Brodogradnja/Shipbuilding/Open access Volume 74 Number 4, 2023

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http://dx.doi.org/10.21278/brod74406 ISSN 0007-215X
eISSN 1845-5859

Research on classification and navigational risk factors of intelligent ship

UDC 004.89:025.44/.47
Review paper

Summary

Based on combing the concept and development of intelligent ship, this paper brings forward the summary and classification of intelligent ships proposed by different institutions, and the main classification schemes are compared accordingly. Then one of these classification schemes is selected to study what are the key navigational risks under each grading level, with a detailed analysis of these risk factors. Finally, the index system of navigational risk factors for intelligent ships under different classification standards is constructed to lay a foundation for a further study of intelligent ship safe navigation, and at the same time avoid some risk factors in advance for the maritime management department, ship management companies, and ship design and research institutes.

Key words: *Intelligent ship; classification; navigational risks; factors analysis*

1. Introduction

Since the beginning of the 21st century, a large number of researches on unmanned vehicle technology have emerged [1], and the fourth industrial revolution represented by artificial intelligence, big data, quantum information and other technologies is coming. As one of the traditional transportation industries, maritime transportation is also developing towards automation and intellectualization. According to a recent report from Eworldship Network (www.eworldship.com) [2], in the next decades' years, the global maritime industry will invest more than $38.4 billion to promote intelligent transformation and development through the mutual integration of big data, Internet of things, blockchain, artificial intelligence and other technologies. On December 5th 2017, the world's first intelligent merchant vessel "Dazhi", a 38,800-ton bulk carrier built in accordance with the regulations of China Classification Society (CCS) for intelligent ships, was officially unveiled at the China International Maritime Exhibition [3], which had a profound impact on the development history of intelligent ships. Compared with traditional ships, the intelligent ship is being widely concerned by people in the maritime industry with the main characteristics of safety, economy, green and high-efficiency. Under the advocacy and promotion of the International Maritime Organization (IMO), other international organizations and countries, the research on intelligent ship has become more and more deeply with an unprecedented prosperity in recent years.

At present, the development of intelligent ship is in the primary stage, the real sense of intelligent ship is still in the process of research, and there is no intelligent ship engaged in maritime cargo transportation. The first consideration of marine transportation is safety, as a result, it is of great significance to avoid risks faced by future intelligent ships as much as possible during the research stage. Though the research on intelligent ship is more and more in-depth, the intelligent ship classification scheme and its autonomy level standard is not clear, and the same goes for the intelligent ship navigation risk quantitative evaluation index. Even more, there is a lack of research on navigation risk factors in view of different types and different classification scheme of the intelligent ship, as well as the corresponding evaluation methods

In recent years, a lot of research has been done on the navigation risk of intelligent ships. For example, Zou [4] selected four aspects of shore-based operating personnel factor, ship factor, environmental factor and management factor to build the navigation risk assessment index system of unmanned ships under complex navigation conditions, and used the analytic hierarchy process to solve the weights of various navigation risk factors, and tested the consistency of the established index system. Through expert investigation, a fuzzy membership set of risk index is established, and a fuzzy comprehensive evaluation model is established to evaluate the navigation risk of unmanned ships under complex navigation conditions. Luo et al. [5] put forward a five-factor risk evaluation index system of "man-machine-pipe-environment-information" from the perspective of risk evolution of ship intelligent navigation safety. Zhang et al. [6] used entropy theory and correlation coefficient method to screen indicators and established an indicator system of navigation safety of unmanned vessels in inland rivers. Zhang et al. [7] identified 50 risk factors related to navigation safety of intelligent ships based on literature collection, and established a risk assessment index system for unmanned inland river ships. Chang et al. [8] combined the failure mode and impact analysis method with evidence reasoning and rule-based Bayesian network method to identify the types of hazards of intelligent ships, so as to establish its evaluation index system. Chen et al. [9] selected the data of Marine accidents occurring in 16 ship types and 13 major navigation areas in the world from 1998 to 2018, and identified the main factors causing Marine accidents based on the improved entropy weight method and the approximate ideal solution ranking method, so as to build its evaluation index system. Besides, many other scholars have adopted many methods to identify and evaluate risks through expert questionnaire [10], historical navigation accident data mining [1], hierarchical holographic modeling framework and risk filtering, rating and management [11], multi-dimensional analysis of accident causes [12], risk classification and ranking based on Marine meteorological conditions [13], Bayesian belief network [14] and other methods. The construction of risk identification and risk evaluation index provides the basic framework support for the corresponding risk evaluation.

The analysis of risk factors of intelligent ship navigation and the construction of evaluation index system is one of the preconditions for the study of intelligent ship navigation safety. It can be seen from the above literature review that most domestic and foreign scholars carry out qualitative or semi-quantitative studies on the risk assessment index system of intelligent ships, but there are few research results on the construction of risk factor index system of intelligent ships navigation based on classification standards. Therefore, in order to further clarify the concept of intelligent ship and its classification standard, this paper starts from the concept of intelligent ship and its development route with a deep discussion of the connotation and extension of intelligent ship. Through a classified summary of intelligent ship classification standards from domestic and international authoritative institutions, this paper compares the differences from two aspects: the background of classification and the selection of classification standards, and a more ideal standard which is advantageous for the practical research is selected to analyse the navigational risk factors, to finally propose a construct a framework of navigation risk factors for intelligent ships based on this classification standard. The research conclusion of this paper has an important reference value for the formation of risk factor analysis scheme in line with its intelligent function and control characteristics, and also lays a theoretical foundation for further navigation risk assessment of intelligent ships.

2. The concept of intelligent ship and its development route

2.1 The concept of intelligent ship

The concept of e-Navigation is put forward by IMO in 2006, representing the origin of the concept of intelligent ships [15]. At that time, the intelligent ship mainly refers to the collection, fusion and display of maritime information on the ship and shore by means of electronic information, so as to realize ship-to-ship, ship-to-shore and coast-to-shore information transmission, and achieve the purpose of ship navigation safety, economy and marine environment protection [16]. In September 2012, the European Union proposed the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project [17]. This project defines the intelligent ship as on board and off ship wireless monitoring and control using the next generation of modular control systems and communication technologies, which includes advanced decision support systems to provide the ability to remotely operate the ship under semi-autonomous or fully autonomous control. In January 2014, Det Norske Veritas (DNV) gave the definition of “The Interconnected Ship” in its science and technology report "The Future of Shipping". Through the fusion of real-time information transfer, computing, modelling, control and sensor application capabilities, a data-centric and responsive global integrated ship transportation network is created [18]. In March 2016, In March 2016, China Classification Society (CCS) issued the “Intelligent Ship Specification”, which defines intelligent ships as follows: Intelligent ship refers to the use of technical means such as sensors, communications and the Internet, to automatically perceive and acquire information and data such as the ship itself, the Marine environment, logistics and port, et al., and realize intelligent operation of the navigation, management, maintenance and transportation through computer technology, automatic control technology and data processing and analysis technology, so as to make the ship safer, more environmentally friendly, more economical and more reliable [19]. In the same year, Bertram [20] defined intelligent ships as "ships with automated software systems that can make decisions and actions independently by providing advice to operators or replacing human decisions at the highest level of autonomy". The American Bureau of Shipping (ABS) defined the intelligent ship as a ship that is equipped with sensors, automatic navigation, propulsion and auxiliary systems, and has the decision-making logic of following the task plan, sensing the environment and adjusting the execution of the task according to the environment, without human intervention [21]. In August 2017, Rødseth Ørnulf and Nordahl Havard [22] defined intelligent ship as a ship whose computer-controlled systems can sense the environment and decide for themselves how to steer in a given situation at the Norwegian Forum for Autonomous Ships (NFAS). In the same year, the Danish Maritime Authority (DMA) also explained the definition of intelligent ship [23], which is a ship that can provide decision support or may take over the control and management of a ship partially or wholly by personnel through automatic process, whether from the ship or from other places. In May 2018, the IMO defined an intelligent ship as a ship that can be independent of human intervention in different degrees in the 99th Maritime Safety Committee [24]. In October 2019, Bureau Veritas (BV) issued an intelligent ship guide that defined the intelligent ship as a ship without crew on board to operate the ship, which can be remotely controlled or supervised by operators or fully automated [25].

From the above definition of intelligent ship by different countries and institutions, although there are some differences, their definitions have some common features, that is, through the integration of relevant information, the ship's autonomous decision-making ability is improved, so as to make ship operation safer, environmentally friendly, economical and reliable. From the high-frequency words "automatic", "unmanned", "remotely control and decision" appearing in the definition of intelligent ship, it also illustrates people's understanding and demand for intelligent ship at the present stage. From the development process of the concept of intelligent ship, it can be seen that different high-frequency words just correspond to different development stages of intelligent ship, and different development stages also match with different levels of intelligence. Therefore, it is of vital significance to study the definition of intelligent ship to accurately and clearly divide the development stage of intelligent ship and the classification standard of intelligent level. In order to avoid restricting the development of intelligent ships, the 99th meeting of the IMO Maritime Safety Committee only made a preliminary definition of intelligent ships, and identified the existing laws and regulations affecting the operation of intelligent ships and related adaptive problems according to the definition. In this paper, in accordance with the above principles, the intelligent ship definition and the high frequency words are deeply studied, and for the next step research of intelligent ship classification and navigation risk under different weather conditions and different water conditions, the intelligent ship is defined as “ships that can provide corresponding auxiliary decision-making or automatically make decisions and take effective actions independently of human intervention, under different levels of automation”.

