Safety Evaluation for Technologies related to Autonomous Ships

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1. INTRODUCTION

1.1 Background

In recent years, technologies such as sensing technology, AI and IoT have made rapid progress and are used in various fields. In the field of ships, research and development of technology related autonomous ships has been actively carried out globally with the aim of improving safety by preventing human error and improving working conditions by reducing the workload on crew. It has already moved from the research stage to the development stage, and some concrete development projects have been launched all over the world. In Japan, the demonstration projects by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) for the three functions of automatic maneuvering function, remote ship maneuvering function, and automatic berthing and unberthing function have been completed in FY2020. The findings obtained from these projects are being summarized. In addition, as represented by the unmanned ship project MEGURI 2040 by The Nippon Foundation, multiple projects have been launched, aiming to put the autonomous ship into practical use by 2025 from both the rule development and technological development.

1.2 Target for Autonomy (Automation/Remote Control)

There are a wide variety of onboard operation on a ship. Therefore, it is necessary to clarify which onboard operation is targeted at first.

The onboard operations can be roughly divided into two departments, deck department and engine department (see Table 1). At the moment, technologies related to automation and remote control of onboard operation related to deck department, especially for navigation task at W/H, is being developed.

Regarding the engine department, technological development related to CBM (Condition Based Maintenance) is advanced with the aim of reducing onboard maintenance work. Since the introduction of these technologies into autonomous ship is being considered, the consideration of autonomous operation of the engine department has come to the agenda recently.

Table 1 Outline of onboard operation

Deck department	Navigation (lookout, radio communication, steering, etc.) Port entry/departure-related (preparation work, mooring/unmooring, anchoring/un-anchoring, recording/reporting, etc.) Hull-related (hull maintenance, patrol, cleaning, etc.) Cargo management (loading plan, cargo status management, cargo handling preparation work, cargo handling control, ship's attitude maintenance, etc.)
Engine department	Navigation (main engine operation, patrol (including trouble shooting), response to alarm, recording, regular maintenance/inspection, etc.) Port entry/departure-related (preparation work (inspection, operation check, changeover of fuel oil, starting stand-by generator, etc.), main engine load adjustment, lubricating oil adjustment during main engine slow down, fuel consumption minimization, seawater intake switching according to water depth , recording, main engine stopping work, etc.) Clean up

1.3 Level of Autonomy for "Ship" and "System"

Various discussions have also been held on the level of autonomous ship. Regarding the level of autonomy for a ship, interim

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definition (Table 2) is provided by IMO. In Japan, the phase of autonomous ship is listed in the roadmap for practical use of automatic operation ship announced by the MLIT (Table 3).

Regarding the level of autonomy for a system, the concept is shown in the guidelines issued by some classification societies (Table 4). The concept that the system will gradually and partially replace the decision-making process that has been carried out by crew is common to major classification societies.

Table 2 Degree of autonomy by IMO (MSC 100/20 / Add.1 Annex 2)

Degree one	Ship with automated processes and decision support
Degree two	Remotely controlled ship with seafarers on board
Degree three	Remotely controlled ship without seafarers on board
Degree four	Fully autonomous ship

Table 3 Phase of autonomous ship by the MLIT

Phase I	Ships utilizing IoT technology
Phase II	Ships that support the crew by remote maneuvering from land or action proposing function through AI etc., but the final decision is made by the crew
Phase III	Highly autonomous ships which the system can make the final decision for some tasks in place of the crew

Table 4 Level of autonomy for a system by classification societies [1-5)]

