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FMECA and FTA Methods of Reliability Analysis for Oil and Gas Pipeline Robot

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Abstract: In this paper, FMECA and FTA methods are presented for oil and gas Pipeline Robot in order to improve the reliability. Take a crawler pipeline cleaning robot as the research object. According to the robot's variable working environment, high failure rate and short service life, in order to reduce the probability of its failure, and to extend its use time limit under the premise of being able to adapt to the complex working environment, and reduce maintenance cost of failure. To realize this purpose, FMECA analysis is fristly proposed, by which obtain the failure modes, causes and effects of each component mechanism, and identify the component mechanism with high risk and failure rate. Secondly, FTA is developed to establish the fault tree model of Cleaning and diameter changing mechanism, retain the underlying fault and the cause of its failure. Simulation results are carried out to illustrate the effectiveness of this proposed method and improvement measures to improve the reliability of the robot.

Keywords: reliability; Pipeline robot; FMECA; FTA

1 Introduction

Oil and natural gas are currently the main important resources in the world and occupy a strategic position in the national resource structure. The transportation of oil and natural gas is particularly important in the extraction and refining use. Pipeline transportation is widely used in the transportation of oil and gas because of its safety, low energy consumption, and low cost[1]. At the same time, cleaning the pollutants in the pipeline to prevent the occurrence of problems such as pipeline blockage and corrosion has become the key to affecting the transmission efficiency and pipeline life[2]. In view of the characteristics of oil and gas pipeline construction, the development of

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various pipeline robots has been promoted.Since the 1950s of the last century, foreign countries have begun related research[3-4], and my country has also followed suit. As a result, pipeline robot systems with different structure types and drive modes have emerged so as to be able to adapt to the requirements of different working conditions[5-6]. At present, at home and abroad, most of them use electric, hydraulic and pneumatic three driving methods[7-8]. First of all, in terms of pipeline robots, wheeled robots are used in early research at home and abroad, but crawler robots are mostly used in the near future. Compared with crawler robots, they can effectively reduce sideslip and increase driving stability. Some robots with unique structures will also use the spiral type to use the fluid pressure difference to drive. In terms of pipeline cleaning, there have been fewer innovations in recent years, mostly traditional physical cleaning, chemical cleaning, jet cleaning, etc. Some research units mainly use new methods to clean the outside of the pipeline and use conventional methods to clean the inside of the pipeline. In 2019, some people have used laser pulse cleaning technology to carry out cleaning tests on oil and gas pipelines and achieved good results[9]. Summarizing the above content, this article is based on the design of the laser pulse cleaning module for oil and gas pipelines based on crawler-type pipeline crawling robots, and its reliability is analyzed.

2 Structure, function and system definition of crawler pipeline cleaning robot

This paper takes the crawler pipe cleaning robot which was built by the Kunming University of Science and Technology Functional Fluid Application and Mine Mechanical and Electrical Engineering Research Team as the research object. The organization consists of 4 parts shown in Figure 1. There are cleaning and diameter changing mechanism (CDCM), walking and diameter changing mechanism(WDCM), main rotating mechanism(MRM) and connecting mechanism(CM). When working, the main rotating mechanism transmitting power so that the entire cleaning module can be rotated 360°. The cleaning and reducing mechanism achieve the passage of the module in different pipe diameters, and the laser cleaning head installed in it cleans the stains attached to the pipe wall. The cleaning and diameter reducing mechanism is installed in the tank of the walking and diameter reducing mechanism through the connecting mechanism. The walking and diameter reducing mechanism can change the diameter to assure it can be attached to the inside of the pipeline tightly. The function of the robot is divided to facilitate further data analysis of the degree of hazard and failure through the reliability analysis method.

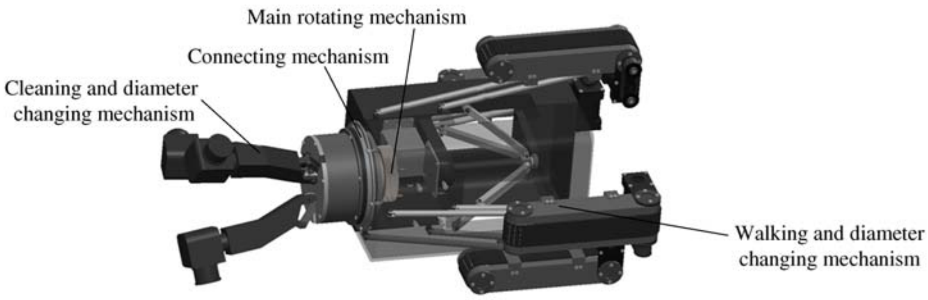

Figure 1 Crawler pipeline cleaning robot

3 Reliability analysis for Crawler pipeline cleaning robot

Reliability analysis targets the entire system. It find the internal and external causes of system failure, summarize the rules further, and give corresponding improvement methods. In the end, it is expected to improve the reliability of the system. The improvement of reliability affects the length of the life cycle of the system, and plays an important role in these respects that the application rate of materials and the control of corresponding costs. There are common specific methods of reliability analysis include failure mode impact and criticality analysis (FMECA), fault tree analysis method (FTA) [10] and so on. The following is the reliability analysis of robots with FMECA and FTA.