2.2 The development of intelligent ship

As the main direction of future ship development, intelligent ship with autonomous navigation ability has become a new hotspot [26, 27]. For intelligent ships, different countries have carried out a large number of prospective studies. The research level and development are getting higher and higher year by year with more and more participants, and the methods and emphasis of the research are also flexible and diverse.

From the timing frame of the development of intelligent ships, Europe started the research and development of intelligent ships earlier, mainly doing the research and development of real ships, and applied in various fields [28-38]. Korea has mainly applied its own intelligent technologies directly to newly built ships [39]. Japan listed the intelligent ship standard as a key task [40]. Our focus is to start with the functions of intelligent ship, and gradually study and solve the intelligent level of each part of the equipment. In addition, the international organizations and major classification societies have issued specifications or guidance documents on intelligent ships [41-47].

The specific development overview is shown in Figure 1.

From the perspective of the development stages of intelligent ships, the development of intelligent ships can be divided into four stages: interconnection, system integration, remote control and autonomous operation, as shown in Figure 2.

Interconnection: It is the initial stage of intelligent ships, where sensing systems are laid out and communication and data sharing capabilities between systems and between ships and shore are built to realize remote monitoring of ships.

System integration: Develop unified ship data standards, gradually integrate multi-source heterogeneous systems into a single integrated system, and realize platform management. It lays the foundation for realizing the goal of "one platform + multiple applications".

Remote control: The management personnel can control the ship by means of remote communication from the shore-based control centre, mother ship and other locations. The premise of remote-controlled application is to solve a series of technical problems such as device health management.

Autonomous operation: On the basis of perception, highly complex software technology and control algorithms such as collision avoidance technology based on game theory are used to form control commands. Ships with autonomous operation are self-adaptive and do not require crew to perform routine operations.

Among them, the technologies of the first and second stages are relatively mature at present, only with different degrees of applications. The remote control of the third stage and the autonomous operation of the fourth stage are the characteristics of the current "fashionable" "unmanned intelligent ship". An unmanned intelligent ship is a ship that can control movement without a crew on board. The unmanned intelligent ship can be a remote-controlled ship or an autonomous operation ship, which requires high reliability and stability of the ship execution system.

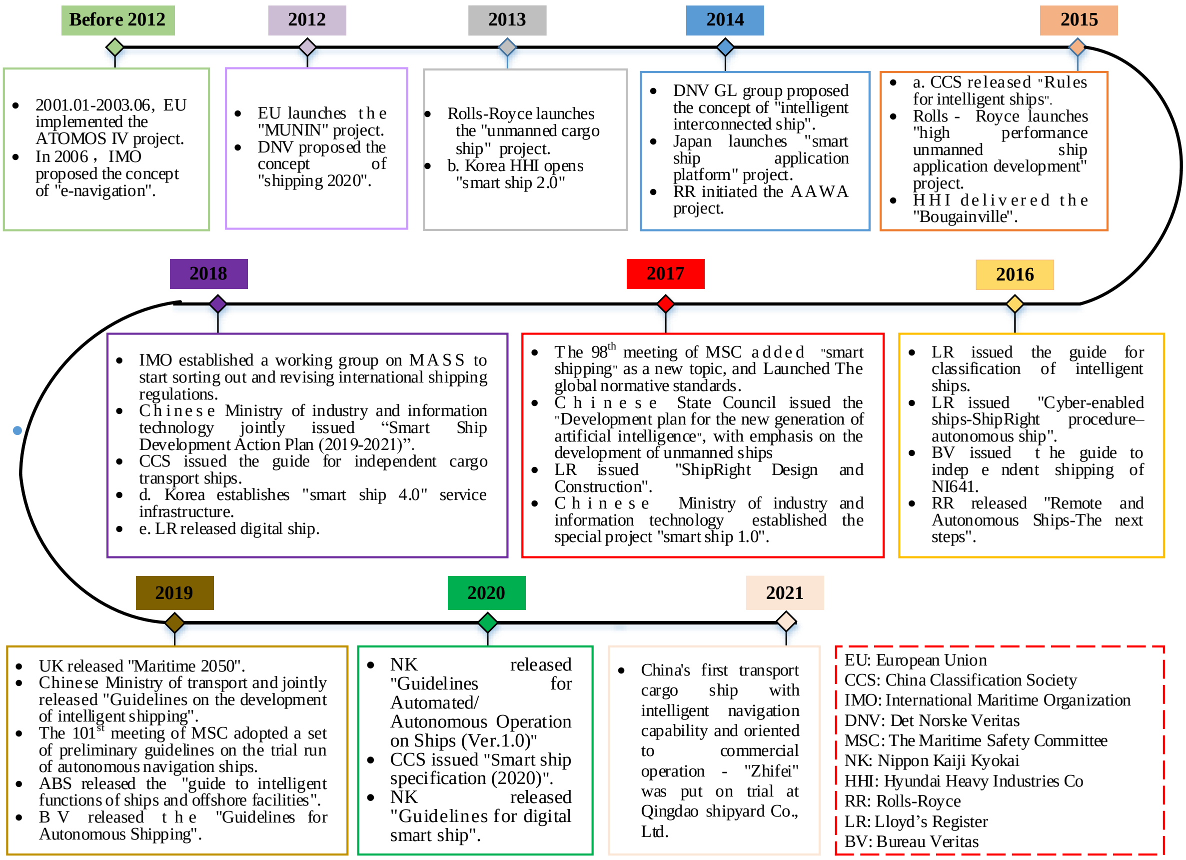

Fig. 1 Overview of intelligent ship development

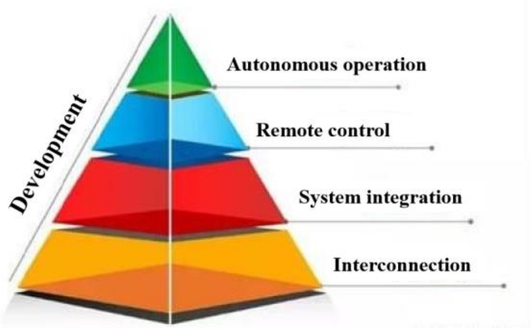

Fig. 2 Development stage of intelligent ship

From the perspective of the focus of intelligent ship research, IMO attaches importance to technology, CCS attaches importance to independent research and development, and LR attaches importance to analysing the relationship between human and ship. RR Company attaches importance to four stages of realizing intelligent ship from the perspective of navigation safety and the accumulation of experience: reducing crew shore-based control, offshore unmanned shore-based control, ocean-going unmanned shore-based control and autonomous navigation. Considering the physical range, data fusion range and intelligence degrees of intelligent ships, some institutions have studied the technologies needed for intelligent ships, such as remote monitoring, big data fusion, network information security and ship-shore information exchange. Therefore, from the focus of the research, the development of intelligent ships is transitioning from the second stage to the third stage.

3. The classification standards for intelligent ships

At present, there are number of different definitions of autonomy levels for intelligent ship classification standards, including AAWA, DNV-GL DMA, IMO, LR, NFAS, RR, MASRWG, BV, ABS, CCS, etc. The following is a detailed introduction to the above classification standards.

3.1 AAWA classification standard of intelligent ship

The Advanced Autonomous Waterborne Application Initiative (AAWA) is a €6.6 million project funded by Tekes (Finnish Funding Agency for Technology and Innovation). In 2016-2017, RR, Brighthouse, NAPA, Deltamarin, DNV GL and Inmarsat conducted a collaborative study with a goal of exploring the economic, social, legal, regulatory and technical issues needed for the realization of unmanned vessels, and developing specification and preliminary designs for the next generation of advanced ship solutions [26]. This project referred to Thomas Sheridan's classification of autonomous systems for a unified understanding of intelligent ships, which includes the division of a continuous range from human control to complete machine autonomy, as shown in Table 1.

