Fuzzy FMECA-Based Reliability Analysis of Welding Robots

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***Abstract* — A welding robot is an advanced piece of machinery in industry, especially in the field of industrial automation. As a complex system, it has a high failure probability because it manipulates, controls and performs complicated objects and tasks. Therefore, more attention has recently focused on the reliability of a welding robot. Reliability is very important because its performance will affect the overall system safety directly. In this paper we attempt to make the welding robot to be reliable and stable by using a fuzzy Failure Mode Effects and Criticality Analysis (FMECA) method. It is applied to determine the key to reliability improvement and maintenance of the welding robot system according to a failure model of hazard classes. Firstly, Failure Mode Effects Analysis (FMEA) of the key parts is carried out to obtain the failure modes. Secondly, the evaluation rules of the failure modes are discussed for experts scoring. Thirdly, the criticality of each failure mode is analyzed by fuzzy comprehensive evaluations. The analysis results are consistent with an actual situation and can verify the effectiveness of the presented method.**

Keywords - fuzzy comprehensive evaluation; FMECA; welding robot; failure mode; reliability

I. INTRODUCTION

With the development of China's manufacturing industry, industry robot has become the core of the manufacturing revolution. As an important branch of industrial robots, welding robot plays an important role in China's manufacturing industry, and its system reliability has drawn an increasing attention of experts and scholars. Dhillon, B.S .presented the results of a survey of Canadian robot users concerning robot reliability and safety [1]. Tsarouhas and Fourlas analyzed the reliability and maintainability (R&M) of a robotic system for industrial application by descriptive statistics of failure and repair data as well as the best fit of them [2]. Hoshino et al. focused on the effectiveness of maintenance in fault-tolerant multi-robot systems and proposed an optimal maintenance strategy, which can maintain high performance on the basis of reliability engineering in fault-tolerant multi-robot systems [3]. Philip and Sharma reported that the machines and robots in a flexible manufacturing module (FMM) are more prone to failures as compared to the traditional manufacturing systems [4]. Cherroun and Boumehraz carried out a navigation method for an autonomous mobile robot in order to equip the robot by capability of autonomy and intelligence in its environment and its reliability [5]. Fourlas studied the reliability analysis for an autonomous mobile robot system by statistics based on failure data, and then obtained the vulnerable section of the system [6] . In order to improve the reliability of space robot ,Gao proposed a space robot system with two alternate drive system, two alternate control system, redundant freedom and two alternate Communicate system[7]. Han analyzed all possible fault causes and modes of parts in the subsystem and their influences on the robot system to find out the potential weak segments and key parts in the robot system by FMEA and Failure Tree Analysis (FTA) based on the fuzzy set theory [8]. Korayem designed a Cartesian robot with three degrees of freedom with conclusion that the vibration of end effect in the bridge model is lesser than in the cantilever model [9].. Baron and Tondu presented a deductive method of safety analysis for medical robot. Firstly some human safety factors were analyzed, and then different failure modes and the effects were obtained by using FMEA and FTA. Finally corrective actions to reduce the hazardous effects were furthermore proposed [10].

FMECA method is a commonly used method of system reliability analysis. It not only can form the statistical failure model, causes and effects of each parts, but also can favor the analysis of each failure model’s severity and the compensation [11] [12]. After hazard analysis of field failure data, the critical failure mode or weakness section of each component can be obtained. However, the traditional FMECA method is a clear-cut without considering the uncertainty and fuzzy state information. So fuzzy theory is wildly utilized. Abdelgawad and Fayek [13] analyzed the shortcomings of the traditional FMEA applications and used fuzzy logic to deal with the limitations of traditional FMEA. Pillay and Wang [14] proposed a fuzzy rule to avoid using traditional Risk Priority Number (RPN),and set up the membership function of the three risk factors (Occurrence, Severity and Detection). In this paper, the fuzzy FMECA is presented by combining traditional FMECA and fuzzy comprehensive evaluation to deal with the qualitative problems from the quantitative view, and afterwards the failure modes of components can be presented clearly.

