Risk Assessment of Autonomous Ship Systems

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1. INTRODUCTION

Various technologies for autonomous ships are being developed. As moves aimed at autonomous ships for commercial use, the EU-funded MUNIN project 1), the DNV GL ReVolt project 2) and Finland-funded the AAWA project led by Rolls-Royce are known as pioneers since the early 2010s 3). Subsequently, businesses throughout the world carried out individual development and trials responding to their different technological capabilities, future outlooks, and needs. In Japan as well, the MEGURI 2040 Project was launched by the Nippon Foundation during FY 2020 with the aim of realizing future unmanned ships, and as part of that project, demonstration experiments are scheduled using ships equipped with various autonomous ship technologies which are the respective strengths of the five consortium members 4).

The automation tasks which these projects intend to demonstrate differ greatly, from a wide-ranging work aiming at total unmanned operation of the ship, to a limited scope of work such as collision avoidance under specific conditions. Their approaches also encompass a diverse range of efforts, from improvement of reliability and user-friendliness by refining existing technologies to experiments with creative new concepts. Naturally, the methods of using the resulting autonomous ship systems and the methods of responding when problems occur are also different.

Accompanying a higher level of activity in technology development related to autonomous ships, efforts that make it possible to apply risk assessment technologies are demanded in the demonstration stage before these autonomous ship systems are used, for example, to ensure the safety of actual-ship experiments or for certification of the system and ship in future commercialization of autonomous ship systems, and this also includes the authors, who are engaged in research on risk assessment methods. But what types of ships, in terms of the ship’s concept, functions, and configuration, should be possible objects of risk assessment as autonomous ships?

The legal system still does not provide concrete regulations applicable to autonomous ships as such, that is, the definition of the autonomous ship or the components necessary for regarding a ship as “autonomous.” Similarly, no specific provisions indicating that automation systems are allowed to replace human functions have been established in the field of ships. On the other hand, as the future image of autonomous ships, many people firmly believe that it is acceptable to allow technology to do the work currently performed by humans, provided that ship operation by the introduced technology is safer, or at least as safe as operation by humans. In the automotive sector, automated vehicles equipped with devices that perform driving tasks in place of the human driver have been approved 5), and based on this, the maritime sector is also discussing whether it is possible to delegate ship operation tasks to an automation system if the safety of the system can be proved 6).

In order to consider whether a new technology secures the same safety as the existing technology, it is necessary to estimate the risk related to that new technology. Even though there are many unknowns, the authors believe that it is possible to conduct risk assessments by expanding conventional risk assessment techniques to handle the unique characteristics of autonomous ships. This paper introduces the current status of risk assessment for autonomous ships, while also incorporating research by the National Marine Research Institute (NMRI) against this background.

2. PROCESS AND SAFETY TARGETS OF GENERAL RISK ASSESSMENT

2.1 Process of Risk Assessment

Here, we will review the general process of risk assessment. Broadly classified, risk assessment comprises a process of identifying hazards and a process of assessing the importance of the identified hazards. The HSE (Health and Safety Executive) in the United Kingdom calls the process of identifying hazards “risk analysis,” and the process which combines this with the

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process of assessing hazards “risk assessment” [7]. In addition to these, the total process including the process of decision-making, that is, the final selection of risk reduction measures considering costs and benefits is called “risk management.” The relationship of these processes is expressed as shown in Fig. 1.

As part of this general concept, the HSE positions the process of hazard identification (HAZID), that is, risk analysis, as a key element to be used in all processes. The tools they list for conducting risk analyses include Judgement, FMEA (Failure mode and effects analysis), SWIFT (Structured What-If checklist Technique), and HAZOP (Hazard and Operability Study). As techniques for risk assessment continued from those mentioned above, Qualitative assessment (risk matrix), Semi-Qualitative use of structured tools (fault trees, event trees), Quantitative assessment (coarse and detailed levels), and consultation with stakeholders have also been enumerated.