ABS	＜System Autonomy Levels＞ Level 1 Smart Level 2 Semi-Autonomous Level 3 Autonomous An autonomous system or function will be one where all four steps in the operational decision loop will be carried out by machines. The role of humans in such systems will be supervisory with the option to intervene and override the actions being carried out by the system.
BV	＜Level of autonomy＞ The level of autonomy should be defined to make a distinction between the role of the human and the role of the system among the various functions of the system. These functions are based on a four-stage model of human information processing and can be translated into equivalent system functions: a) information acquisition b) information analysis c) decision and action selection d) action implementation. The four functions can provide an initial categorization for types of tasks in which automation can support the human. Level 0 Human operated Level 1 Human directed Level 2 Human delegated Level 3 Human supervised Level 4 Fully autonomous
DNV	＜Levels of autonomy for navigation function＞ 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). It is necessary to break the degree of autonomy further down. Below is a method that may be used to clarify which part of a function that is intended to be solved by a human and which to be solved by a system. Initially the control of a function can be divided into four main parts: - Detection - Analysis - Planning - Action
LR	＜Autonomy level (AL)＞ AL0) Manual AL1) On-board Decision Support AL2) On &Off-board Decision Support AL3)'Active' Human in the loop AL4) Human on the loop, Operator/ Supervisory AL5) Fully autonomous: Rarely supervised operation where decisions are entirely made and actioned by the system. AL6) Fully autonomous: Unsupervised operation where decisions are entirely made and actioned by the system during the mission.
NK	Combination of 1) to 3). 1) Scope of automation Level 0: Humans executes all subtasks Level I: Computer systems execute some decision-making subtasks Level II: Computer systems executes all subtasks 2) Scope of remote operation Level 0: Crew onboard execute all subtasks Level I: Some decision subtasks remotely executed Level II: All decision subtasks remotely executed 3) Fallback executor Level 0: Human executes Fallback Level I: Fallback execution is shared between humans and computer systems. Level II: Computer system execute fallback

Each Classification Societies has its own way of dividing the decision-making process, but ClassNK divides it into three categories: situation awareness, decision, and action, as shown in Fig. 1.

When considering the safety of an autonomous ship, it is important to sort out things such as which functions of the ship (maneuvering, propulsion, power management, cargo management, etc.), to what extent (part or all of the decision-making process), and who responds in the event of an emergency.

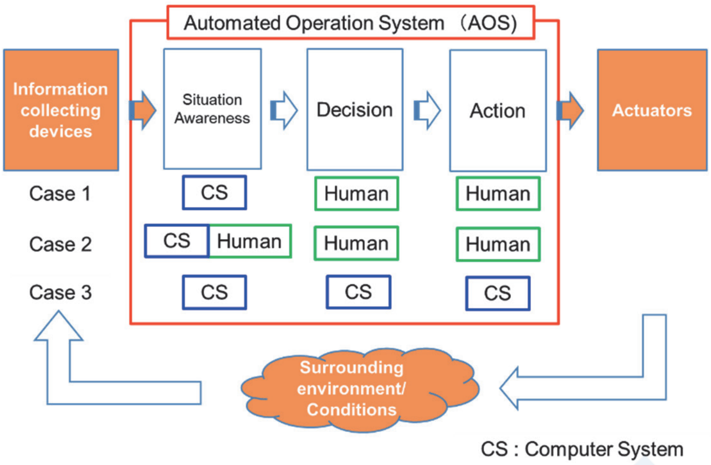

Figure 1　Conceptual diagram of Automated Operation System

1.4　Concept of Operation (ConOps)

In recent years, the term ConOps (Concept of Operation) has come to be often seen in documents related to autonomous ships. As far as the author has investigated, it seems to be a term used in system engineering, and it is described in ISO / IEC / IEEE 29148 (see Fig. 2). ConOps refers to a document that summarizes the concept and outline of system usage and operation, and it is positioned as an important document for eliciting stakeholder requirements and system requirements. Although system requirements tend to focus on the required capabilities and functions, it is possible to define requirements without omission (or few) by drawing a usage/operation scenario that covers the entire life cycle of the system.

