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Special feature:
Autonomous Operation

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―　CONTENTS　―

Special Feature Articles on Autonomous Operation

(Foreword: Invited Paper)

Current Status and Future Outlook of Automated Driving

……………………… *Professor Emeritus, The University of Tokyo, Japan Automobile Research Institute*
Minoru KAMATA……… 1

Various studies on automated driving are underway in the automotive field, and it is thought that many aspects of these moves are also applicable to automated operation of ships. Therefore, this paper describes the current status and future outlook of automated driving of automobiles in the hope that this may serve as a useful reference when studying automated operation of ships.

Risk Assessment of Autonomous Ship Systems

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Hiroko ITOH, Tomohiro YUZUI, Megumi SHIOKARI, Eiko ISHIMURA, Rina MIYAKE, Junichi KUDO…… 11

With increasing activity in technology development related to autonomous ships, there are many cases in which risk assessments of systems for automatic navigation are necessary before introduction. Risk assessment of those systems is difficult, as they utilize software-centered technologies which are difficult to assess by the conventional risk assessment technologies for hardware equipment, etc. and assume diverse methods of use. However, assessments are gradually becoming possible by the introduction of leading-edge analysis techniques and extension of conventional techniques. This paper introduces those types of risk assessment methods for automatic navigation systems, including examples of efforts by the National Maritime Research Institute (NMRI).

Development of Comprehensive Simulation System for Autonomous Ships

……*National Maritime Research Institute, National Institute of Maritime, Port and Aviation Technology*
Makiko MINAMI, Kentaroh KOKUBUN, Mitsuru KOBAYASHI, Kenjiro HIKIDA,
Kenji YOSHIMURA, Keiji SATO, Eiko SAITO, Ryohei SAWADA…… 25

In recent years, efforts toward the realization of Maritime Autonomous Surface Ships (MASS) have been promoted in many countries, including Japan. In autonomous ships and unmanned ships, prevention of accidents due to human factors and improvement of safety are demanded, but on the other hand, social acceptance is also necessary for commissioning of those ship operations. Thus, it is necessary to show that autonomous ships are safe. The National Maritime Research Institute (NMRI) is studying methods for evaluating safety and the construction of the system necessary in such evaluations. Among those efforts, this paper reports on a study of a total simulation system consisting of multiple simulation systems, beginning with a ship handling simulator, and an evaluation method using simulations.

Automation Levels of Automated/Autonomous Ships

·· *Japan Ship Technology Research Association Junji FUKUTO*······ 35

The image of ships and ship operation evoked by the terms automated ship and autonomous ship is not necessarily fixed and differs depending on the individual. In reality, the modes of ship operation using automated systems include a diverse spectrum from manual operation to fully automated operation, and it is important that those concerned have a shared recognition of the image of the automation system which is the target of development or evaluation. Therefore, this paper surveys the content of past studies of automation levels aimed at achieving a common understanding of the relationship between humans and the functions of various types of automation systems, and summarizes the outline and factors used in classifying automation levels for the automation levels of automobiles and drones, as automation is progressing in those fields, together with the automation levels proposed by various types of maritime-related organizations and several ship classification societies up to the present.

Technical Topics

Initiatives for Ship Fire Safety Measures

··························· *Machinery Rules Development Department, Material and Equipment Department*······ 51

This paper presents a commentary on trends in fire safety measures currently under discussion in the IMO for container carriers and car carriers. The efforts of ClassNK responding to moves to implement additional fire safety measures being promoted voluntarily by ship owners and ship management companies that operate container carriers in advance of future revisions of the SOLAS Convention, and fire safety measures for car carriers proposed in a Japanese working group are introduced.

Estimation of Stress on Ship Structures Using Full-Scale Measurement Data and Machine Learning

··· *Research Institute*······ 59

From the viewpoint of ensuring the safety of ships, it is important to understand the history of stresses generated on the ship structures. Since stress measurement is costly, it is desirable to have a method to grasp the stress of the whole ship with fewer measurement points or establish a method for stress estimation. For understanding the history of the stress, an approach using machine learning, which has been developed in recent years, is considered to be effective. In this paper, the contents of the ongoing research on estimation of stress generated on ship structures using full-scale measurement data and machine learning will be introduced.

Consideration of Utilization of Autonomous Drone for Ship Surveys/Inspections

··· *Research Institute*······ 67

In recent years, the application of robotics technologies, such as drones, has become increasingly active in various fields, and expectations are rising for the effective utilization of these latest technologies in surveys by classification surveyors and in inspections by crew. the Society has been extracting technical requirements for drones that can fly autonomously and stably in non-GNSS and dark environments such as cargo holds and has been studying survey/inspection schemes suitable for ship survey when using autonomous drones. This paper describes the results of demonstration experiments using an autonomous drone equipped with vision sensor.

This article introduces recent topics discussed at IMO (International Maritime Organization). At this issue, a summary of the decisions taken at 76th Marine Environment Protection Committee (MEPC 76) is provided.

Current Status and Future Outlook of Automated Driving

Minoru KAMATA*

1. INTRODUCTION

Various studies on automated driving are underway in the automotive field, and it is thought that many aspects of these moves are also applicable to autonomous ships. Therefore, this paper describes the current status and future outlook of automated driving of automobiles in the hope that this may serve as a useful reference when studying autonomous ships.

2. OVERVIEW OF AUTOMATED DRIVING

2.1 Background

Growth Strategy 2017 presents a broad vision of efforts in automated driving with the aims of “Realization of Mobility Revolution” and “Extension of Healthy Lifespan” 1).

The image of the mobility revolution consists of four items, (1) Truck platooning (convoy-type truck transportation), (2) Unmanned automated driving to provide human mobility services (Mobility as a Service: (MaaS), (3) Package delivery using drones and (4) Autonomous ships, targeting demonstration of each of these items by 2020. In the automotive field, demonstrations of (1) Unmanned travel by following vehicles on an expressway and (2) Unmanned automated driving using an abandoned rail line have been carried out, and the targets were achieved. Other efforts in the Growth Strategy 2017 included “Experiments Ahead of the World,” “Strategic Collection and Use of Data, Expansion of Cooperating Fields” and “Development of Systems looking to International Inter-system Competition.” Many of these aims have also been realized.

Growth Strategy 2018, which was published the following year, placed even greater emphasis on automated driving for “Manpower shortage due to migration and the logistics revolution and Reducing the number of vulnerable persons” 2).

2.2 Questions concerning Automated Driving

(1) When will fully automated driving be realized?

It is considered that it will not be possible to realize fully automated driving which enables travel in any environment in the near term due to the high degree of difficulty involved. On the other hand, automatic travel in restricted areas and spaces can be realized almost immediately if funding is available. In this case, a separate study will be necessary to determine the appropriate level of funding.

(2) How will popularization of automated driving change society?

It is reasonable to think that the current relationship between people and automobiles will change. For example, if a passenger can call an unmanned automated taxi simply by using a smartphone app, it may be cheaper to travel by taxi than to own and drive a car oneself. In the future, this might mean the end of the current concept of private ownership of automobiles.

(3) What are the differences between automated driving in Japan and other countries?

In Japan, there are strong expectations for unmanned operation of commercial vehicles (buses, trucks) due to a remarkable shortage of drivers. For this reason, I think that unmanned commercial vehicles will be realized in Japan at an earlier date than in other countries.

2.3 Methods for Realizing Automated Driving

There are basically two methods for realizing automated driving, infrastructure coordination and autonomous technology. Infrastructure coordination is a method in which various types of equipment are installed in the infrastructure, and the vehicle travels automatically while communicating with that equipment. Autonomous technology means the vehicle travels autonomously, without depending on the infrastructure, by using various types of sensors installed on the vehicle itself.

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Looking back on history, in the 1990s, the main approach was infrastructure coordination, for example, using magnetic nails embedded in the roadway, and in 1996, Japan led the world in demonstrating vehicle platooning using magnetic nails on the Joshin-Etsu Expressway before that highway was opened. However, this kind of project was not continued beyond that point, as it would have been difficult to create the same magnetic nail infrastructure throughout the country due to its extremely high cost. After 2010, autonomous technology became the main stream thanks to active research in response to unmanned automated driving contests for military purposes conducted by the Defense Advanced Research Projects Agency (DARPA) in the United States and the construction and operation of the Google self-driving car in 2012. But there was a strong sense that the Google project was a demonstration, rather than product development with the aim of social implementation, because the LiDAR sensors installed on the Google self-driving car were very expensive at the time.

In spite of an ongoing argument about whether infrastructure coordination or automated driving is the better approach for realizing automated driving, it is thought that automation will be realized in the near future, while also controlling costs, by skillful use of infrastructure coordination and automated driving. For instance, on predetermined routes traveled by regular buses or scheduled trucks, it would be possible to utilize infrastructure coordination by constructing the necessary infrastructure only on those sections.

2.4 Social Issues

Japan currently has the world’s highest percentage of older persons, at 28.7 %, and this is forecast to exceed 30 % in 2030 and reach 40 % by 2055. As the working-age population decreases, a corresponding increase in productivity will be necessary in order to maintain the country’s GDP. It also goes without saying that the costs of social security, medicine and nursing care increase as the population continues to age.

The “Grand Design of National Spatial Development towards 2050” prepared by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) summarizes the outlook for Japan’s future 3). To mention examples from that document, it is generally thought that Japan’s population will gradually decrease, and will fall below 100 million in 2050. Furthermore, the distribution of that population will be concentrated in large metropolitan areas such as Tokyo and Nagoya, and 20 % of the currently inhabited grid squares will become uninhabited.