Table 1 Levels of Autonomy (AAWA) [26]

Autonomy Level	Description
10	The computer does everything autonomously, ignores human
9	The computer informs human only if it (the computer) decides so
8	The computer informs human only if asked
7	The computer executes automatically, when necessary informing human
6	The computer allows human a restricted time to veto before automatic execution
5	The computer executes the suggested action if human approves
4	Computer suggests single alternative
3	Computer narrows alternatives down to a few
2	The computer offers a complete set of decision alternatives
1	The computer offers no assistance, human in charge of all decisions and actions

3.2 DNV-GL classification standard of intelligent ship

In September 2018, Det Norske Veritas (DNV-GL) released a guide called "Autonomous and remotely operated ships" [48], which covered main principles, qualification and approval process, navigation functions, vessel engineering functions, remote control centres, and communications functions, etc. In addition, the guide distinguishes the roles of human and machine system from the perspectives of perception, analysis, decision-making and execution. Based on the operational requirements and navigation risks, and according to whether the navigation function or task is covered by the autonomous system or by the operator, the autonomy level of ship navigation function is divided into five levels, with the detailed descriptions shown in Table 2.

Table 2 Levels of Autonomy (DNV-GL) [48]

Autonomy Level	Description
M	Manually operated function.
DS	System decision supported function.
DSE	System decision supported function with conditional system execution capabilities (human in the loop, required acknowledgement by human before execution).
SC	Self-controlled function (the system will execute the operation, but the human is able to override the action. Sometimes referred to as 'human on the loop'.
A	Autonomous function (the system will execute the function, normally without the possibility for a human to intervene on the functional level).

3.3 DMA classification standard of intelligent ship

Danish Maritime Authority (DMA) has submitted the final report “analysis of regulatory barriers to the use of autonomous ships” on the regulatory obstacles to the application of MASS to the 99th MSC of IMO [23], in which the role of ship operators under different levels of autonomy is elaborated, together with four levels of ship autonomy: M, R, RU and A, from the perspective of government supervision, as shown in Table 3.

Table 3 Levels of Autonomy (DMA) [23]

Autonomy Level	Description
M	Manual navigation with automated processes and decision support. The operator (master) is on board controlling the ship which is manned as per current manning standards. Subject to sufficient technical support options and warning systems, the bridge may at times be unmanned with an officer on standby ready to take control and assume the navigational watch.
R	Remote-controlled vessel with crew on board. The vessel is controlled and operated from shore or from another vessel, but a person trained for navigational watch and maneuvering of the ship will be on board on standby ready to receive control and assume the navigational watch, in which case the autonomy level shifts to level M.
RU	Remote-controlled vessel without crew on board. The vessel is controlled from shore or from another vessel and does not have any crew on board.
A	Autonomous vessel. The operating system of the vessel calculates consequences and risks. The system is able to make decisions and determine actions by itself. The operator on shore is only involved in decisions, if the system fails or prompts for human intervention, in which case the autonomy level will shift to level R or RU, depending on whether there is crew on board or not.

3.4 IMO classification standard of intelligent ship

The International Maritime Organization (IMO) adopts the classification standard proposed by DMA at the 99th MSC Conference in May 2018. According to whether the ship is manned or not, and from the perspective of autonomous remote control, the degrees of ship autonomy can be divided into four levels, L1-L4, and it is emphasized that MASS may sail with one or more degrees of autonomy during the voyage. However, remote control and autonomy are not defined and explained [24], as shown in Table 4.

Table 4 Levels of Autonomy (IMO) [24]

Autonomy Level	Description
L1	Ship with automated processes and decision support.
L2	Remotely controlled ship with seafarers on board.
L3	Remotely controlled ship without seafarers on board
L4	Fully autonomous ship

3.5 LR classification standard of intelligent ship

In July 2016, Lloyd's Register of Shipping (LR) has published particular levels of autonomy in the maritime industry, where the vessels are anticipated to follow an "adjustable autonomy" scheme depending on the condition of the ship herself and the mission being executed, and it has been devided into 7 levels from AL0-AL6 in terms of system function [49]. Covering everything from ship design to operation, the document provides a clear and accurate definition of the characteristics of each level and explains the possible risks. In this classification standard, ordinary ships without autonomous functions are "AL0", and autonomous ships with autonomous functions are divided into 6 grades from AL1 to AL6 [50, 51], as shown in Table 5.

Table 5 Levels of Autonomy (LR) [49]

Autonomy Level	Description
AL0	No autonomous function – all decision making is performed manually, i.e. a human controls all actions at the ship level.
AL1	On-ship decision support – all actions at the ship level are taken by a human operator, but a decision support tool can present options or otherwise influence the actions chosen, for example DP Capability plots and route planning.
AL2	On and off-ship decision support – all actions at the ship level taken by human operator on board the vessel, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or offff the ship, for example DP capability plots, OEM recommendations, weather routing.
AL3	'Active' human in the loop – decision and actions at the ship level are performed autonomously with human supervision. High-impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them. Data may be provided by systems on or off the ship.
AL4	Human on the loop: operator/supervisory – decisions and action are performed autonomously with human supervision. High impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them.
AL5	Fully autonomous – unsupervised or rarely supervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.
AL6	Fully autonomous – unsupervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.

3.6 NFAS classification standard of intelligent ship

On October 10, 2017, Norwegian Forum for Autonomous Ships (NFAS) classified autonomous vessels into four categories in its first approved public version: autonomous auxiliary bridge, regularly unmanned bridge, regularly unmanned vessel and continuously unmanned vessel [52]. Meanwhile, the autonomous operation levels of intelligent ships can be divided into four levels: decision support, automation, limited autonomy and full autonomy. On this basis, NFAS defines 6 autonomy levels for manned and unmanned bridge respectively, as shown in Table 6.

Table 6 Levels of Autonomy (NFAS) [52]

Level/Description	Manned bridge	Unmanned bridge - crew on board	Unmanned bridge - no crew on board	Level/Description
Decision support	Direct control, No autonomy	Remote control	Remote control	Decision support
Automatic	Automatic bridge	Automatic ship	Automatic ship	Automatic
Constrained autonomous	-	Constrained autonomous	Constrained autonomous	Constrained autonomous
Fully autonomous	-	-	Fully autonomous	Fully autonomous

3.7 RR classification standard of intelligent ship

The Rolls-Royce company (RR) classification standard mainly focuses on the division of human and system roles in the execution of operation tasks, which can be divided into three aspects: control role, over-ride role, and system task capability. This standard can be considered as a tailoring of AAWA or an extension of NFAS, with a wider scope of application and relatively specific technical description [34], as shown in Table 7.

Table 7 Levels of Autonomy (RR) [34]

Level	Name	Definition	Control role	Over-ride role	system task capability
0	Non-autonomy	Human makes all decisions and controls all functions.	Human	Human	-
1	Partial-Autonomy	The target task is done by the human and the sub-task is handled by the system.	Mainly controlled by human, with ship system as an aid.	Human	Some operation tasks
2	Conditional-Autonomy	In the case of unmanned intervention, the system will complete the target task, and the rest of the tasks will be completed by people, who are responsible for safe operation.	Mainly controlled by ship system, with human as an aid	Human	Most operation tasks
3	High-Autonomy	The system is responsible for most of the main tasks, people are responsible for a few tasks, and the system is responsible for safe operation.	Mainly controlled by ship system, with human as an aid	Ship system	Most operation tasks
4	Full-Autonomy	All tasks in all environments are performed by automatic control systems.	Ship system	Ship system	All operation tasks

3.8 MASRWG classification standard of intelligent ship

In September 2014, the British government funded the establishment of Maritime Autonomous Systems Working Group (MASRWG), which aims to identify and confirm the gaps in the current IMO standard system for maritime autonomous systems and its solutions. MASRWG launched the "Industry Specification for the Design, Construction and Operation of Autonomous Maritime Systems" at the 3rd Conference in Southampton on 16 November 2017, and released version 2.0 in November 2018 [53]. According to this specification, the autonomy level of MASS is divided into 6 levels from 0 to 5 from the perspective of control ability. Among them, level 0 is manual operation, and level 1-5 is set as unmanned ship, as shown in Table 8.

Table 8 Levels of Autonomy (MASRWG) [53]

Level	Description
0	Manned-Vessel/craft is controlled by operators aboard
1	Operated-Under Operated control all cognitive functionality is controlled by the human operator. The operator has direct contact with the Unmanned Vessel over e.g., continuous radio (R/C) and/or cable (e.g., tethered UUVs and ROVs). The operator makes all decisions, directs and controls all vehicle and mission functions.
2	Directed-Under Directed control some degree of reasoning and ability to respond is implemented into the Unmanned Vessel. It may sense the environment, report its state and suggest one or several actions. It may also suggest possible actions to the operator, such as e.g. prompting the operator for information or decisions. However, the authority to make decisions is with the operator. The Unmanned Vessel will act only if commanded and/or permitted to do so.
3	Delegated-The Unmanned Vessel is now authorised to execute some functions. It may sense environment, report its state and define actions and report its intention. The operator has the option to object to (veto) intentions declared by the Unmanned Vessel during a certain time, after which the Unmanned Vessel will act. The initiative emanates from the Unmanned Vessel and decision-making is shared between the operator and the Unmanned Vessel.
4	Monitored-The Unmanned Vessel will sense environment and report its state. The Unmanned Vessel defines actions, decides, acts and reports its action. The operator may monitor the events.
5	Autonomous-The Unmanned Vessel will sense environment, define possible actions, decide and act. The Unmanned Vessel is afforded a maximum degree of independence and self-determination within the context of the system capabilities and limitations. Autonomous functions are invoked by the on-board systems at occasions decided by the same, without notifying any external units or operators.