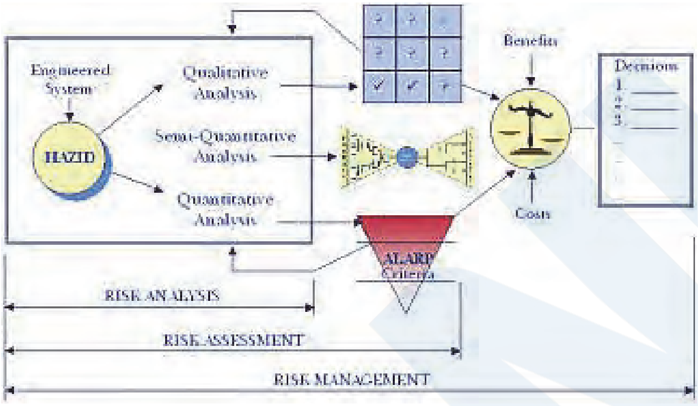

Figure 1　Risk assessment approaches by HSE [7]

Although the acceptability (tolerability) of the results must be judged when a risk assessment is conducted, the interpretation of the results is a concern in many cases, for example, in case a semi-quantitative assessment technique must unavoidably be selected because sufficient data, such as the frequency of occurrence, is not available. Regarding this point, the HSE [7] states that “in the semi-quantitative approach it is not necessary to evaluate likelihoods, the structure of the tree is sufficient to demonstrate how major hazards arise,” and the adequacy of the safeguards (both number and quality) can be judged by teams in judging acceptability. This supports the validity of expert judgments when quantification is difficult in decision-making. While it increases the burden on the judgment of the analysis team, it can provide an important method for automated navigation systems, where situations in which quantification is difficult are assumed, as will be described in the following.

2.2　Concept of Safety Goals

Even though unified criteria for safety goals do not exist, it is desirable to use agreed risk evaluation criteria [8]. The concept shown in Fig. 2, which is presented by the HSE [9], is used relatively often as a base for interpretation of safety goals. According to this concept, “tolerability of risk” is understood in terms of a framework consisting of a “broadly acceptable region” on the low-risk side and an “unacceptable region” on the high-risk side. A “tolerable region” exists between those two regions, and the boundaries between the regions are criteria. To determine these criteria, the HSE estimates the public’s risk tolerance considering the number of deaths due to accidents and disease occurring at present and the behavioral choices that people make based on those results, while these criteria are held by the public. As a result, the HSE states that “a risk of death of one in a million per annum,” regardless of whether one is a worker or member of the general public, should be used as a guideline for the upper limit of the “broadly acceptable” region. The lower limit of the “unacceptable” region for workers is a risk of death of 1 in 1 000 per annum. While also proposing a value of 1 in 10 000 per annum as the risk limit for the general public, the HSE notes that the actual risk level is far lower than the figures mentioned above. Because tolerability depends on the aggregate of the target population and is thought to change with the times, it is desirable to set these criteria accordingly.

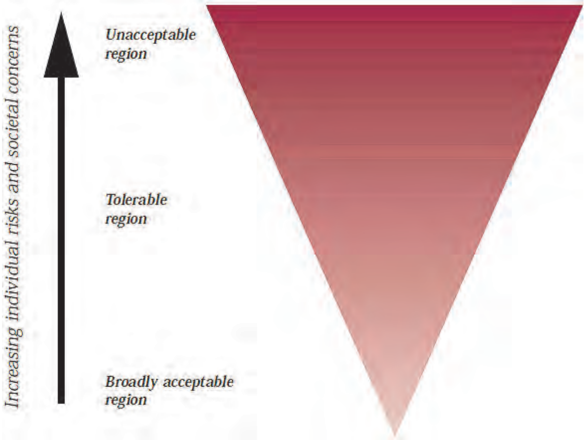

Figure 2　HSE framework for the tolerability of risk 9)

3.　RISK ASSESSMENT OF AUTONOMOUS SHIPS

3.1　Viewpoint of Ship Design and Design of Marine Equipment

Autonomous ships have two aspects, namely, equipment (i.e., the ship itself and its machinery) and ship operation using that equipment. Some autonomous ship systems have been developed based on an operational concept that integrates these two aspects. Among the two aspects, conventionally, equipment design is deeply related to risk assessment. Tracing this back to its early stages, in 1997, risk assessment was introduced in rule-making by the Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule-Making Process 10), which was approved by the International Maritime Organization (IMO) in that year, and has continued up to the present as the Revised Guidelines for FSA for use in the IMO Rule-Making Process 8). The title of the Guidelines includes the language "for use in the IMO Rule-Making Process," but because risk assessment techniques used there are basics and the content is comparatively substantial, it is often used outside the context of "rule-making," as a guideline for general risk assessment techniques when assessing the safety of ships and their equipment.