Accompanying the increased number of older drivers in recent years, accidents caused by older drivers have become a social problem. As countermeasures, the National Police Agency is studying the possibility of training for older persons, and in the future, the introduction of a practical driving skill test. Community buses and demand-responsive transport sponsored by local governments are available for persons who have returned their driver’s license, but in reality, those systems are still inadequate. Heightened expectations are placed automated driving as a means of solving these issues.

3. CURRENT STATUS OF AUTOMATED DRIVING

3.1 History of Automated Driving

Efforts related to automated driving have been underway since the 1970s. In Japan, automated driving experiments were conducted, for example, by the Mechanical Engineering Laboratory, Agency of Industrial Science and Technology (now the National Institute of Advanced Industrial Science and Technology, AIST) under the Ministry of International Trade and Industry (MITI). In 1977, a vehicle called an “intelligent car” was built, and was capable of recognizing the white line on roadways by using an onboard camera.

In the 1990s, automated driving was possible by following a route marked by magnetic nails embedded in the pavement, and as mentioned previously, a demonstration of automatic vehicle platooning was carried out on the Joshin-Etsu Expressway in 1996, before the highway was opened to traffic.

Around 2000, Toyota developed a “platoon” system for buses called IMTS (Intelligent Multimodal Transit System), which was first operated commercially at EXPO 2005 in Aichi, Japan.

In 2004, the above-mentioned DARPA in the United States held a competition called the “Grand Challenge” in which vehicles travelled autonomously without using infrastructure coordination. Initially, this contest was held in the desert, the vehicles were quite large, as shown in Photo 1, and the vehicles used were quite different from ordinary cars. Later, the name was changed to Urban Challenge, and the contest was conducted with ordinary automobiles equipped with various sensors in a setting simulating an urban area. Photo 2 shows vehicles used in the Urban Challenge.

In 2012, Google Inc. of U.S. started public road testing of driverless vehicles.

Photo 1　Vehicle used in Grand Challenge [4)]

Photo 2　Vehicles used in Urban Challenge [5)]

In Japan, then-Prime Minister Abe took test rides in self-driving cars developed by three companies in 2013, and declared that the country would devote effort to automated driving. In the years that followed, Japan put great effort into the development of automated driving, and a series of demonstration tests were conducted widely in all parts of the country between 2017 and 2019 [6) 7)]. Figure 1 shows the main demonstration tests carried out in Japan in and after 2019.

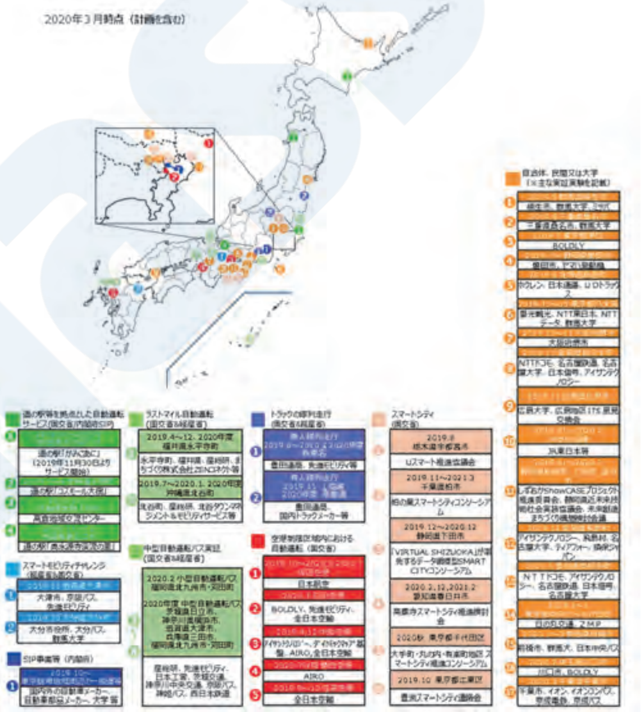


Figure 1　Main demonstration tests of automated driving conducted in and after 2019 (Japanese) [7)]

3.2　Classification of Driving Automation Levels

Driving automation is generally classified according to the definitions of the six levels of driving automation established by the Society of Automotive Engineers (SAE), as shown in Table 1. The image of automated driving held by many people corresponds to Levels 4 and 5.

In Level 1, either forward/backward operation (acceleration/deceleration) or right/left operation (steering) is automated. In Level 2, both forward/backward and right/left operations are automated, but up to Level 2, driving is performed primarily by the driver, and the driver bears the responsibility (liability) for driving. Therefore, Levels 1 and 2 should be understood as advanced driver assistance systems.

At Level 3, the automated driving system operates within a range that satisfies certain specific conditions, but when the conditions exceed that range, driving operation is turned over to the driver. However, many experts have raised questions whether operational authority can be transferred appropriately from the automated driving system to the driver (that is, how many seconds should be allowed for the transfer of driving authority). The National Police Agency requires the driver to take over operation of the vehicle immediately in situations where a transfer of authority is necessary, but under the MLIT guidelines, the vehicle must be stopped safely if this is not possible.

At Levels 4 and 5, driving is performed primarily by the automated driving system and not by the driver. Early realization of Levels 4 and 5 under the mixed traffic conditions of public roads is not possible due to the high degree of technical difficulty involved, but it is thought that these higher levels can be realized relatively easily assuming a combination of dedicated space or restricted space and low speed.

Table 1 Levels of driving automation [8)]

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/acceleration support to the driver	These features provide steering AND brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering OR • adaptive cruise control	• lane centering AND • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

3.3 Purpose of Automated Driving

(1) Safety

Human error is considered to be the cause of 90 % of traffic accidents. The purpose of automated driving is to prevent such traffic accidents due to human error. In Japan, implementation of automated driving began from expressways, and Level 3 was realized in 2021, although with conditions during congested periods on expressways. However, if priority is placed on reducing the aforementioned accidents caused by older drivers, reducing driving mistakes by older drivers by focusing on driver assistance, rather than automated driving, is also a possible approach that contributes to safety.

(2) Driver shortages

With the population of Japan in the process of decreasing, there is a remarkable shortage of drivers, especially for buses, taxis and trucks. Therefore it has been increased that the expectations for unmanned driving by automated driving, which does not require a driver. Particularly in under-populated areas, development is being promoted, while continuing to pursue Levels 4 and

5 and truck platooning on expressways (lead truck with driver, following trucks unmanned). Development is not limited only to unmanned driving, but also includes remote monitoring and remote operation. In Level 2, the remote operator bears the responsibility (liability) for driving. Since there is no reduction in the number of drivers if one remote operator monitors one remote vehicle, the aim is to develop a system which makes it possible for one person to monitor multiple vehicles.

(3) Added value

As the significance of automated driving, the ability to do other work while traveling, rather than simply driving the automobile, is considered important in other countries. Naturally, the ability to do other work while traveling increases work productivity. Moreover, if a long-distance driver can rest during traveling time while not actually driving the vehicle, this will also lead to improvement of work conditions. Effectiveness can be increased further if it is possible to enhance the added value of connected cars by installing automated driving systems to other vehicles. Automated driving is also expected to contribute to urban development. If all automobiles are automated, it is thought that the existing road space can be redistributed based on a review of the relationship between traffic volume and road capacity, thereby contributing to effective use of surplus land. For example, if the concept of private ownership of automobiles is eliminated, parking lots will no longer be necessary, and that space can be utilized effectively. It will also become possible to manage expressways with fewer lanes, and that space can be used for solar panels or bicycle roads. (See Figs. 2 and 3; driving automation eliminated the need for the roadway areas shown in red.)

Figure 2 Image of use of parking lot [9)]

Figure 3 Image of use of surplus lanes of expressway [9)]

3.4 Efforts by Japan to Realize Automated Driving

The Japan Economic Revitalization Secretariat of the Cabinet Secretariat organized a Public-Private Council for Automated Driving, which held discussions with the participation of the related ministries and agencies, the private sector and experts. Improvement of the legal system is necessary for social implementation of automated driving, this issue was discussed in the Council. In response to this, early improvement of the system has been realized thanks to a prompt response by the related ministries and agencies in line with the requests of the private sector and experts. Legal provisions were incorporated in various laws, including the Road Transport Vehicle Act and the Road Traffic Act, and in matters related to liability, the Act on Securing Compensation for Automobile Accidents, etc. In addition, automated driving systems were defined in the revisions of the Road Traffic Act and the Road Transport Vehicle Act in 2019.

In order to avoid the so-called “Galapagos syndrome,” in which the legal system in Japan evolves in way that is incompatible with the systems in other countries, discussions are in progress in the United Nations under Japanese leadership, and there is a trend toward the creation of international standards in the form of the skillful incorporation of Japan’s arguments.

On the other hand, even assuming progress in technological development and improvement of the legal system in a way that enables use of automated driving, whether automated driving is actually accepted by society is also extremely important. In other words, it is important to ensure social acceptance, including not only the persons who use self-driving vehicles, but also other persons who may be affected.

Although the Public-Private ITS Initiative / Roadmaps 2018 [6)] set targets up to FY 2020, almost none of those goals were realized by that date. Therefore, in the Public-Private ITS Initiative / Roadmaps 2020 7) efforts for the future during the 2020 decade are divided into short-, medium- and long-term, how the efforts in each timeframe should be realized is summarized. METI, MLIT and other related parties are grappling with various projects with large budgets toward realization of this Roadmap.