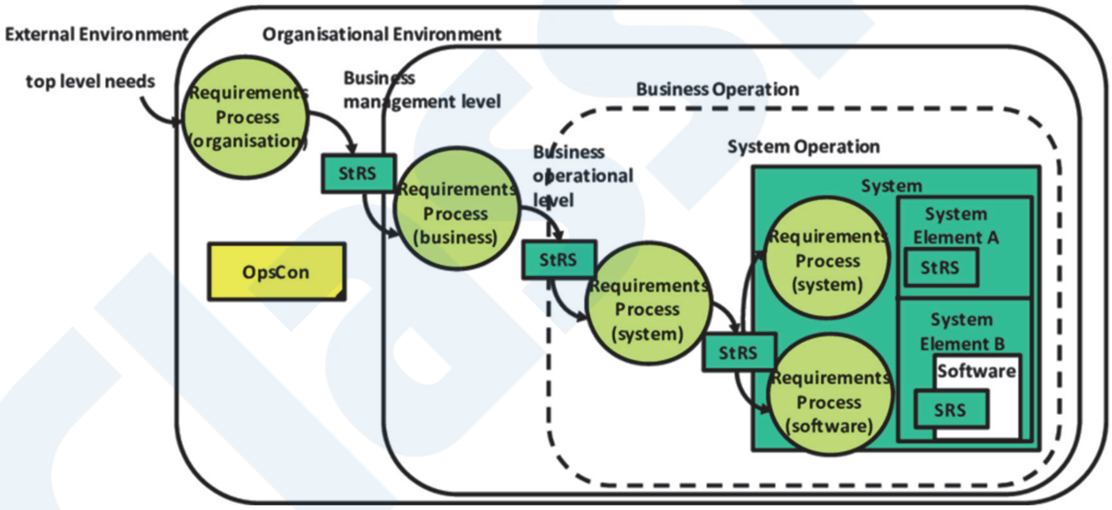

Figure 2　Example of requirement definition process flow and corresponding requirement specifications (Source: ISO / IEC / IEEE 29148)

In the case of autonomous ships, a highly complicated system will be installed, and it is difficult to set uniform requirements for such a large-scale system. This is because even if the systems have the same functions, the requirements and performance standards that should be specified are different depending on the conditions under which the system is operated. From this point of view, the approach of setting requirements after clarifying ConOps can be said to be an effective approach when verifying the safety of systems related to autonomous operations.

1.5　Technology Development

There are several ways to develop technologies related to autonomous ships. There are various approaches, for example, bringing in the latest technology such as AI, bringing in technology that has not been used in ships but has already been used in other industries, and combining existing technology that has already been used in ships in an unprecedented way so that it can realize new functions, and so on. Considering the nature of the target onboard task, it is being attempted to realize autonomous operation by appropriately selecting or combining two types of technologies, automation and remote control.

1.6 Rule Development

For implementation of the technology related to autonomous operation in society, the development of rules must be promoted in parallel to technology development.

At the IMO, autonomous ships have been taken up as an agenda item since MSC98 held in June 2017, and the framework and methodology for Regulatory Scoping Exercise (RSE) has been started. At MSC101 held in June 2019, interim guidelines for MASS(Maritime Autonomous Surface Ships) trials [6] (hereinafter referred to as IMO interim guidelines) were approved, and it summarizes the basic policies that should be taken into consideration when conducting trial operations of systems and infrastructure related to autonomous ships. At MSC103 held in May 2021, it was reported that RSE has been accomplished. In result of RSE, potential gaps between the current IMO instruments and requirements for MASS, and priorities for further work, were identified. In conclusion, it was agreed to consider a separate MASS instrument from existing IMO instruments.

In January 2020, ClassNK issued guidelines for automated/autonomous operation on ships (Ver. 1.0) (hereinafter referred to as NK guidelines) (see Fig. 3). The guidelines show the concept and certification procedure for automatic operation technology from the viewpoint of classification society.

Figure 3 Guidelines for automated/autonomous operation on ships (Ver. 1.0)

It is necessary to understand what kind of technology is currently being developed. It is important to correctly understand the "difference" from the conventional technology and share it with the parties concerned including the classification society from the conceptual design stage. Rather than uniformly defining normative requirements from the beginning, it is necessary to rationally evaluate autonomous technology while utilizing methods such as risk evaluation.

By following this process, the classification society can proceed with the development of rules, and the system owner can build a concrete usage image (business image). System suppliers and system integrators can also clarify the direction of development. In addition, by clarifying the procedure for certification of autonomous operation technology, it becomes easier for system suppliers, system integrators, and system owners to understand when and what they must do. It is expected that NK guidelines contribute to accelerate social implementation.

Further cooperation in the maritime industry including the classification society will become important.

2. SAFETY OF AUTONOMOUS SHIPS

2.1 Definition of Safety

It is necessary to clarify "what is safety". For example, ISO / IEC GUIDE 51: 2014 defines safety as "no unacceptable risk". Needless to say, "Zero risk (absolute safety)" is ideal, but it would be the definition as described above from a realistic point of view. Applying this definition of safety to ships, the means to eliminate "unacceptable risks" is the crew in the case of conventional ships, and the cooperation between system and crew in the case of autonomous ships.