Discussion of risk-based approval of design has also progressed since the start of the 2000s, and various guidelines with different scopes have been introduced, including the Guidelines on alternative design and arrangements for fire safety 11) in the SOLAS Convention Annex, Chapter II-2, and the Guidelines on alternative design and arrangements for SOLAS Chapters II-1 and III 12) for engines, electrical equipment, and lifesaving equipment in the Chapters in the SOLAS Convention Annex. Meanwhile, the EU's SAFEDOR research project, which began in 2005, introduced the concept of risk-based design for ships, and as a result, a risk-based ship design technique was proposed 13) 14). These concepts were ultimately be passed on to the IMO's Guidelines for the approval of alternatives and equivalents, which can be applied more widely to risk-based design 15) 16).

Where automated navigation is concerned, from the guidelines of ship classification societies in Japan and other countries, it can be understood that the risk-based approach, that is, verifying that safety equivalent to the conventional prescriptive design, is also the predominant approach for ship design and equipment 17-20). Depending on the ship classification society, some societies treat risk assessment as a main part of the approval process, for example, by setting the entire process including approval in accordance with the IMO Guidelines 15), and also stating that a ship is acceptable if its safety and reliability are equivalent or superior to those under the society's rules, indicating a kind of risk-based approval 18).

Thus, in the design aspect, a certain theoretical foundation for the application of regulations has been constructed, and this can provide the basis for studying methods of approval suited to the ship design which a company wishes to target and its equipment needs in autonomous ships.

3.2　Viewpoint of Navigation and Operation Methods

Compare to the above equipment design viewpoint, discussion of the aspect of navigation seems to be somewhat difficult, since there is little historical background or theoretical basis for the risk-based approach. Even so, as in the case of design, it is expected to be possible to assign some of the roles of human operators to machines by verifying that the equivalent safety is secured in human operation and in operation by an automated navigation system 6).

In the case of autonomous ships, there are parts in which operation and equipment cannot be considered separately due to the nature of the operational concept whereby tasks performed by human operators are replaced by the automated navigation system.

For this reason, the guidelines of ship classification societies point out the importance of verifying the concept of the operation and equipment use methods 18), but do not go so far as to recommend concrete assessment methods.

On the other hand, considering the fact that actual-ship experiments with autonomous ships will be conducted in ocean waters, the IMO approved Interim Guidelines for MASS Trials (MASS: maritime autonomous surface ships) 21). According to these Guidelines, action should be taken for risks related to safety, security, and environmental protection when conducting actual-ship experiments, and identification of the risks accompanying experiments and implementation of the related countermeasures are required. It is also necessary to prepare an emergency plan and countermeasures in advance for foreseeable incidents or failure. Therefore, if an experimental actual-ship operation is carried out based on this Guideline, it is acceptable if the main hazards are identified by a risk assessment of operation using the automated navigation system which the operator wishes to demonstrate, and preparations for foreseeable hazardous events are made in advance.

3.3 Use of Risk Assessment for New Designs

The concrete procedures for risk assessments required to obtain final approval still have not been clarified for the two above-mentioned aspects of equipment and operation. Regarding this point, a further reading of the IMO Guidelines 15) for the approval of alternatives and equivalents, which was mentioned in Section 3.1, shows that approval is possible by demonstrating that a new technology provides the equivalent level of safety as a design conforming to the conventional prescriptive rules, even for challenging technologies which were not assumed in the prescriptive rules, and a process for achieving that is described.

According to that process, to demonstrate the same level of safety, it is necessary to establish the functional requirements and performance criteria of the basic ship functions and show that the design in question satisfies those requirements and criteria, or to conduct a risk analysis and compare the results with the total risk acceptance criteria of the ship. Under conditions where it is difficult to establish the functional requirements and performance requirements, as in the present stage, it is thought that demonstration of safety will depend on the latter method. However, with that method, risk assessment results must be obtained for the totality of the target autonomous ship, and this is not simple. Furthermore, because there are no generally agreed safety goals for the risk acceptance criteria of the whole ship which should be used in the comparison, this approach is premised on deciding the criteria by a consensus among the related parties.

3.4 Securing Safety in Automated Vehicles

Here, we may ask what kinds of safety goals are used to ensure the safety of automated driving systems in the automotive sector, where certification has already begun. Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) defines the degree of driving automation in the levels 0 to 5, following the definitions by the SAE (Society of Automotive Engineers) in the United States. In Level 3 automated driving, which was authorized recently, the system executes all dynamic driving tasks within its operational design domain (ODD), and when a continued operation is difficult, a fallback-ready driver must respond appropriately to a request for intervention from the system. Level 3 automated driving exempts the driver from some of the driving duties normally performed by a human driver during the period when certain conditions are satisfied 5) 22) 23).