3.5 Safety Standards for Automated Driving

In considering automated driving, how to create standards and ensure compliance with those standards is important. First, MLIT established Safe Technology Guidelines for Self-Driving Vehicles 10) to specify the safety targets for standards. As a basic concept, since the goal is a society in which the system theoretically causes 0 accidents resulting in personal injury or death, avoiding accidents with objects that are foreseeable and avoidable was set as a target. However, because the allowable range of what is “foreseeable” differs depending on the country, there are divisions on this issue, even in international forums.

Revision of the Road Transport Vehicle Act is necessary for actual practical application of Level 3 or higher, Therefore, the proper form of accuracy necessary for comprehensively securing safety from the self-driving vehicle design and production processes to the use process was studied in a subcommittee of the Transportation Policy Council 11).

4. FUTURE OUTLOOK

4.1 Recognition of the Current Condition

Because a condition in which a driver is present and can take over driving at any time is regarded as Level 2, demonstration tests can be carried out easily on public roads. Even in case a driver is not present in the driver’s seat, demonstration tests can be conducted if remote monitoring and remote operation is possible. A license plate number can be issued, even if the vehicle is not equipped with a steering wheel or pedals, and a demonstration test can be conducted, then it can be considered the vehicle is compatible with the security standards, provided remote monitoring and remote operation is possible and the necessary conditions are satisfied. Thus, Japan is an environment in which demonstration tests can be carried out easily when the automated driving system is considered Level 2.

Moreover, it can be said that Japan possesses a technology level which is capable of achieving full automated driving if the necessary funding is available and the environment is simple.

At present, various studies on cost reduction and adaptation to complex environments are being carried out, and the problem of liability is under study. A response to legal and regulatory issues is also in progress in accordance with the Outline of Institutional Development of Automated Driving 12).

4.2 Legal Framework

Within the range of Level 2 demonstration tests, the current legal framework has been arranged in a form in which it is possible to conduct tests even with vehicles without a driver’s seat. In the case of remote monitoring, 1 : 3 demonstration tests (1 remote operator : 3 vehicles) have already been completed, aiming at the time when 1 : 1 becomes 1 : N. Discussions on the final form of the system of liability will begin from the present. If Level 4 or higher is achieved, remote monitoring will not be necessary under normal conditions. Although AI is expected to progress to a level where that can be achieved, it is difficult to discuss theories of liability without seeing a condition that sufficiently achieves that level in the technical aspect.

In the legal framework, opinions are divided on the extent to which safety should be required. Requiring a level that prevents accidents caused by the other party is a high hurdle. It is not possible to design products unless a certain direction is set for equipment reliability requirements, and in international competition, it is necessary to consider where the target level and speed of achievement should be set.

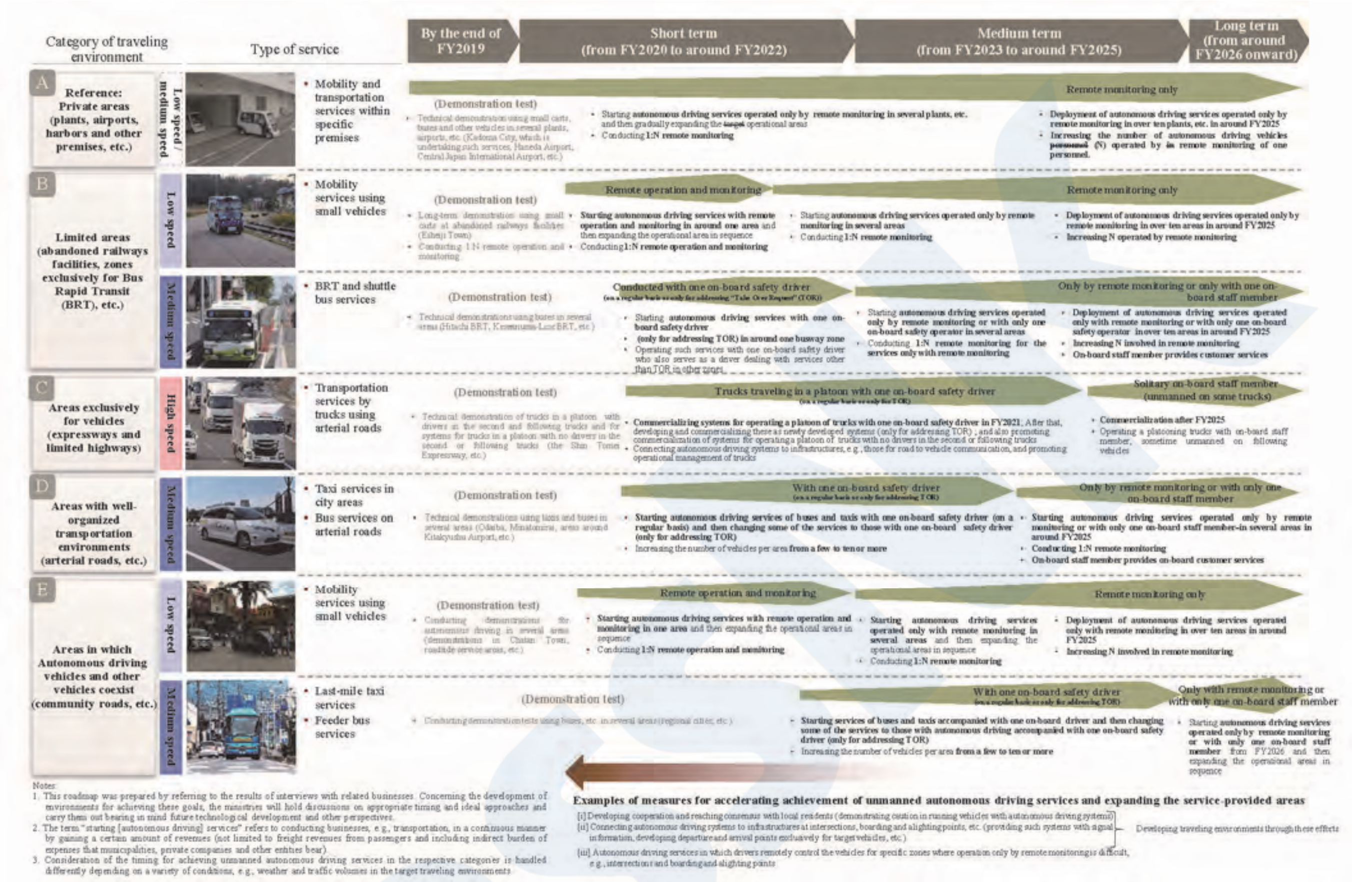
On the other hand, development of safety standards and certification and auto inspection requirements for vehicles with advanced driver assistance and automated driving functions are also progressing, as Level 3 has become possible under the revisions of the Road Traffic Act and Road Transport Vehicle Act. The necessary conditions for conducting a transportation business have also been summarized.

4.3 Future Image

Up to 2020, commercialization of Level 3 during congested periods on expressway, Level 3 in limited spaces, and construction of a technology for truck platooning were realized. However, it is still difficult to realize automated driving on local roads even at Level 2. In addition to improvement of maps, various agreements will be necessary for this.

How Level 3 will develop is unknown, but for the time being, an extension of the range of operation on expressways is considered likely. The image of commercialization of remote monitoring and remote operation at Levels 4 and 5 is also unknown.

In commercial vehicles for which personnel costs can be reduced, and in privately-owned passenger cars, how money is spent on sensors and other equipment will change. In addition, a roadmap to around the year 2030 has been prepared 13) in the Subcommittee on Business Discussions on Autonomous Driving Technologies, while continuing to study the outlook for work on treaties and standards, social acceptance and other issues. (See Fig. 4).



A Reference: Private areas (plants, airports, harbors and other premises, etc.)

- Mobility and transportation services within specific premises

(Demonstration test)

- Technical demonstration using small carts, buses and other vehicles in several plants, airports, etc. (Kadoma City, which is undertaking such services, Haneda Airport, Central Japan International Airport, etc.)

Remote monitoring only

- Starting **autonomous driving services operated only by remote monitoring in several plants, etc.** and then gradually expanding the ~~target~~ operational areas
- Conducting **1:N remote monitoring**
- **Deployment of autonomous driving services operated only by remote monitoring in over ten plants, etc. in around FY2025**
- **Increasing the number of autonomous driving vehicles ~~personnel~~ (N) operated by ~~in~~ remote monitoring of one personnel.**

B Limited areas (abandoned railways facilities, zones exclusively for Bus Rapid Transit (BRT), etc.)

- Mobility services using small vehicles

(Demonstration test)

- Long-term demonstration using small carts at abandoned railways facilities (Eiheiji Town)
- Conducting 1:N remote operation and monitoring

Remote operation and monitoring

- **Starting autonomous driving services with remote operation and monitoring in around one area** and then expanding the operational area in sequence
- Conducting **1:N remote operation and monitoring**

Remote monitoring only

- Starting **autonomous driving services operated only by remote monitoring in several areas**
- Conducting **1:N remote monitoring**
- **Deployment of autonomous driving services operated only by remote monitoring in over ten areas in around FY2025**
- **Increasing N operated by remote monitoring**

- BRT and shuttle bus services

(Demonstration test)

- Technical demonstrations using buses in several areas (Hitachi BRT, Kesennuma-Line BRT, etc.)

Conducted with one on-board safety driver (on a regular basis or only for addressing "Take Over Request" (TOR))

- Starting **autonomous driving services with one on-board safety driver**
- **(only for addressing TOR) in around one busway zone**
- Operating such services with one on-board safety driver who also serves as a driver dealing with services other than TOR in other zones

Only by remote monitoring or only with one on-board staff member

- Starting **autonomous driving services operated only by remote monitoring or with only one on-board safety operator in several areas**
- Conducting **1:N remote monitoring for the services only with remote monitoring**
- **Deployment of autonomous driving services operated only with remote monitoring or with only one on-board safety operator in over ten areas in around FY2025**
- **Increasing N involved in remote monitoring**
- **On-board staff member provides customer services**

C Areas exclusively for vehicles (expressways and limited highways)

- Transportation services by trucks using arterial roads

(Demonstration test)

- Technical demonstration of trucks in a platoon with drivers in the second and following trucks and for systems for trucks in a platoon with no drivers in the second or following trucks (the Shin Tomei Expressway, etc.)

