Research Article

Study on the Risk Model of the Intelligent Ship Navigation

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Received 6 June 2022; Revised 6 July 2022; Accepted 15 July 2022; Published 22 August 2022

Academic Editor: Kuruva Lakshmana

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The perception of risks is a prerequisite for establishing an intelligent ship navigation system based on ship-shore cooperation. According to the research conclusions on the ship-shore collaboration, the technical characteristics of the intelligent ship navigation system, and the analysis of the test results of the ship “ZHI FEI” featured with intelligent navigation, we study and construct the conceptual model and mathematical expression model for risk evolution of the intelligent ship navigation. We further explore the unmanned trend, the general law, and the characteristics of risk evolution based on navigation scenarios and chain effects. The present study provides insight into the risk perception, management, and government governance of intelligent ship navigation and the construction of an intelligent ship navigation system based on ship-shore collaboration.

1. Introduction

Safe navigation is an essential prerequisite for advancing the technological development of intelligent ship navigation. Compared with conventional navigation, intelligent ship navigation integrates various cutting-edge technologies such as artificial intelligence, visual and perceptual computing, edge computing, big data, remote control and motion control, integrated communication, positioning and navigation systems, and spatiotemporal geographic information. Theoretically, it can effectively reduce the risks of water traffic accidents caused by human factors. However, given the current technical strengths and the development history of shipping, intelligent ship navigation is still in its infancy. Therefore, it is necessary to optimize the applied theory and technology through extensive testing iteratively. Additionally, it will take a long time to formulate the international navigation guidelines, legislation, and standards applicable to the coexistence of manned and unmanned vessels [1].

The scientific understanding of the safety risks of intelligent ship navigation and the development of detailed risk management and control strategies are the basic tasks that the government, academia, and industry need to work on and are related to the commercialization of intelligent ships. The International Maritime Organization (IMO) proposed the concept of the maritime autonomous surface ship (MASS) at the 98th Maritime Safety Committee (MSC) in 2017, successively performed studies on the concept, grading, and legislative scope of MASS, and released the first document on MASS, Interim Guidelines for MASS Trials [2, 3], in 2019. The work by the IMO provides directions for the research and development, grading, testing, and risk prevention of technologies related to autonomous ships worldwide. In this regard, a host of scholars have focused on exploring the challenges and risks brought by unmanned and autonomous ships to the shipbuilding industry, maritime environment, maritime supervision, etc., from the perspective of government governance [4–10], and put forward risk assessment methods and prevention and control strategies at the governance level. Currently, the academic community has mainly delved into collision and cyber security risks of autonomous ships and conducted risk identification and assessment through expert investigation methods [11, 12], deep reinforcement machine learning [13], model predictive control (MPC) algorithms [14], evolutionary optimization algorithms [15], field theory [16], causality [17, 18], human reliability analysis [19], system theory [20, 21], etc. Autonomous collision avoidance navigation systems [13, 15], route planning systems [22], cyber risk countermeasures systems [22], and other systems have also been developed. Meanwhile, issues such as the potential failure of collision avoidance based on COLREG [23, 24], the lowest safety
requirements for autonomous ships “at least no lower than manned driving [25],” and the ethics of artificial intelligence [26]—“collision avoidance in critical situations”—have been raised during the exploration. In [27], the authors proposed risk-based predictive control method to avoid ship collision risk. Velocity obstacle (VO) method is an important model for collision risk analysis. Wang et al. [28] proposed a collision avoidance decision-making system for autonomous ship based on modified velocity obstacle method. In [29], Geng et al. proposed motion plan of autonomous ships by dynamic programming using VO model for collision avoidance and speed optimization.

In summary, the current research on the safety risks of intelligent ship navigation mainly focuses on autonomous ships. The risk identification framework that supports the establishment of an intelligent ship navigation system has not been built from the perspective of ship-shore coordination. The research on risk evolution from manned driving, assisted driving, remote driving to autonomous driving, and from open waters to complex waters has not been performed.