According to the MLIT Guidelines regarding Safety Technology for Automated Vehicles 23), the safety goal for automated vehicles is specified as a level that ensures that "automated vehicle systems shall not cause any traffic accidents resulting in injury or death which are reasonably foreseeable and preventable." This does not mean preventing problems with the vehicle, such as poor maintenance, or problems caused by deliberate human behavior, for example, someone intentionally running out in front of the car. Rather, it requires that the accidents that are caused by inadequate verification of the functions of automated driving systems, and that also cause damage such as injury or death do not occur. Since many traffic accidents are caused by human error, the introduction of this kind of safety technology is expected to lead to improved safety, but the extent to which safety can be required in the technology is still under discussion.

A fundamental issue in the SAKURA Project 24), which is developing safety assurance methodologies for automated driving systems, is "How safe is safe enough?" That is, "In comparison with the human operation, how much safety should be required?" To answer this question, full-scale data acquisition and analysis are being carried out based on 32 scenarios in which expressways were arranged systematically 25) 26). Acceptance criteria, as shown in Fig. 3, are to be determined by defining foreseeable conditions based on scenarios structured according to driving functions and by real-world traffic data, and then identifying the preventable conditions among them 24). The specified conditions are then used as test scenarios for simulation and physical tests.

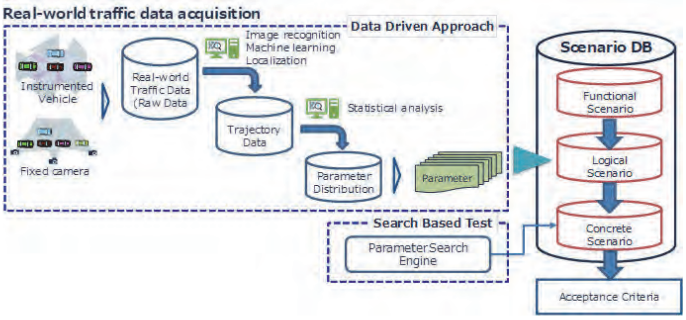

Figure 3 Test scenario generation process for automated driving safety assurance in the SAKURA Project 24)

4. DEVELOPMENT OF RISK ASSESSMENT METHOD FOR AUTONOMOUS SHIPS

4.1 Features as of Autonomous Ships as Target of Risk Analysis

As explained in Chapter 2, one of the critical processes among those in general risk assessment is risk analysis, that is, the process of identifying hazards. To carry out risk analysis, first, it is necessary to clarify the target of the analysis, namely, to arrange the information related to the purpose, components, and use methods of the technology. Since clarification of the analysis target facilitates the identification of hazards (dangers hidden in the target), if comprehensiveness is required, it is essential to define these items appropriately to enable concrete assumption and identification of hazards in different parts of the target and in different use situations.

Adequately arranged definitions are also important for the systems that comprise an autonomous ship. However, many ship systems that require risk assessment have traditionally been hardware-centered systems such as engine systems or power supply systems, but software plays more roles in autonomous ship systems. Moreover, even assuming the ultimate aim is to enable unmanned operation through full automation, until that is realized, some forms of sharing tasks and cooperation between systems and humans (navigation officer and engineer) will be important features of autonomous ships.

4.2 Risk Analysis of Autonomous Ship Systems

Since conventional hardware-oriented risk analysis techniques focus on physical components such as mechanical and electrical parts, it is difficult to apply those techniques directly to systems consisting largely of software because the software portion is treated as a black box when breaking down a system into components. In order to handle software, it is necessary to define the tasks that the software performs, that is, the object of calculation, and the types of input for and output from the calculation. In addition, considering the fact that an autonomous ship is a system that includes humans, it is important to understand the tasks performed by humans and software by first organizing them into the processes of information acquisition, information arrangement, interpretation, decision-making, and machinery control, then relating these processes to the components responsible for them, and finally defining the total system as an aggregate to which these components belong and interact with each other. It is also important to define the situations in which this kind of total system operates, and to verify its behavior in various assumed situations.

This concept is one of the system-theoretic approaches. The STAMP/STPA (Systems-Theoretic Accident Model and Processes/System-Theoretic Process Analysis) 27) 28) is known as a representative hazard analysis technique of this type, which focuses mainly on the relationship among components. This technique was developed mainly targeting the problem of software safety. It is used widely in the engineering field including aircraft sector, and in the medical field 29). Application to risk analysis of autonomous ships has already been attempted as well 30).