Trucks traveling in a platoon with one on-board safety driver (on a regular basis or only for TOR)

- **Commercializing systems for operating a platoon of trucks with one on-board safety driver in FY2021**; After that, developing and commercializing these as newly developed systems (only for addressing TOR); and also promoting commercialization of systems for operating a platoon of trucks with no drivers in the second or following trucks
- Connecting autonomous driving systems to infrastructures, e.g., those for road to vehicle communication, and promoting operational management of trucks

Solitary on-board staff member (unmanned on some trucks)

- **Commercialization after FY2025**
- Operating a platooning trucks with on-board staff member, sometime unmanned on following vehicles

D Areas with well-organized transportation environments (arterial roads, etc.)

- Taxi services in city areas
- Bus services on arterial roads

(Demonstration test)

- Technical demonstrations using taxis and buses in several areas (Odaiba, Minatomirai, areas around Kitakyushu Airport, etc.)

With one on-board safety driver (on a regular basis or only for addressing TOR)

- **Starting autonomous driving services of buses and taxis with one on-board safety driver (on a regular basis) and then changing some of the services to those with one on-board safety driver (only for addressing TOR)**
- Increasing the number of vehicles per area **from a few to ten or more**

Only by remote monitoring or with only one on-board staff member

- **Starting autonomous driving services operated only by remote monitoring or with only one on-board staff member-in several areas in around FY2025**
- **Conducting 1:N remote monitoring**
- **On-board staff member provides on-board customer services**

E Areas in which Autonomous driving vehicles and other vehicles coexist (community roads, etc.)

- Mobility services using small vehicles

(Demonstration test)

- Conducting demonstrations for autonomous driving in several areas (demonstrations in Chatan Town, roadside service areas, etc.)

Remote operation and monitoring

- **Starting autonomous driving services with remote operation and monitoring in one area** and then expanding the operational areas in sequence
- Conducting **1:N remote operation and monitoring**

Remote monitoring only

- **Starting autonomous driving services operated only with remote monitoring in several areas** and then expanding the operational areas in sequence
- Conducting **1:N remote monitoring**
- **Deployment of autonomous driving services operated only with remote monitoring in over ten areas in around FY2025**
- **Increasing N involved in remote monitoring**

- Last-mile taxi services
- Feeder bus services

(Demonstration test)

- Conducting demonstration tests using buses, etc. in several areas (regional cities, etc.)

With one on-board safety driver (on a regular basis or only for addressing TOR)

- **Starting services of buses and taxis accompanied with one on-board driver and then changing some of the services to those with autonomous driving accompanied with one on-board safety driver (only for addressing TOR)**
- Increasing the number of vehicles per area **from a few to ten or more**

Only with remote monitoring or with only one on-board staff member

- Starting **autonomous driving services operated only by remote monitoring or with only one on-board staff member** from FY2026 and then expanding the operational areas in sequence

Notes:
1. This roadmap was prepared by referring to the results of interviews with related businesses. Concerning the development of environments for achieving these goals, the ministries will hold discussions on appropriate timing and ideal approaches and carry them out bearing in mind future technological development and other perspectives.
2. The term "starting [autonomous driving] services" refers to conducting businesses, e.g., transportation, in a continuous manner by gaining a certain amount of revenues (not limited to freight revenues from passengers and including indirect burden of expenses that municipalities, private companies and other entities bear).
3. Consideration of the timing for achieving unmanned autonomous driving services in the respective categories is handled differently depending on a variety of conditions, e.g., weather and traffic volumes in the target traveling environments.

Examples of measures for accelerating achievement of unmanned autonomous driving services and expanding the service-provided areas

[i] Developing cooperation and reaching consensus with local residents (demonstrating caution in running vehicles with autonomous driving systems)
[ii] Connecting autonomous driving systems to infrastructures at intersections, boarding and alighting points, etc. (providing such systems with signal information, developing departure and arrival points exclusively for target vehicles, etc.)
Developing traveling environments through these efforts
[iii] Autonomous driving services in which drivers remotely control the vehicles for specific zones where operation only by remote monitoring is difficult, e.g., intersections and boarding and alighting points

Figure 4　Roadmap for Deployment of Autonomous Driving Services 13)

4.4　Future of the Automobile Industry

The region of automated driving technology will expand to mobility services and public transportation services, and to urban development. On the other hand, with the rise of connectivity, competition for territory with the ICT industry will also begin. Although emerging competitors still do not possess the technologies necessary to move an automobile weighing 1 ton or more safely at a speed exceeding 100 km/h, or the technologies that support high reliability and durability, this is no reason for complacency. While technology will evolve rapidly, the people who use that technology will not necessarily evolve at the same pace, but rather, may regress due to aging and other factors. The time is coming when the automobile industry must consider whether its current simple business model of merely building and selling cars is sufficient.

4.5　Methods of Utilizing Automated Driving

Even with Level 2 functions, automated driving can play an important role in securing safety through driver assistance.

On the other hand, there are various hurdles to unmanned driving for labor saving. Unmanned automated driving will begin from deployment in limited locations where it is possible. In spite of the strong expectation that unmanned driving will make labor costs unnecessary, the cost of driving automation is high. Thus, it is necessary to examine whether a business model based on automated driving is feasible or not.

Automated driving is merely simplifies the means of transportation. What is important is not simply developing a more advanced means of mobility, but utilizing it to vitalize human mobility and logistics. From this viewpoint, it can be said that the most important aim of automated driving technology is the development of attractive cities and towns.

4.6 Directions in Urban Development

Even assuming automated driving technology progresses and a legal framework which is capable of responding to the challenges of that technology is developed, how to achieve social implementation, including the cost aspect, is important. As Japan's population decreases in the years to come, it is difficult to think that simply using automated driving by itself will create a better society. This suggests the need for sustainable urban development which enables easy use of self-driving vehicles, or utilizing automated driving to make people's lives easier even assuming a declining population. This will be difficult to realize unless we create a grand design of how driving automation should be utilized as one means of transportation in urban development.

4.7 Summary

If our descendants look back on history 50 or 100 years from now, the current period will probably be considered a major turning point in the field of mobility. In the years to come, there is no question that electrification of automobiles will progress and great advances will be made in automated driving and connected cars. On the other hand, there are points that require a response to a mature society and a society with a declining population, and cannot be addressed simply by technical development. Because the population of Japan will inevitably decrease to less than 100 million persons around the year 2050, it is necessary to develop a grand design that enables an affluent life for the population of ca. 80 million within the range of a certain part of the country's land. As part of this, it is important to present a precise vision of the future of mobility, to have the automobile industry play the role of a mobility services industry that supports everyday life, and to create a trend in which the national government also supports this goal.

5. CONCLUSION

This paper has described automated driving in the automotive field, centering on its outline and purposes, history to date and outlook for the future. On the other hand, it can perhaps be said that the issues confronting automated driving of automobiles are the same as those in the field of autonomous ships. For example, this paper has described the three issues of safety, labor shortages and added value as purposes of automated driving of automobiles, but these also apply to the maritime industry. It is generally said that about 80 % of maritime accidents are the result of human factors (improper maneuvering, inadequate lookout, etc.). Where labor shortages are concerned, aging of crew is progressing, and particularly in the case of coastal ships, crew shortages are expected to become a real problem. Moreover, due to the diverse range of crew duties on ships, which include maneuvering, lookout, propulsion and power system management, and cargo management, the burden on crew is large, and there is a great need for technologies that contribute to improvement of the working environment. Thus, autonomous ship technologies are also expected to provide a means of preventing accidents, solving labor shortages and improving the working environment.

In recent years, multiple development projects in connection with autonomous ships have also been started, represented by demonstration projects of MLIT and the Nippon Foundation's unmanned ship project, MEGURI 2040, and it is thought that the development of regulations and technological development aiming at implementation will also progress at an ever faster pace in the future. Although the path to realization may not be easy, it is hoped that the example of automated driving for automobiles introduced in this paper will be of assistance when studying autonomous ships.

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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.

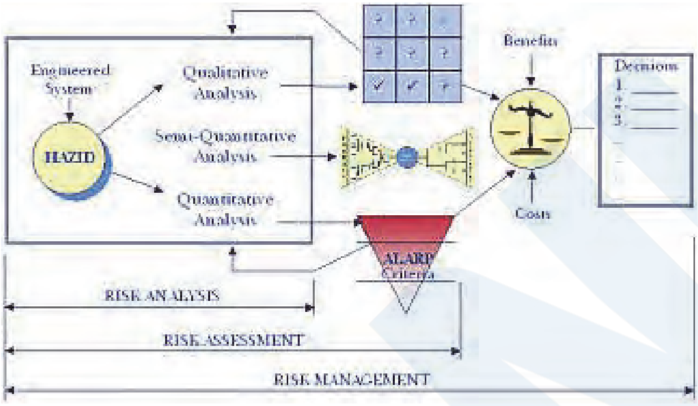

Figure 1　Risk assessment approaches by HSE 7)

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.