3.9 BV classification standard of intelligent ship

In December 2017, Bureau Veritas (BV) released the "Guide for Autonomous Shipping", which classified the autonomy of intelligent ships into five levels from 0 to 4, as shown in Table 9 [25], in terms of control methods, decision making, implementation and whether personnel carry out the autonomy of intelligent ships on board.

Table 9 Levels of Autonomy (BV) [25]

Degree of Automation	Definition
A0	Human operated-Automated or manual operations are under human control. Human makes all decisions and controls all functions.
A1	Human directed-Decision support: system suggests actions. Human makes decisions and actions.
A2	Human delegated-System invokes functions. Human must confirm decisions. Human can reject decisions.
A3	Human supervised-System invokes functions without waiting for human reaction. System is not expecting confirmation. Human is always informed of the decisions and actions.
A4	Full automation-System invokes functions without informing the human, except in case of emergency. System is not expecting confirmation. Human is informed only in case of emergency.

3.10 ABS classification standard of intelligent ship

In 2019, the American Bureau of Shipping (ABS) classified intelligent ships into 4 levels according to the necessary degree of human intervention on ships [54], as shown in Table 10.

Table 10 Levels of Autonomy (ABS) [54]

Level	Description
0	Manual: No system augmentation of human functions
1	Smart: Passive decision support; System augmentation of human functions (i.e. Health Monitoring)
2	Semi-Autonomy: Human augmentation of system functions; Human in the loop for supervisory/override.
3	Full Autonomy: No human augmentation of system functions; Human out of the loop (informed as requested).

3.11 CCS classification standard of intelligent ship

On December 4, at the senior Maritime Forum dedicated to shipping and ports of China International Maritime Exhibition, China Classification Society (CCS) issued the "Intelligent Ship Specification (2020)", in which the classification of intelligent ships was explained in detail [55], as shown in Table 11.

Table 11 Levels of Autonomy (CCS) [55]

Level	Description
Decision-Support D	All actions at the ship level are taken by a human operator, part of the system can assist in decision making.
Remote-controlled R1	The main functions of the ship are controlled and operated by the remote-controlled station. The crew on the ship can monitor the state of the ship and take over the operation of the ship in case of emergency or when necessary.
Remote-controlled R2	The main functions of the ship are controlled and operated by a remote-controlled station without crew on board
Partial-Autonomy A1	The ship can operate autonomously from anchorage to anchorage and be monitored by the remote-controlled station, which can control the ship when necessary. The entry, exit and berthing of the ship are operated by the crew and/or pilot.
Partial-Autonomy A2	The ship can operate autonomously from anchorage to anchorage and be monitored by the remote-controlled station, which can control the ship when necessary. The entry, exit and berthing of the ship are operated by a remote-controlled station.
Full-Autonomy A3	The ship can operate autonomously from berth to berth and be monitored remotely. When necessary, the remote-controlled station can control the ship remotely.

3.12 SSRDI classification standard of intelligent ship

Shanghai Ship Research and Design Institute (SSRDI) classified intelligent ships into five levels from the aspects of ship control, monitoring and failure response, and based on the intervention degree of human and system in various operating conditions of the ship, including decision-making assistance, partial autonomy, conditional autonomy, high autonomy and full autonomy [56], as shown in Table 12.

Table 12 Levels of Autonomy (SSRDI) [56]

Level	Description
1	Decision-Support
2	Partial-Autonomy
3	Conditional-Autonomy
4	High-Autonomy
5	Full-Autonomy

The above classification standards comprehensively consider the control degrees of "man-system". However, considering the comprehensive evaluation needs of intelligent ships for remote control and autonomous navigation, whether the classification standard can be quantified and whether the coupling relationship between influencing factors can be defined are important issues to be considered in the selection process of the scheme.

In general, the intelligent level classification standard includes two directions: remote-controlled operation and autonomous operation. Since intelligent ship contains numerous scenarios (navigation, berthing and departing, inward and outward, anchoring, etc.), and the timing or progressive relationship between different systems is difficult to define. Based on the intelligent technology maturity and industry demand, combined with the above analysis, this paper will focus on the comparison of intelligent ship classification standards by main classification societies, in order to lay the foundation to choose classification standard in the next step.

4. Comparison of intelligent ship classification standards by main societies

The main classification societies have classified the autonomous levels of intelligent ships differently [57], as shown in Table 13. The International Maritime Organization has also classified autonomous ships into four levels at the 100th Maritime Safety Meeting. Through horizontal comparison, we can draw the following conclusions:

(1) IMO classifies the grades of ship autonomy into four levels, L1-L4, mainly from the perspective of whether there are people on board and the remote-controlled autonomy. But remote control and autonomy are not defined and explained.

(2) China Classification Society maintains a high degree of consistency with IMO. Its autonomous operation canbe divided into three levels: A1- anchorage to anchorage, manned; A2- Anchorage to anchorage, remote control; A3- Berth to berth, fully autonomous. This detailed segmentation is a good inspiration for new business models.

(3) Other classification societies do not take whether there are people on the ship as the basis for the classification of autonomy, and do not carry out too much discussion on remote control. Take the British Classification Society as an example [58], from A3 to A6, the supervision requirements of personnel gradually decrease, but the regulations do not require supervision on the ship, remote supervision can be acquiesced. Classification societies distinguish the autonomous level of intelligent ships mainly based on the decision-making ability of machines and the degrees of human intervention. The higher the level of autonomy, the higher the decision-making level of the machine, the less the dependence on people.

(4) Perception, cognition, decision making and execution are the four classical steps of intelligent systems, and the same for intelligent ships. Most classification societies refer to these four steps to distinguish the classes of intelligent ships. The traditional ship is the combination of crew perception and machine perception. The cognition and decision are realized by human, and the execution is realized by machine. And fully autonomous ships, from perception to cognition, from decision to execution are all realized by machines.

Table 13 Comparison of different classification standards for intelligent ships proposed by IMO and classification societies of various countries

IMO (2018)		CCS (2016/2020)		LR (2016)		NK (2020)		ABS (2019)		DNV (2018)		BV (2017)	
level	Description	level	Description	level	Description	level	Description	level	Description	level	Description	level	Description
L1	human operator on board assisted driving			A0	manually	Group I	Equipment and human share the execution	Manual	-	M	-	A0	manually
				A1	On-ship decision support					DS	Decision support	A1	human operated Decision support
				A2	On and off-ship decision support			Smart	Decision support	DSE	Ability to make decisions, but need operator confirmation.	A2	System suggested Human decision
L2	Remote control with seafarers on board to monitor.	R1	Same as L2										
L3	Remote control without seafarers on board.	R2	Same as L3										
L4	Fully autonomous ship without seafarers on board.	A1	from anchorage to anchorage, with crew operated	A3	Highly human supervision	Group II	System decision, human in the loop	Semi-Autonomy	Human in the loop	SC	Self controlled Human on the loop	A3	Self controlled Human is always informed of the decisions and actions.
		A2	from anchorage to anchorage, with remote control operated	A4	Weekly human supervision	Group III	System decision and backup, pre-set scenes	Full-Autonomy	Human out of the loop	A	Self controlled	A4	Self controlled Human is informed only in case of emergency.
		A3	from berth to berth	A5	Rarely human supervision	Group IV	System decision and backup, all scenes				Without interference		
				A6	Fully autonomous, unsupervised operation								
Summary		Maintain a high degree of consistency with IMO, more detailed		Don't focus on whether with human on board, but focus on execution and supervision (can be remotely supervised)		The concept of scene presupposition is introduced to distinguish the role of human and system in decision-making and contingency measures		The roles of human and system are distinguished from data processing, decision making and action execution		Distinguish the roles of human and system from the perspectives of perception, analysis, decision making, and execution		Distinguish the roles of human and system from four aspects: information acquisition, information analysis, decision authorization and action execution initiation	

(5) The classification of intelligent ships by classification societies is basically carried out on the basis of theoretical research, and there is generally a lack of analysis of a large number of practical data, so the scientificity, practicability and standardization need to be further verified. The custom symbol and related descriptions also vary greatly, which need to be further unified and standardized. Intelligent ship classification is still in the preliminary stage of research and needs to be studied with the passage of time and the development of artificial intelligence and other technologies.

5. Analysis of navigation risk factors of intelligent ships under different standards

Risk control is the key to intelligent ships. Regarding risk, the regulations of classification societies of different countries also reflect different views [57], which can be shown in Table 14.

