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Failure Mode Analysis of Intelligent Ship Positioning System Considering Correlations Based on Fixed-Weight FMECA

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Abstract: Currently, intelligent ships are still in the early stages of development in terms of autonomous navigation and autonomous berthing, so almost no source of fault data can be obtained. Conducting an in-depth analysis of the failure modes of intelligent ships is critical to optimizing the design of smart ships and ensuring their normal and safe navigation. In this paper, the fixed-weight Failure Mode Effects and Criticality Analysis (FMECA) is combined with the decision-making trial and evaluation laboratory (DEMATEL) method to analyze the failure modes and effects of intelligent ship positioning systems. This combined method not only overcomes the failure of traditional FMECA methods to differentiate between severity, incidence, and detection rates but also allows the correlation of failure causes to be analyzed, bringing the results of the analysis closer to reality. Through the expert scoring of failure modes, the failure modes of this system are risk-ranked, and the key failure causes of this system are identified. Correlations between the critical failure causes are then considered. According to the analysis results, the high-accuracy attitude sensor was identified as the subsystem with the highest level of risk. Unavoidable, unknown failures and environmental factors were found to be key factors in causing positioning system failures. The conclusions can provide a reference for the design of equipment safety for intelligent ship positioning systems.

Keywords: fixed-weight; FMECA; intelligent ship; positioning system; risk identification

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1. Introduction

Due to the large potential for saving energy consumption on ships and reducing ship crew, the intelligent ship has become the focus of the industry and the trend in its development. According to the China Classification Society (CCS) [1], an intelligent ship requires the use of sensors, communications, the Internet of Things, and other technical means to automatically sense and obtain information and data about the ship itself, the marine environment, logistics, and ports. Intelligent operation is applied to ship navigation, management, maintenance, and cargo transportation. This makes intelligent ships safer and more environmentally friendly than traditional ships.

The technology of intelligent ships includes intelligent navigation, autonomous berthing, status detection, and fault diagnosis. Currently, research work in intelligent navigation is focused on collision avoidance and algorithmic optimization of path planning. Agnieszka [2] proposes a new deterministic approach using the concept of a trajectory database to calculate the safe, optimal path of a ship, considering its dynamic properties and static and dynamic obstacles. He et al. [3] proposed an open-water intelligent navigation decision method capable of dynamically adapting to system residual errors and random maneuvers of the target vessel. By utilizing the velocity obstacle (VO) theory and dynamic collision avoidance mechanism, the vessel is able to navigate autonomously in an open water environment with multiple static and dynamic objects. Since autonomous berthing requires high ship maneuverability, the existing research work is mainly focused on berthing control tasks and controller design. Lee et al. [4,5] used fuzzy control and LOS algorithms to experiment with a 4 m-long boat to solve the problem of small boat position and navigation accuracy to achieve side booster-assisted berthing. Mizuno et al. [6–8] solved the problem of automatic berthing under uncertainty disturbances using an artificial neural network approach.

Although the technology has received a lot of attention, it still requires development. There are still many unresolved issues, and the weaknesses of intelligent ships cannot be clarified. Intelligent ships, compared with traditional ships, involve more fields and disciplines, and their components are more numerous and complex. The harsh conditions at sea lead to extremely violent ship movements. The equipment, components, signal transmission, and structures on ships are, therefore, also extremely vulnerable to failure [9]. According to the data published by Allianz Global Corporate & Specialty (AGCS) [10], more than 1000 ships of more than 100 gross tons have been lost in the last decade. More than one-third of shipping accidents are caused by mechanical damage or failure, out of more than 20,000 reported in the last 10 years. It is conceivable that the failure of intelligent ship equipment, which relies on equipment and information transfer, can also suffer from similar serious consequences. Currently, there is little data available on the failure of intelligent ship equipment. Therefore, research on risk identification related to equipment must be conducted in order to prevent or mitigate potential hazards. Through Failure Mode Effects and Criticality Analysis (FMECA), finding the weak points of equipment and proposing targeted repair and maintenance strategies can significantly improve the reliability of intelligent ships.

An intelligent ship mainly includes a hull structure, power propulsion system, positioning and navigation system, control system, communication system, and interaction system. Among them, the positioning system plays an extremely significant role in normal operation. Its functions involve ship positioning, external environment sensing and platform state sensing, providing the necessary data sources for motion decision and control as well as its own state monitoring. The causes of the failure of certain subsystems and components in positioning systems have been investigated. Alan et al. [11] studied the effects of data reliability and human error on the Automatic Identification System (AIS) in the positioning system and showed that many input errors in the navigation state are due to personnel memory errors or negligence in performing the required operations. Pallotta [12] and Tsou [13] et al. studied the impact of data redundancy on AIS. Philipp et al. [14] investigated the effects of antenna height and environmental changes on information transmission. If the system fails, serious consequences will occur, such as intelligent navigation deviation, autonomous berthing and unberthing failure, and even collision between the ship and obstacles. Therefore, it is necessary to analyze its failure mode to ensure its safety. However, relevant risk identification research, especially for positioning system equipment, has not been reported. This paper intends to focus on equipment failure mode and its impact on the positioning system.

One of the main methods for failure mode analysis is the FMECA method. The key to failure analysis by the FMECA method is usually based on three risk parameters: severity (S), occurrence (O), and detection (D). The magnitude of the risk priority number (RPN), the product of the three, measures the severity of potential system problems. By prioritizing the high-risk failure modes and guiding maintenance management strategies. Although the traditional FMECA method is widely used, it is still criticized for its many drawbacks. Different values of S, O, and D can get the same RPN value, which is theoretically the same priority as the two, but in practice, the priority of the two risk ranks is different.

Therefore, many enhanced versions have been proposed in the literature. Some scholars have proposed measuring risk in more dimensions. For example, Carmignani [15] suggested the use of a fourth parameter, profitability, in the RPN calculation. Bevilacqua et al. [16] proposed that the RPN can consist of a weighted sum of six parameters (safety, importance of the machine to the process, maintenance cost, failure frequency, downtime, and operating conditions). Other studies combine FMECA methods with other methods. Zammori et al. [17] combined FMEA with analytical network process (ANP) techniques [18] to consider the possible interactions between the main causes of failure. Silvia et al. [19] proposed a method combining reliability analysis and a multi-criteria decision-making approach to improve the maintenance activities of complex systems. Some scholars combine FMECA with Analytic Hierarchy Process (AHP) to solve the problem that the traditional FMECA method cannot distinguish the different weights of risk factors by giving different weights to the evaluation parameters so that the risk ranking of failure modes is closer to the actual results. Braglia [20] proposed the analysis hierarchical method (AHP) [21] to compare pairs of potential failure causes by assuming the classical risk factors *S*, *O*, and *D* and the expected cost caused by the failure as criteria. Xiao et al. [22] proposed a weighted RPN evaluation method, which multiplied the RPN value with the weight parameter representing the importance of the fault causes in the system and then ranked them. Zhang et al. [23] proposed a new method for FMECA failure mode ranking based on incentive variable weight AHP. Li et al. [24] proposed a fixed-weight FMECA method. The method considers that the scales of *S*, *O*, and *D* and their weights are different and designs a normalization method to convert *S*, *O*, and *D* to the same scales as their weights and then generates the RPN of the cause of the failure as well as the failure mode. This method not only improves the problem of different weights of *S*, *O*, and *D* but also solves the sorting problems with the same RPN values. Due to the insufficient ability of traditional AHP to deal with fuzziness, many scholars use fuzzy theory to solve this problem. Many researchers have proven the effectiveness and superiority of fuzzy theory in dealing with fuzzy information. Luqman et al. [25] proposed an FMEA risk assessment technology based on TPFNs and DGMA. Akram et al. [26] proposed a mixed solution of TOPSIS and ELECTRE I with Pythagorean fuzzy information, using the Pythagorean fuzzy weighted average operator to aggregate their independent evaluations into group evaluations. Some studies also combine fuzzy theory and traditional AHP methods to manage the lack of information acquisition on complex problems, such as Liu et al. [27].

However, these FMECA methods do not consider the correlation between the failure factors, making the results obtained from the analysis somewhat one-sided. Many existing studies have proposed solutions to the problem of correlation of structural reliability, mainly involving integral methods [28,29] and numerical simulation (Monte Carlo method) [30]. The integral method could solve the multidimensional integration problem, but the procedure is complicated and not practical when the system composition is large. The Monte Carlo method uses a huge number of samples to simulate the variables obeying the desired distribution, and the more simulations there are, the higher the accuracy. However, it requires a lot of time and computing capacity and is less efficient [31]. Unlike structural faults, equipment faults do not allow for the construction of limit state equations. It is, therefore, difficult to apply reliable indicator vector methods for accurate correlation assessment. In this paper, the decision-making trial and evaluation laboratory (DEMATEL) method is used for the computational analysis of equipment failure correlations. The DEMATEL method was first proposed by Gabus and Fontela [32] of the Battelle Memorial Association in Geneva and aimed to analyze the causal relationships between the elements of a complex system and the degree of mutual influence [33].