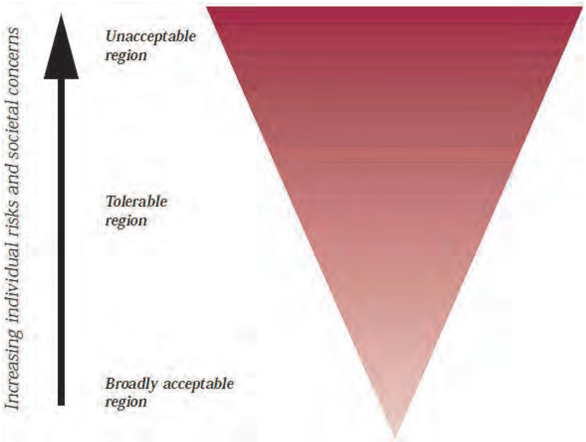

Figure 2 HSE framework for the tolerability of risk [9)]

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.

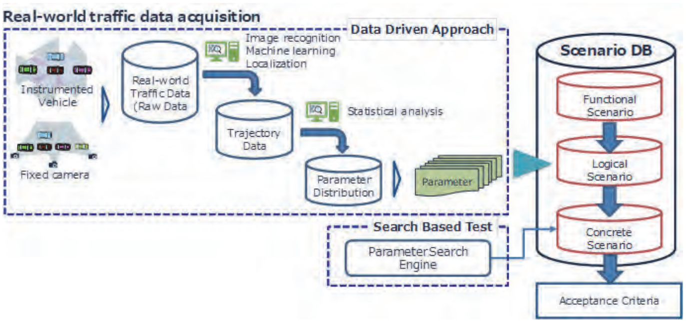

Figure 3 Test scenario generation process for automated driving safety assurance in the SAKURA Project 24)

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.

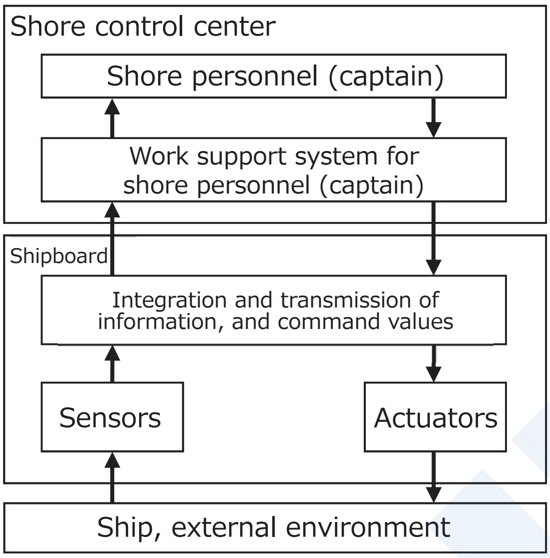

Figure 4　Example of conceptual structure of hypothetical autonomous ship [32)]

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.

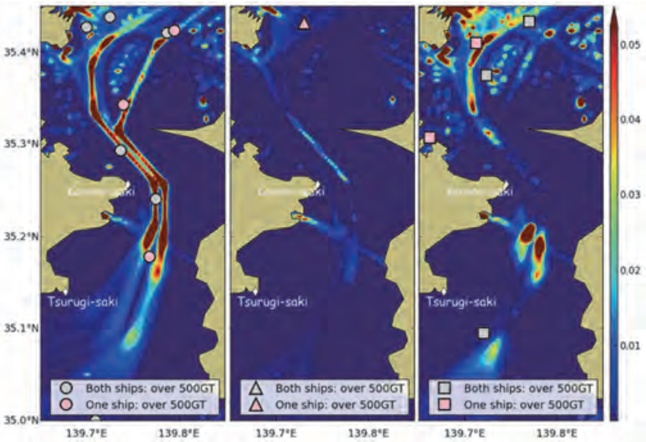

Figure 5　Estimation of geometrical collision frequency distributions by type of encounter situation (left: overtaking, middle: head-on, right: crossing) 42)

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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Development of Comprehensive Simulation System for Autonomous Ships

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1. INTRODUCTION

Interest in Maritime Autonomous Surface Ships (MASS) has increased in recent years, and efforts to realize MASS are also underway in Japan. The roadmap for practical use of autonomous ships released by Japan’s Ministry of Land, Infrastructure, Transport and Tourism (MLIT) proposes realization of highly automated autonomous ships (Phase III), in which the system makes some final decisions, targeting the year 2025. The Nippon Foundation’s unmanned ship project, MEGURI 2040, also aims at practical use of unmanned ships in 2025 through demonstration experiments and other activities. In autonomous ships and unmanned ships, prevention of accidents due to human factors and improvement of safety by support by the autonomous system are demanded. On the other hand, not only technological development but also social acceptance is necessary for operation of autonomous ships. In order to gain social acceptance, it is necessary to show that autonomous ships are safe, that is, the assumed risks have been reduced to the allowable range. The National Maritime Research Institute (NMRI) is studying methods for evaluating safety and construction of the system necessary in such evaluations. This paper reports on a comprehensive simulation system consisting of multiple simulation systems, beginning with a ship handling simulator, and an evaluation method using simulations.

2. FLOW OF DEVELOPMENT AND CERTIFICATION OF AUTONOMOUS MANEUVERING SYSTEMS

Figure 1 shows the process of commercialization of unmanned automated driving services in the automotive sector, where automation advanced from an earlier date. The figure shows that the series of processes consisting of 1) Setting of the use case, 2) Setting of the traveling environment and operating conditions, 3) Vehicle technologies, development and selection of automated systems, development and improvement of infrastructure and peripheral technologies, 4)Demonstration of technology in a simulated environment, test course and public roads and 5) Demonstration of services, is carried out while conducting reviews based on the issues identified in the course of these processes [1]. In 4) Demonstration of technology and 5) Demonstration of services, problems are identified and test scenarios are confirmed through cooperation between the developer and the certifying entity, and the performance standards, etc. necessary for certification are studied simultaneously with development. It is thought that study of commercialization and certification of automatic operation systems for ships will be carried out by a similar process, and in the process of demonstration of technology by test course operation and simulations, a comprehensive simulation system which can be used in place these demonstrations will be necessary. Moreover, since these verifications are carried out in cooperation with the developer, providing the functions necessary in development was also one purpose of the system discussed in this paper.

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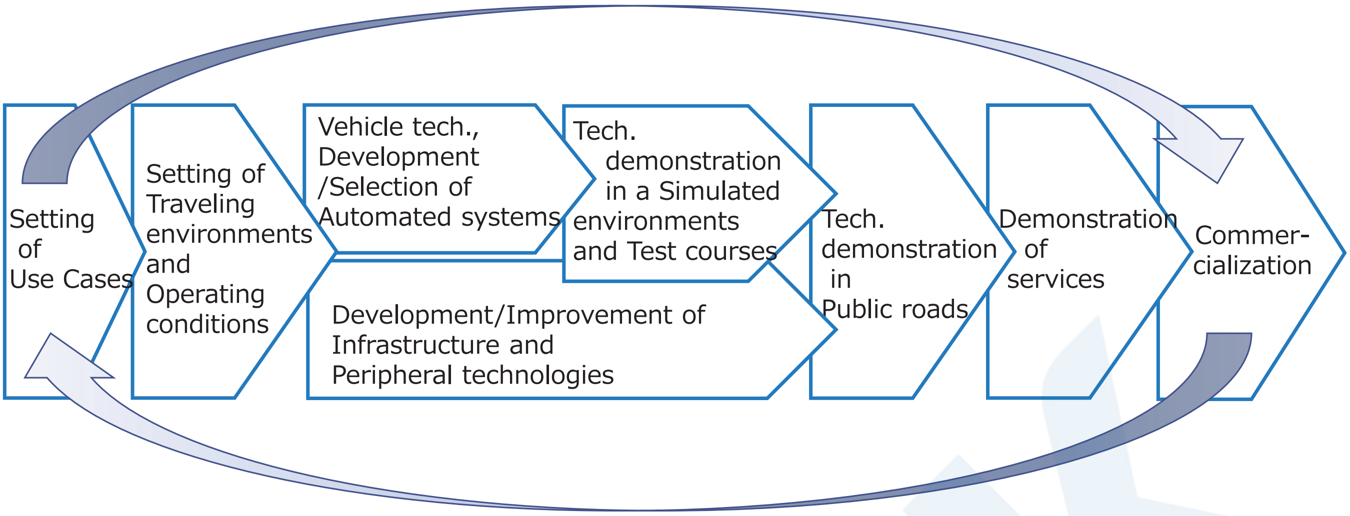

Figure 1 Process of commercialization of automated driving services (source: “Progress report on efforts to support the development of autonomous driving technologies and create adequate policies Version 5.0”)

3. OVERVIEW OF COMPREHENSIVE SIMULATION SYSTEM

Configuration of the comprehensive simulation system utilizing the following five systems is under study.

1) Ship Handling Simulator (SHS)

This is a full mission-type ship handling simulator. Various types of evaluations considering human involvement are possible, including evaluation of the human machine interface (HMI), evaluation of the timing of transfer of ship operation authority to the crew in emergencies, evaluation of maneuvering actions in waters shared with existing ships, etc.

2) Fast Time Ship Simulator (FTSS)

This system makes it possible to conduct simulations in a significantly shorter time than the actual time, and conduct comprehensive verifications under set conditions.

3) Sensor verification system

Enables verification of the detection performance of the system that detects the condition of navigation by other ships, which is connected to the automation system.

4) Evacuation simulation

Enables verification of the evacuation condition under abnormal conditions such as fires, etc.

5) Engine remote monitoring system

Enables monitoring of the engine condition from shore.