3.1 FMECA method

Failure mode impact and criticality analysis (FMECA) is a technique that identifies potential failure modes of the system and screens them according severe degree. Through the analysis of failure modes, the influence of the each failure mode on the overall work is further determined. Then according to the severity and probability of failure mode to determine the degree of harm, summarize the harm degree[11]. FMECA is usually composed of two parts: one is to define failure modes and effects, also known as failure modes and effects analysis (FMEA), and the other is to perform criticality analysis (CA) based on the probability and severity of failure modes[12].

3.2 FMECA analysis

3.2.1 System definition

Analyzes the function composition of each part and the reliability block diagram, defines the system, divides the primary and secondary levels of the entire system structure which can be divided into the initial agreement level, the agreement level, and the lowest agreement level. The initial agreed level represents the functions required by the crawler pipeline cleaning robot, and is the highest level. The agreement level include 4 components that constitute the system: the clean and diameter reducing mechanism, the connecting mechanism, the main rotating mechanism, the walking and diameter reducing mechanism. The lowest level of agreement is the lower level of the basic components that make up each organization. The final structural hierarchy diagram is shown in Figure 2.

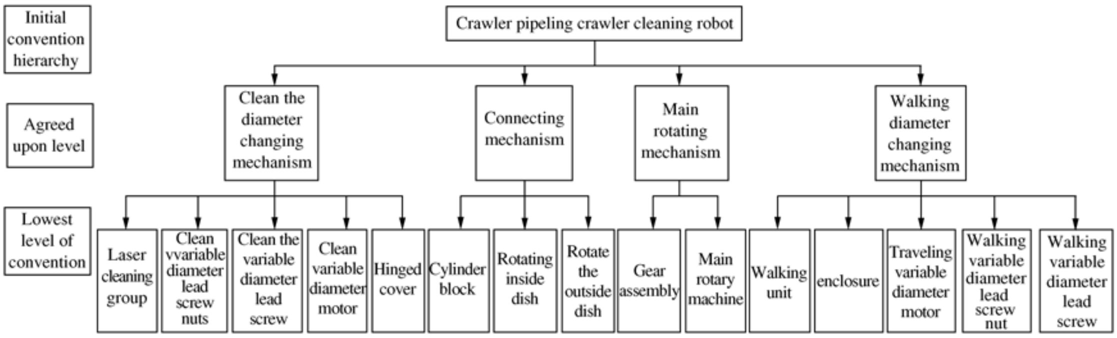

Figure 2 Structure hierarchy diagram

Summarize the various levels of the crawler pipeline cleaning robot, the corresponding functions of each mechanism, the entire system, and the system functional goals. Its hierarchical function framework is shown in Figure 3.

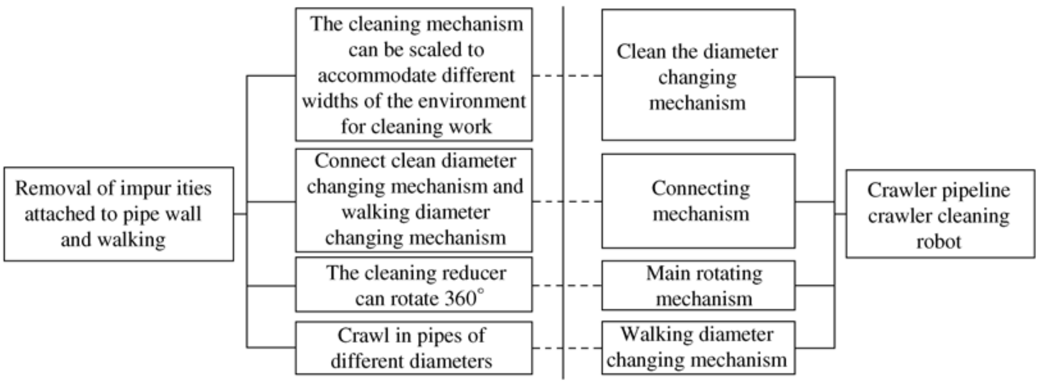

Figure 3 Hierarchical function diagram

Since the six mechanisms constituting the crawler pipeline cleaning robot are in series, it means that when one of the mechanisms cannot work, the crawler pipeline cleaning robot cannot work normally. Therefore, the reliability block diagram of the crawler pipeline cleaning robot is shown in Figure 4.