Combining the above issues, considering the complex structural composition and many failure modes of the positioning system of intelligent ships, this paper uses a combination of fixed-weight FMECA and DEMATEL to study the system. On the one hand, it improves the problem of unreasonable distribution of *S*, *O*, and *D* weights in the traditional FMECA method, and on the other hand, it also considers the correlation between failure modes and improves the problem of mutual independence among failure causes. The results are closer to reality and increase the credibility of the failure mode analysis.

The remainder of the paper is organized as follows: Section 2 introduces the fixed-weight FMECA method. Section 3 performs FMECA analysis on the positioning system to obtain critical failure modes. Section 4 analyzes the correlation between the key failure modes, and Section 5 gives the conclusions.

2. Method

2.1. Fixed-Weight FMECA Approach to Modeling

FMECA includes Failure Mode and Effects Analysis (FMEA) and Criticality Analysis (CA), which is an analysis technique based on failure modes and targeting the effects or consequences of failures. FMECA is performed by finding all possible failures of the product, analyzing them according to the failure mode, determining the impact of each failure on the operation of the product, and identifying the hazards of the failure mode in the order of the RPN. RPN is the risk prioritization number, whose value is equal to the product of the values of severity (S), occurrence (O) and detection (D), calculated by the following formula:

$$RPN = S \times O \times D \tag{1}$$

Although the traditional FMECA method is widely used in production practice, it still has many drawbacks. For example, the same weights are assigned to severity, occurrence, and detection. However, in practice, the weights of the three in the system are not exactly equal. For some irreparable systems, the weights of factors S and O should be higher than the weights of D. In this paper, the fixed-weight FMECA method [24] is used to eliminate the above effects. This FMECA method generates the RPN of component failure caused by using the severity, incidence, and detection rates of each item and their relative weights. Considering that the scales of each factor (severity, incidence, and detection rate) and their weights are [1, 10] and [0, 1], S, O, and D are converted to the same scales as their weights before calculating the RPN.

Denote β_{Si}, β_{Oi} and β_{Di} as the average value of the severity, occurrence and detection of the fault cause, i, given by the expert. The weights of the factors: $\psi = \begin{bmatrix} K_S & K_O & K_D \end{bmatrix}$. K_S, K_O, and K_D are the weights for severity, occurrence and detection, respectively. Thus, the raw values of severity, occurrence, and detection given by the experts can be expressed as follows:

$$\begin{bmatrix} \beta_{S1} & \beta_{S2} & \cdots & \beta_{Si} & \cdots & \beta_{Sn} \\ \beta_{O1} & \beta_{O2} & \cdots & \beta_{Oi} & \cdots & \beta_{On} \\ \beta_{D1} & \beta_{D2} & \cdots & \beta_{Di} & \cdots & \beta_{Dn} \end{bmatrix} \tag{2}$$

Denote

$$\xi_{Kij} = \frac{\beta_{Ki}}{\beta_{Kj}} \tag{3}$$

where, K represents severity, occurrence, and detection.

Therefore, the comparison matrix is attained as:

$$\begin{bmatrix} \xi_{K11} & \xi_{K12} & \cdots & \xi_{K1n} \\ \xi_{K21} & \xi_{K22} & \cdots & \xi_{K2n} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{Kn1} & \xi_{Kn2} & \cdots & \xi_{Knn} \end{bmatrix} \tag{4}$$

The normalized matrix is defined as:

$$\begin{bmatrix} \phi_{K11} & \phi_{K12} & \cdots & \phi_{K1n} \\ \phi_{K21} & \phi_{K22} & \cdots & \phi_{K2n} \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{Kn1} & \phi_{Kn2} & \cdots & \phi_{Knn} \end{bmatrix} \tag{5}$$

where

$$\phi_{Kij} = \frac{\xi_{Kij}}{\sum_{i=1}^{n} \xi_{Kij}} \tag{6}$$

The adjusted value of index K of failure cause i is defined as:

$$\gamma_{Ki} = \frac{\sum_{j=1}^{n} \phi_{Kij}}{n} \tag{7}$$

According to Equations (6) and (7),$\gamma_{Ki} \in [0,1]$, which is the same as the scale of the weight vector of indices $\psi = \begin{bmatrix} K_S & K_O & K_D \end{bmatrix}$.

Hence, the weighted RPN of failure cause i is defined as:

$$RPN_i = \psi \times \Gamma_i = \begin{bmatrix} K_S & K_O & K_D \end{bmatrix} \begin{bmatrix} \gamma_{Si} \\ \gamma_{Oi} \\ \gamma_{Di} \end{bmatrix} \tag{8}$$

The method first transforms the absolute values of S, O, and D into the same values as their weight scales, and the S, O, and D transformed values take values in the range [0, 1]. The larger the original S, O, and D values will still be larger after transformation and will not affect the order of RPN. The importance of the cause of failure does not change. When using the fixed-weight FMECA method, the calculation of RPN involves the S, O, and D values as well as the weights. However, the range of the two values is different, [1, 10] and [0, 1], respectively. This could bias the final calculated RPN. The consistent scale conversion of both before calculating the RPN prevents each type of parameter from affecting the results more than the other.

2.2. Selection of Weights

For intelligent ships, we should pay more attention to the consequences of their failure occurrences and the value of severity. This is because failures with low incidence can still occur, and detectable failures can still occur. The occurrence of faults can affect certain functions of intelligent ships and even lead to major accidents if certain critical units are affected. Therefore, the weight value of importance should be the largest among the three. At the level of occurrence and detection, the likelihood of failure occurrence is significantly more important than detection. Whether a fault occurs or not is the combined result of the physical properties of the system and the internal and external effects, and it does not change with whether the fault is detectable or not, so the occurrence degree should be given more weight than the detection degree. The selection of risk evaluation index weights should follow the principle that the severity degree is greater than the occurrence is greater than the detection.

According to the basic guideline that the selection of risk evaluation index weights should follow that the severity degree is greater than the occurrence degree is greater than the detection degree, and according to reference [23], combined with the risk characteristics of the intelligent ship positioning system, the failure mode analysis conducted in this paper selects the following weight vector:

$$\psi = \begin{bmatrix} 0.40 & 0.35 & 0.25 \end{bmatrix} \tag{9}$$

2.3. DEMATEL Method

The reason for the correlation assessment of hazardous units is that failure modes that are closely linked to other failures may lead to more severe consequences than relatively independent failure modes. Therefore, identifying correlations between failure modes can lead to more reliable results. The main steps of the DEMATEL method are as follows:

(1) Establishing assessment criteria. The degree of correlation between the assessment elements is quantified by means of expert scoring. The assessment scale ranges from 0 to 4, in the order of no impact, very low impact, low impact, high impact, and very high impact. The scoring values are entered into a direct impact matrix (10).

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1(n-1)} & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2(n-1)} & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{(n-1)1} & a_{(n-1)2} & a_{(n-1)3} & \cdots & 1 & a_{(n-1)n} \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{n(n-1)} & 1 \end{bmatrix} \quad (10)$$

where a_{ij} indicates the degree of influence of factor i on factor j.

(2) The direct relationship matrix is normalized by Equations (11) and (12) such that each value of the matrix lies between [0, 1].

$$S = \max_{1 \le i \le n} \sum_{j=1}^{N} a_{ij} \quad (11)$$

$$\boldsymbol{K} = \frac{\boldsymbol{A}}{\boldsymbol{S}} \quad (12)$$

(3) The total impact matrix M is obtained by Equation (13), where I denotes the unit array.

$$M = K(I - K)^{-1} \quad (13)$$

(4) The sum of each column and each row of the total impact matrix is calculated by Equations (14) and (15), denoted as D and R, respectively.

$$D_i = \left[\sum_{i=1}^{n} m_{ij} \right]_{1 \times n} \quad (14)$$

$$\boldsymbol{R_i} = \left[\sum_{j=1}^{n} \boldsymbol{m_{ij}} \right]_{\boldsymbol{n \times 1}} \quad (15)$$

where, $M = m_{ij}$, i, j=1, 2, ..., n.

(5) Perform the calculation of $Ri + Dj$, $Ri - Dj$. $Ri + Dj$ indicates the extent to which factor i plays a role in the problem, with a positive $Ri - Dj$ indicating that factor i assigns influence to other problems and a negative $Ri - Dj$ indicating that factor i receives influence from other factors.