II. THE STRUCTURE OF THE WELDING ROBOT SUBSYSTEM ONTOLOGY

The ontology of PR1400 welding robot is a six DoF articulated robot, whose main functions are to ensure the

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welding torch can reach the specified position and trajectory as shown in Figure 1. The structure of the robot usually includes rotated base, big arm, small arm, wrist and so on. From Figure 2, it can be seen clearly that the Ws axis in the vertical direction is the rotation center of the robot around the axis of, which can be considered as PR1400 robot's waist joints (axis1). Sh axis in the horizontal direction, is the rotation center of the big arm, which can be considered as the shoulder joint (axis2). Eb axis in the horizontal direction, is the rotation center of the small arm, which can be considered as the elbow joints (3 axis). The wrist consists of three mutually perpendicular axis, namely the Rt (4) axis, Bn(5)axis, Tr (6) axis. A welding wire feeder is fixed with the small by a slide connection board. By adjusting the position of the wire feeder in the slide connection board, the small arm can be counter weighted. The movement of each joint relies mainly on the motor drive reducer.

Figure 1. Welding robot ontology.

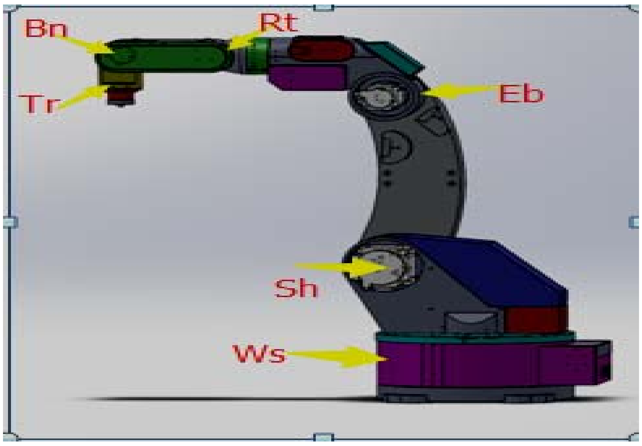

Figure 2. 3 D model of the welding robot ontology.

III. METHODOLOGY

The application diagram of fuzzy FMECA [15] are shown in Figure 3.

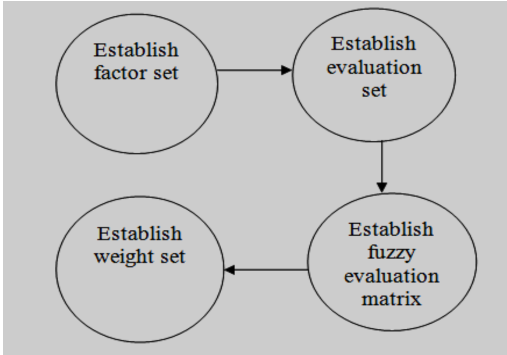

Figure 3. The application diagram of fuzzy FMECA.

The basic steps of fuzzy FMECA method:

A. Establish factor set and evaluation set

1)Factor set is a collection of various influence factors of the objects to be evaluated as indicated by Equation (1), where different elements represent different factors, and u_i^k (i=1,2,...,) denotes the factor set of kth failure model:

$$\mathrm{U}_{\mathrm{i}}^{\mathrm{k}} = \{u_1^k, u_2^k, u_3^k, \ldots, u_n^k\} \quad (1)$$

2) Evaluation set consists of various possible evaluation results for the objects to be evaluated, usually indicated as:

$$\mathrm{V}_{\mathrm{j}}^{\mathrm{k}} = \{v_1^k, v_2^k, v_3^k, \ldots, v_m^k\} \quad (2)$$

Where: v_j^k (j=1,2,...,m)denotes the jth possible evaluation results indicator of various possible total evaluation results.

B. Establish fuzzy evaluation matrix

Firstly, form an expert table. Weight vector among the various faults obtained by analytic hierarchy process, while the membership of each fault severity levels, the probability level, the difficulty of detecting the levels of membership table needs to be obtained by the way of expert questionnaire, on the basis of investigate by relevant experts can get relatively accurate data, and the results obtained by mathematical statistics, secondly, quantify the table.

$$\mathrm{R}_{\mathrm{i}}^{\mathrm{k}} = \left\{\frac{h_{i1}^k}{h}, \frac{h_{i2}^k}{h}, \frac{h_{i3}^k}{h}, \ldots, \frac{h_{im}^k}{h}\right\} = \{r_{i1,}^k r_{i2,}^k r_{i3,}^k \ldots, r_{im}^k\} \quad (3)$$

Where:

$\mathrm{R}_{\mathrm{i}}^{\mathrm{k}}$: represents a vector of the failure judgment.