Table 14 Intelligent ship risk considerations of different classification societies

	CCS	LR	NK	ABS	DNV	BV
Summary	Application Guide for Integrated risk-based Ship Safety Assessment	Risk-based assessment	Risk identification Establish risk scenario Risk assessment How to mitigate risks	Risk matrix (probability of failure VS consequences of failure) Risk assessment Risk factor	Risk-based approach Minimum risk state	Risk technology assessment Hazard identification Risk index Risk assessment Risk control
Risk factors	✓ Network security system	✓ Human-computer interaction ✓ Data quality ✓ System architecture ✓ hardware ✓ software ✓ Communication network ✓ security ✓ System integration	✓ human-computer interaction error ✓ The impact of ship automation ✓ Risk to communication networks ✓ Reliability of computer systems ✓ Sensor failure ✓ Network attack ✓ External physical invasion	✓ The role of intelligent function ✓ Software and hardware complexity, data analysis, algorithms ✓ Reliability of hardware, software, network, and data exchange ✓ Redundant design ✓ Loss of power ✓ Algorithm and model accuracy and robustness ✓ Data integrity, network security ✓ Operation error, human factor	-	✓ Voyage risk ✓ Navigational risk ✓ Perceived risk ✓ Communication risk ✓ Ship system risk ✓ Remote control risk ✓ Security risk

China Classification Society suggests that risk assessment can be carried out with reference to the CCS "Guide for the Application of Comprehensive Safety Assessment of Ships". In the specification of intelligent ship, there is no special chapter to discuss the risk. It only emphasizes that intelligent ship has great risks in power plant stability, remote control reliability, human factors, information transmission security and software security.

Based on risk control, Lloyd's Register of Shipping (LR) discusses 9 risk factors including human-computer interaction, data quality, system architecture, hardware, software, communication network, security and system integration from four dimensions: scope, objective, function and performance [58].

Nippon Kaiji Kyokai (NK) emphasizes risk identification, construct risk scenario, conduct risk assessment, and finally consider how to mitigate the risk. The risk factors are mainly considered from the aspects of human-computer interaction, ship automation, communication network, reliability of computer system, sensor failure, network attack, external physical invasion, etc.

American Bureau of Shipping (ABS) puts forward the concept of risk matrix and risk factor to evaluate the risk. In terms of risk factors, the main considerations are: the role of intelligent function; hardware and software complexity, data analysis, algorithms and models; reliability of software and hardware, network and data communication; redundant design of onboard systems; Loss of electricity; analysis model and data uncertainty; accuracy and robustness of algorithms and models; data integrity, software quality and network security; operation error and human factors; the potential global impact of the data; the potential failures from integration and interoperability.

Det Norske Veritas (DNV) has also adopted the risk-based principle in its specifications and proposed the concept of minimum risk conditions. In terms of risk management and control, DNV has put forward a complete set of novel design processes.

Bureau Veritas (BV) has a separate section on the technical assessment of risks, in which the requirements for hazard identification, risk indices, risk assessment and risk control are presented. In terms of risk factors, BV considers the risks from several aspects, such as voyage risk, navigation risk, perceived risk, communication risk, ship system risk, remote control risk and security risk, and subdivides the risks from each aspect.

Through the above comparison of the classification standards of intelligent ships by different countries and institutions and the consideration of the risk factors faced by them, it is not difficult to see that the environmental factors faced by the navigation risks of intelligent ships under different classification standards are the same, but the human factors and scientific and technological factors are different. The human factors can be divided into people on board and shore-based operators, while scientific and technological factors mainly include intelligent equipment, intelligent systems and network security. In order to further study the navigation risk of intelligent ships, this paper finally selected IMO classification standard as ship autonomy levels to study the navigation risk factors of intelligent ships under different classification standards.

The L1 level ships are not very different from traditional ships, and we consider their intelligence level to be basically zero, as a result we will not discuss it here. In the following sections, the navigation risks of fully autonomous ships and remote-controlled ships are mainly studied, where the remote-controlled ships can be divided into remote-controlled ships equipped with seafarers or without seafarers. The environmental factors of intelligent ships under different levels are the same, while the human factors and scientific & technological factors are different. Therefore, it is of great significance to analyze the risk factors of intelligent ships according to the characteristics of intelligent ships in different levels.

5.1 Analysis of navigation risk factors of fully autonomous ships

There are many factors affecting the navigation risk of intelligent ships. According to the characteristics of fully autonomous ships, in order to facilitate the subsequent research work, the navigation risk of fully autonomous ships is divided into three parts: autonomous navigation system, environmental factor, and shore-based supervision and support. The factors of the three parts interact and influence each other, and there is a complex causal relationship. As a result, it would be more convenient and intuitive to describe them separately. Among them, environmental factor has a great impact on all three parts, and need to be close attention in the whole navigation process of fully autonomous ships.

5.1.1 Autonomous navigation system

The core part of a fully autonomous ship is the autonomous navigation system, which is highly intelligent and mainly includes three factors: navigation environment perception, autonomous navigation decision and automatic ship control.

Navigation environment perception mainly includes perception equipment and its ability, such as whether it is equipped with perception equipment, whether the ability of the equipped perception equipment is good or bad, and whether it can play a good perception effect. Perceptual data fusion ability, such as the data fusion ability of dynamic sailing conditions such as ship position, ship speed and heading, and the data fusion ability of static sailing conditions such as ship type, size, tonnage and age. In addition, the perception errors (false positives, missed positives, etc.) may occur when the perception system performs multi-sensor fusion. Dynamic target perception reliability, such as whether the function of the equipped sensing equipment is reliable or not, whether it can timely identify dangers and obstacles, etc. Static target perception reliability mainly refers to the accuracy of electronic chart.

The autonomous navigation decision mainly includes navigation situation judgment ability, risk calculation ability, collision avoidance decision generation ability and route independent optimization ability. Among them, the navigation situation judgment ability is mainly the analysis and judgment ability in multi-target encounter situation and complex environment. The risk calculation ability mainly refers to the accuracy of calculation, the size of calculation error, whether there is a strong self-learning ability and whether the calculation is simple, etc. The collision avoidance decision generation ability mainly refers to the timeliness and accuracy of decision generation. The route independent optimization ability mainly refers to whether it has the ability to obtain shore-based support information or the ability to self-correct without relying on shore-based support.

The automatic ship control mainly includes the stability of the control system and the sensitivity of the control system. Among them, the stability of the control system mainly refers to whether the ship control system can operate stably under the influence of external factors. The sensitivity of the control system mainly refers to how long the system can respond, etc. In addition, the control system failure or loss of power during the voyage is also a kind of risk worth paying attention to.

5.1.2 Environmental factor

The external natural environmental factor has a greater impact on the navigation safety risk of ships whether it is manned or unmanned ships. According to the statistical analysis of data, a considerable number of maritime traffic accidents occur in the harsh natural environment or complicated navigation conditions [47]. Due to the complex and changeable maritime environment, there are many uncertainties, such as the accuracy of traffic environment estimation and the accuracy of hydrometeorological prediction, etc. Under certain circumstances, it is difficult for human judgment, and the misjudgement may lead to disasters and accidents. In addition, some severe environmental weather is also irresistible. After comprehensive analysis and study of various internal and external environmental factors, we can divide the environmental factors involved in the risk assessment and analysis of fully autonomous ships into three aspects: meteorological conditions, hydrological conditions and navigable conditions.

According to the demand analysis of fully autonomous ships for external navigation safety information, this paper divides the meteorological conditions into visibility, wind, rain, lightning and illumination. The hydrological conditions are divided into flow rate and surge; The navigable conditions are specifically divided into traffic flow, obstructing objects and floating objects on the sea.

5.1.3 Shore-based supervision and support

The traditional manned ship involves the cooperative management of the ship pilot team, the cooperative management of the pilot team and the Marine engineering department, and the management of the ship company and the maritime department. For fully autonomous ships, shore-based supervision and support mainly include shore-based information service capability, safety early warning capability and emergency rescue capability. Among them, the shore-based information service capability includes maritime safety information service, meteorological information service and real-time chart correction information service.

5.2 Analysis of navigation risk factors of remote-controlled ships

Remote-controlled ships are divided into remote-controlled ships with seafarers and without seafarers. This paper only studies the navigation risk factors of remote-controlled ships without seafarers. Different from fully autonomous ships, remote-controlled ships have remote-controlled centres, but without autonomous navigation systems. The navigation risk factors of remote-controlled ships mainly include navigation environment perception, remote-controlled centre, environmental factors and emergency management. Navigation environment perception and environmental factors are the same as those in ully autonomous ships, while the remote-controlled centres and emergency management are specifically analysed in this section.

5.2.1 The remote-controlled centre

The remote-controlled centre mainly includes human factors, ship-shore communication, ship-shore navigation scene reproduction ability and network security.