The necessary capability for crew is specified in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). It is necessary to discuss whether these capability requirements should be applied to the system as they are, but in an autonomous ship, if the system partially replaces the capability of crew, how the system achieves these capability requirements is an important point of view.

2.2 Functional Safety

Safety includes intrinsically safe and functional safety. Intrinsically safe means reducing or eliminating the cause of a machine's harm to humans and the environment. Functional safety means ensuring an acceptable level of safety by introducing functional devices (functions to ensure safety: safety functions).

Functional safety has been adopted in various industries, and there are functional safety standards such as IEC 62278 for railways and ISO 26262 for automobiles. As an example, ISO 26262, which is a functional safety standard for automobiles, aims for zero human damage based on the concept of functional safety. The background of the enactment is to fulfill accountability by visualizing the entire development work and to prepare evidence that can withstand the litigation.

Functional safety standards for ships do not yet exist, but the concept of functional safety is also helpful for autonomous ships.

2.3 Equivalency

When discussing the safety of autonomous ships, one approach is to compare it with the safety of conventional ships. The purpose of installing an advanced system on a ship is not only improving safety, but also improving convenience or economy. Therefore, it is not necessary to require more safety than conventional ships just because it is an autonomous ship.

Conventional ships are operated safely by crew (qualified persons who have received formal training), and this procedure has been agreed globally. The conventional ship can be said to be “in a state where the risk is minimized” by the crew.

In an autonomous ship, this “state in which the risk is minimized” will be realized by the autonomous technology (automation and/or remote control). In other words, it is necessary to confirm the difference between the conventional ship and the autonomous ship, and to confirm that the safety of the conventional ship is not impaired by the difference.

2.4 Safety in Normal Condition and Safety in Emergency Condition

It is necessary to consider safety separately for “normal condition” and “emergency condition”. In “normal condition”, the minimum requirements defined in advance must always be satisfied. On the other hand, in an “emergency condition”, the situation has been already below the predefined minimum requirements (safety requirements in normal condition), so it is important to “not make the situation worse”.

2.5 MRC and MRM

In the case of automated driving of automobiles, the term Minimum Risk Maneuver (MRM) is used. It refers to vehicle motion control up to the Minimum Risk Condition (MRC) (stopped state where the accident risk is sufficiently low) as a countermeasure when an event that does not allow safe driving occurs. On the other hand, in case of ships, it is difficult to uniformly define a state in which the risk of accidents in an emergency is sufficiently low (MRC in an emergency). Unlike automobiles, ships that are affected by waves and tides will drift if the main engine is stopped. Also, anchoring to stay in one place can rather endanger the condition of the vessel in some circumstances. It is necessary to take flexible measures in consideration of the surrounding conditions, the atmosphere, the abnormal mode that occurred on the ship, and so on. In the case of conventional ships, the crew appropriately decide actions to “do not make the situation worse” (MRM in automobiles) according to the situation, and this flexible responsiveness of the crew supports the safe operation of the ship.

It is technically very difficult for the system to be in charge of MRM in an emergency on an autonomous ship. Therefore, the crew will need to fallback for the time being. A fully autonomous ship will appear when the system can handle emergency automatically, or when the probability of occurrence can be approached to zero.

2.6 Risk Assessment

For autonomous ships, due consideration in various operational scenarios must be given to prevent predictable accidents. As a method for this purpose, risk assessment is effective. Some Classification Societies, including ClassNK, have already issued guidelines on autonomous ships, and risk assessment is emphasized in all of them. IMO Interim Guidelines [6] and Guidelines issued by some flag states [7-9] also specify the implementation of risk assessment. There is no doubt about the international trend of utilizing risk assessment to verify the safety of autonomous ships.

2.7 Basic Elements for Safety Evaluation

The NK guidelines state that it is important to clarify or consider the following eight basic elements for safety evaluation from the conceptual design stage. ClassNK will verify the safety of system for autonomous ships in combination of these elements rather than isolation.