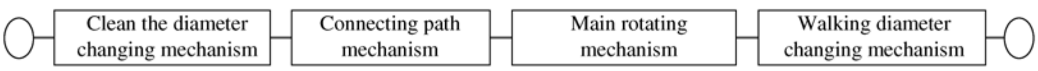

Figure 4 Robot reliability structure diagram

3.2.2 Analysis of failure modes

By calculating and comparing the failure rate of robot parts, the main failure modes are clean and the reducing mechanism cannot work, cleaning and the reducing mechanism work abnormally, and the walking reducing mechanism loses walking. Function and the like. According to the corresponding national standards in the《Guidelines for Failure Modes, Effects and Criticality Analysis》, the severity of the failure effects caused by the failure modes is divided into severity levels[13], and the consequences of the corresponding failures are divided into four levels. They are mild failure, moderate failure, severe failure, and catastrophic failure, and the results are shown in Table 1.

Table 1 Definition of severity of pipeline robot

Degree of severity	Severity	Influence level
Mild failure	IV	Slight impact on robot and being ignored
Moderate failure	III	Abnormal secondary functions, no effect on primary functions
Major failure	II	Loss of some major functions in the pipeline robot
Major failure	I	Loss of all functions in the pipeline robot and endangers equipment and personnel

Use the FMECA method to establish, analyze the cause and impact of the fault, give the severity, probability and weight of the corresponding fault according to the corresponding standard manual. According to the relevant standards in the《Guidelines for Failure Mode, Impact and Criticality Analysis》, the value of the probability β which belong to the failure effect is shown in Table 2. The fault information is summarized and sorted into FMECA analysis table. The FMECA analysis table of crawler pipeline cleaning robot is shown in Table 3.

Table 2 Recommended value of GB7826 failure and impact probability β value

Influence degree	Values
Positive injury	1
Possible damage	0.5
Very unlikely	0.1
No effect	0

Table 3 FMECA analysis of crawler pipe crawling cleaning robot

Minimum agreed level	Failure mode	Cause of issue	Failure effect	Severity	α	β	Cr
Laser cleaning group	The laser cleaning group cannot perform cleaning work	The cleaner is damaged; the light pipe is severely deformed;	The CDCM cannot work	Ⅱ	89	1	124.8
	The laser cleaning group is working abnormally	Abnormal laser connection; slight deformation of the light pipe, etc.	Abnormal operation of the CDCM	Ⅲ	11	0.5	3.755 0
Clean the reducing screw nut	The nut is stuck	Poor contact	The CDCM cannot work	Ⅱ	18	1	0.020 9
	Bad connection between nut and support rod	The connection is faulty	Abnormal operation of the CDCM	Ⅲ	82	0.1	0.004 8
Clean the reducing motor	Motor deformation	Suffer a huge impact	The CDCM cannot work	Ⅱ	1	1	0.011 4
	Abnormal number of motor revolutions	Poor internal contact of the motor	Abnormal operation of the CDCM	Ⅲ	37	0.5	0.105 6
	Motor burned out	Open circuit, short circuit, overload, overload work and end of life	The CDCM cannot work	Ⅱ	62	1	0.707 9

Continued Table 3

Minimum agreed level	Failure mode	Cause of issue	Failure effect	Severity	α	β	Cr
Hinged end cap	Severe deformation of the hinged end cap	Caused by huge external impact	The CDCM cannot work	Ⅱ	31	1	0.108 0
	Worn hinged end caps	Pitting, oxidation, contact wear	Appearance wear of the CDCM	Ⅳ	69	0.1	0.002 4
Cylinder block	Slightly deformed cylinder	Contact with foreign objects caused by force	The CM works abnormally	Ⅲ	23	0.1	0.000 1
	The cylinder body is severely deformed	Suffered from a huge external force collision	CM cannot work	Ⅱ	6	1	0.001 0
	Cylinder surface wear	Pitting, oxidation, contact wear	Outer wear of CM	Ⅳ	71	0.1	0.000 1
Rotating inner disk	Increased inner diameter of inner disc	Natural wear and tear with working hours	The CM works abnormally	Ⅲ	85	0.1	0.035 1
	The inner disc is slightly deformed	Impacted by external forces	The CM works abnormally	Ⅲ	10	0.1	0.004 2
	The inner plate is badly deformed	The inner disk is squeezed by a strong external force	CM cannot work	Ⅱ	5	1	0.020 7