3. Fixed-Weight FMECA of Positioning Systems

3.1. Positioning System Introduction

The intelligent ship positioning system is built for the needs of digitalization, networking, visualization, and intelligence in ship positioning. It can realize the rapid circulation of ship information and effective management of ships by using the BeiDou positioning system, automatic control, and other technologies, combined with the data update of dynamic changes in ocean climate, to conduct emergency command of ocean ships.

The positioning system includes five subsystems: a high-precision attitude sensor, the BeiDou positioning system, the electronic chart display information system (ECDIS), the automatic identification system (AIS), and a mobile communication receiver. The structure diagram of the positioning system is shown in Figure 1. The high-precision attitude sensor is used to capture dynamic reference signals. The BeiDou positioning system is used to receive satellite positioning signals and, in conjunction with ECDIS, to precisely locate the ship's position at sea. The AIS and mobile communication receiver are responsible for sending and receiving to the ships and shore stations in the nearby waters so that the neighboring ships and shore stations can grasp the dynamic and static information of all the ships in the nearby sea and can immediately talk to each other for coordination. They can also calculate the voyage heading and take necessary avoidance actions to effectively ensure the safety of ship navigation.

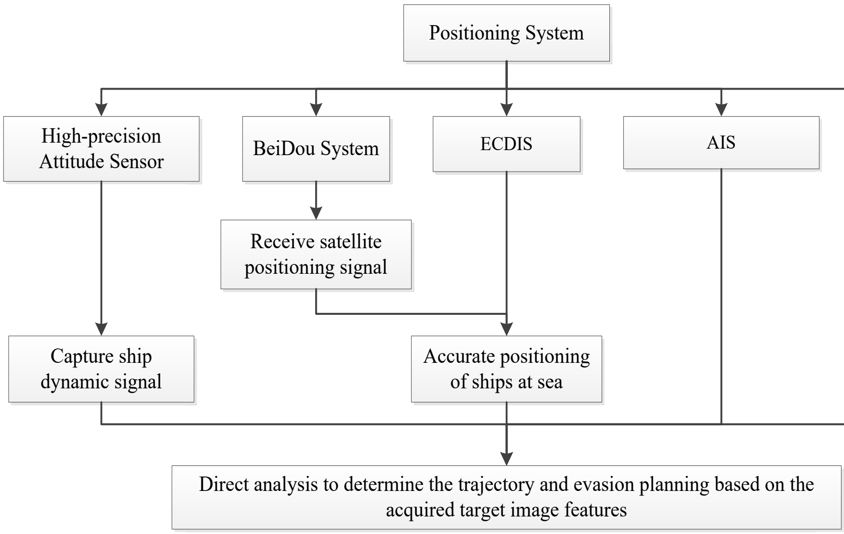

Figure 1. Schematic diagram of positioning system structure.

3.2. FMECA of Positioning Systems

Based on the composition and working principle of the positioning system and the human factors and environmental influences identified in scholarly research, this section will analyze the reliability of the intelligent ship positioning system based on the fixed-weight FMECA method [24]. The scoring of each failure mode and failure cause of the intelligent ship positioning system is based on the evaluation table, and the results are shown in Table 1. Detailed failure causes, transformed values for severity, occurrence and detection, and risk number ranking for each failure mode are also given in Table 2.

Table 1. Evaluation table of failure model risk evaluation indicators.

Score	Severity (S)	Occurrence (O)	Detection (D)
1–3	The device function is disturbed by faults but basically does not affect the overall function	The probability of occurrence is less than 1/1000	The probability that the failure can be detected is greater than 80%
4–5	The device loses some functionality and has a partial impact	The probability of occurrence is between 1/100 and 1/1000	The probability that the failure can be detected is greater than 60%
6–7	The device functionality is severely impacted	The probability of occurrence is between 1/10 and 1/100	The probability that the failure can be detected is 50%
8–10	Total loss of device function	The probability of failure is greater than 1/10	The probability of failure detection is less than 20%

Table 2. FMECA of the positioning system of intelligent ships.

Subsystems	Unit	Failure Mode	Failure Effects	Code	Cause of Failure	S	O	D	Conversion Value of S, O, and D			RPN	Rank
									S	O	D		
High-precision attitude sensor	Tri-axis gyroscope	A Drift fault	Severe lack of attitude measurement accuracy	A1	Interference torque due to friction of gyroscope elements	5	6	6	0.00684	0.01342	0.01575	0.0114	19
				A2	The gyro has a residual unbalance moment	5	3	7	0.00684	0.00671	0.01837	0.0097	44
				A3	Thermal decomposition and deformation	5	7	2	0.00684	0.01566	0.00525	0.0095	47
				A4	Component damage	5	4	5	0.00684	0.00895	0.01312	0.0091	57
				A5	Static imbalance caused by imperfect assembly	5	2	7	0.00684	0.00447	0.01837	0.0089	60
		B Vibration fault	Gyroscope vibration, attitude measurement accuracy is seriously lacking	B1	Damaged gyro motor	6	3	6	0.00821	0.00671	0.01575	0.0096	46
				B2	Rotor imbalance	6	7	6	0.00821	0.01566	0.01575	0.0127	4
				B3	Insufficient power supply voltage	6	6	3	0.00821	0.01342	0.00787	0.0099	40
				B4	Bearing wear	6	6	2	0.00821	0.01342	0.00525	0.0093	51
		C High-temperature shock failure	Affect the normal operation of the gyroscope	C1	High-temperature environment influence	6	6	2	0.00821	0.01342	0.00525	0.0093	51
		D Poor contact	Discontinuous gyroscope signal	D1	Vibration and shock factors	4	7	6	0.00547	0.01566	0.01575	0.0116	9
		E Loose and worn components	Gyroscope damage, not working properly	E1	Vibration and shock factors	7	7	4	0.00958	0.01566	0.01050	0.0119	6
		F Rotor imbalance	Attitude measurement accuracy is severely lacking	F1	High-intensity and high broadband electromagnetic interference	7	8	5	0.00958	0.01790	0.01312	0.0134	1
		G Stuck gyro motor	The gyroscope does not work properly	G1	Humidity factors	8	8	4	0.01094	0.01790	0.01050	0.0133	2
	Three-axis accelerometer	H Low sensitivity	Cannot accurately judge the ship's status	H1	Temperature effects	6	8	2	0.00821	0.01790	0.00525	0.0109	21
				H2	Hardware decline of sensors	6	6	7	0.00821	0.01342	0.01837	0.0126	5
				H3	Data connection failure	6	5	2	0.00821	0.01119	0.00525	0.0085	67
	Electronic compass	I Measurement result deviation, difficult to correct	Ship's direction deviation, unable to avoid collision	I1	Magnetic field interference	8	7	5	0.01094	0.01566	0.01312	0.0131	3
				I2	Hardware failure	8	3	6	0.01094	0.00671	0.01575	0.0107	25
		J Voltage is too low	Ship's direction deviation, unable to avoid collision	J1	Insufficient power supply	7	3	2	0.00958	0.00671	0.00525	0.0075	88
	ARM Processor	K No output of signal	Ship's direction deviation, unable to avoid collision	K1	Processor hardware damage	9	5	4	0.01231	0.01119	0.01050	0.0115	17
				K2	Circuit connection failure	9	6	3	0.01231	0.01342	0.00787	0.0116	10