Here, general names which indicate the system function are used as the names of these systems, except for the FTSS. The following discussion will center on the SHS and FTSS, as study of the concepts (e.g., clarification of verification targets, etc.) of the sensor verification system, the evacuation system and the engine remote monitoring system began in FY 2021. In addition, the work on shipboard is diverse, and the evaluation methods differ depending on the target. The evaluation targets for the SHS and FTSS are items related to ship handling, and comprise the following functions.

1) Automatic ship handling (berthing/deberthing, collision avoidance, ship handling during stormy weather)
2) Remote monitoring and maneuvering
3) Emergency (transfer of ship handling from system to crew)

In order to use the SHS or FTSS in development and certification, it is necessary to connect the target automation system (algorithms for automatic collision avoidance maneuvering, etc. or the system incorporating algorithms). A standard interface called a functional mock-up interface (FMI) is used for this purpose. In addition, we are also studying the creation of a maneuvering operation model database to reproduce target ships and creation of a scenario database that generates scenarios considering information such as on the target sea area, etc.

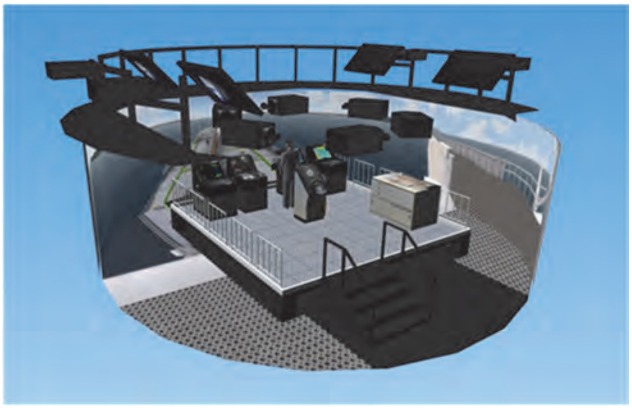

Figure 2 Image of ship handling simulator (prepared in March 2021)

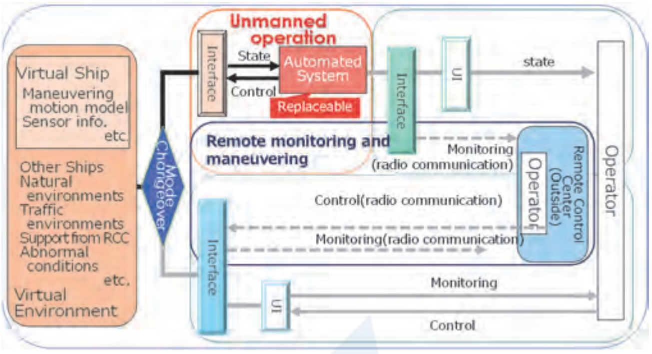

Figure 3 Conceptual diagram of ship handling simulator

4. FUNCTIONS OF SIMULATION SYSTEM

4.1 Ship Handling Simulator (SHS) (Fig. 2)

Regarding the levels of MAAS or automation systems, it can be thought that there are several steps from the current level, where seafarers make judgments and carry out ship handling and the system supports those activities, to the level of a fully autonomous automated ship which navigates without the need for human involvement, and development will advance based on those steps. In particular, in the stage of development where work on the ship's bridge reaches fully autonomous, automated ship operation, it will be necessary to conduct a safety evaluation that considers the involvement of the crew. For example, it will be necessary to verify that the necessary time and information can be secured when it is judged that the system is unable to respond in an emergency, etc. and ship operation is transferred to the crew. Regardless of the development stage of the ship, it is necessary to consider coexistence with existing ships operating under human control. In this case, the target of evaluation is operation that does not cause feelings of unease to operators on those ships.

One distinctive feature of the SHS is the fact that evaluations considering this kind of human involvement are possible. This is also necessary in order to verify various conditions, including trouble and environments which are difficult to reproduce in actual-sea experiments.

The functions required in the SHS are as follows, and are also shown schematically in Fig. 3.

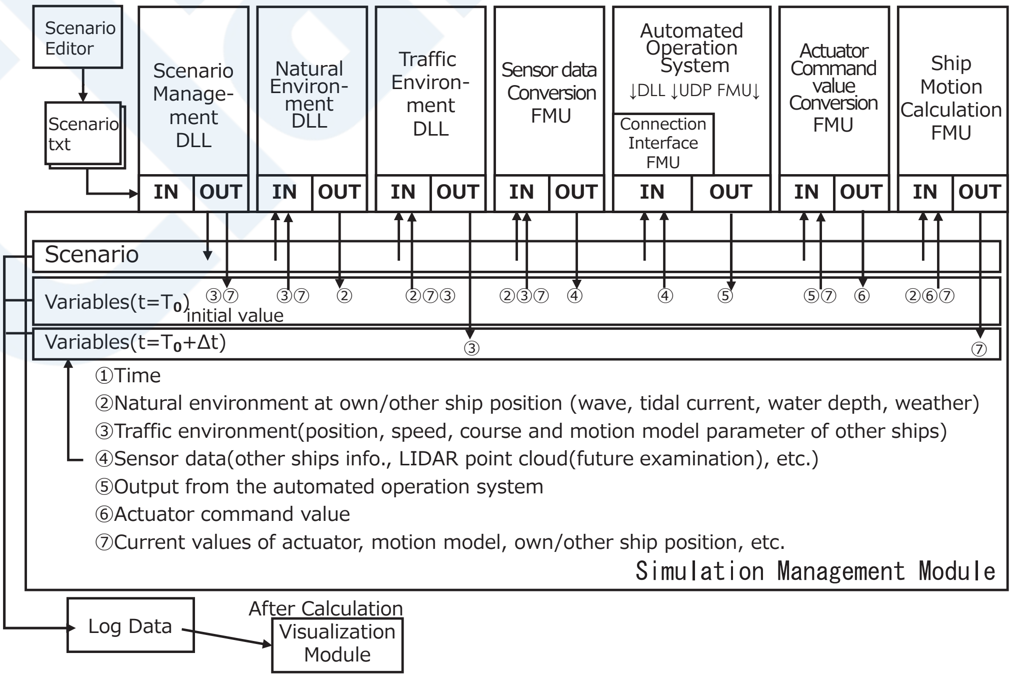

Figure 4 Overview of operation of fast time ship simulator

1) Automatic ship operation
  - Connection of arbitrary automatic ship operation program
  - Incorporation of ship motion model corresponding to evaluation target
2) Remote monitoring and maneuvering
  - Remote telecommunication system
  - Reproduction of information presentation function
  - Reproduction of telecommunication speed, lack of data, etc.
3) Transfer of ship operation to crew, evaluation of HMI
  - Reproduction of information provision function
  - Reproduction of ship operation switching device and functions
  - Reproduction of display and operation devices corresponding to evaluation target
  - Free layout of navigation equipment, function for connection with equipment brought in from outside
4) Incorporation of various types of information
  - Incorporation of own ship's collision avoidance function in other ships
  - Preparation of various types of sensor information
  - Formation of sensor information suited to the evaluation object
  - Reproduction of information accuracy (noise, lack of data, updating interval, etc.)
  - Incorporation of engines, thrusters, steering gear
  - Function for expression of abnormal events
  - Reproduction of malfunction of sensors, engine, power supply, etc.
5) Testing environment
  - Test case creation function
  - Display of ship operation results and results of analysis of various types of indexes

The SHS also includes new functions not available in existing ship handling simulators, and we are conducting a study aiming at implementation of those functions.

4.2 Fast Time Ship Simulator (FTSS)

In safety evaluations by the SHS, simulations under a diverse range of conditions are necessary. In cases where it is not necessary to consider human involvement, use of the Fast Time Ship Simulator (FTSS) is effective, as calculations are executed at high speed, and output is not limited to real time.

Figure 4 shows the outline of the FTSS. The SHS and the simulation modules that operate on the FTSS, including the environment, other ship, sensor, ship motion calculation modules, are connected with the simulation management module as DLL (Dynamic Link Library) through FMI as an FMU (Functional Mock-up Unit), and function as an FTSS in which the total system tests the operation of the autonomous ship. The outline of the respective modules is as follows.

1) Simulation management module

   This is module performs the series of operation including starting the modules that comprise the simulator, initializing the modules based on the scenario, executing the modules, controlling the data output from the modules, outputting logs, outputting for visualization, judging completion based on the scenario, time update, etc., and manages the operation of the FTSS.

2) Scenario management DLL

   This module is in charge of scenario management. It prepares scenarios in response to the simulation management module and is used when executing simulations. The purpose of the scenario management DLL is to read the setting items necessary to execute a simulation from the scenario file, and load the scenario information so it can be used by the simulation management module.

3) Natural environment calculation DLL

   The purpose of this module is to output ocean surface winds and tidal currents, which change depending on the time and position of the own ship and other ships. It outputs information on ocean surface winds, tidal currents, the water depth, weather and night or day conditions based on the time and the coordinates of the own ship and other ships. In order to improve the calculation speed, it has a function which prepares datasets by calculating the grid data for these items in advance for 24-hour time periods.

4) Traffic environment DLL
   Based on the values set by the scenario, this module generates a set number of other ships and performs navigation and automatic collision avoidance for each of the other ships.

5) Sensor data conversion FMU
   Based on the real values obtained by the own ship state, other ship state and natural environment simulation calculations, this module creates and supplies sensor data which are consistent with the input of the SHS by superimposing noise simulating the measurement error of measuring instruments and performing processing in a form that simulates the output of the ship's navigation equipment.

6) Ship operation system connection interface
   This is an interface for connecting ship operation automation systems constructed with interfaces other than FMI to the simulation system by FMI. Because ship operation automation systems were thought to have diverse execution forms and input formats, easy revamping of this interface is necessary. At present, connection via networks other than FMI connection is assumed.