Bearing in mind autonomous ships as analysis target, the authors have carried out research with the aim of establishing a technology for hazard analysis by clarifying the definition of a system which includes both humans and software and applying the SWIFT technique to the defined system 31-36). As part of that work, we pointed out the importance of a definition of the target system that includes the functions of the components and information necessary for execution of those functions, which are not handled explicitly in the system model according to the STAMP/STPA approach, and proposed a technique for identifying hazards by defining the target system and identifying hazards by application of the class diagram, a type of UML (Unified Modeling Language) diagrams, which is used in modeling of software 31-33). Figure 4 shows a structure which modeled the hypothetical autonomous ship at the most conceptual level 32), and risk analysis is performed by modeling the tasks performed and information used by each of the components described in the diagram of the conceptual level as a system definition diagram.

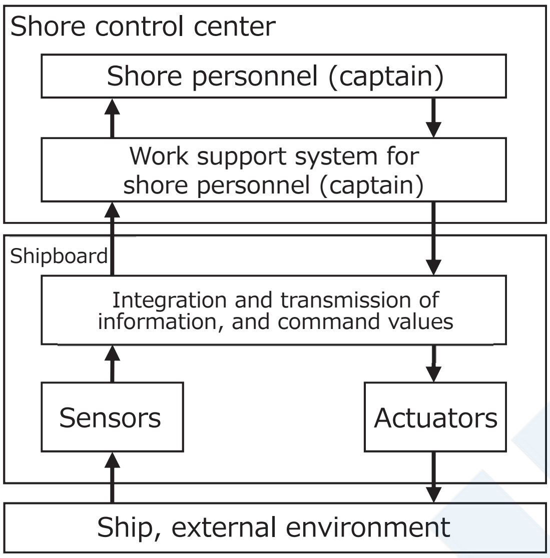

Figure 4　Example of conceptual structure of hypothetical autonomous ship [32)]

As a characteristic of autonomous ships, there is a large change in operation in that an autonomous ship system replaces human tasks. For this reason, it can be thought that hazards exist in the manners by which components such as human operators and software perform tasks, and in the manner by which tasks are transferred between the human operators and software. To identify those hazards, in addition to the above-mentioned modeling technique, a task-based risk analysis method that focuses on tasks is also effective by defining the concrete tasks that comprise the operation and the entities which perform those tasks [34-36)].

In many cases, the technologies for autonomous ships are implemented on conventional technologies that have been developed for conventional ships. For example, attempts to realize automatic navigation have been made by expanding and improving the hardware and software of navigation support systems. Even if a ship is newly designed or newly constructed, the functions that the owner wishes to automate for a specific new method of use are realized by adding new elements. In doing so, an accurate understanding of the new elements and the new method of use is essential in the risk analysis. Therefore, in addition to the development of the above-mentioned hazard analysis technique, NMRI is also conducting joint research with ClassNK on a method for performing this type of analysis by STAMP/STPA.

5.　APPROACH TO RISK ASSESSMENT OF AUTONOMOUS SHIPS

In the development stage, there are areas where quantitative consideration of the risk of the target is impossible because the necessary data do not exist. On the other hand, there are also parts where data on conventional ships and human work accumulated over long years can be referenced. For example, data are available for the frequency of accidents at sea involving conventional ships and data in the field of human reliability engineering concerning the success or failure of work on ships. The following introduces several examples that can be used as a reference in risk assessments.

5.1　Assessment of Risks Related to Marine Navigation

Risks due to marine navigation, like other types of risk, are estimated by the magnitude of the loss, such as fatalities, property damage, and environmental damage, associated with marine navigation, and their frequency of occurrence. Although the following explanation mainly concerns the loss of human life, the thinking on other types of damage is similar.

According to the Japan Coast Guard [37)], in Japan, a large number of deaths and injuries constantly occur as a result of marine accidents involving small craft, namely, fishing boats and pleasure boats. Looking at the number of vessels involved in accidents that result in death or injury, these two types account for more than 80 % of the total. In cargo ships and other commercial vessels, the frequency of occurrence is low, but a single accident may result in many fatalities. Since collisions between ships and single-ship collisions account for more than half of the types of accidents involving death and injury, collisions are considered to be one of the main factors in risk related to marine navigation.

Collision risk is a probabilistic representation of the extent of loss due to collisions. For example, if the information on the frequency of collisions and the resulting magnitude of damage in a certain group of ships is available, it is possible to calculate the collision risk of that group of ships. In Japan, most collision accident reports are possible to obtain with information on the damage accompanying the accident, if the accident resulted in the loss of life, from the Marine Accident and Incident Reports of the Japan Transport Safety Board. In other countries, information summarizing the number of accidents, number of deaths, etc. over a 19-year period 38) can be found that uses the IHS databases [*1], which collect information on accidents and ships worldwide. A simple calculation using this information shows that the average number of fatalities in one collision accident is 0.16.