(1) Target of autonomous operation on a ship
(2) Division of roles between machines and humans
(3) Prerequisite specification for system installation
(4) Operation Design Domain (ODD)
(5) Fallback
(6) Human Machine Interface (HMI)
(7) Cyber security
(8) Reliability of Computer Systems

Adding the above-mentioned concept of MRC and MRM to these elements gives an image as shown in Fig. 4. It is very important for safety evaluation to verify how define the ODD including geographical conditions, environmental conditions, presence of land support, etc., and under what circumstances the system is operated (ConOps), as well as how transfer tasks to crew (fallback) when the system cannot work appropriately due to deviation from the ODD.

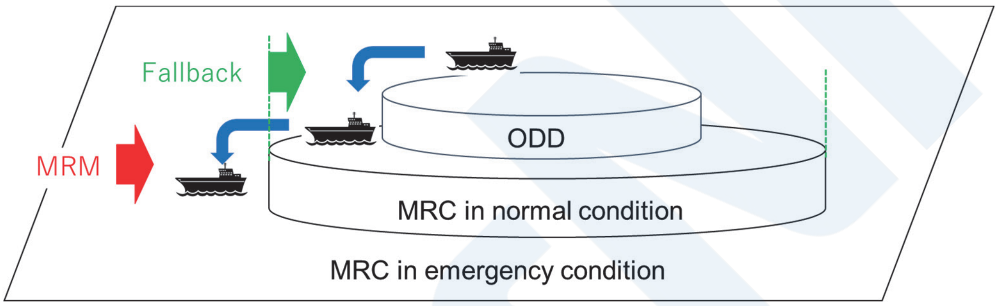

Figure 4 Relationship between ODD, Fallback, MRC, and MRM

2.8 Challenges

As mentioned, risk assessment is effective as a method for evaluating the safety of autonomous ships, but there are challenges. Since there are a wide variety of onboard operations and the magnitude of risk varies depending on the circumstances, which operations are autonomous, to what extent, and who (crew or system) responds at what timing in the event of an emergency, it is necessary to extract hazards from very multifaceted angles in risk assessment. In addition, countermeasures will be taken to mitigate the risk caused by the extracted hazards to an "acceptable level", but it is difficult to quantify this "acceptable level". For the time being, it is necessary to proceed with verification using whether or not it is "equivalent to a conventional ship" as an index, and to accumulate knowledge for quantification.

3. SYSTEM EXAMPLE FOR SHIP MANEUVERING

3.1 Target

Due to the wide variety of onboard operations on ships, discussions related to autonomous ships tend to diverge. Especially in conceptual level discussions, individual knowledge levels and term definitions are often inconsistent. To promote constructive discussions efficiently, it is necessary to give concrete examples as much as possible. It is important to form a common understanding and create a situation where each expert can bring their own specialties and have discussions.

In this paper, a virtual study was conducted on the system required for autonomy of ship maneuvering. The staffing of crew is based on the premise that they comply with the current rules, and unmanned ships are not assumed. Similar studies [10] have also been conducted, and it is expected that these researches contribute to accelerate the formation of a common understanding in the industry.

3.2 An Example of System for Ship Maneuvering on an Autonomous Ship

Figure 5 shows an image of maneuvering operation on an autonomous ship. In this figure, the components of maneuvering task are divided into five modules, information collecting device, situation awareness, decision, action, and actuators. In the remote operation center, it is assumed that the remote operator would monitor, support, and/or control some modules other than actuators as needed.

(1) Information collecting device

In addition to existing sensors, it is assumed that a sensor that supports or replaces the lookout by the crew (hereinafter lookout sensor) will be installed. It seems difficult to develop a lookout sensor that is a perfect substitute for lookout by the crew, but if such a lookout sensor is developed, it is necessary to develop performance standards which can evaluate the equivalence with lookout by the crew, as well.

(2) Situation awareness

It is necessary to integrate the information obtained from the information collecting device, confirm the reliability of the information, and accurately grasp the situation in which the ship is placed.

By improving the reliability and integrity of information by sensor fusion technology, an information display device with a human-machine interface devised to make it easier for crew to understand, that can display the risk of collision with other ships and the risk of grounding, will be developed as well as the algorithms which can accurately analyze the state of the own ship from the given information.