In this regard, from the perspective of ship-shore coordination, we have systematically studied the general evolution law and characteristics of the risks related to intelligent ship navigation based on the intelligent navigation tests of “ZHI TENG” and “ZHI FEL.” Additionally, we have established the conceptual model and mathematical expression model for the risk evolution grounded on the interrelationship between multiple elements, spaces, scenarios, and modes to provide insight into risk perception and control, government governance of intelligent ship navigation, and the construction of the intelligent ship navigation and control system based on ship-shore collaboration.

### 2. Conceptual Model of Risk Evolution

#### 2.1. Method

As Figure 1 shows, at first, the common risk factors of ship navigation are analyzed through the literature review. Then, based on the test of the intelligent ship “ZHI TENG” and “ZHI FEL,” we participated in the development. The special risk factors of intelligent ship navigation are obtained, and the risk evaluation index system is established through the expert method and brainstorming method.

Finally, it is expressed through the conceptual model and mathematical model, and the unmanned trend, AI Ethics (chain accident effect), and the balance between safety and efficiency are analyzed.

#### 2.2. Conceptual Model

The construction of a conceptual model for the risk evolution of intelligent ship navigation facilitates the intuitive understanding of the risk perception framework of the entire system, the analysis of the nature of risk, the clarification of the boundaries, the identification of the core elements, and the establishment of the links between them, thus revealing the general laws and characteristics of risk evolution. Based on the research conclusions on ship-shore cooperation [30, 31], we have constructed a conceptual model for the evolution of intelligent ship navigation. The model consists of five factors, four modes, three spaces, three scenarios, and five phases from the perspective of risk perception and takes the ability of machines to replace humans as a basis for studying the risk evolution, as shown in Figure 2.

#### 2.3. Five Elements of “Human, Ship, Management, Environment, and Information and Technology.”

“Human, ship, management and environment” are the four basic factors widely used in various industries for identifying security risk sources. Specially, it provides a quantitative basis for risk management by refining the secondary risk indicators of the four factors, assigning weights according to some principles and working out the risk probability with the mathematical formula.

Through the brainstorming, we analyzed the applicability of the four factors of “human, ship, management, and environment.” By summarizing the opinions of 32 representatives, including captains, regulatory authorities, shipping companies, and scientific research departments, and given the characteristics of the three driving modes of intelligent ship navigation, we proposed the fifth factor, namely, the “information and technology.” We refined the attributes and indicators of each factor; used “factors” to characterize the risk sources of risk identification, assessment, and control; and took “elements” to represent the main components.
that constitute the intelligent ship navigation system, as shown in Table 1.

2.4. Three Modes of “Assisted, Remote, and Autonomous” Driving. Assisted, remote, and autonomous driving are the three driving modes of intelligent ship navigation. Assisted driving is a mode that can be achieved through the current technology. In this mode, some operations are automated, which can provide decision-making support for ship drivers. The remote driving realizes the remote operation and control of the vessel via the command interaction between the ship and the shore. Autonomous driving is a mode in which decisions can be made entirely by machine systems without a human. The three modes can be switched based on different scenarios on the same voyage.

2.5. The “Physical, Rule, and Cyber” Space. Physical space, rule space, and cyberspace are further abstractions of the five factors of “human, ship, management, environment, and information and technology.” Physical space is used to characterize concrete things in the real world. The rule space refers to the behavior restriction established by humans based on the material space. Cyberspace is a new concept introduced to intelligent ship navigation. It plays an essential role in the realization of ship-shore coordination, remote driving, and autonomous driving. The governance of cyberspace will be the main means of securing intelligent ship navigation [32].

2.6. Three Scenarios of “Inland Rivers, Coasts, and Oceans.” Inland rivers, coasts, and oceans are the three major scenarios for ship navigation. The three scenarios have significantly different requirements for different factors, modes, and spaces, in terms of channel conditions, structures, communication conditions, and personnel [33, 34], so they were used as boundary conditions for the analysis of risk evolution.