Next, to calculate the collision frequency, that is, the number of collisions that occur in a certain timeframe, it is necessary to know the total navigation time of the target ship group and the number of accidents that occurred in that timeframe. In Japan, the number of major collision accidents can be found in the above-mentioned reports, but it is difficult to accurately calculate the total navigation time with the current technology. Approximate methods include estimation from the annual data on the number of registered ships from the above-mentioned IHS databases 38) 39), estimation from ship track data using AIS (Automatic Identification System), estimation from port call data, and estimation from the results of behavior observation by radar or satellite photography. Although these methods have technical limitations and high accuracy cannot be expected, they are sufficient if understood as rough estimates.

Since it is difficult to obtain accurate information by this type of observation, analytical methods for obtaining the frequency of collisions have also been studied. The analytical method is to estimate the number of cases in which two vessels collide from information on the traffic flows on each route. Because it can be applied if traffic information is available, it has the advantage of being possible to estimate events for which data cannot be acquired at the present, such as the collision frequency in the future after traffic rules are introduced. Although the analytical method includes several approaches, the following will briefly introduce an estimation method using the product of the geometrical collision frequency and the collision causation probability 40).

The geometrical collision frequency is the frequency with which two ships in a group of navigating ships enter into an encounter relationship that may result in a collision. This “encounter situation” means a combination of ship positions and courses that will necessarily lead to a collision if collision avoidance action is not successful. In calculating the number of occurrences of encounter situations, first, “routes” are set by consolidating similar courses among the observed course tracks, and next, a probability calculation or simulation is performed using information such as the number of ships using each route, the timing of navigation, the positioning of ships on the route. The number of occurrences of the target encounter situations can be estimated from this, and it is also possible to obtain the geometrical collision frequency by converting the results to unit time.

Figure 5 shows an example in which the distribution of geometrical collision frequency in Tokyo Bay was estimated by the type of encounter situation using AIS track data. Here, the target waters were divided into small sea areas, and the distribution was obtained by calculating the geometrical collision frequency from the traffic data for each small area. From this, it can be understood that the frequency of occurrence of encounter situations resulting in a collision differs greatly depending on the sea area being navigated and the assumed route.

[*1] Accident database and ship database of IHS Markit, Ltd.

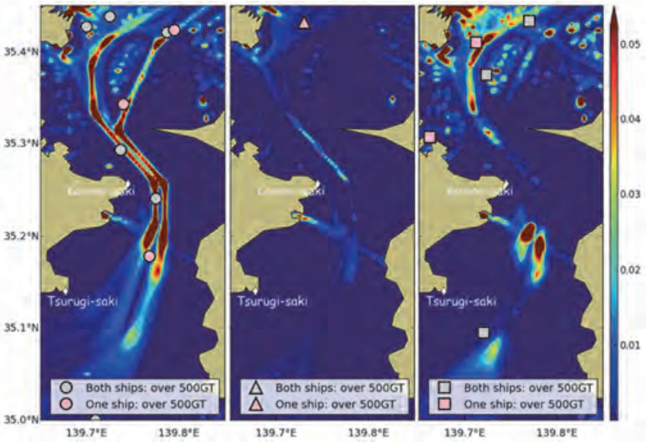

Figure 5　Estimation of geometrical collision frequency distributions by type of encounter situation (left: overtaking, middle: head-on, right: crossing) 42)

The collision causation probability is the probability that two ships in an encounter situation leading to a collision will not succeed in collision avoidance and eventually a collision will occur. As shown in Table 1, examples of reports in which the collision causation probability was obtained for different encounter situations and sea areas can be found in research literature 41) 42). These values are thought to be influenced by the type of encounter situation, the complexity of the waters, and other factors, and are also affected by changes in the ship operating environment, including navigation support systems, with the times. From this table, it can be understood that the probability of collision is roughly between 10^{-5} and 10^{-4} in waters where traffic control such as a Traffic Separation Scheme (TSS) has been introduced. This means collision avoidance is not successful 1 case in several 1 000 cases. In other waters, the probability is from 10^{-4} to 10^{-3}, that is, 1 case in several 100 cases.

Up to this point, we have introduced a method for estimating collision risk from the damage caused by collisions and the collision frequency, considering the sea area. As another method, information on collision risk by ship type/size or type of accident independent of the sea area can be obtained from the above-mentioned IHS databases. This is useful when it is necessary to know the number of fatalities per ship-year or the like. As an example, Table 2 summarizes the fatalities per ship-year by ship type 39) and can be used as a reference for the potential loss of life for each ship type.