(3) Decision

Quantitative indexes are necessary for computer system to decide whether to maintain the route/speed or move to avoidance action. In addition, when avoidance action is required, the function of planning an avoidance action is also required. It is assumed that a highly reliable automatic collision avoidance algorithm will be developed in consideration of these factors. It is believed that the autonomous operation will be introduced in stages, and it will be introduced from the style in which the crew approve what the system proposes. When the system operation results are accumulated and the reliability of the system algorithm is sufficiently confirmed, it will be possible to take action without human approval under the supervision of a crew.

Since it is related to the reliability and integrity of the situation awareness, it is considered that the crew onboard will be responsible for the decision in maneuvering of autonomous ship for the time being. If crew onboard and remote operators at remote operation center work together, authority and responsibilities for final decision are to be clarified center in advance.

(4) Action

In both cases that it is to maintain the route or to take avoidance action, calculations are made to control the ship along the designated route. Since HCS (Heading Control System) and TCS (Track Control System) already exist, it is conceivable that these technologies will be applied.

The required accuracy such as off-track width, etc. needs to be adjusted appropriately in consideration of the maneuverability of the own ship and the parameters used in the avoidance route planning of the decision module.

(5) Actuators

It is assumed that conventional devices will be used for the time being.

(6) Remote operation center

For the information collection module, it is assumed that the remote operation center will provide support such as updating the latest meteorological and ocean conditions, traffic information, and medium- to long-term voyage plans.

In situation awareness module, the work content in the remote operation center changes greatly depending on the comprehensiveness and timeliness of the information sent from the ship. For example, when a remote operator performs remote maneuvering (maneuvering a ship outside of sight), cognition including visual images is also required at the remote operation center, and cognitive quality almost equivalent to that on board is required. In addition, whether or not high-quality cognition can be stably reproduced depends on the communication environment. On the other hand, if the purpose is to monitor the condition of onboard equipment or evaluate the condition from information such as sensor data, the required communication environment is also relaxed.

In decision module, it is assumed that support such as action planning and advice to the crew onboard will be the main focus.

It is assumed that the module of action and actuators will not be supported.

When evaluating the safety of a ship maneuvering system, a two-step verification will be carried out. After confirming the

reliability of each of the above five modules, check the functions with these modules integrated.
Technological development continue and each module will be updated. In such a case, making it easier to take the difference is a great merit of proceeding with verification on a module-by-module basis.