The human factors include: a sense of responsibility which is a main human factor, refers to understanding the responsibilities of all parties involved in an operation; the control skills, refer to understanding the working principle, control rules, safe control principles and operation restrictions of intelligent ships, and being able to effectively and accurately control the ship remotely, conduct ship scheduling and correction, and carry out task planning; maritime situation awareness, refers to the timely identification of accidents; emergency treatment, refers to controlling the ship with appropriate emergency treatment measures such as communication interruption; communication, refers to reliable and adequate communications between the intelligent ship operator and other relevant parties (other ships, VTS, maritime manned structures, etc.).

The ship-shore communication mainly includes the transmission capability of scenes between shore and ship, the reliability of control instruction transmission between shore and ship, the real-time performance of control instruction transmission between shore and ship, and the reliability of instruction execution on board.

Due to the unstable ship network, the ship-shore navigation scene reproduction ability mainly includes risks of abnormal data input of the sensing system, abnormal manual/autonomous control switching, and the failure of decision output to be efficiently executed by the control system.

Network security mainly includes defence against hacker attacks, defence against hacking into shipborne systems, control systems and equipment, interference with satellite navigation communications and data transmission; Preventing viruses, preventing damage to shipboard systems, equipment and communication networks; Encrypt data to prevent leakage of key data.

5.2.2 Emergency management

Emergency management mainly includes infrastructure support, emergencies such as bad sea conditions, pirate attacks, ships encountered fire or water, etc. Like traditional ships, intelligent ships still have the risk of not being able to sail normally when encountering bad sea conditions. They are more likely to be hijacked when encountering pirate attacks. And they are more likely to miss rescue opportunities when encountering fire, water, infrastructure damage and other emergencies because no personnel are on the scene.

6. Construction of navigation risk factor index system for intelligent ships based on classification standards

Intelligent ship navigation risk research is a large-scale, coupling, more complex systems engineering, and the relationship between its risk factors is complicated. Different scenarios of risk source are generated jointly by the internal environment and external environment. As a result, it is unable to achieve effective risk control objectives by a general study of intelligent ship navigation risk, and it is necessary to analyse and study the intelligent ships under different classification standards. In the above sections, the navigation risk factors of intelligent ships under different classification standards proposed by IMO are analysed. In order to comprehensively and accurately identify risk sources, based on the idea of repeated iteration, Delphi Method [59] is adopted in this section to further screen the factors and indicators related to the navigation risks of intelligent ships, where the specific iterative analysis pocess of risk factors is shown in Figure 3.

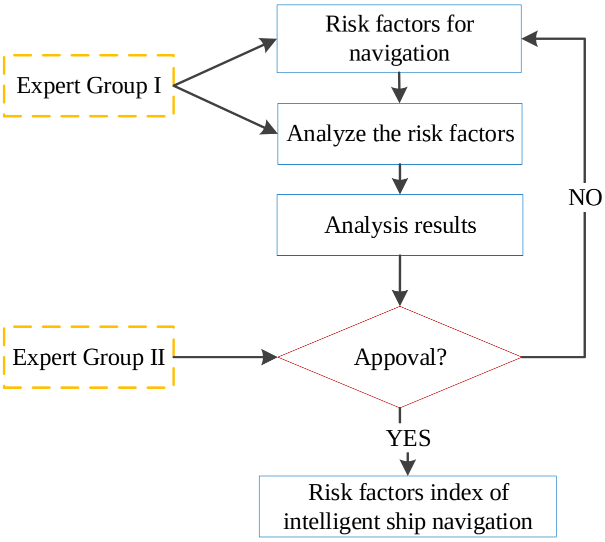

Fig. 3 Iterative analysis process of risk factors

In the specific research process, two expert groups were set up respectively to carry out specific research work through discussion. The background information of specific experts is shown in Table 15. Expert Group I includes investigators of maritime agencies, staff engaged in ship management, staff engaged in safety management of classification societies, water research researchers and ocean shipping captains, etc. The selected experts have more than ten years of work and management experience, and have a deep understanding of navigation risk management of traditional ships and modern intelligent ships. Expert Group II includes professors and associate professors of well-known maritime universities, senior engineers of unmanned ship Research Institute, researchers of Ship Management Research Institute and senior engineers of Ship Design Research Institute, etc. Firstly, the experts in Group I are organized to analyse the collected risk factors of intelligent ship navigation, complete the first screening and obtain the preliminary analysis results, and then the experts in Group II are organized to review the preliminary analysis results obtained above to check their comprehensiveness, operability and scientificity. If the results are approved, the corresponding factor indicators and the final analysis results can be obtained according to the screening results, otherwise, improvement suggestions are given and the above procedures are repeated.

Table 15 Background information of the experts

Experts	Age	Occupation	Education level	Certificate level	Description
Expert Group I					
E1	50	Marine investigator	M.S.	Captain	He worked as an ocean carrier captain for six years before becoming a maritime investigator with the Maritime Agency.
E2	43	Shipping manager	M.S.	First mate	He is currently leading a project on the impact of conventional and intelligent ship staffing on navigation safety.
E3	46	Sailor	B.S.	Captain	He is an experienced captain of a highly automated ocean transport ship.
E4	44	Safety manager of classification society	M.S.	First mate	He is an ocean-going practical experience engaged in safety management and technical specification research personnel.
E5	45	Researcher	Ph.D	Second mate	He is now in charge of the national key research and development Program project on risk management of intelligent ship navigation.
Expert Group II					
E6	53	Professor	Ph.D	Captain	He is a professor at a maritime university with his research focuses on the safety of intelligent ships.
E7	45	Senior engineer	Ph.D	Chief engineer	He is employed by a high-tech research institute dedicated to the intelligent production of ships.
E8	42	Researcher	Ph.D	Captain	He has focused on intelligent ship safety issues for more than 5 years.
E9	35	Associate professor	Ph.D	First mate	He has been following the research on risk assessment and control of intelligent ship navigation since his PhD graduation.
E10	40	Senior engineer	Ph.D	non	He focuses on safety issues that need to be considered duringship design.

Through many iterations of analysis and review, an index system of navigation risk factors of intelligent ships based on classification standards is established in this paper, as shown in Figure 4 and Figure 5.

7. Conclusions

The development of intelligent ships is the general trend, especially in the future when there is no crew in the ship. It is of particularly importance how to predict some sailing risks in advance and avoid them. To accomplish that, the concept, development path and risk factors of intelligent ships should be analysed in detail, and a special risk factor index system should be constructed, which can lay the foundation for the next step of risk assessment of intelligent ships. Therefore, this paper makes a relatively detailed and analysis of the concept and development of intelligent ship route, summarizes in category the intelligent ship classification standards proposed by different institutions, and then compares classification standards proposed by the main classification societies. The IMO classification standard is selected in this paper to study the navigation risks of intelligent ship under different levels. Finally, an index system of navigation risk factors of intelligent ships based on classification standards is constructed. Due to the lack of existing data on real ships, this paper only combed and analysed the risks of intelligent ships through the method of expert questionnaire, and many problems still need to be further studied.

In a word, the actual operation of fully intelligent merchant ships will be realized in the near future, but how to improve the navigation safety of intelligent ships still has a long way to go. We should plan ahead before a large number of intelligent ships have really entered the commercial market. Maritime authorities should actively promote the formulation of policies, legislation and rules on intelligent ships, layout shore-based remote control centers in advance, and improve the corresponding standard system. Shipping companies should expand the training of crew members, especially in remote control skills. Maritime colleges and research institutions should strengthen the core technology research in intelligent ship risk identification and control, and strive to form a complete set of risk identification, risk assessment, risk management and control system of intelligent ships.