H : stands for the number of experts.

h_{ij}^k : (j=1,2,...,m) :stands for the number of experts who considers that failure model k belongs to rank V_j^k .

C. Establish weight set

According to the important degree of each factor, give different weights, then establish the weight sets. Generally, using analytic hierarchy process（AHP）seeking weight by following these steps.

Firstly, a_{ij} stands for the relative importance values of factors u_i and u_j, the values can be selected according to table I. To construct judgment matrix A:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn1} \end{bmatrix} \quad (4)$$

TABLE I AHP JUDGMENT MATRIX SCALE

Proportional scale	Signification
1	Compared with two elements,the former and the latter are equally important
3	Compared with two elements,the former is slightly important than the latter
5	Compared with two elements,the former is obviously important than the latter
7	Compared with two elements,the former is distinctly important than the latter
9 2,4,6,8	Compared with two elements,the former is definitely important than the latter Show the intermediate value

In this paper, square-root method is adopted to calculate the weights of various factors. Calculation steps are as follows:

1)Calculate product elements in the row of matrix:

$$M_i = \sqrt[n]{\left(\prod_{j=1}^{n} a_{ij}\right)}, i = 1,2,3,\cdots n \quad (5)$$

2)The normalized vector M:

$$w_i = \frac{M_i}{\sum_{j=1}^{n} M_j}, i = 1,2,3,\cdots n \quad (6)$$

The weight vector for $W = \left(w_1, w_2, w_3, \cdots, w_n\right)^T$

3)Calculated largest eigenvalues of matrix:

$$\lambda\max = 1/n \sum_{i=1}^{n} \frac{\left(AW_i\right)}{w_i} \quad (7)$$

4)Consistency check:

$$R_C = I_C / I_R \quad (8)$$

Where:

R_C: stands for consistency ratio which is used to determine the judgmental matrix's consistency.

I_C: stands for consistency index which is used to determine whether and to what extent decisions violate the transitivity rule.Ic=(λmax-n)/(n-1).

I_R :stands for random index and the values of IR for matrices of different scales are shown in Table II.

TABLE II THE VALUE OF THE RANDOM INDEX(IR)

Scale	1	2	3	4	5	6	7	8	9
I_R	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The general rule is that R_C<= 0.1 should be maintained for the matrix to be consistent.

D. One-level fuzzy comprehensive evaluation

Changed the failure model of k factor weighting sets vector form.

$$B_k = W_k \bullet R_k = \left(b_1^k, b_2^k, b_3^k, \cdots, b_m^k\right) \quad (9)$$

Where:

B_K: stands for fuzzy comprehensive evaluation vector of fault mode K.

E. The determination of comprehensive hazard rating

In order to more intuitive to see the results, by the weighted average method to deal with B_K, a simple numerical D to represent the evaluation results:

$$D = B \bullet V^T \quad (10)$$

Where:

D: stands for the failure mode of comprehensive hazard rating.

VI. FUZZY FMECA -BASED RELIABILITY ANALYSIS OF WELDING ROBOT

After deep investigations of engineering practice and literature review, the fault statistics and analysis of PR1400 arc welding robot system can be obtained as shown in table III. It can be concluded that the servo motor, the RV reducer, synchronous cog belt, synchronous belt wheel, flange, bearing are the key to the reliability of PR1400 arc welding robot system. Therefore it is of great importance to consider these parts for reliability analysis of PR1400 arc welding robot by fuzzy FMECA.

TABLE III FMEA OF THE KEY PART

Part	Failure model	Failure cause	Effects of robot	Fault detection method
Servo motor	Abnormal noise	1.Bearing wear 2.Armature becomes loose 3.Lack of lubricating oil 4.High voltage power supply	Some Abnormal noise occur toe robot	Condition check
	Abnormal vibration	1.Large bearing clearance 2.Uneven air gap	The robot arm or wrist produce	Observation