Continued Table 3

Minimum agreed level	Failure mode	Cause of issue	Failure effect	Severity	α	β	Cr
Rotating outer dis	Inadequate contact between the outer disk and the inner disk	Caused by wear of inner and outer discs	The CM works abnormally	Ⅲ	20	0.5	0.020 7
	Outer disc deformation	Squeeze impact	CM cannot work	Ⅱ	12	0.5	0.045 6
	Outer disc surface wear	Pitting, oxidation, contact wear	Outer wear of CM	Ⅳ	68	0.1	0.002 8
Main rotating motor	The main rotating motor is burned out	Open circuit, short circuit, overload, overload work and end of life	The MRM cannot work	Ⅱ	62	1	0.707 9
	Motor deformation	Huge impact	The MRM cannot work	Ⅱ	1	1	0.011 4
	Abnormal number of motor revolutions	Poor internal contact of the motor	The MRM works abnormally	Ⅲ	37	0.5	0.105 6
Big and small gear set	The big and small gears do not mesh properly	Installation error or change of relative position by external force	The MRM works abnormally	Ⅲ	89	0.5	0.594 0
	The gear has broken edge and broken edge	The main rotating mechanism was hit by a huge external force	The MRM cannot work	Ⅱ	11	1	0.293 7

Continued Table 3

Minimum agreed level	Failure mode	Cause of issue	Failure effect	Severity	α	β	Cr
Walking mechanism group	Abnormal diameter change of walking mechanism	The hinged connecting rod is slightly bent and deformed, and the gap between the connecting rod and the screw nut is too large	The diameter changing function of the WDCM is abnormal	Ⅲ	8	0.1	0.259 8
	Abnormal walking function of walking mechanism	The walking of the caterpillar walker is discontinuous and abnormal	The walking function of the WDCM is abnormal	Ⅲ	74	0.5	2.402 9
	Loss of path changing function of walking mechanism	Hinge connecting rod serious bending deformation; screw connecting rod bending deformation	The WDCM loses the diameter changing function	Ⅲ	5	0.5	0.162 4
	Loss of walking function of walking mechanism	Crawler walking machine can not walk	The WDCM loses its walking function	Ⅰ	11	1	2.687 0
	The appearance of walking mechanism is worn	Walking wear of caterpillar walking machine	Wear on the surface of WDCM	Ⅳ	2	0.1	0.002 7

Continued Table 3

Minimum agreed level	Failure mode	Cause of issue	Failure effect	Severity	α	β	Cr
Enclosure	Box bending deformation	Extrusion force	The WDCM loses the function of walking and diameter changing	Ⅰ	22	1	0.038 3
	Small pits appear in the box	Colliding with something else	The diameter changing function of WDCM is abnormal	Ⅲ	78	0.1	0.006 8
Walking reducing motor	Walking reducing motor burned out	Circuit break, short circuit overload overload work and reach service life	The WDCM loses the diameter changing function	Ⅲ	62	1	0.234 1
	Deformation of the motor	Tremendous impact force	The WDCM loses the diameter changing function	Ⅲ	1	1	0.004 6
	The rotation of the Walking reducing motor is unstable	Line fault	The diameter changing function of WDCM is abnormal	Ⅲ	37	0.5	0.229 5

Continued Table 3

Minimum agreed level	Failure mode	Cause of issue	Failure effect	Severity	α	β	Cr
Walking reducing screw nut	The clearance of Walking reducing screw nut is too large	Wear cause	The diameter changing function of WDCM is abnormal	Ⅲ	86	0.5	0.010 2
	The Walking reducing screw nut is stuck on the lead screw	Impurities clogging	The WDCM loses the diameter changing function	Ⅲ	14	1	0.001 2
Screw	The lead screw corroded and rusted	External corrosion	The diameter changing function of WDCM is abnormal	Ⅲ	92	0.1	0.001 0
	Screw bending	The walking machine was hit by a massive force	The WDCM loses the diameter changing function	Ⅲ	8	0.5	0.000 9

The summations for *Cr* of each severity are $Gr_{\text{I}} = 2.725\ 3$, $Gr_{\text{II}} = 126.728$, $Gr_{\text{III}} = 7.938\ 5$ and $Gr_{\text{IV}} = 0.008\ 0$. Obtain the robot's lowest-level failure mode and criticality and other parameters, and obtain the robot's criticality matrix after calculation and statistics, as shown in Figure 5.