Table 1　Estimates of collision causation probability for crossing ships.

Collision causation probability	Source	Remarks
1.2E-04	Macduff (1974)*	
1.11E-04	Pedersen (1995)*	Without Traffic Separation Scheme (TSS)
9.5E-05	Pedersen (1995)*	With TSS
1.3E-04	Fowler and Sørgård (2000), Fujii et al.(1998), Pedersen and Zhang (1999)*	
8.48E-05	Otto et al. (2002)*	In good visibility
6.83E-05	Otto et al. (2002)*	In good visibility with VTS zone
5.8E-04	Otto et al. (2002)*	In poor visibility
4.64E-04	Otto et al. (2002)*	In poor visibility within VTS zone
5.10E-04–6.00E-04	Rosqvist et al. (2002)*	In the Gulf of Finland with mandatory reporting system, VTS and AIS
2.52E-05	Kawashima et al. (2021) 42)	Tokyo Bay (Nakanose Traffic Route, Uraga Channel, and surrounding areas)
1.85E-05	Kawashima et al. (2021) 42)	Bisan Seto (East, North and South Traffic Routes and surrounding areas)

*Adapted from Kujara et al. 41)

Table 2 Fatalities per shipyear, Time Pefiod 1990–2012.
(Adapted from Papanikolaou et al.[39])

Ship type	Fatalities per shipyear
Passenger Ro-Ro Cargo	1.24E-01
Passenger	1.61E-02
General Cargo	8.22E-03
Cruise	7.55E-03
Bulk Carriers	4.29E-03
Reefer	4.16E-03
Ro-Ro Cargo	3.70E-03
LNG	2.26E-03
Fishing	2.21E-03
Car Carriers	2.01E-03
Large Crude oil	1.68E-03
LPG	1.34E-03
Cellular Containerships	1.16E-03
Total	1.09E-02

5.2 Success and Failure of Tasks Targeted by Automation Systems

As explained in Chapter 4, when considering the delegation of a certain part of the tasks conventionally performed by the crew in a ship to a new automation system, how well the system can perform the substituted task is an important index. Although the concept of “perform well” is broad, determining the success/failure rate in the task to be performed by the automation system can be considered a minimum requirement. Since the context (conditions and assumptions made) of human operation and automated operation will not be completely identical, strictly speaking, a comparison of the success/failure rate of the automation system and a human operation is not possible. Although care is necessary in this regard, knowing the strengths and weaknesses of the system is nevertheless important when studying the safety of the target system.

If this is the case, how can the human success/failure rate be obtained as a target for comparison? If the ship-handling tasks in ship navigation are decomposed from the viewpoint of cognitive engineering, many tasks consist of elementary tasks such as information acquisition, decision-making, and execution of actions, and these tasks are performed repetitively to realize a single task[43]. Data concerning the success/failure rate of tasks decomposed in this manner have been accumulated since an early date in the field of human reliability engineering. While it would be difficult to apply this data directly to the repetitive task of ship-handling, it is thought that referring to these research results can be of assistance in understanding.

Table 3 is an excerpt from the literature[44] showing the probability of occurrence of various kinds of error when the processes of the cognitive process are decomposed into observation, interpretation, planning, and action, as summarized from various information sources. According to this, several cognitive processes have a large error probability exceeding 10^{-2}, that is, 1 in 100 times. Here, the data indicating that the frequency of faulty diagnosis in the interpretation process is approximately 1 in 5 times is particularly interesting.

5.3 Risk Accompanying Failure of Automated Navigation System and Deviation from ODD

In risk assessments, the damage accompanying various hazards is assumed, including cases of erroneous operation by the automated navigation system and deviation from the design preconditions (Operational Design Domain: ODD) assumed for the automated navigation system. This means that it is necessary to study conditions that generally seem to be exceptional in the same manner as other hazards if there is a sufficiently high possibility that those exceptional cases may occur.

In exceptional circumstances, as in other cases, it is necessary to know the frequency of occurrence and the damage caused to grasp the risk. Damage depends on the process from the hazard to the consequence, but at present, there are considered to be many cases in which the planned response to unexpected events in autonomous ships is the same as that in conventional ships. In such cases, the data on damage for conventional ships is a sufficient reference.