2.7. Three Processes of “Navigation Outside the Port, Entering, and Exiting the port, Berthing, and Unberthing.”

Figure 2: Conceptual model for the risk evolution of intelligent ship navigation.

The safety and efficiency in complex traffic scenarios are important indicators reflecting the technical level of intelligent navigation systems. Intelligent Ship Specifications (2020) classifies intelligent navigation functions into basic and advanced functions. The former refers to the design and optimization of the route and speed, and the latter includes autonomous navigation and fully autonomous navigation in open waters [35]. The fully autonomous navigation can be performed in three scenarios of the narrow waterway, complex environment, and automatic berthing and unberthing, and it puts forward relevant requirements from the three aspects of natural conditions, traffic conditions, and ship technology. On this basis, we proposed the five stages of ship navigation, namely unberthing, exiting the port, sailing, entering the port, and berthing, to highlight changes in external conditions.

3. Mathematical Expression Model of Risk Evolution

3.1. Definitions. To accurately depict the risk evolution law and characteristics of intelligent ship navigation, it is necessary to convert the conceptual model into a mathematical expression model for judgment, calculation, and trend prediction.

Definition 1. The intelligent navigation system (expressed as I) is a complex system composed of five factors: human, ship, management, environment, and information and technology. The formula is as follows:

\[ I = Fp + Fs + Fe + Fm + Fi, \]  

where \( Fp \) denotes human, \( Fs \) denotes the ship, \( Fe \) denotes environment, \( Fm \) denotes management, and \( Fi \) denotes information and technology.
Definition 2. Intelligent navigation safety risk (expressed as RI) refers to the danger that the system may encounter and the threat that may cause adverse consequences. If \( w \) represents the weight parameter, then the formula is as follows:

\[
R_I = (F, w) \{ F_p, F_s, F_m, F_e, F_i \}.
\] (2)

Definition 3. The accident (expressed as AC) is an event that has caused adverse consequences. If the risk factor (indicator) causing an accident is expressed as \( r_i \), then the formula is as follows:

\[
AC = f(r_i) \cdot T \cdot S \cdot ri \subseteq R_I,
\] (3)

where \( T \) and \( S \) refer to the time domain and spatial domain in which the accident occurred, and \( r_i \) denotes the subset of RI.

Definition 4. Assuming that the element attributes, risk indicators, and accident types of the inland river, coastal, and ocean scenarios of intelligent navigation have been clarified, the inland waters are expressed as BI, the coastal waters as BC, and the ocean waters as BO.

3.2. Risk Evolution Expression of the Unmanned Tendency. If we use manual driving (\( M_{MM} \)), assisted driving (\( M_R \)), and autonomous driving (\( M_A \)) to characterize the modes from manned to unmanned driving, the following formulas can be obtained:

\[
\delta M : \delta M_M \rightarrow \delta M_R \rightarrow \delta M_A,
\]

\[
\{SH\}_B = F_{dw} = \delta M, \quad B = \{B_I, B_C, B_O\}, \quad (4)
\]
where $\delta M$ denotes the changing state of the risk set under different modes. The change can be further represented by the distribution and trend ($F_{sw}$) of the weight ($w$) of the factors ($F$) in the three modes, to obtain the risk evolution relation $SH_1$ under specific boundary conditions.

Given the lack of numerous risk accidents related to intelligent navigation, anonymous feedback can be obtained based on the expert investigation method to score the weight of the five factors and relevant risk indicators. Figure 3 and Table 2 show the weight distribution of data normalization based on the above-mentioned conclusions of the expert sample database, reflecting the importance of each factor in the system within the cognitive scope of the sample database. Note that the sum of risk factor is normalized to 1 for clarity of comparison.

3.3. Expression of Chain Effect of Risk Accidents. It can be seen from Formulas (2) and (3) that the accident is a function of $r_i$ in the $T$ domain and $S$ domain, and $r_i$ is a subset of $R_i$. Therefore, we can conclude that the risk accident is the result of the risk evolution triggered by a specific event in a specific space and time, with randomness and uncertainty.