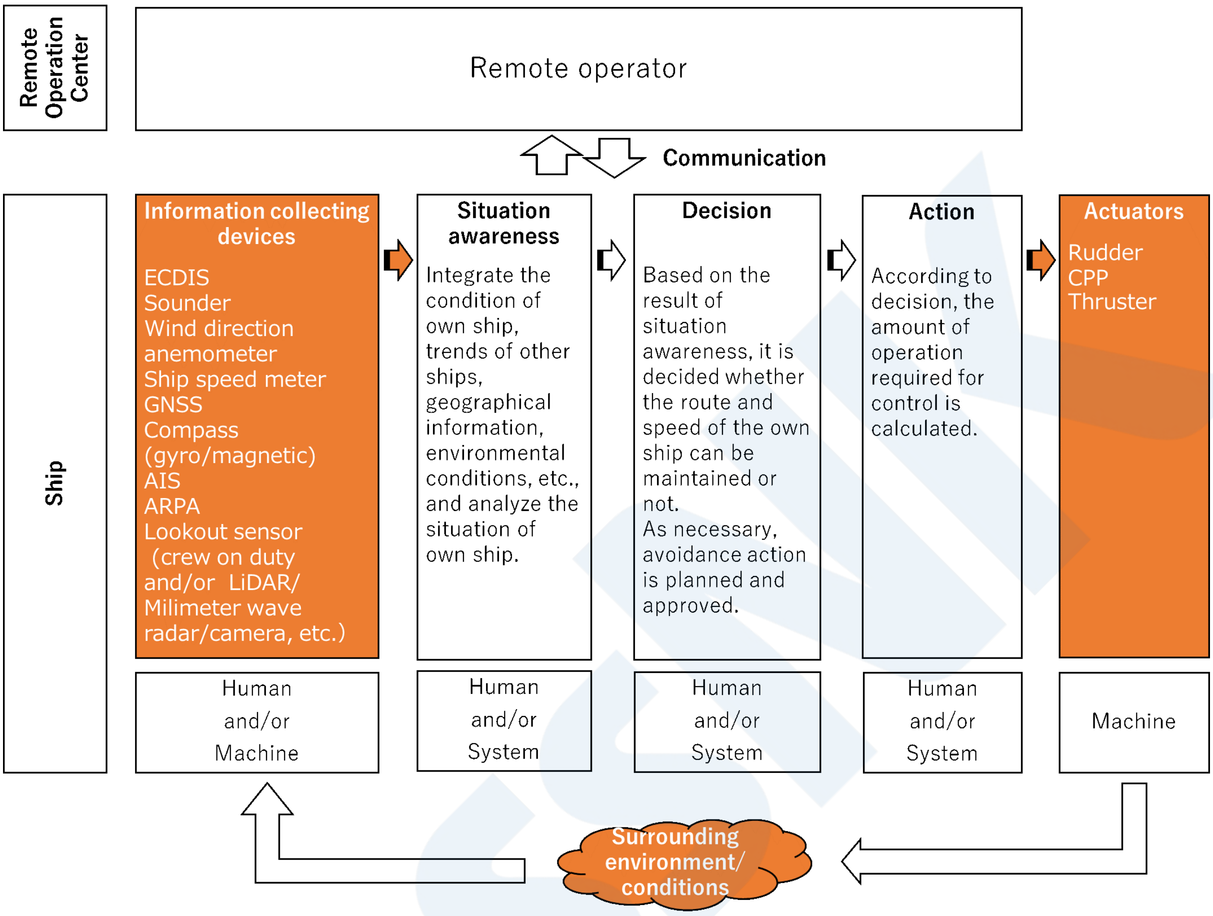

Figure 5　Image of maneuvering operation on an autonomous ship

4.　INITIATIVES OF RESEARCH INSTITUTE OF CLASSNK

ClassNK is carrying out R&D on specific methods for conducting safety evaluations. Especially, methods of extracting hazards during risk assessment and computer simulation for quantitative evaluation are focused.

As mentioned above, since there are a wide variety of technologies related to automatic operation, the Society has narrowed down the target of autonomy to ship maneuvering operation, and detailed studies are being conducted. Based on the knowledge gained there, the verification study will be expanded to autonomy of other onboard operations.

4.1　Study for Comprehensive Hazard Extraction Method

In case of auto-driving cars, it seems that the idea is to prevent foreseeable accidents, and the same is true for autonomous ships. Hazard extraction is performed after considering under what circumstances, what task is automated, how much remote control is performed, and who (crew or system) responds at what timing in the event of an emergency. Then, the magnitude of those risks is estimated. For that purpose, it is necessary to accurately grasp where the difference in technology from the conventional ship exists. It is believed that the overall risk will be lower when comparing autonomous ships with conventional ships, but there is a possibility that new risks will arise that conventional ships did not have. For the time being, it will be important to properly identify such risks, and operate with an appropriate safety margin.

For that reason, the ClassNK guidelines describe eight basic elements for safety evaluation. Based on these basic elements, ClassNK is also researching ways to make it easier to extract hazards by organizing the functions of autonomous systems while considering the decision-making process. The findings obtained from the demonstration projects, etc. that ClassNK has been involved in are being organized in the format shown in Table 5. We are sorting out common requirements and special requirements by comparing and verifying multiple cases in a unified format.

In risk assessment of autonomous ships, it is important to verify hazards related to inter-system cooperation and cooperation between systems and humans, in addition to hazards focusing on equipment failures. From that point of view, ClassNK is proceeding with verification from the following viewpoints.

(1) Hazard that occurs when the system and human collaborate
(2) Hazard hidden in the decision-making process flow (Information collection device→Situation awareness→Decision→Action→Actuators)
(3) Validity verification of ODD
(4) Extraction of fallback occurrence scenarios
(5) Hazard that may occur when switching modes

The reliability of HMI, cyber security, and computer systems in individual modules will be verified when the detailed design is completed. As a verification method at that time, methods such as connection tests on actual machines and computer simulations might be more suitable than risk evaluation.