Table 3 Example of nominal values for cognitive function failures
(Summarized from Hollnagel [44)])

Observation	Basic value
Wrong object observed	1.0E-03
Wrong identification	7.0E-02
Observation not made	7.0E-02
Interpretation	
Faulty diagnosis	2.0E-01
Decision error	1.0E-02
Delayed interpretation	1.0E-02
Planning	
Priority error	1.0E-02
Inadequate plan	1.0E-02
Execution	
Action of wrong type	3.0E-03
Action at wrong time	3.0E-03
Action on wrong object	5.0E-04
Action out of sequence	3.0E-03
Missed action	3.0E-02

On the other hand, in the frequency of occurrence, cases where the cause is in the automated navigation system and those which are not caused by the system must be considered separately. As when considering the damage, it is possible to gain a certain understanding of cases that are not caused by the system by referring to the data for conventional ships. In contrast, in cases caused by the system, the frequency of occurrence of cases varies depending on the composition and composition of the system used, and thus an estimation that considers these factors is necessary.

As an exceptional condition, the following assumes a fire on a ship in which a certain automated navigation system was introduced. If a fire occurs on that ship, the measures are the same as for a conventional ship. According to the report of an analysis of accident data for conventional ships [39)], as a very rough estimate, the damage accompanying fires on ships is considered to be about 0.33 fatalities per fire, and the frequency of fires is on the order of 1 fire in 1 000 ship-years. As for damage, because the response to the fire is the same as conventional ships, refers to the value for conventional ships. The value of the frequency of occurrence needs to be revised in consideration of the system configuration. In obtaining that revised value, the possibility that the damage is affected by the contribution of the hardware and software used by the autonomous ship, the contribution of human error related to the use of the automated navigation system, and the contribution of the relationship between these components is conceivable. If the frequency of occurrence is considered hypothetically to be 1.1 times that of a conventional ship, the risk of fatalities due to a fire per ship-year for this ship is estimated to be $(0.33 \times 1/1\,000 \times 1.1 =)\ 3.63 \times 10^{-4}$ (fatalities). In this example, the calculation shows an increased risk because functions that defend against fires and respond after a fire occurs are not assumed in the automated navigation system. Conversely, if functions that can reduce the frequency and damage of fires are assumed, the estimate will consider those reductions.

In reality, estimation is frequently impossible due to a large number of uncertainties in the contributions of these factors and the insufficient availability of data. In such cases, rather than attempting a quantitative assessment, one conceivable method as a technique for decision-making based on a risk assessment, as described in Chapter 2, is to conduct screening by dividing the hazards into several levels, from hazards that are considered broadly acceptable to unacceptable hazards by a semiquantitative assessment, select the hazards that are thought to have a high degree of importance, and implement countermeasures that are acceptable to the analysis team.

5.4 Development to More Advanced Automation Systems

Referring to the automation levels of automobiles, at more advanced automation levels, the range of automation becomes wider and human monitoring is no longer assumed. As a result, items of concern which may become safety issues include whether tasks corresponding to confirmation of condition and maintenance, which have been performed by humans, can be adequately transferred to the operation system of a new automation system, and whether the control can be returned reliably to a human operator in cases where a response by the automation system becomes difficult, for example, when conditions deviate from the ODD of the automation system.

Examples of problems related to the reliability of methods for returning control to a human operator can be found in the literature on automated vehicles. In introducing Level 3 automated driving, that is, a system which does not require constant monitoring by the driver, the conditions and state in which the driver is placed during automated driving can become a new hazard. That is, because the system is operating normally in most of the time, there is concern that the driver may not be able to respond adequately when necessary due to reduced vigilance or involvement in non-driving-related tasks. Depending on that subtask, the driver might not be able to use his hands or might be over-concentrating on that task. To prevent these situations, previous reports have noted the importance of reducing the continuation (duration) of tasks that may encourage drowsiness and tasks that require a high level of engagement, effectively communicating the necessity of handover of driving control to the driver and ensuring the necessary time for the handover 45) 46).

Likewise, in ship operation, it can be amply assumed that the same situations will occur if the automation system assumes handover to a fallback human operator, and this may result in serious accidents. Thus, when planning new automation levels and new methods for using automation systems, it is also necessary to consider these new viewpoints.

6. CONCLUSION

This paper has presented an overview of techniques for risk assessment of automated navigation systems, which are considered necessary accompanying the growing trend toward the realization of autonomous ships. Various automated navigation systems have been proposed, and experience in risk assessments for such systems is gradually accumulating. By sharing such experience, we hope to contribute to the development of autonomous ships, risk assessments for ships based on new concepts that will be proposed in the future, and improvement of the safety of ships.

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