The predictability of accidents can be directly used for the evaluation of consequences and losses, which is crucial for the machine to make reasonable choices when facing complex events. By defining the autonomous driving mode ($M_A$) of the intelligent navigation system, the chain effect ($SH_2$) of the risk of accident can be expressed as

$$SH_2 = M_A \cdot f(AC_2) \cdot C_{sc} \longrightarrow AC_3,$$

where $AC_1$ denotes the accident that has occurred, $C_{sc}$ denotes the machine decision-making algorithm, and $AC_2$ denotes the chain accident that may occur.

Based on Formula (5), it is concluded that $C_{sc}$ is the triggering event of the chain effect of risk accidents, and the subsequent risks are only related to $F_s$, $F_i$, and $F_e$, which are expressed in pseudocode as shown in Algorithm 1:

$$SH_3 = P \cdot \frac{R_i}{\delta F_e} \cdot d_{safety} \cdot d_{efficiency},$$

$$P = \{P_1, P_2, P_3, P_4, P_5\},$$

$$B = \{B_1, B_3, B_5\},$$

where $\delta F_e$ denotes the environmental change at different navigation phases. The environment changes at different navigation phases are measured by the sensing system of the ship, including the relative positions to surrounding ships and shore. $d_{safety}$ and $d_{efficiency}$ denote the safety and efficiency, respectively, and their ratio represents the derivative of safety and efficiency.

The probability of risk occurrence significantly increases linearly when ships travel from open waters to complex waters [21]. With other conditions stable, the risk evolution of the intelligent navigation system is mainly manifested in the adaptability of manned and autonomous driving under different environments, that is, to ensure safety while optimizing efficiency.

4. Discussion

4.1. Risk Evolution under the Unmanned Trend. The process from manned driving to assisted driving, remote driving, and autonomous driving is essentially a continuous improvement of technology to replace humans. Human have always been the main factor causing ship accidents [36]. It is a scientific hypothesis that requires long-term observation and demonstration in the field of intelligent navigation whether the trend of the unmanned ship can continuously lower the probability of ship accidents and

![Figure 3: Weight distribution of each factor in different driving modes.](image)

**Table 2: Normalized data of weights for each factor in different driving modes.**

| Risk factor         | $M_H$ | $M_s$ | $M_b$ | $M_A$ |
|---------------------|-------|-------|-------|-------|
| Human               | 0.69  | 0.65  | 0.55  | 0.02  |
| Ship                | 0.09  | 0.13  | 0.04  | 0.12  |
| Management          | 0.08  | 0.08  | 0.02  | 0.1   |
| Environment         | 0.12  | 0.06  | 0.07  | 0.2   |
| Information & tech  | 0.02  | 0.08  | 0.32  | 0.56  |
relevant losses. Moreover, given the significant differences in the three spaces of sea, land, and air, it is hard to answer this question based on the evolution of the autopilot system of vehicles and airplanes.

The main characteristics of the risk evolution of unmanned trend are as follows:

(i) Under the manned and assisted driving modes, human is the main risk source. In the assisted driving mode, the information and technology is included in the risk factors, with the weight distribution slightly adjusted

(ii) In the remote driving mode, the precise control of the hull motion and the communication provided by human through the remote driving system are the main risk sources. In this regard, remote driving will inevitably go through a long-time transition period from manned to an unmanned mode, and it will become a norm. Furthermore, remote driving involves personnel on ship and shore and requires higher ship-handling skills for shore-based personnel than for traditional ship maneuvering personnel

(iii) The autonomous driving mode requires little human intervention and relies heavily on information and technology, significantly enhancing the influence of ship-shore coordination on the relationship between government, port, and ship

(iv) The manned-autonomous driving mode requires little human intervention and relies heavily on the perception and cognition of the intelligent navigation system, significantly enhancing the influence of ship-shore coordination on the relationship between government, port, and ship. The manned-autonomous driving mode may become the norm