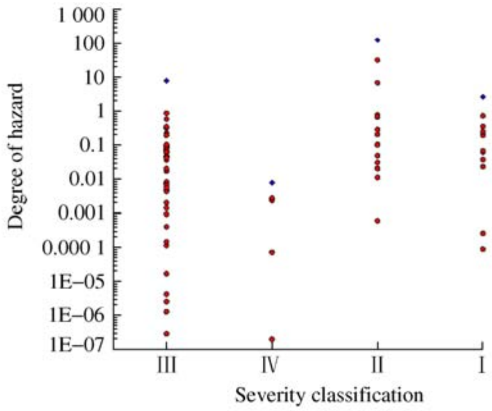

Figure 5 System hazard matrix

In the Figure 5, the most harmful is severity II, followed by severity I, the third is severity IV, and the lowest is severity III. According to the severity definition table, severity I causes the greatest harm. It can cause the loss of all functions of the pipeline robot and endanger the safety of equipment and personnel, but its size is only 2.725 3. The severity of severity II is 126.728 5, which is far greater than severity I. Therefore, the next step of fault tree analysis is focused on the severity of II to further analyze the impact which pertain to failure modes.

3.3 Fault tree method

Failure refers to any phenomenon in mechanical products where the specified function cannot be completed or the performance index deteriorates beyond the specified range. Fault Tree Analysis, abbreviated to as FTA that is a graphical deduction method. FTA is a logical reasoning method for failure events under certain conditions[14], suitable for the reliability and safety analysis of large complex systems[15]. In system analysis, the factors (such as hardware, software, environment, human factors) that cause the loss of system function with a certain probability are analyzed, and a logical block diagram (fault tree) is drawn to determine various possible combinations or combinations of system failure causes. The probability of occurrence is to calculate the probability of system failure and take corresponding preventive and corrective measures to improve the reliability of the system.Severity Ⅱ is that the pipeline robot cannot perform cleaning work. In this chapter, the main component mechanism of the robot-the clean reducing mechanism which leads to the final impact, is used as an example to perform a fault tree analysis. Define the clean reducing mechanism, and define the "Cleaning and diameter changing mechanism" as the top event 1.

3.4 Fault tree analysis

3.4.1 Establishment of fault tree

For given event 1, according to the corresponding establishment rules, the establishment of the corresponding fault tree for given event 1 is carried out. According to the regulations on the boundary conditions of the fixed event, the bottom event of the fixed event fault analysis can only be used for the failure modes contained in the component parts. The analysis of fault tree includes qualitative analysis and quantitative analysis[16]. Make the following agreement on the relevant condition:

1) Does not include faults caused by human operation;

2) The cause of the fault does not include air pressure, temperature changes, etc.

The fault tree model established for the fixed event 1 ″Clean and reducing mechanismfailure″ is shown in Figure 6–Figure 8.