7) Actuator command value conversion FMU
   This device converts the maneuvering commands received from the ship operation automation system by way of a FMI, etc. to a form that the actual actuators can receive as inputs, simulates the mechanical response of the actuators, and outputs the results to the ship motion calculation FMU as the present values of the actuators (rotation speed, rudder angle, etc.).

8) Ship motion calculation FMU
   In the ship motion calculation FMU, the ship operation information and quantities of state of the natural environment calculated by the actuator command value conversion FMU and the natural environment calculation DLL are input via an FMI, and the module performs time update calculations of the quantities of state of the own ship and outputs the results to the simulation management module by way of an FMI. We are also studying the creation of a maneuvering motion simulation tool which outputs the maneuvering motion parameters necessary in setting the maneuvering motion model based on the main items and actuator composition, and use of the parameters generated by that tool by this FMU in evaluations of collision avoidance maneuvering, etc.

9) Visualization module
   A function for more detailed analysis of the execution results is provided by visualizing the visualization log output from the simulation by display of electronic charts, 3D display and evaluation indexes, as shown in Fig. 5. The evaluation indexes are described in Chapter 5.

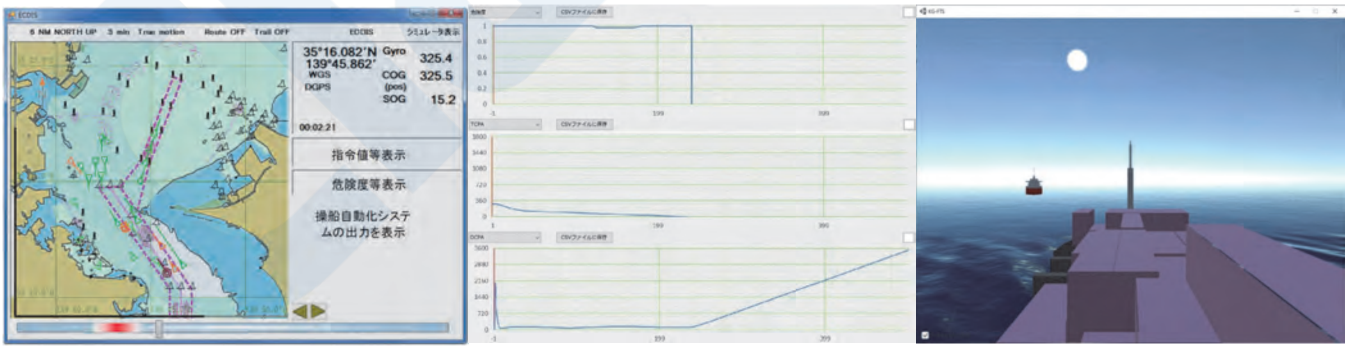

Figure 5 Visualization of results
Left: Display of electronic chart, middle: display time-series indexes, right: 3D display

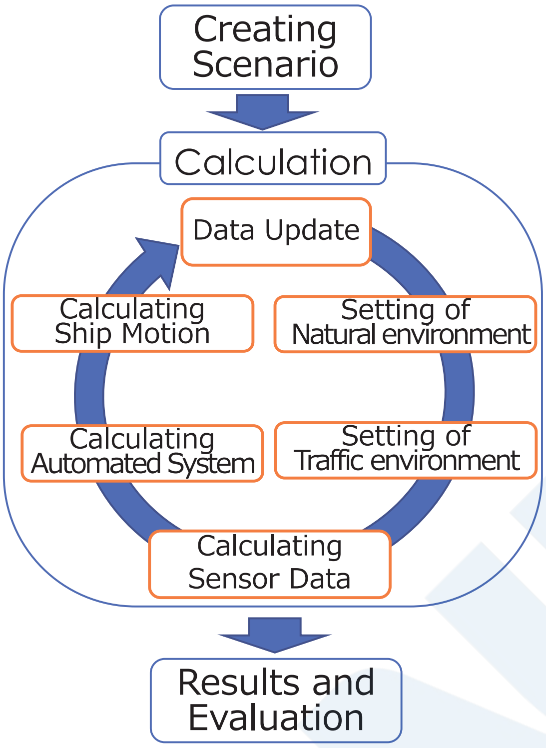

Figure 6 Simulation execution procedure

4.3 Simulation Execution Procedure

Figure 6 shows the simulation execution procedure using the FTSS as an example. When a calculation is executed in the SHS, this procedure also includes the creation of data for display items such as scenery images and displays of the ship's navigation equipment; however, the basic flow is the same.

1) Scenario creation

In scenario creation, the initial conditions of the simulation are set. The items set here include the own ship's state, position and planned course (information on course change points), the traffic flow, such as the position, speed and other information concerning other ships, the conditions of the natural environment, such as waves, wind, day or night, etc., and geographical conditions such as the water depth, obstacles to navigation and the like. A text file is created using the scenario creation editor. The scenario management DLL mentioned in Section 4.2 2) is in charge of loading the scenario file.

2) Calculation execution

In simulation calculations, the data are updated in each cycle, as shown in Fig. 6, and calculations are continued until the results satisfy the condition for completion of the simulation. Although the condition for completion is determined by the scenario, cases such as arrival at the final course change point, etc. may be used. The modules described in Section 4.2 3) to 8) are responsible for this operation.

3) Analysis and evaluation of results

In addition to the course track, heading and speed of the own ship and other ships, the output of the autonomation system, etc. is also recorded, making it possible to evaluate the ship operation results. We are also studying construction of a debugging environment which enables easy feedback to the target system during development, for example, by making it possible to reproduce the results from any arbitrary timing.

4.4 Standard Interface (FMI)

FMI is a free standard that defines the container and interface for the exchange of dynamic models using a combination of XML files, binary and C code zip-compressed into 1 file. The code and documents are publicly available [2].

Development and use have been promoted in the automotive sector. In system development, it is difficult to connect models described with the various simulation tools of each development company, but unification of the simulation tools would be unrealistic. Therefore, FMI was constructed as a public project in Europe with the aim of standardizing a common interface for model connection which does not depend on the tool and exchanging and connecting models between different simulation tools.

Construction of a simulation platform applying FMI has also been promoted in the maritime sector, centering on Norway, and a specialized code is publicly available 3).

In the NMRI simulation system, the automation system, sensor data, actuator and ship motion modules, which differ depending on the developer and development target, as mentioned previously, were also constructed by using FMI, enabling connection of any desired system.

5. STUDY OF EVALUATION METHODS USING SIMULATIONS

5.1 SHS and FTSS

The SHS is mainly used to obtain subjective evaluations by ship operators and ship operation results for limited scenarios. In evaluations of the collision avoidance maneuvering function, it is used in evaluations of the appropriateness of the condition of collision avoidance by the own ship and other ships, and in evaluations of the HMI with the automatic collision avoidance maneuvering function. In case collision avoidance maneuvering is not possible and ship operation is transferred to the human ship operator, it is also used to evaluate whether this transfer can be carried out properly.

In evaluations by the SHS, the results of evaluations corresponding to more realistic navigational environments are obtained together with subjective evaluations based on use experience, but it would be difficult to evaluate all of the possible scenarios for encounter situations. For this reason, the FTSS is used in evaluations for confirmation of the system safety validation based on a validation plan and validation tests under comprehensive environmental conditions set by the certifying entity. It is thought that efficient and effective evaluations can be carried out by targeting verification of scenarios that are difficult to judge in an evaluation by FTSS for verification by experienced ship operators using the SHS.

Table 1 Degree of collision risk

Target	Evaluation index	Outline
Degree of collision risk	CJ 12)	The degree of collision risk is calculated based on the relative heading with the other ship and its rate of change, and the distance between the 2 ships and its rate of change.
	SJ 13)	The changes in the relative distance and relative heading with the other ship are given in fuzzy representations in 3 levels, considering encounter situations, and the degree of collision risk of the 2 ships calculated based on a combination of the two variables is shown by an index system ranging from 3 (safe) to −3 (dangerous).
	CR 14)	Using TCPA and DCPA as variables, the degree of collision risk of 2 ships is shown by fuzzy inference, considering the ship lengths and maneuvering performance.
Degree of maneuvering difficulty	BC 15)	The degree of maneuvering difficulty is evaluated by obtaining the degree of obstruction by ships existing in the surrounding waters (collision avoidance space obstruction) by multiplying the degree of risk of a collision by another ship by a weight corresponding to the preference of the means of collision avoidance by speed change or course change.
	ES 16)	The magnitude of the load borne by the ship operator is shown by quantification, by substituting the time margin until the risk of collision with an obstacle or another ship becomes manifest for the sense of risk felt by the ship operator.
	OZT 11)	The region where the direction of progress of the own ship is obstructed by the presence of other ships is defined as an OZT (Obstacle Zone by Target), and the margin for collision avoidance maneuvering by the own ship is evaluated based on the distribution of the OZT.

5.2 Scenarios for Use in Evaluations

In certification of automation systems such as an automatic collision avoidance function, etc., the reliability and appropriateness of the software is set as a test item by designating hazards, and a simulation is carried out under those conditions to confirm that there are no problems. As hazards, scenarios are set under comprehensive environmental conditions, considering encounters with other ships, judgment of an encounter situation, lost signals and the like, and are then used in the test.