Table 5 Format for analysis of decision-making process flow based on basic elements for safety evaluation

Task	Mode	Prerequisite specification for system installation								ODD	Fallback
		Information collecting device (Input)	Situation awareness		Decision		Action		Actuators (Output)		
			Excuter	Place	Excuter	Place	Excuter	Place			
Ex)											
Maneuvering	Congested sea area	ECDIS Sounder Wind direction anemometer Ship speed meter GNSS Compass (gyro/ magnetic) AIS ARPA Lookout sensor	Support system + Crew	Ship	【Planning】 System + 【Approve】 Cres	Ship	System	Ship	Radder	Geographical conditions: Environmental condition: Other conditions:	Crew

4.2 Establishment of Quantitative Evaluation Method

It is difficult to achieve social implementation through risk assessment alone. As a classification society, it is necessary to set certain standards and ensure they are cleared. From such a perspective, ClassNK is paying particular attention to computer simulation. Figure 6 shows an image of the quantitative evaluation method currently under consideration.

To evaluate the safety of the developed ship maneuvering algorithm, it is necessary to verify whether or not it can appropriately respond to scenarios that lead to accidents. The combination of various other ship encounter patterns and disturbances will be comprehensively verified by fast-time simulation. In addition, conducting real-time simulations using a full-mission simulator to verify the timing of handing over tasks to crew in an emergency and the required HMI is also considered.

For quantitative evaluation of the simulation results, it is necessary to determine the evaluation index. Therefore, a method for quantitative evaluation of ship maneuvering [11-12] is being also developed in cooperation with captains who have rich experience. Study for scenarios for computer simulation and appropriate index for evaluating the simulation results are being steadily proceeded, and the study results will be summarized during this fiscal year.

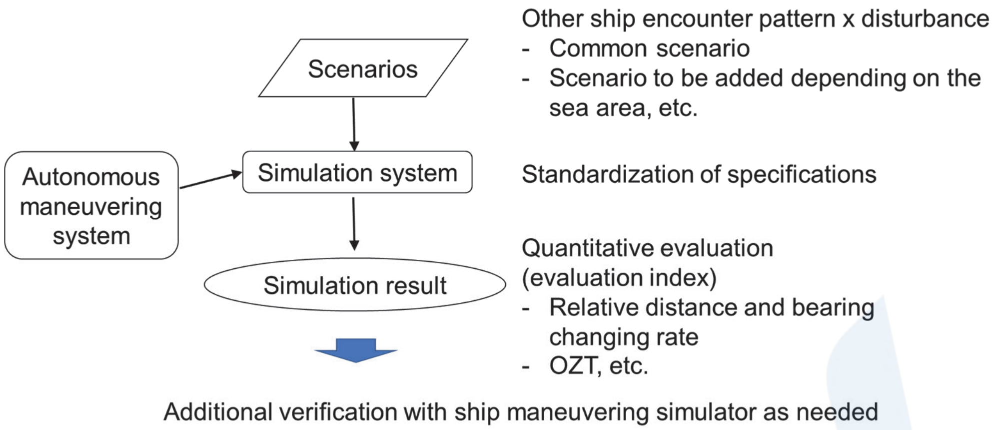

Figure 6　Quantitative evaluation method for ship maneuvering system

4.3　Establishing Requirements for Remote Control

There are three types of remote control technology for autonomous ships, monitoring, support (information provision, planning support, etc.), and control (direct operation of actuator, etc.). The requirements to be specified are different depending on the nature of the task to be carried out in the remote operation center.

It is also necessary to consider the characteristics peculiar to remote control. Specifically, it is necessary to sort out the requirements for the communication infrastructure, the equipment used in remote operation center, and the operators involved, etc. These are not complete with the ship alone. In the case of automation technology, it is necessary to pay attention to the part of cooperation between humans and machines onboard, but in the case of remote technology, it is necessary to pay attention to how and to what extent communication between crew onboard and remote operators is planned. It means important to clarify the ConOps.

In consideration of the characteristics peculiar to such remote technology, ClassNK is proceeding the study from the following three main viewpoints.

(1)　Establishment of evaluation method for communication stability
(2)　Clarification of requirements for remote control facilities
(3)　Clarification of requirements for remote control workers

5.　CONCLUSION

It is the role of the classification society to develop rational rules for autonomous ships. The Society has been steadily making preparations in cooperation with stakeholders, such as issuing guidelines in May 2018 and January 2020. In the future, the Society is going to continue to proceed with a solid sense of balance so that ClassNK can establish the necessary and sufficient safety requirements for autonomous ships without delaying technological development.

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