Table 2. *Cont.*

Subsystems	Unit	Failure Mode	Failure Effects	Code	Cause of Failure	S	O	D	Conversion Value of S, O, and D			RPN	Rank
									S	O	D		
BeiDou System	BeiDou Navigation Satellite	L Disconnection	The entire BeiDou positioning system of a ship fails	L1	Mechanical Failure	9	2	2	0.01231	0.00447	0.00525	0.0078	84
				L2	Space wear and tear	9	2	2	0.01231	0.00447	0.00525	0.0078	84
	Master Control Station	M disconnected	The entire BeiDou positioning system of a ship fails	M1	Mechanical failure	9	2	2	0.01231	0.00447	0.00525	0.0078	84
				M2	Wear and tear	9	2	2	0.01231	0.00447	0.00525	0.0078	84
	Terminal satellite receiver	N disconnected	Vessel BeiDou positioning system failure	N1	Interference from various external factors	9	3	3	0.01231	0.00671	0.00787	0.0092	54
	ARM processor	O No signal output	Vessel's direction deviates, unable to avoid collision	O1	Processor hardware damage	9	5	4	0.01231	0.01119	0.01050	0.0115	17
				O2	Circuit connection failures	9	6	3	0.01231	0.01342	0.00787	0.0116	10
	Multi-interface terminal	P Poor contact	Poor contact or disconnection of terminal	P1	Environmental erosion	6	4	3	0.00821	0.00895	0.00787	0.0084	72
				P2	Wear and tear	6	4	3	0.00821	0.00895	0.00787	0.0084	72
	Cable	Q Poor contact or disconnection	Poor contact or disconnection of terminal	Q1	Overload by tensile stress	6	4	3	0.00821	0.00895	0.00787	0.0084	72
	Display screen	R System dead	Unable to navigate and avoid collision	R1	Software design defects	8	2	6	0.01094	0.00447	0.01575	0.0099	41
		S Partial loss of function	Unable to navigate and avoid collision	S1	Imperfect software function design	8	4	4	0.01094	0.00895	0.01050	0.0101	37
		T Signal failure	Unable to navigate and avoid collision	T1	Part of the industrial control machine board is damaged	8	7	3	0.01094	0.01566	0.00787	0.0118	8
	Display screen	U No signal output	Unable to navigate and avoid collision	U1	Control panel part of the circuit damage	9	4	2	0.01231	0.00895	0.00525	0.0094	48
				U2	Display screen damage	9	3	3	0.01231	0.00671	0.00787	0.0092	54
	Power connector	V Bad or broken contact	The whole system cannot operate without electricity	V1	Aging or external wear and tear	6	4	3	0.00821	0.00895	0.00787	0.0084	72
		W No signal output	Cannot send this radar information to external systems	W1	The interface part of the circuit is damaged	9	6	3	0.01231	0.01342	0.00787	0.0116	10
	Enclosed cover	X cracked	The terminal is susceptible to moisture or dust erosion	X1	Aging	4	6	3	0.00547	0.01342	0.00787	0.0089	61
				X2	External wear and tear	4	6	3	0.00547	0.01342	0.00787	0.0089	61
ECDIS	Image display	Y Black screen	The image cannot be displayed	Y1	Circuit Failure	6	5	3	0.00821	0.01119	0.00787	0.0092	56
				Y2	Display failure	6	6	2	0.00821	0.01342	0.00525	0.0093	51
				Y3	System program error	6	3	4	0.00821	0.00671	0.01050	0.0083	79

Table 2. *Cont.*

Subsystems	Unit	Failure Mode	Failure Effects	Code	Cause of Failure	S	O	D	Conversion Value of S, O, and D			RPN	Rank
									S	O	D		
	Text Display	Z No signal output	The image cannot be displayed	Z1	Part of the control panel circuit is damaged	6	3	4	0.00821	0.00671	0.01050	0.0083	79
				Z2	Display screen damage	6	3	4	0.00821	0.00671	0.01050	0.0083	79
		AB Black screen	Data cannot be reflected correctly	AB1	Circuit failure	8	5	3	0.01094	0.01119	0.00787	0.0103	35
				AB2	Display screen malfunction	8	6	2	0.01094	0.01342	0.00525	0.0104	30
				AB3	System program error	8	3	4	0.01094	0.00671	0.01050	0.0094	49
		AC Data error	Cannot reflect data correctly	AC1	System program error	8	3	4	0.01094	0.00671	0.01050	0.0094	49
				AC2	Data detection error	8	4	5	0.01094	0.00895	0.01312	0.0108	22
	Navigation system interface	AD Poor GPS positioning accuracy	Cannot locate the vessel accurately	AD1	Poor sea conditions	7	6	3	0.00958	0.01342	0.00787	0.0105	28
				AD2	Interference from outside	7	5	4	0.00958	0.01119	0.01050	0.0104	31
	Radar interface	AE Radar detection interference	Reduced detection accuracy	AE1	GPS is seriously interfered with	8	4	5	0.01094	0.00895	0.01312	0.0108	22
				AE2	Frequency synthesis module failure	8	5	5	0.01094	0.01119	0.01312	0.0116	13
	Radar interface	AF No signal output	Unable to send this radar information to external systems	AF1	Fuse breakage, AC/DC module damage	8	5	5	0.01094	0.01119	0.01312	0.0116	13
				AF2	The interface part of the circuit is damaged	8	5	5	0.01094	0.01119	0.01312	0.0116	13
		AG cannot be recognized	Cannot identify tracking vessel information	AG1	Transmission data loss	9	1	2	0.01231	0.00224	0.00525	0.0070	91
				AG2	Poor wireless communication signal	9	2	3	0.01231	0.00447	0.00787	0.0085	70
	Compass interface	AH Externally influenced	Failed to get heading information	AH1	Large calibration error	6	4	3	0.00821	0.00895	0.00787	0.0084	72
				AH2	Influenced by magnetic fields	6	4	4	0.00821	0.00895	0.01050	0.0090	58
	Rangefinder interface	AI Failure of the speed measurement component	Unable to calculate range, speed, track	AI1	Wear of velocity measurement components	7	3	4	0.00958	0.00671	0.01050	0.0088	65
				AI2	Affected by water flow	7	5	4	0.00958	0.01119	0.01050	0.0104	31
		AJ Calculation component failure	Unable to calculate range, speed, track	AJ1	Program error	7	2	3	0.00958	0.00447	0.00787	0.0074	89
	Probe interface	AK Abnormal beam reception	Unable to measure	AK1	Voltage and power not up to standard	7	2	3	0.00958	0.00447	0.00787	0.0074	89
				AK2	Receiving probe problem	7	4	4	0.00958	0.00895	0.01050	0.0096	45
				AK3	System Handling Failure	7	3	3	0.00958	0.00671	0.00787	0.0081	82
	Anemometer interface	AL Data abnormality	Data cannot be collected properly	AL1	Unstable mobile signal	5	4	4	0.00684	0.00895	0.01050	0.0085	68
				AL2	Poor sensor response	5	4	3	0.00684	0.00895	0.00787	0.0078	83
				AL3	Insufficient supply voltage	5	2	4	0.00684	0.00447	0.01050	0.0069	93

Table 2. *Cont.*

Subsystems	Unit	Failure Mode	Failure Effects	Code	Cause of Failure	S	O	D	Conversion Value of S, O, and D			RPN	Rank
									S	O	D		
	Processor	M Dead during startup, error report, black screen	The server cannot be started	AM1	Poor contact or broken pins	8	4	2	0.01094	0.00895	0.00525	0.0088	63
		AN File error during startup	The server cannot be started	AN1	Wrong working parameter setting	8	4	2	0.01094	0.00895	0.00525	0.0088	63
		AO Only boot in safe mode or command line mode	Reduced efficiency	AO1	Wrong setting of working parameters	5	4	4	0.00684	0.00895	0.01050	0.0085	68
	Data storage	AP Bad contact of memory stick	The server cannot be started	AP1	Poor contact between memory stick and motherboard	8	4	4	0.01094	0.00895	0.01050	0.0101	37
		AQ System message about memory error	Unable to operate the server efficiently	AQ1	Insufficient memory	6	4	3	0.00821	0.00895	0.00787	0.0084	72
AIS	VHF Transmitter	AR power unit failure	The power light does not light up after the host is turned on, and the whole machine has no power	AR1	No DC24V voltage output due to failure of the voltage regulator	7	4	5	0.00958	0.00895	0.01312	0.0102	36
				AR2	Host fuse blown	7	5	3	0.00958	0.01119	0.00787	0.0097	43
		AS antenna failure	Poor reception and transmission signal of VHF equipment	AS1	Antenna failure	6	6	4	0.00821	0.01342	0.01050	0.0106	26
	VHF Receiver	AT No GPS ship position signal	The fault alarm of the main unit sounds every once in a while, and the display shows no GPS ship position signal.	AT1	GPS data distributor malfunction or poor wiring contact	6	6	6	0.00821	0.01342	0.01575	0.0119	7
				AT2	Improper setting of GPS signal input mode of VHF device	6	6	5	0.00821	0.01342	0.01312	0.0113	20
				AT3	GPS signal output format change	6	2	3	0.00821	0.00447	0.00787	0.0068	94
	Navigation system interface	AU Antenna failure	Poor receiving and transmitting signal of VHF equipment	AU1	Antenna hardware or circuit failure	6	6	4	0.00821	0.01342	0.01050	0.0106	26
		AV GPS poor positioning accuracy	Cannot locate the ship accurately	AV1	Poor sea conditions	7	6	3	0.00958	0.01342	0.00787	0.0105	28
				AV2	Interference from outside	7	5	4	0.00958	0.01119	0.01050	0.0104	31
	Rangefinder interface	AW Speed measurement component failure	Cannot calculate the range, speed, track and other information	AW1	Wear of speed measurement components	7	3	4	0.00958	0.00671	0.01050	0.0088	65
				AW2	Affected by current	7	5	4	0.00958	0.01119	0.01050	0.0104	31
	Compass interface	AX External influence	Failure to obtain heading information	AX1	Large calibration error	6	4	3	0.00821	0.00895	0.00787	0.0084	72
				AX2	Affected by magnetic field	6	4	4	0.00821	0.00895	0.01050	0.0090	58