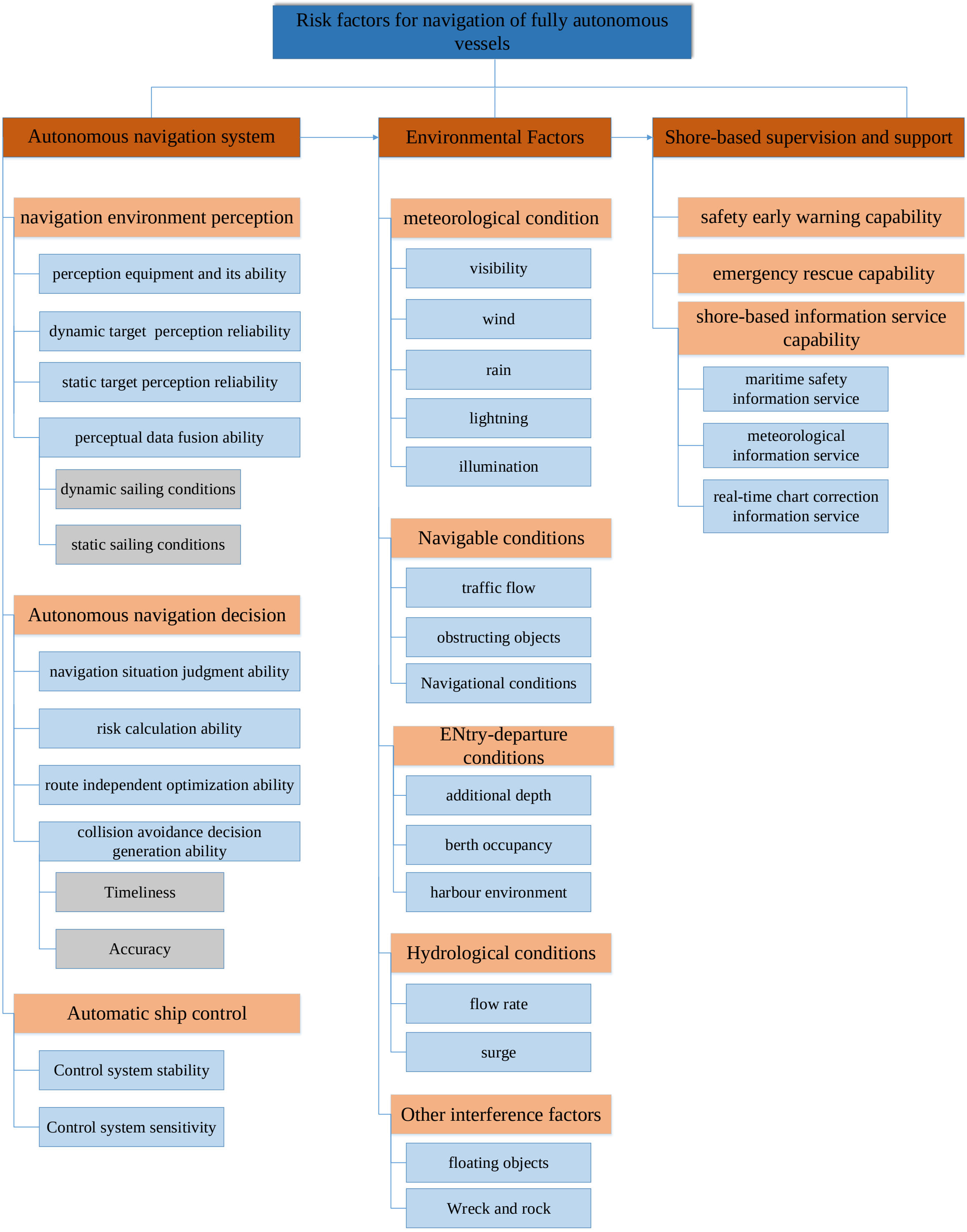

Fig. 4 Navigation risk factor index system of fully autonomous ships

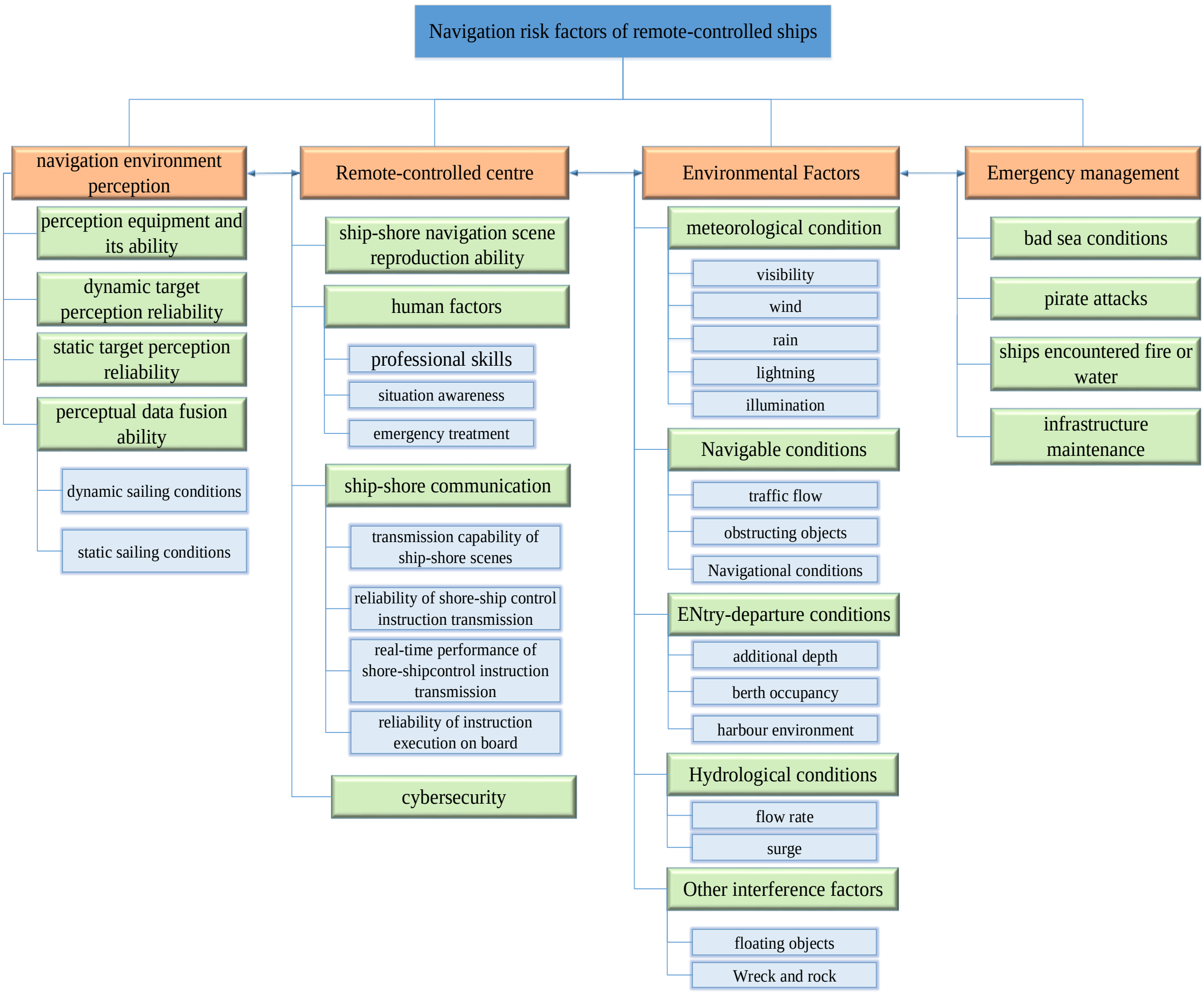

Fig. 5 Navigation risk factor index system of remote-controlled ships

ACKNOWLEDGEMENT

This paper is supported by the Key Project of the National Natural Science Foundation of China (No. 52231014).

REFERENCES

[1] Wróbel, K., Montewka, J., Kujala, P., 2017. Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. *Reliability Engineering & System Safety*, 165, 155-169. https://doi.org/10.1016/j.ress.2017.03.029

[2] http://www.eworldship.com/html/2019/ship_inside_and_outside_0906/152520.html. Accessed 6th September 2019.

[3] Xu, M., 2017. The land-marking significance of "Great Intelligence". *China Ship Survey*, (12), 28-31, 94-95.

[4] Zou, Z., 2020. Navigation risk assessment algorithm for unmanned ships under complex navigation conditions, Dalian Maritime University.

[5] Luo J., Zhang B., Geng X., et al, 2021. Research on safety risk and its evolution of ship autonomous navigation. *Navigation of China*, 44(4), 130-135.

[6] Zhang, W., Zhang, Q., Yang, J., Tu, M., Cong, Z, Yang, Y., 2019. Research on index system for inland unmanned ships navigation safety status. *China Safety Science Journal*, 29(05), 105-110.

[7] Zhang, W., Zhang, Q., Yang, J., Cong, Z., Luo, J., Chen, H., 2019. Safety Risk Analysis of Unmanned Ships in Inland Rivers Based on a Fuzzy Bayesian Network. *Journal of Advanced Transportation*, 4057195. https://doi.org/10.1155/2019/4057195

[8] Chang, C. H., Kontovas, C., Yu, Q., Yang, Z., 2021. Risk assessment of the operations of maritime autonomous surface ship. *Reliability Engineering & System Safety*, 207. https://doi.org/10.1016/j.ress.2020.107324

[9] Chen, J., Bian, W., Wan, Z., Yang, Z., Zheng, H., Wang, P., 2019. Identifying factors influencing total-loss marine accidents in the world: Analysis and evaluation based on ship types and sea regions. *Ocean Engineering*, 191, 106495. https://doi.org/10.1016/j.oceaneng.2019.106495

[10] Fan, C., Wróbel, K., Montewka, J., Gil, M, Wan, C., Zhang, D., 2020. A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships. *Ocean Engineering*, 202, 1-15. https://doi.org/10.1016/j.oceaneng.2020.107188

[11] Zhang, W. J., Zhang, Y. J., Qiao, W. L., 2022. Risk Scenario Evaluation for Intelligent Ships by Mapping Hierarchical Holographic Modeling into Risk Filtering, Ranking and Managemen. *Sustainability*, 14(4), 2103. https://doi.org/10.3390/su14042103

[12] Qiao, W. L., Liu, Y., Ma, X. X., Liu, Y., 2020. Human Factors Analysis for Maritime Accidents Based on a Dynamic Fuzzy Bayesian Networ. *Risk analysis*, 40(5), 957-980. https://doi.org/10.1111/risa.13444

[13] Azevedo L., Duarte H., Galvao D., Michima, P., Veleda, D., Kreuger, A., 2021. Methodology for Maritime Risk Assessment in Ports due to Meteo-oceanographic Factors: The Case of the port of Suape, Brazil. *Risk analysis*, 41(10), 1823-1839. https://doi.org/10.1111/risa.13677

[14] Zhang J. F., Teixeira A. P., Soares C. G., Yan, X., Liu, K., 2016. Maritime Transportation Risk Assessment of Tianjin Port with Bayesian Belief Networks. *Risk analysis*, 36(6), 1171-1187. https://doi.org/10.1111/risa.12519

[15] Yan X., 2016. Status and development trends of smart ships. *Public Utilities*, 3(1), 23-26.