4.2. The Chain Effect of Risk Accidents. The occurrence and spread of accidents caused by intelligent ship navigation in the time and spatial domain are featured with the effect of the causal chain proposed by Heinrich [37]. Based on the channel network model, the cellular automata [38] can be used to describe the traffic state at different times accurately. The general law and specific features are as follows:

(i) Navigational risk is a systemic failure caused by the interaction of fine-grained risk indicators and is statistically expressed as a causal relationship dominated by a single risk factor and affected by multiple risk factors

(ii) The single risk can spread as a dependent variable that causes the concurrent chain of multiple risks

(iii) The ethical issues caused by autonomous driving under machine learning may lead to the uncertainty of risk spread. Hence, it is necessary to prioritize human, other ships, or other things

(iv) A navigation incident is not a single event

4.3. Balanced Evolution of Safety and Efficiency. The classification of a single scenario can be used as the limiting condition for the study of risk evolution law, and the system’s decision-making capacity can be constantly iterated through the combination of different scenarios. Figure 4 is the decision diagram of “ZHI FEI” when it avoided collision on 30 September 2021. Specifically, after another vessel passed the abeam of “ZHI FEI,” “ZHI FEI” still made a detour around the stern of that vessel. By changing its planned route, “ZHI FEI” successfully avoid the collision risk. The real route is shown in the solid line in Figure 4, and the “ZHI FEI” is shown in Figure 5.
But note that the fuel consumption generally increases for the ship generally to seal longer route for collision avoidance. Based on the aforementioned conclusions on the risk evolution expression model, the evolution characteristics of safety and efficiency in complex scenarios are obtained as follows:

(i) The improvement of safety may lower the navigation efficiency to some extent

(ii) The optimal balance between safety and efficiency can be used to characterize the highest technical requirements for the intelligent ship navigation system

(iii) Under the same conditions, in the five phases of unberthing, exiting the port, sailing, entering the port, and berthing, safety presents a normal distribution, while the efficiency shows an inverse normal distribution

4.4. Simulation Verification of the Model. In order to validate and continuously improve the risk model and autonomous collision avoidance algorithm, we developed a risk twin system. Based on AIS real-time data, the system records and calculates the trajectory of other ships in the safety field of autonomous ships and analyzes the risk coefficient of autonomous ships according to the speed and course of other ships.

The system is also connected to the meteorological system and the Maritime Safety Information receiving system at the same time. Through the AIS data and these two types
of data, the navigation-assisted information can be provided to the autonomous ship in real time, so as to observe the reliability of the decision-making strategy of the autonomous ship navigation system. Risk details can be viewed through 2D and 3D conversion. The 3D view twins the navigation scene in real time and displayed the relevant values, as shown in Figure 6.

5. Conclusions

The cognition of safety risks is a prerequisite for establishing an intelligent ship navigation system based on ship-shore cooperation. Based on theoretical and practical test analysis, we proposed to take information and technology as the fifth factor apart from "human, ship, management, and environment" and draw the following conclusions:

1. The role of humans in navigation safety is even more important in remote driving mode than in manual and assisted driving modes

2. Information and technology greatly impacts the safety governance of the intelligent ship navigation system. It not only involves communication and network, but also involves the accuracy, precision and reliability of ship perception, shore-to-ship, and ship-to-ship information

3. Risk spread has a chain effect. Avoiding accident losses caused by the chain reactions of risk spread requires multifaceted effort in various fields, such as legislation, technology, and standards

4. The balanced evolution of safety and efficiency is a technical indicator of the intelligent ship navigation system, and it is also the main research direction in the next stage

5. The risk assessment and simulation system is a necessary means to promote the autonomous ship technology. The real-time twin of risks can effectively verify the safety and efficiency of the algorithms of the autonomous collision avoidance system and the route planning system

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no competing interest.

Acknowledgments

This work was supported by the National Key R&D Program of China under grant 2019YFB1600601.

Supplementary Materials

Supplementary Video S1: risk twin system demonstration video. (Supplementary Materials)

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