Table 2. *Cont.*

Subsystems	Unit	Failure Mode	Failure Effects	Code	Cause of Failure	S	O	D	Conversion Value of S, O, and D			RPN	Rank
									S	O	D		
	AIS Information Processor	AY Unable to process information	Cannot identify and track vessel information	AY1	Loss of transmission data	9	1	2	0.01231	0.00224	0.00525	0.0070	91
				AY2	Poor wireless communication signal	9	2	3	0.01231	0.00447	0.00787	0.0085	70
	Radar interface	AZ Interference with radar detection	Reduced detection accuracy	AZ1	Severe GPS interference	8	4	5	0.01094	0.00895	0.01312	0.0108	22
				AZ2	Frequency synthesis module failure	8	5	5	0.01094	0.01119	0.01312	0.0116	13
	ECDIS interface	BC Data loss	Failure to transmit electronic charts	BC1	Network connection error or information channel failure	8	4	4	0.01094	0.00895	0.01050	0.0101	37
Mobile Communication Receiver	Antenna	BD No signal accepted. The signal receiver does not work (no signal output)	Affect the communication signal or even lead to a short circuit by burning the components	BD1	Water in the antenna	5	2	1	0.00684	0.00447	0.00262	0.0050	105
				BD2	Sealing measures are not done	5	2	2	0.00684	0.00447	0.00525	0.0056	102
				BD3	Antenna impedance mismatch	5	2	3	0.00684	0.00447	0.00787	0.0063	98
	Antenna Switch	BE No signal or weak signal, signal not transmitting or difficult to transmit	Lead to mobile communication receiver work difficult or not work	BE1	Switch itself quality problems	3	1	1	0.00410	0.00224	0.00262	0.0031	111
				BE2	Physical damage or water ingress	3	2	1	0.00410	0.00447	0.00262	0.0039	109
	Filter	BF Low voltage fuse is blown, and the signal is not screened	The system does not work normally. The signal does not play a filtering role	BF1	Narrow passband, high loss	4	2	3	0.00547	0.00447	0.00787	0.0057	101
				BF2	Short circuit caused by the breakdown of capacitors	4	2	2	0.00547	0.00447	0.00525	0.0051	104
	Mixer	BG Signal is not mixed	Frequent automatic shutdown	BG1	Damage to the charging resistor	4	3	3	0.00547	0.00671	0.00787	0.0065	96
				BG2	The module circuit burned out	4	2	4	0.00547	0.00447	0.01050	0.0064	97
	Demodulator	BH Signal is not restored, error code appears	Results in system abnormalities. Signal lights show failure	BH1	The power supply connection line is not connected properly	4	2	1	0.00547	0.00447	0.00262	0.0044	106
				BH2	The quality of the problem itself	4	1	1	0.00547	0.00224	0.00262	0.0036	110
	Power supply	BI There is no power supply phenomenon. There is an instantaneous high- or low-voltage phenomenon	The power supply is damaged, the system stops working, or other parts of the machine are damaged	BI1	Power line aging, static electricity, power supply itself problems	4	3	2	0.00547	0.00671	0.00525	0.0059	100

Table 2. *Cont.*

Subsystems	Unit	Failure Mode	Failure Effects	Code	Cause of Failure	S	O	D	Conversion Value of S, O, and D			RPN	Rank
									S	O	D		
	CPU	BJ Work overload, and work instructions are not delivered	The system does not receive commands and cannot work properly	BJ1	Poor heat dissipation performance	6	5	4	0.00821	0.01119	0.01050	0.0098	42
	Memory Chip	BK No signal reception record, data loss	Mobile communication receiver does not have the function of storing signal information, and some modules do not work properly	BK1	Model mismatch	6	2	1	0.00821	0.00447	0.00262	0.0055	103
				BK2	Chip burned out	6	2	3	0.00821	0.00447	0.00787	0.0068	94
	Power Management Chip	BL off, not docked well, more confusion in the system	The conversion, distribution, detection and other power management functions of electrical energy in the electronic equipment system fail	BL1	Programming too high voltage	6	2	2	0.00821	0.00447	0.00525	0.0062	99
	Peripheral Circuits	BM Not energized, or the circuit is wrong	The system does not work, and the signal cannot be received and transmitted	BM1	Human error	4	2	1	0.00547	0.00447	0.00262	0.0044	106
				BM2	Circuit aging	4	2	1	0.00547	0.00447	0.00262	0.0044	106

In this section, five subsystems of the intelligent ship with a total of 111 fault causes are analyzed, as shown in Figure 2. The RPN values of each fault cause in the positioning system and its RPN share in the respective unit are given in Figure 3.

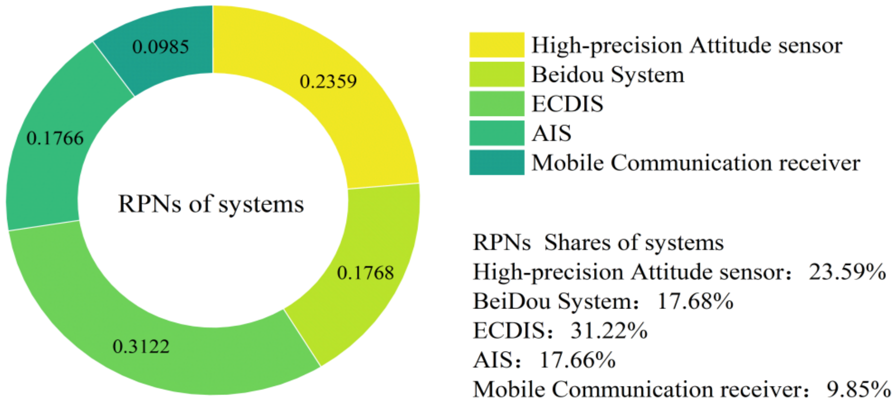

Figure 2. RPNs' share of each subsystem of the positioning system.

The FMECA table shows that, overall, the ECDIS is the most important system for positioning systems (RPN of 0.3122), followed by high-precision attitude sensor (0.2359), BeiDou positioning system (0.1768), AIS (0.1766), and mobile communication receivers (0.0985). On the one hand, the RPN values of the fixed-weight FMECA method are additive, and systems with more failure modes will have larger RPN values. In terms of RPN values of subsystems, ECDISs, and high-precision attitude sensors have numerous failure modes, both of which occupy more than half of the RPN and are important subsystems that cause the failure of positioning systems. On the other hand, to determine the critical failure mode for locating the system, it is important to consider not only the magnitude of the RPN value but also the average value of the RPN. Analyzing the importance of the failure from an average perspective can better evaluate the risk ranking of the system failure causes. The mean values of RPN for the causes of failure for these five systems were 0.0092, 0.0107, 0.0093, 0.0098, and 0.0055, respectively.

The total RPN value of the ECDIS is higher than that of the high-precision attitude sensor, while the average value of RPN is lower than that of the high-precision attitude sensor, indicating that although the failure modes of the ECDIS are many, the severity of their failure consequences is smaller compared to that of the high-precision attitude sensor. The average RPN of mobile communication receivers is much lower than other subsystems, and the risk level is low. Combining the results of the RPN values as well as the average RPN values, the high-precision attitude sensor was identified as the riskiest subsystem of the positioning system, followed by the ECDIS, AIS, and BeiDou, and finally, the mobile communication receiver.

3.3. Critical Failure Cause Analysis

The identification of critical failure causes is related to the development and planning of restorative and preventive measures. And the identification of critical failure units mainly lies in the selection of risk thresholds. Lorenzo et al. [34] proposed a new RPN threshold estimation method for FMECA. The method requires the following:

a. Calculate the RPN values for each failure mode;
b. Identify the main statistical parameters of the RPN values (maximum, 75% quantile, median, mean, 25% quantile, and minimum);
c. Draw box plots based on the main statistical parameters of the RPN values;
d. Identify critical faults. Based on the resulting box plot, critical faults (RPN above the 75th percentile) and negligible faults (RPN below the median) are identified. Faults between the median and the 75th percentile are classified by the designer, and some of the causes of failure that cannot be ignored are classified as critical failure factors.