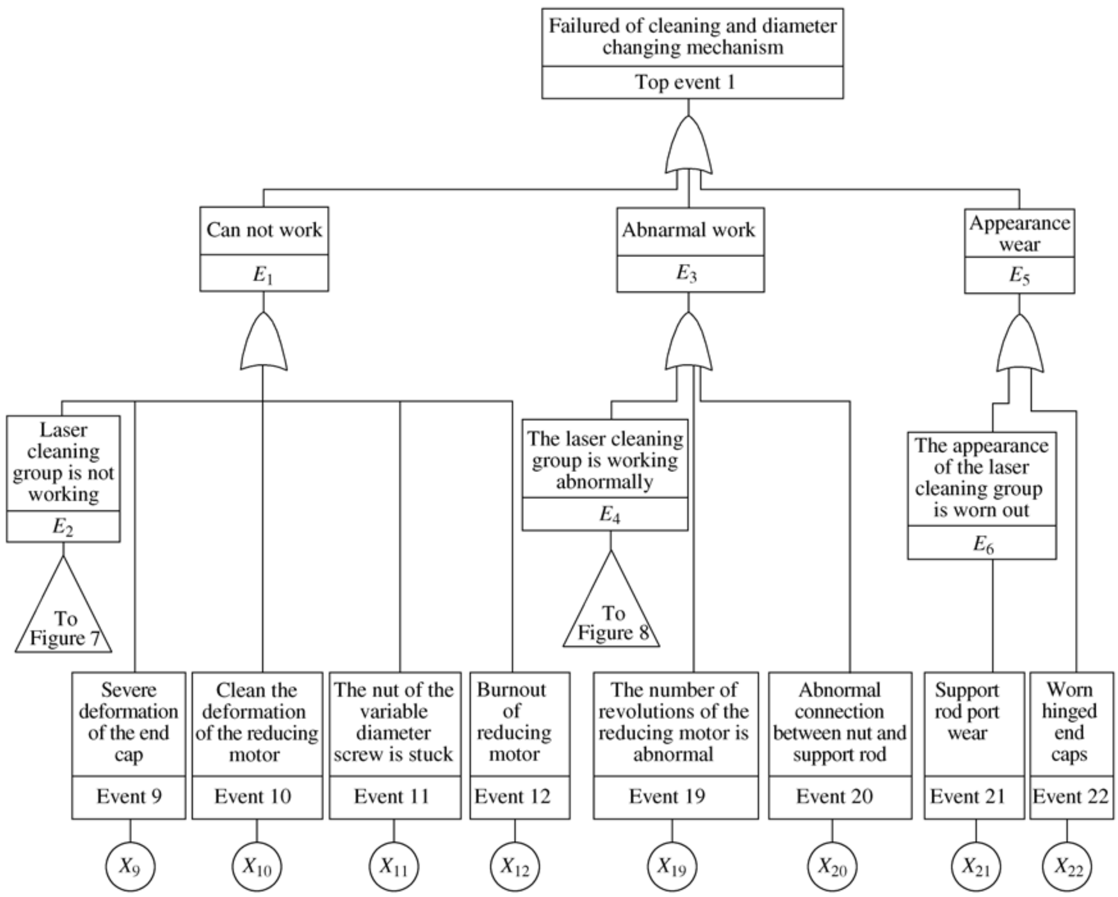

Figure 6 The fault tree of top event 1

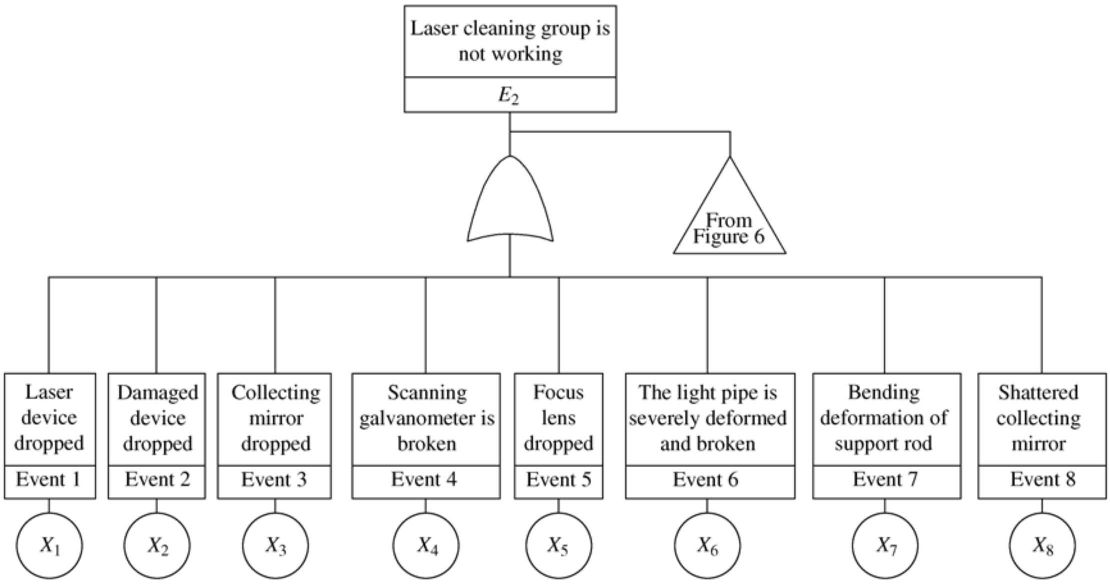

Figure 7 The fault tree of intermediate event E_2

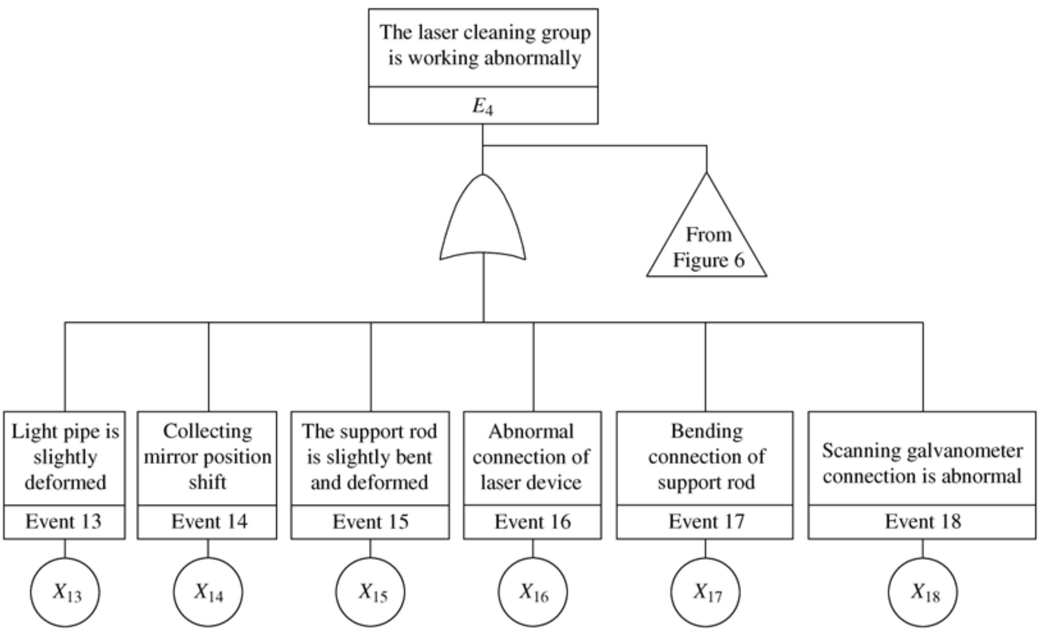

Figure 8 The fault tree of intermediate event E_4

3.4.2 Qualitative analysis of top event 1

A qualitative analysis of the top event 1 is to summarize the failure modes that can lead to the "failure of Cleaning and diameter changing mechanism". The failure mode is also called a collection of bottom events. List the minimum cut sets that is some events in the bottom event, when these events do not occur, the top event will not occur immediately. The purpose of qualitative analysis is to find all the smallest cut sets, the set of bottom events that contains the smallest number and is the most necessary. According to the fault tree established in 3.4.1, qualitative analysis of top event 1 is performed, and all the minimum cut sets of top event 1 "failure of Cleaning and diameter changing mechanism" are: {event X_1}, {event X_2}, {event X_3}, {event X_4}, {event X_5}, {event X_6}, {event X_7}, {event X_8}, {event X_9}, {event X_{10}}, {event X_{11}}, {event X_{12}}, {event X_{13}}, {event X_{14}}, {event X_{15}}, {event X_{16}}, {event X_{17}}, {event X_{18}}, {event X_{19}}, {event X_{20}}, {event X_{21}}, {event X_{22}}.

According to the qualitative analysis, the minimum number of cut sets for top event 1 "failure of Cleaning and diameter changing mechanism" is 22. When any cut set in 22 occurs, top event 1 will also occur.

3.4.3 Quantitative analysis of top event 1

Perform quantitative analysis on top event 1 to calculate the relative probability importance of the bottom event, the relative probability importance is the relative change rate of the top event's occurrence probability reflected when the occurrence probability of each event changes slightly[17]. By comparing the magnitude of the relative probabilistic importance, according to the criterion that the greater the importance of the bottom event causes the greater the probability of the top event, the bottom event is finally arranged according to the relative probability importance[18].