		3.Armature imbalance 4.High voltage power supply	jitter and vibration	
	Fail to re star of the motor	1.The motor is not connected 2.Fuse does not work 3.Overcurrent relay works not normal 4.Control device connection error	Arm or wrist can't move then the robot works abnormal ly	Observation or check and repair circuit
	Motor overheati ng	1.Overload Operation 2.Poor heat dissipation 3.The current is too large	There is somethin g wrong with the motor and robot can't work	Observation and check the motor
Reducer	Abnormal vibration	1.Device fixed not good 2.Bearing wear 3.Bolt loosening	The robot produce jitter slightly during moveme nt	Using the sensor
	Exception al Input or Output	1.Spline connection failure 2.Bearing wear 3.Foreign matter enter into	The robot doesn't work	Observation
	Reducer overheati ng	1.Lack of lubricating oil 2.Overload operation 3.Improper transmission link	A slight influence on robot	Observation and Check the reducer
Synchrono us belt wheel	Wear	1.Overload 2.Belt tension is too large 3.Foreign matter enter into	A slight influence on robot	Observation
Synchrono us cog belt	Fracture	Fatigue,Overl oad	The robot can't work normally	Observation
	Wear	1.Overload 2.Belt tension is too large 3.Depth of parallelism is substandard	A slight influence on robot	Observation
Flange	Small crack	1.Fatigue 2.Intensity is not enough	A slight influence on robot	Nondestructive inspection (NDT)
	Loosen	Bolt loosening	Some abnormal noise or jitter occur to the moveme nt of robot	Observation
Bearing	Large bearing clearance	Wear, Less smoothness	When bearing clearance is too large the robot can't work	Nondestructive examination(N DE)
	Bearing retainer damage	Wear, Overload	The robot works abnormal	Observation

Secondly, From table III it is obvious that there are 14 failure modes. Then each fault model is evaluated using fuzzy comprehensive evaluation as follows.

F. *Establish factor set U and evaluation set V*

Chose the severity, occurrence, detection as an effective factor in the failure model. That is to say, U = {severity, occurrence, detection} . With the result of the influence of various factors are divided into five grades respectively that V = {1, 2, 3, 4, 5} factors hierarchies are shown in table IV below.

TABLE IV EVALUATION RULES OF FAILURE MODE

Ran k	Occurrence degree		Severity degree		Detection degree	
1	Lowes t	The low possibil ity of fault model	Slight	Won't impact on the robot system, the user won't notice the slight fault	Lowes t	Testing procedu res can detect potential design fault
2	Lower	A lower risk of failure mode occurre d	Low	Has a slight effect on robot system function failure, the user may notice and cause minor complaints	Low	Inspecti on procedu res have bigger chance to check out the potential design fault
3	Mediu m	The medium possibil ity of fault mode	Mediu m	Cause robot system performanc e degradation failure, the user will feel uncomforta ble and unhappy	Mediu m	Inspecti on procedu res may check out the potential design fault
4	Highe	The	Highe	Major fault	Highe	Inspecti

	r	higher possibility of fault mode	r	interrupt operation, the user feel strong dissatisfaction, but such failures don't cause safety consequences, and not in violation of government regulations.	r	on procedures may not check out the potential design fault
5	Highest	The highest possibility of fault mode	Highest	Life, property loss caused fatal fault or not compliance with government regulations	Highest	Inspection procedures can not check out the potential design fault

G. *Establish the factor assessment matrix*

Firstly, invite 8 experts in the design department to assess each failure mode of table 1, then statistic the assessment results can obtain the failure occurrence probability fuzzy set, severity fuzzy set, detection difficult fuzzy set of each failure mode. take mode 1(abnormal noise of servo motor)as an example, according to the analysis, the occurrence probability fuzzy set $r_1^1=\left\{\frac{2}{8},\frac{2}{8},\frac{4}{8},0,0\right\}$,severity fuzzy set $r_2^1=\left\{\frac{1}{8},\frac{6}{8},0,\frac{1}{8},0\right\}$,detection difficulty fuzzy set $r_3^1=\left\{\frac{3}{8},\frac{2}{8},\frac{2}{8},0,\frac{1}{8}\right\}$,so the fuzzy assessment metric is $R_1=\begin{bmatrix}\frac{2}{8} & \frac{2}{8} & \frac{4}{8} & 0 & 0\\ \frac{1}{8} & \frac{6}{8} & 0 & \frac{1}{8} & 0\\ \frac{3}{8} & \frac{2}{8} & \frac{2}{8} & 0 & \frac{1}{8}\end{bmatrix}$ Similarly, can get the rest of the failure mode of fuzzy evaluation matrix.