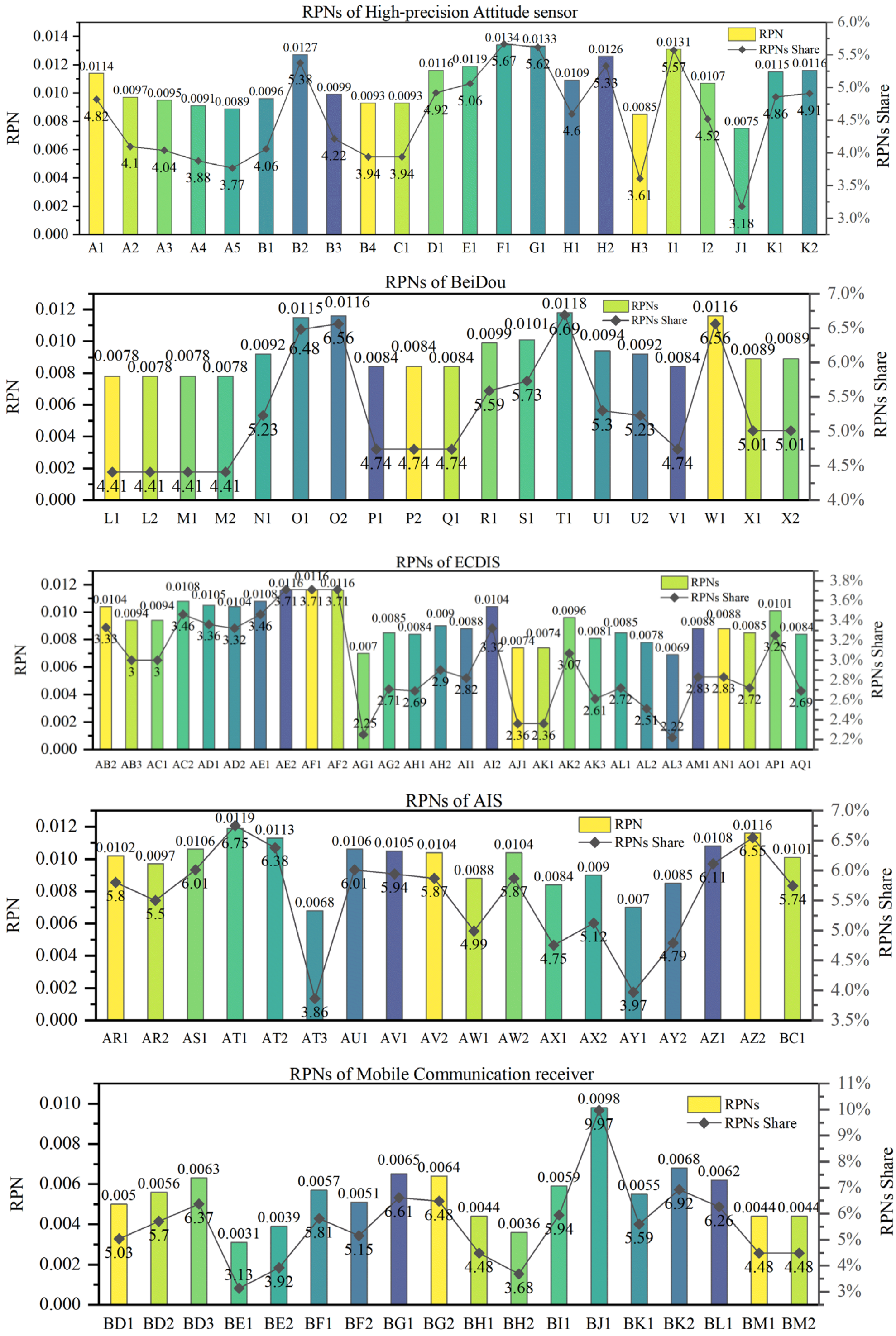

Figure 3. RPNs value and percentage of each cause of failure in the positioning system.

In this section, the critical cause identification schematic of the intelligent ship positioning system equipment is drawn according to the RPN threshold estimation method proposed by Lorenzo et al., as shown in Figure 4. The 28 failure causes in the top 25% of the RPN value ranking of the intelligent ship positioning system are identified, plus two of the pending failure causes are identified, and a total of 30 failure causes are identified as critical failure causes, as shown in Table 3.

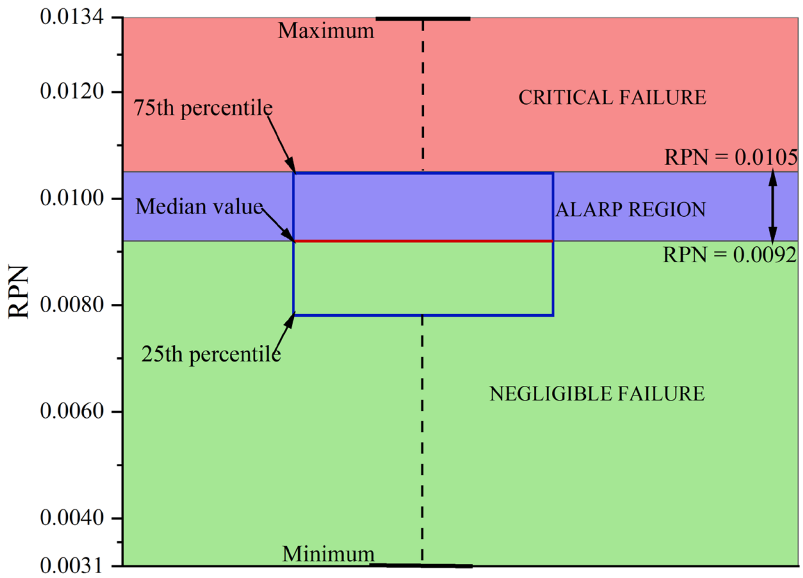

Figure 4. Box diagram of the positioning system RPN.

Table 3. Critical failure causes of the positioning system.

Subsystems	Unit	Cause of Failure	Share of RPN	Subsystems	Unit	Cause of Failure	Share of RPN
High-precision attitude sensor	Three-axis gyroscope	A1	1.14%	BeiDou System	Display	T1	1.18%
		B2	1.27%		Power connector	W1	1.16%
		D1	1.16%	ECDIS	Text Display	AB1	1.03%
		E1	1.19%			AC2	1.08%
		F1	1.34%		Navigation system interface	AD1	1.05%
		G1	1.33%		Radar interface	AE1	1.08%
	Triaxial accelerometer	H1	1.09%			AE2	1.16%
		H2	1.26%			AF1	1.16%
	Three-axis electronic compass	I1	1.31%			AF2	1.16%
		I2	1.07%	AIS	VFH transmitter	AS1	1.06%
	Arm Processor	K1	1.15%		VFH receiver	AT1	1.19%
		K2	1.16%			AT2	1.13%
BeiDou system	Terminal ARM Processor	O1	1.15%			AU1	1.06%
		O2	1.16%		Radar interface	AZ1	1.08%
	Display	S1	1.01%			AZ2	1.16%

The high-precision attitude sensor relies on multiple precision sensing units and contains 12 critical failure causes. Not only does this subsystem have many failure modes, but the consequences of failure are severe, and the risk level of the equipment is extremely high. The main causes of high precision attitude sensor failure are design-related factors (interference torque due to friction, resonance), environmental factors (magnetic field interference, temperature and humidity effects), and unavoidable unknown failures (hardware failure, device wear and tear). Serious causes of failure are interference caused by environmental factors such as F1 (electromagnetic interference, 1.34% of RPN), G1 (humidity factor, 1.33%), and I1 (magnetic field interference, 1.31%). The three-axis gyroscope, which in turn concentrates most of the key failure causes (A1–G1), is the key unit of the high-precision attitude sensor. This subsystem is related to whether the intelligent ship can accurately identify the surrounding environment. This affects the capability of the intelligent ship to complete berthing and unberthing and may even lead to the ship colliding with the shore wall. Close attention should be paid to this subsystem.

The BeiDou positioning system is one of the cores of the positioning system, which consists of BeiDou satellites, ground base stations, receivers, terminal processors, displays and other units. The system includes 5 key causes of failure. The main causes of BeiDou positioning system failures are design-related factors (poorly designed software functions) and unavoidable unknown failures (circuit damage, hardware failure). The serious causes of failure are O1 (processor hardware damage, 1.15%), O2 (circuit failure, 1.16%), and T1 (display the IPC part of the board damage, 1.18%). In general, BeiDou positioning system units are not prone to problems [35] (the BeiDou navigation system is the responsibility of the state and has a low probability of failure).

ECDIS is mainly used to accurately display the position of ships at sea. It consists of image display, text display, processor, data storage, and various data interfaces, including 7 key fault causes. The causes of system failure include unavoidable unknown faults (failure of frequency synthesis module, circuit damage), environmental factors (magnetic field interference, poor sea conditions), and human factors (wrong setting of operating parameters). The serious causes of failure are AE2 (failure of frequency synthesis module, 1.16%) and AF1 (damage to AC/AD module, 1.16%). Among them, the radar interface concentrates more critical failure causes and is the key unit of the electronic chart system. The majority of the remaining failures are minor, easy to detect and repair, and do not significantly affect the overall positioning system.