Let the probability of occurrence of each bottom event be $q_1, q_2, q_3, q_4, q_5, q_6, q_7, \cdots, q_{20}, q_{21}, q_{21}, q_{22}$, and then define the failure probability function is the probability of the occurrence of the top event when all the bottom events constituting the fault tree are independent of each other and do not interfere with each other; also known as the function of the probability of the bottom event, denoted as $Q = Q(q_1, q_2, \cdots, q_n)$[19]. The calculation formula for I_C which can obtain the relative probability importance of the i-th bottom event is.

$$I_C(i) = \frac{q_i}{P(T)} \cdot \frac{\partial}{\partial q_i} Q(q_1, q_2, \cdots, q_n) \tag{1}$$

$$Q = 1 - \prod_{i=1}^{r} [1 - P(K_i)] \tag{2}$$

$$P(T) = \sum_{i=1}^{r} P(K_i), i = 1, 2, \cdots n \tag{3}$$

Where: r is the number of minimum cut sets; K_i is the i-th smallest cut set; $P(K_i)$ is the probability of occurrence of the smallest cut set which number is i. It can be assumed that the bottom events included in the i-th minimum cut set are $(X_1, X_2, \cdots, X_n)$, which is the probability of occurrence of X_n, let $p(x_n) = q_{xn}$, under the premise that the bottom events do not interfere with each other, we can get the probability importance of the i-th bottom event; $P(T)$ obtained in formula (3) is expressed as the probability of occurrence of a given event[20]. Further calculate the probability of failure of top event 1 as:

$$P(T_1) = P(X_1) + P(X_2) + P(X_3) + P(X_4) + P(X_5) + \cdots + P(X_{19}) + P(X_{20}) + P(X_{21}) + P(X_{22}) = 55.529 \times 10^{-6} \quad (4)$$

Then the failure probability function of top event 1 is:

$$Q(T_1) = 1 - \prod_{i=1}^{22}(1 - P(K_i)) \quad (5)$$

$$\prod_{i=1}^{22}(1 - P(K_i)) = (1 - q_{x_1})(1 - q_{x_2})\cdots(1 - q_{x_{22}}) \quad (6)$$