[16] Song Z., 2017. The connotation evolution of E-Navigation and its Chinese translation. *Journal of Dalian Maritime University (Social Science Edition)*, 16(03), 111-116.

[17] Burmeister H.C., Bruhn W., Rødseth Ørnulf J., Porathe, T., 2014. Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective. *International Journal of e-Navigation and Maritime Economy*, 1, 1-13. https://doi.org/10.1016/j.enavi.2014.12.002

[18] Longva T., Holmvang P., Guttormsen V., et al., 2014. A broader view: The Future of Shipping. *Norway: Det Norske Veritas.*

[19] Chinese Classification society, 2015. Rules for Intelligent Ships. *Chinese Classification society*, Beijing.

[20] Bertram V., 2016. Autonomous ship technology - Smart for sure, unmanned maybe. *Proceedings of the International Conference on Smart Ship Technology*, 26-27 January, London, United Kingdom.

[21] John J., 2016. Autonomous Vessels: ABS' Classification Perspective. *American Bureau of shipping*, London.

[22] Rødseth Ørnulf J., Nordahl H., 2017. Definition of autonomy levels for merchant ships. *Norwegian Forum for Autonomous Ships*, Trondheim.

[23] Danish Maritime Authority, 2017. Analysis of regulatory barriers to the use of autonomous ships. *Danish Maritime Authority*, Korsr.

[24] IMO, IMO takes first steps to address autonomous ships [EB/OL], (2018-05-25), [2021-03-04], https://www.imo.org/en/MediaCentre/PressBriefings/Pages/08-MSC-99-MASS-scoping.aspx.

[25] Bureau Veritas, 2019. Guidelines for Autonomous Shipping. *Bureau Veritas Marine & Offshore*, Paris.

[26] Nielsen Jens D., Izadi-Zamanabadi R., Schioler H., 2002. Fault tolerance and reliability in integrated ship control - The ATOMOS concept. *Proceedings of the 2002 IEEE International Conference on Control Applications*, 18-20 September, Glasgow, United Kingdom.

[27] Bošnjak, R., Kezić, D., Vidan, P., 2017. Methodology of synthesis of the supervisors by using petir net. *Brodogradnja*, 66(3), 57-66. https://doi.org/10.21278/brod68304

[28] Luo B., Xie Y., 2006. Present situation and trend of Integrated Information Service System (RIS) for Inland Waterway Navigation in Europe. *Water Transport Digest*, 6, 43-47.

[29] Wu, G. X., Li, Y. C., Jiang, C. M., 2022. Multi-Vessels Collision Avoidance Strategy for Autonomous Surface Vehicles based on Genetic Algorithm in Congested Port Environment. *Brodogradnja*, 73(3), 69-91. https://doi.org/10.21278/brod73305

[30] Justin, N., 2015. A vision of the intelligent ship. *Rolls-Royce plc*, Hamburg.

[31] Chen, L., Yang, L., 2019. The Status of Intelligent Ship Development in Main Shipbuilding Countries in the World. *Ship Standardization Engineer*, 52(04), 10-14.

[32] Esa J., 2016. Remote and Autonomous Ships-The next steps. *Rolls-Royce*, London.

[33] Asle, S. The first ever zero emission, autonomous ship, (2018-03-14). https://www.yara.com/knowledge-grows/game-changer-for-the-environment/. Accessed 2021-05-23.

[34] Rolls-Royce, Rolls-Royce demonstrates world's first remotely operated commercial vessel, (2017-06-20). https://www.rolls-royce.com/media/press-releases/2017/20-06-2017-rr-demonstrates-worlds-first-remotely-operated-commercial-vessel.aspx. Accessed 2021-05-23.

[35] Wärtsilä Conducts Autonomous Ferry Voyage and Docking, (2018-11-28), https://www.maritime-executive.com/article/waertsilae-conducts-autonomous-ferry-voyage-and-docking. Accessed 2021-05-23.

[36] Lloyd's Register, 2016. Cyber-enabled ships: Deploying information and communications technology in shipping-Lloyd's Register's approach to assurance. *Lloyd's Register*, Southampton, UK.

[37] Lloyd's Register, 2017. Cyber-enabled ships: ShipRight procedure assignment for cyber descriptive notes for autonomous & remote access ships. *Lloyd's Register,* Southampton, UK.

[38] American Bureau of Shipping, 2019. Smart Functions for Marine Vessels and Offshore Unites. *American Bureau of Shipping*, Texas.

[39] Wang, S., 2021. South Korea intelligent ship development path. *China Ship Survey*, 03, 14-17.

[40] Wang, S., 2021. Japanese Intelligent Ships Strategy. *China Ship Survey*, 03, 18-22.

[41] Yan, X., Wang, S., Ma, F., 2021. Review and prospect for intelligent cargo ships. *Chinese Journal of Ship Research*, 16(01), 1-6.

[42] Yin, F., Yang, Z., Wang, S., 2016. An overview of the development of intelligent ships. *12th Yangtze River Delta Shipbuilding Industry Development Forum and the third Zhejiang Shipbuilding Industry Collaborative Development Summit Forum*, Zhoushan, Zhejiang, 140-145.

[43] Liang, Y., Xie, J., Chen H., 2017. Research and Development Review on Smart Ships. *Journal of Ship Mechanics*, (1), 651-664.

[44] Liu, W., Shang, J., 2017. The study of the development of intelligent ships and China's development strategy. *Ship Science and Technology,* 39(21), 189-193.

[45] The Maritime Safety Committee, 2019. Interim Guidelines for mass trial. *The Maritime Safety Committee*, London.

[46] Wu Z., 2017. Ship automatic navigation and navigation intelligence. *China Maritime Safety*, 8, 16-19.

[47] Ivanovsky, N., Chernyi, S., Sokolov, S., Zhilenkov, A., & Zhinchenko, A., 2021. Algorithm design for ship's steering with specified limitations under various weather conditions. *Brodogradnja*, 72(4), 19-32. https://doi.org/10.21278/brod72402

[48] DNVGL-CG-0264, 2018. Autonomous and remotely operated ships. *DNV-GL*.

[49] LLOYDS Register, 2016. Cyber-enabled ships-ShipRight procedure-autonomous ships. *LR*, Southampton.

[50] Wróbel, K., Montewka, J., Kujala, P., 2018. System-theoretic approach to safety of remotely-controlled merchant vessel. *Ocean Engineering*, 152, 334-345. https://doi.org/10.1016/j.oceaneng.2018.01.020

[51] Wróbel, K., Montewka, J., Kujala P., 2018. Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels. *Reliability Engineering & System Safety*, 178, 209-224. https://doi.org/10.1016/j.ress.2018.05.019

[52] Rødseth Ørnulf J., Havard N., 2017. Definition for autonomous merchant ships. *Norwegian Forum for Autonomous Ships*, Trondheim.

[53] MASRWG, 2018. Maritime Autonomous Surface Ships UK Code of Practice. *Southampton: Society of Maritime Industries*.

[54] American Bureau of Shipping, 2019. Autonomous Ships/Vehicles: Classification Society Perspective. *American Bureau of Shipping*, Washington, DC.

[55] Chinese Classification society, 2020. Rules for Intelligent Ships. *Chinese Classification society*, Beijing.

[56] Zhou, X., Yang, X., Fei, S., 2022. A review of the standards for dividing the level of ship autonomy and autonomy. *World Shipping,* 45(09), 1-10.

[57] Pan, D., Sun, W., Zhao, J., 2021. Comparison of smart ship specifications of the world's major classification societies. *China Ship Survey*, 05, 68-72.

[58] LLOYDS Register, 2017. Design Code for Unmanned Marine Systems. *LR*, London.

[59] Lmer, F., Seifert, I., Kreibich, H., Thieken, A. H., 2010. A Delphi Method Expert Survey to Derive Standards for Flood Damage Data Collection. *Risk analysis*, 30(1), 107-124. https://doi.org/10.1111/j.1539-6924.2009.01325.x

Submitted: 03.07.2023.
Accepted: 11.09.2023.

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