AIS consists of a VHF receiver/transmitter and an AIS information processor, and each part of the interface contains six critical failure causes. The system relies on the reception and processing of GPS data, so in practice, the failure of the working unit itself and the loss of GPS data caused by external interference are the main factors causing the system to fail. The faults with high RPN are the lack of GPS position signal caused by AT1 (GPS data distributor of VHF/TDMA receiver unit has a fault or poor connection, 1.19%). Overall, the system has a high failure rate, but failures occur less frequently, are easier to detect, and are less likely to cause very serious effects.

A mobile communication receiver is used to receive and send communication information. It consists of an antenna, filter, mixer, demodulator, CPU, and peripheral circuits and none of the failure causes are identified as critical failure causes. The unit of this subsystem was low in precision, and the basic failure modes were divided into circuit damage and capacitor breakdown due to the power supply and the aging and substandard quality of the equipment in the unit itself. In practice, receiver failures are less frequent and can be easily inspected and repaired. And temporary damage to the mobile communication receiver does not seriously affect the work of the entire positioning system and is the least dangerous in failure mode analysis.

From the analysis results, it is clear that the main reasons for the failure of the positioning system of intelligent ships are unavoidable unknown failures, environmental factors, and design-related factors.

The unavoidable unknown failures are mainly circuit failures, hardware damage, and parts damage. In order to cope with such failures, the control of key and fragile parts of intelligent ships should be strengthened, and good-quality parts should be used. At the same time, fragile parts and units should be checked regularly. It will also be beneficial to strengthen the research on condition monitoring, fault warning, and diagnosis of intelligent ships and improve the inspection system of intelligent ships to ensure the normal use of intelligent ship units and parts.

Intelligent ship positioning systems are highly susceptible to the influence of the surrounding environment. Interference from magnetic fields and other factors in the environment can easily affect the use of the positioning system and lead to deviations in positioning, which can easily lead to dangerous situations. In order to reduce the influence of the environment on intelligent ship navigation, research on extreme environmental conditions should be strengthened, especially the influence of magnetic field disturbance, strong wind, and strong waves on intelligent ship equipment.

Failures caused by design-related factors include interference torque due to gyroscope component friction, vibration, and poorly designed positioning system software functions. To avoid such failures, the design process should be improved, and the development of software should be enhanced.

4. Correlation Analysis of Critical Failure Cause

The complexity of intelligent ship systems leads to numerous failure modes; therefore, calculating the correlation between each two failure modes would take a lot of effort, and, in addition, further analysis of low-risk failure modes would be of limited significance. Therefore, only the critical failure causes obtained in Section 3.3 are subject to correlation analysis. The units analyzed are shown in Table 4. After scoring by three experts based on the steps in Section 2.3, the total relationship matrix was calculated, as shown in Table 5. The influence degree of factors is shown in Table 6.

Table 4. Analyzed units.

Subsystems	Code	Unit
High-precision attitude sensor	FM1	gyroscope
	FM2	accelerometer
	FM3	electronic compass
BeiDou system	FM4	Arm Processor
	FM5	Display
	FM6	Power connector
ECDIS	FM7	Text Display
	FM8	Navigation system interface
	FM9	Radar interface
AIS	FM10	VFH transmitter
	FM11	VFH receiver

Table 5. The matrix of total relation.

Factors	FM1	FM2	FM3	FM4	FM5	FM6	FM7	FM8	FM9	FM10	FM11
FM1	0.136	0.184	0.241	0.086	0.055	0.011	0.064	0.056	0.143	0.095	0.095
FM2	0.231	0.128	0.248	0.090	0.062	0.012	0.099	0.073	0.131	0.096	0.096
FM3	0.213	0.189	0.130	0.062	0.062	0.024	0.067	0.024	0.064	0.085	0.085
FM4	0.031	0.027	0.032	0.119	0.288	0.050	0.234	0.056	0.077	0.195	0.195
FM5	0.020	0.017	0.022	0.056	0.120	0.041	0.240	0.046	0.049	0.067	0.067
FM6	0.097	0.086	0.097	0.284	0.363	0.079	0.309	0.142	0.155	0.198	0.198
FM7	0.034	0.032	0.051	0.051	0.184	0.009	0.100	0.012	0.017	0.023	0.023
FM8	0.049	0.016	0.021	0.117	0.117	0.044	0.175	0.066	0.021	0.032	0.032
FM9	0.167	0.142	0.156	0.144	0.135	0.013	0.169	0.042	0.095	0.142	0.142
FM10	0.041	0.039	0.044	0.134	0.146	0.011	0.145	0.014	0.021	0.130	0.258
FM11	0.041	0.039	0.044	0.134	0.146	0.011	0.145	0.014	0.021	0.258	0.130

Table 6. The influence of the degree of factors.

Factor	Ri + Di	Ri-Di
FM1	2.225	0.105
FM2	2.165	0.368
FM3	2.091	−0.082
FM4	2.581	0.027
FM5	2.423	−0.934
FM6	2.312	1.704
FM7	2.283	−1.212
FM8	1.236	0.146
FM9	2.143	0.554
FM10	2.303	−0.338
FM11	2.303	−0.338

In this study, we set the threshold (k) in the total relationship matrix to 0.2. 0.2 is the most appropriate value obtained from the attempt. The causality diagram of the total relationship obtained according to k > 0.2 is shown in Figure 5.

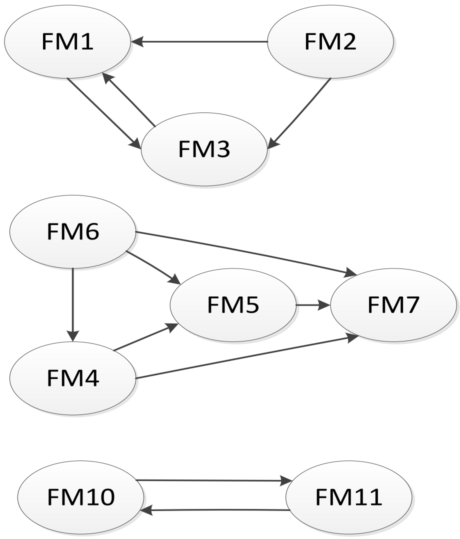

Figure 5. The causal diagram of total relation (k > 0.2).

The results of the analysis show that there is a high degree of correlation between the gyroscope, accelerometer, and electronic compass. That is, the failure of any one of the three components has the probability of leading to the failure of the other two units. All three belong to the same high-precision attitude sensor unit, which is a high-precision unit for monitoring the ship's attitude and is highly susceptible to interference from the external environment. The Arm processor, display, power interface, and text display are another group of units with a high degree of relevance. These four failure modes mainly concern the compass positioning system as well as the electronic charting system. The VFH transmitter and VHF receiver are more influenced by each other than by the other hazard units. The navigation system interface and the radar system interface weakly influenced other units and were barely influenced by other units, being two more independent units.

This section further determines that the high-precision attitude sensor is the most dangerous subsystem of the positioning system. It not only has many failure modes and serious consequences but also has a high degree of correlation between failure modes. It is easy to break down. Failure of this system will result in inadequate ship positioning accuracy, posing a serious safety hazard for intelligent navigation and autonomous berthing operations, and it should be given high priority. Regular servicing of similar high-precision components can effectively improve the reliability of smart ships.

Equipment failures on smart ships do not occur in isolation; each failure that occurs may lead to the occurrence of another. The correlation between failure modes shows that in reliability analysis, where failure modes have a cascade relationship with each other, we cannot simply consider the failure modes as independent of each other. To obtain reliable results, correlations between failure modes must be taken into account. The combined approach can be used not only for equipment failure analysis of smart ships but also for failure analysis of other marine engineering equipment.

5. Conclusions

This paper considers the shortcomings of the traditional FMECA method in that the weights of severity, occurrence, and detection are unreasonably assigned, and the correlation between failure modes is taken into account. The failure modes of the positioning system of an intelligent ship are analyzed using a combination of fixed-weight FMECA and DEMATEL, and the failure causes of the failure modes are identified. The following conclusions were reached.

(1) High-precision-attitude sensors are the most dangerous subsystem of the positioning system. It has many failure modes and serious consequences, and the correlation between failure modes is high;
(2) Unavoidably unknown failures (mechanical and component failures) and environmental factors (magnetic fields and temperature disturbances) are the key causes of positioning system failures. Regular maintenance of components and reducing environmental interference with precision components will be effective means of improving the reliability of smart ships;
(3) The critical fault units of the subsystems in the positioning system were derived. The correlation between the critical fault units was also evaluated. In order to conduct an accurate risk assessment of the entire system, it is essential to clarify the correlation between each failure mode.