According to formula (6), the result is 0.148 959 12. Immediately from the arrangement of each cut set in the qualitative analysis, find the relative probability importance of each cut set. For example, the relative probability importance of bottom event $9-X_9$ is calculated as, $I_C(X_9) = \frac{q_9}{P(T_1)} \cdot \frac{\partial Q(T_1)}{q_9} = \frac{q_9}{P(T_1)} \cdot \prod_{i=1}^{22}(1-P(K_i))$, and the result is 0.000 643 5. The relative probability importance values of the remaining cut sets can also be obtained in the same way. After calculating the relative probability importance of the crowd cut set, arrange the relative probability importance values of the top event 1 "cleaning and reducing mechanism failure" into a table, as shown in Table 4.

Table 4 Rank of relatively probability importance of the bottom event in the top event 1

The serial number	Base event number	Bottom event description	Relative probability importance
1	X_2	Damaged laser device	0.076 018 26
2	X_1	Laser device dropped	0.018 815 95
3	X_{16}	Abnormal connection of laser device	0.018 815 95
4	X_{13}	Light pipe is slightly deformed	0.004 967 37
5	X_{12}	Burnout of reducing motor	0.001 899 02
6	X_{14}	Collecting mirror position shift	0.001 494 86
7	X_5	Focus lens dropped	0.001 494 86
8	X_6	The light pipe is severely deformed and broken	0.001 419 24
9	X_{19}	The number of revolutions of the reducing motor is abnormal	0.001 133 29
10	X_{21}	Support rod port wear	0.000 907 39

3.5 Result analysis and preventive measures

From the calculation and analysis of these two chapters, the following conclusions are obtained:

1) The crawler-type pipeline crawling cleaning robot analyzed in this paper is divided into four institutions as a whole. The failure mode analysis and FMECA calculation and analysis of the mechanism show that the impact of causing the pipeline robot to be unable to walk and clean is the most important, and the corresponding failure rate is also the largest.

2) The focus of the robot's function is first to realize the removal of impurities in the pipeline, and the fault severity of the cleaning reducing mechanism is Ⅰ, therefore, the fault tree is established for the cleaning reducing mechanism. In the fault tree of the defined top event 1"failure of Cleaning and diameter changing mechanism", the relative probability importance of each bottom event is obtained according to the relevant calculation of the bottom event. According to the ranking in Table 4, the damage and drop of the laser contribute the most to the "failure of Cleaning and diameter changing mechanism", followed by the top event caused by the failure of the light pipe, hinge connection, focusing lens, and condenser lens.

After finding the bottom faults that can affect the cleaning and reducing mechanism, understand the impact of the bottom events of different relative probability importance. Analyze the causes of the bottom event, and then list the corresponding preventive measures for each failure cause. The specific failure causes and preventive measures are shown in Table 5.

Table 5 Cause analysis and measures of important failure modes of Cleaning and diameter changing mechanism

Fault	Cause of problem	preventive measure
Laser failure	The cleaning head with the laser was hit by a force; Damage caused by infiltration of subtle impurities; Poor fastening at installation	The cleaning head is equipped with a buffer device to reduce the impact of external force on the laser; The installation place of the laser is treated with anti-permeability, and it is tightened; It is necessary to remove the fine impurities attached to the outside of the laser at intervals

Continued Table 5

Fault	Cause of problem	preventive measure
Light guide tube is faulty	The light guide tube is bent and deformed due to the collision at work; Erosion of light guide tube by external environment	Ensure that the weight limit, as far as possible to choose strong material to install the light guide tube; Surface treatment to reduce external erosion
Focus lens failure	To shatter by collision with sharp objects; The long time working vibration causes the focus mirror to loose and fall off	A baffle plate is installed outside the focusing mirror to resist sharp objects; An elastic fixing device is installed at the fastening part of the focusing mirror; Check whether the focus lens is tight and cracked before work

4 Conclusions

This article first analyzes the function of the crawler-type pipeline crawling cleaning robot, and then conducts fault analysis and FMECA analysis to obtain the failure mode of each mechanism. Among the lowest-level failure modes, the severity of Ⅱ is the most harmful. Aiming at the realization of the cleaning function guaranteed by this robot, the cleaning reducing mechanism with an importance level of Ⅱ implements fault tree analysis. According to the relative probability importance, the bottom events that cause the failure of the cleaning reducing mechanism are ranked. Make a list of the causes of the main underlying faults and pre-improvement measures. This article uses FMECA and FTA methods to provide a basis and corresponding measures for improving the reliability of crawler-type pipeline crawling cleaning robots. This paper does not exist in experiments, and will be verified by experiments in follow-up research.

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