to develop and put the reliability evaluation system into actual application in demonstration enterprise. Findings from the ongoing investigation will be reported separately in the near future.

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