The relevant conclusions can provide a reference for the maintenance of intelligent ship positioning system equipment. The safety of intelligent ships in navigation can be ensured by reducing the possibility of malfunctioning or reducing the severity of damage caused by intelligent ship equipment.

However, this paper analyzes the intelligent ship positioning system by fixed-weight FMECA using only one weight assignment method. In practice, the intelligent ship positioning system is a complex system integrated with multiple components. The failure mechanism and failure characteristics of the system itself and its components vary greatly. In the future, it is expected to consider variable and floating risk evaluation index weights, combine real data information, and select specific weights for different systems and components for FMECA analysis.

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References

1. China Classification Society. *Rules for Intelligent Ships*; China Classification Society: Beijing, China, 2015.
2. Lazarowska, A. A new deterministic approach in a decision support system for ship's trajectory planning. *Expert Syst. Appl.* **2017**, *71*, 469–478. [CrossRef]
3. He, Y.; Liu, X.; Zhang, K.; Mou, J.; Liang, Y.; Zhao, X.; Wang, B.; Huang, L. Dynamic adaptive intelligent navigation decision making method for multi-object situation in open water. *Ocean. Eng.* **2022**, *253*, 111238. [CrossRef]
4. Lee, S.D.; Tzeng, C.Y.; Shu, K.Y. Design and experiment of a small boat auto-berthing control system. In Proceedings of the 2012 12th International Conference on ITS Telecommunications, Taipei, Taiwan, 5–8 November 2012; pp. 397–401.
5. Lee, S.D.; Tzeng, C.Y.; Kehr, Y.Z.; Kang, C.K.; Huang, C.C. Design and application of an image-processing-based fuzzy autopilot for small-boat approaching maneuvers. *J. Mar. Sci. Technol.* **2010**, *18*, 558–567. [CrossRef]
6. Mizuno, N.; Uchida, Y.; Okazaki, T. Quasi Real-Time Optimal Control Scheme for Automatic Berthing. *IFAC-PapersOnLine* **2015**, *48*, 305–312. [CrossRef]
7. Mizuno, N.; Tamai, Y.; Okazaki, T.; Ohtsu, K. A ship's minimum-time maneuvering system using neural networks. In Proceedings of the IEEE 2002 28th Annual Conference of the Industrial Electronics Society, IECON 02, Seville, Spain, 5–8 November 2002; pp. 1848–1853.

8. Mizuno, N.; Kakami, H.; Okazaki, T. Parallel Simulation Based Predictive Control Scheme With Application To Approaching Control For Automatic Berthing. *IFAC Proc. Vol.* **2012**, *45*, 19–24. [CrossRef]
9. Zhang, X.; Ni, W.; Sun, L. Fatigue Analysis of the Oil Offloading Lines in FPSO System under Wave and Current Loads. *J. Mar. Sci. Eng.* **2022**, *10*, 225. [CrossRef]
10. Allianz Global Corporate and Specialty Company (AGCS). *AGCS Safety Shipping Review*; Allianz Global Corporate and Specialty Company (AGCS): Munich, Germany, 2019.
11. Harati-Mokhtari, A.; Wall, A.; Brooks, P.; Wang, J. Automatic Identification System (AIS): Data Reliability and Human Error Implications. *J. Navig.* **2007**, *60*, 373–389. [CrossRef]
12. Pallotta, G.; Vespe, M.; Bryan, K. Vessel Pattern Knowledge Discovery from AIS Data: A Framework for Anomaly Detection and Route Prediction. *Entropy* **2013**, *15*, 2218–2245. [CrossRef]
13. Tsou, M.C. Discovering Knowledge from AIS Database for Application in VTS. *J. Navig.* **2010**, *63*, 449–469. [CrossRef]
14. Last, P.; Hering-Bertram, M.; Linsen, L. How automatic identification system (AIS) antenna setup affects AIS signal quality. *Ocean. Eng.* **2015**, *100*, 83–89. [CrossRef]
15. Carmignani, G. An integrated structural framework to cost-based FMECA: The priority-cost FMECA. *Reliab. Eng. Syst. Saf.* **2009**, *94*, 861–871. [CrossRef]
16. Bevilacqua, M.; Braglia, M.; Gabbrielli, R. Monte Carlo simulation approach for a modified FMECA in a power plant. *Qual. Reliab. Eng. Int.* **2000**, *16*, 313–324. [CrossRef]
17. Zammori, F.; Gabbrielli, R. ANP/RPN: A multi criteria evaluation of the Risk Priority Number. *Qual. Reliab. Eng. Int.* **2012**, *28*, 85–104. [CrossRef]
18. Saaty, T.L.; Ozdemir, M.S. *The Encyclicon: A Dictionary of Decisions with Dependence and Feedback Based on Analytic Network Process*; RWS Publications: Pittsburgh, PA, USA, 2005.
19. Carpitella, S.; Certa, A.; Izquierdo, J.; La Fata, C.M. A combined multi-criteria approach to support FMECA analyses: A real-world case. *Reliab. Eng. Syst. Saf.* **2018**, *169*, 394–402. [CrossRef]
20. Braglia, M. MAFMA: Multi-attribute failure mode analysis. *Int. J. Qual. Reliab. Manag.* **2000**, *17*, 1017–1033. [CrossRef]
21. Saaty, T.L. *The Analytic Hierarchy Process*; McGraw Hill Company: New York, NY, USA, 1994.
22. Xiao, N.; Huang, H.Z.; Li, Y.; He, L.; Jin, T. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. *Eng. Fail. Anal.* **2011**, *18*, 1162–1170. [CrossRef]
23. Zhang, S.Z.; Zeng, Q.D.; Zhang, G. A New Approach for Prioritization of Failure Mode in FMECA Using Encouragement Variable Weight AHP. *Appl. Mech. Mater.* **2013**, *289*, 93–98. [CrossRef]
24. Li, H.; Diaz, H.; Soares, C.G. A developed failure mode and effect analysis for floating offshore wind turbine support structures. Renew. *Energy* **2021**, *164*, 133–145.
25. Luqman, A.; Akram, M.; Alcantud, J.C.R. Digraph and matrix approach for risk evaluations under Pythagorean fuzzy information. *Expert Syst. Appl.* **2021**, *170*, 114518. [CrossRef]
26. Akram, M.; Luqman, A.; Alcantud, J.C.R. Risk evaluation in failure modes and effects analysis: Hybrid TOPSIS and ELECTRE I solutions with Pythagorean fuzzy information. *Neural Comput. Appl.* **2020**, *33*, 5675–5703. [CrossRef]
27. Liu, Y.; Eckert, C.M.; Earl, C. A review of fuzzy AHP methods for decision-making with subjective judgements. *Expert Syst. Appl.* **2020**, *161*, 113738. [CrossRef]
28. Song, B.F. A numerical integration method in affine space and a method with high accuracy for computing structural system reliability. *Comput. Struct.* **1992**, *42*, 255–262. [CrossRef]
29. Drezner, Z. Computation of the Multivariate Normal Integral. *ACM Trans. Math. Softw.* **1992**, *18*, 470–480. [CrossRef]
30. Da Silva, A.M.L.; Fernandez, R.A.; Singh, C. Generating Capacity Reliability Evaluation Based on Monte Carlo Simulation and Cross-Entropy Methods. *IEEE Trans. Power Syst.* **2010**, *25*, 129–137. [CrossRef]
31. Ni, W.; Zhang, X.; Zhang, W. Modified approximation method for structural failure probability analysis of high-dimensional systems. *Ocean. Eng.* **2021**, *237*, 109486. [CrossRef]
32. Gabus, A.; Fontela, E. *Perceptions of the World Problematique: Communication Procedure, Communicating with those Bearing Collective Responsibility*; DEMATEL Report No.1; Battelle Geneva Research Centre: Geneva, Switzerland, 1973.
33. Tzeng, G.H.; Chiang, C.H.; Li, C.W. Evaluating intertwined effects in e-learning programs: A novel hybrid MCDM model based on factor analysis and DEMATEL. *Expert Syst. Appl.* **2007**, *32*, 1028–1044. [CrossRef]
34. Catelani, M.; Ciani, L.; Galar, D.; Patrizi, G. Risk Assessment of a Wind Turbine: A New FMECA-Based Tool With RPN Threshold Estimation. *IEEE Access* **2020**, *8*, 20181–20190. [CrossRef]
35. Zhang, X.; Ni, W.; Liao, H.; Pohl, E.; Xu, P.; Zhang, W. Improved condition monitoring for an FPSO system with multiple correlated components. *Measurement* **2020**, *166*, 223–237. [CrossRef]