H. *Building the Weight Set*

Based on practical experience and statistical data ,select scaling, set up the judgment Matrix U:

$$\begin{bmatrix} U & u_1 & u_2 & u_3 \\ u_1 & 1 & 3 & 7 \\ u_2 & 1/3 & 1 & 5 \\ u_3 & 1/7 & 1/5 & 1 \end{bmatrix}$$

According to type(5),(6)calculated:W_1=(0.649, 0.279, 0.072);According to type(7),(8)calculated: $R_C=0.032<0.1$ show the consistency of the judgment matrix can be accepted.

I. *One-level fuzzy comprehensive evaluation*

B stands for the failure model of fuzzy evaluation set, so $B_1= W_1R_1=$ [0.224125, 0.3895, 0.3425,0.034875,0.009]. In other words, $B_1=\frac{0.224125}{1}+\frac{0.3895}{2}+\frac{0.3425}{3}+\frac{0.034875}{4}+\frac{0.009}{5}$ .According to the biggest membership degree principle can be concluded that failure model of harm degree level is level 2.In the same way,

$B_2=W_2R_2$=[0.261375,0.581125,0.07875,0.07875,0];

$B_3=W_3R_3$=[0.13513,0.65563,0.10463,0.0698,0.03488];

$B_4=W_4R_4$=[0.386375,0.474125,0.1395,0,0];

$B_5=W_5R_5$=[0.30525,0.491,0.159875,0.043875,0];

$B_6=W_6R_6$=[0.594875,0.186875,0.1485,0.06975,0];

$B_7=W_7R_7$=[0.62075,0.177875,0.201375,0,0];

$B_8=W_8R_8$=[0.359375,0.5090,0.122625,0.0090,0];

$B_9=W_9R_9$=[0.44163,0.27038,0.11363,0.10463,0.0698];

$B_{10}=W_{10}R_{10}$=[0.28725,0.55525,0.1575,0,0];

$B_{11}=W_{11}R_{11}$=[0.51375,0.197125,0.1575,0.131625,0];

$B_{12}=W_{12}R_{12}$=[0.11713,0.4585,0.27588,0.11363,0.03488];

$B_{13}=W_{13}R_{13}$=[0.197125,0.5835,0.131625,0.07875,0.009];

$B_{14}=W_{14}R_{14}$=[0.386375,0.3245,0.1755,0.07875,0.03488].

In order to convenient for comparing the relative hazard degree between different failure modes ,its results needs to be diversification, $D_1=B_1V^T=2.218$, $D_2=B_2V^T=1.976$, $D_3=B_3V^T=2.217$, $D_4=B_4V^T=1.746$, $D_5=B_5V^T=1.943$, $D_6=B_6V^T=1.696$, $D_7=B_7V^T=1.58$, $D_8=B_8V^T=1.782$, $D_9=B_9V^T=2.094$, $D_{10}=B_{10}V^T=1.871$, $D_{11}=B_{11}V^T=1.91$, $D_{12}=B_{12}V^T=2.428$, $D_{13}=B_{13}V^T=2.122$, $D_{14}=B_{14}V^T=2.055$. Therefore all of the welding robot ontology failure mode are sorted according to the harm degree as:

$D_{12}>D_1>D_3>D_{13}>D_9>D_{14}>D_2>D_5>D_{11}>D_{10}>D_8>D_4>D_6>D_{13}>D_7$.

V. CONCLUSION

Designers can confirm which parts should be paid with more attention according to the above analysis results. That is to say, designers should pay more attention to the parts with high goals of the fuzzy comprehensive evaluation for further design and management improvement as far as possible to minimize or eliminate the failure mode to improve the reliability of the robot system. From the obtained results of our research, it can be clearly seen that loose flange is the highest failure mode, due to loose bolts, which will lead to the jitter of the robot arm with bad welding precision. As for this high degree of harm fault mode, strict training of assembly workers may be undertaken to improve the assembly quality as well as the related performance test to ensure the reliability of the robot before sale. Meanwhile, two of the top three failure modes are from the servo motor. So it can be concluded that the servo motor is the most important.

In this study, hazard analysis of the main components of the robot subsystem are carried out by fuzzy FMECA and find out the most important failure mode and component for the robot system reliability. Hazard analysis is combined with FMEA to find out the solution to the fault mode. The analysis results can not only provide the design reference to the reliability of robot subsystem, but also have guidance significance on repair and maintenance of welding robot.

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