The evaluation scenarios when evaluation of a collision avoidance algorithm is to be carried out by FTSS are considered to comprise scenarios for verifying the basic functions in 1 to 1 encounter and in multiple overlapping encounters with other ships, which are assumed to occur in congested waters. For 1 to 1 encounter, the number of necessary scenarios is limited by restricting the range to the area where watchkeeping is performed, and the scenarios are created by comprehensively setting the arrangement, course and speed of the other ship. However, an infinite number of scenarios can be prepared for multiple overlapping encounters. Therefore, when the collision avoidance maneuvering function is the subject of verification, the scenarios are prepared from the following viewpoints:

1) Random setting of other ships encountered by the own ship
2) AIS (Automatic Identification System): Encounter situations which occur frequently and encounter situations in which maneuvering seems difficult are extracted from the tracks recorded in data, etc.
3) Collection of scenarios used in evaluations of the collision avoidance maneuvering function from the literature on collision avoidance maneuvering, etc. 4)
4) Extraction of scenarios from cases of maritime accidents 5)

Regarding preparation of scenarios using AIS data, in the automotive sector, a data storage/classification type scenario-based approach 6) has been proposed, in which a scenario database is created by classifying and storing the accumulated traffic flow observation data in systematic categories. Since AIS data includes information such as ship positions, ground speeds, headings, MMSI, IMO number, destination(s) and the like 7), the individual data can be assigned to each ship based on information specific to the ship, such as MMSI, etc., and course tracks can then be obtained by sorting in time order. Therefore, the construction of a scenario database by using a similar technique is under study. In particular, we are also studying the creation of models that reflect the current condition and addition of scenarios to reproduce ships that are not equipped with AIS. For coastal ships with displacements of less than 500 GT, this would be based on estimation from data acquired by AIS-equipped ships, use of radar data, etc., and for fishing boats, surveys of the condition of navigation in the targeted waters would be conducted through interviews with fishing cooperatives and others.

5.3 Study of Evaluation Indexes

The conceivable evaluation indexes for collision avoidance maneuvering include a combination of the distance to the closest point of approach (DCPA) and time to the closest point of approach (TCPA) using course track and ship operation records obtained during experiments and conventional quantitative evaluations of the degree of collision risk, as shown in Table 1. A method for evaluating the suitability of this approach for legal compliance has also been advocated, particularly by Norway 8) 9). In this evaluation method, an evaluation of collision avoidance is conducted for head-on, crossing and overtaking encounters, which are the three types of ship encounter situations mentioned in The Convention on the International Regulations for Preventing Collision at Sea (COLREGs). Several other evaluation methods have also been proposed, for example by the subjective degree of risk and subjective evaluation of collision avoidance of ship operators 10), and evaluation utilizing OZT, 11), among others.

Although compliance with the rules of navigation by autonomous ships is important for preventing maritime accidents, quantitative evaluation is difficult because the existing rules include ambiguity premised on human ship operation 7). In the method proposed by Norway, the rules are evaluated by a mathematical formula using multiple parameters which were derived from papers described past accidents or collision avoidance. While there is room for further study, the proposed method is extremely interesting as a quantitative evaluation method. Furthermore, in encounters where multiple ships interact, compliance with good seamanship by the seafarers is demanded. For encounters where a clear relationship exists, evaluation in accordance with the rules is necessary, and for complex encounters, an evaluation index corresponding to the target is required, for example, evaluation utilizing subject viewpoints. However, either type of evaluation must satisfy the system requirements.

6. CONCLUSIONS

This paper has presented an overview of the comprehensive simulation system which is now under development by the National Maritime Research Institute (NMRI), and has described evaluation methods for automatic collision avoidance maneuvering. Safety evaluation will be indispensable in realizing practical use of autonomous ships, and those standards will also provide a guideline for future development. The authors hope to improve the comprehensive simulation system, which will support that development, and the standards for safety evaluations in cooperation with the related companies, beginning with developers that participated in the MEGURI 2040 Project.

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Automation Levels of Automated/Autonomous Ships

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1. INTRODUCTION

Against the backdrop of rapidly progressing ICT and sensor technology, research and development of automated and autonomous ships is now advancing with the aims of enhancing navigational safety and improving the maritime work environment. Demonstration experiments and similar activities for practical application are also underway, not only in Japan, but also in many other countries, with the momentum to reach commercial use within several years. In Japan, the MEGURI 2040 Project (Joint Technological Development Program for the Demonstration of Unmanned Ships) is being promoted with the support of the Nippon Foundation, and demonstrations of six unmanned ships by a consortium of five partners will be conducted under the project by the end of FY 2021 (March 2022).

On the other hand, acceptance by society is essential for practical application of these systems, and public knowledge of autonomous ships and understanding that they are safe is necessary for heightening acceptance and achieving wide dissemination. In order to support practical application of autonomous ships and heighten their acceptance in society so as to support dissemination, the Japan Ship Technology Research Association (JSTRA) is carrying out the “Safety Assessment of Unmanned Ships Project” in conjunction with the MEGURI 2040 Project with the support of the Nippon Foundation under a 4 year plan that began in FY 2020. In this project, the JSTRA will prepare the safety evaluation environment for conducting a preliminary evaluation and safety assessment of the demonstration experiments in the MEGURI 2040 Project and will also summarize the safety requirements for realizing unmanned navigation and unified guidelines for handling automated and remotely operated ships and unmanned ships.

Although the expressions “unmanned ship” or “automated ship” have been used until now, these terms do not necessarily give a firm image of the ships and ship operation which is envisioned. For example, in the case of an unmanned ship, what does “unmanned” actually mean? Does it include intervention by the crew during operation? The images assumed by people differ. In particular, the modes of operation considering human involvement are diverse, ranging from manual operation to fully automated operation. A common recognition of the system image, for example, which modes of automated operation are the targets of development and evaluation, which is shared by all related parties is necessary.

Therefore, this report describes the automation levels which define automation system and their relationship with the ship operators that use them, and their necessary conditions.

2. CONTROL MODES AND AUTOMATION LEVELS

In general, when a human operator performs a task, such as maintaining or transitioning a controlled object, for example, ship operation, to a desired state, the operator acquires information on the controlled object through his or her own five senses, recognizes the situation based on the acquired information, and makes decision of the action that should be taken. The operator then gives commands concerning the action to be executed to the actuator of the controlled object through the controllers, and the task is realized by repeating this loop. When the controlled object is large or in a remote location, information on the controlled object is acquired by collecting information by sensors in addition to the operator’s five senses, and integrating and displaying the information on a display device. In this case, the control loop comprises the controlled object, sensors, information display device, operator, controllers and actuators. In automation, a control system is included in this loop, and performs the processes of integrated display of the sensor information, decision making of actions, and issuance of operational commands to realize those actions in place of the human operator.

There are several stages in this control, ranging from manual control to fully automated control. Sheridan defined the control

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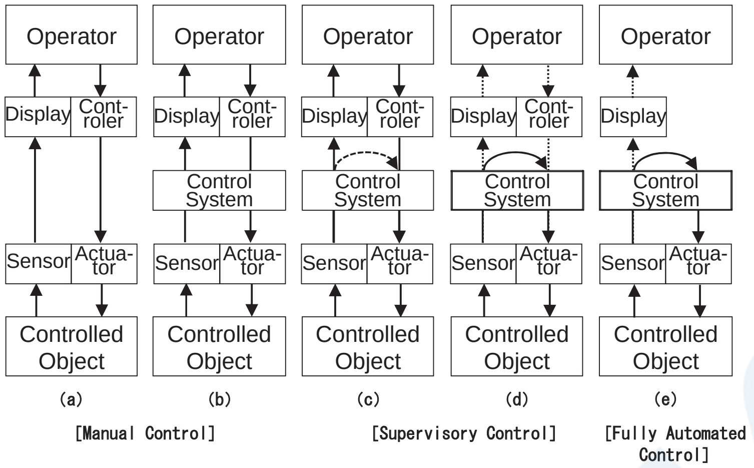

Figure 1 Range of control modes 1)

modes 1) shown in Fig. 1 through research on supervisory control of teleoperator robots.

In Fig. 1, (a) shows the diagram of the “Manual Control” mode. In (b), a control system is included in the loop, and performs information acquisition and display, and transmits the control commands set by the operator to the actuator, but control itself is performed by the operator. In (c) and (d), the control system performs some fraction of control, and minor loops are closed through the computer. In (c), the operator’s loop is responsible for the main fraction of control, and the control system loop provides assistance, and in (d), the relationship is reversed, as the control system performs the main fraction, and the operator provides assistance. The control mode in (c) and (d) is called the “Supervisory Control” mode, since the operator supervises the process of the control and the actions of the control system. When necessary, the operator intervenes in control by the control system by issuing control commands to realize the control target. Finally, (e) is the “Fully Automated Control” mode. In this mode, the operator can monitor the controlled object and the actions of the control system by way of information display devices, but cannot intervene in the control system. The concept of these modes is an index which expresses the relationship between the operator and control.

Sheridan also proposed a 10-step “Scale of degrees of automation” 1) as levels that show the relationship between an automatic control system and the human operator. These automation levels are summarized centering on operation methods that can be taken with information given by the operator. Table 1 shows the automation levels.

Table 1 Automation levels according to Sheridan 1) 2)

Automation level	Definition
1	The human operator performs all tasks without support from the control system.
2	The system offers a complete set of action alternatives, and the operator selects and executes one of those alternatives.
3	The system suggests a small number of effective action alternatives to the operator. The operator decides whether to execute one of the small number of alternatives or not, and the action is executed by the operator.
4	The system offers one suggestion to the operator. The operator decides whether to execute that suggestion or not, and the action is executed by the operator.
5	The system suggests one the most effective action to the operator. If the operator approves the suggestion, it is executed by the system.
6	The system offers one suggestion to the operator. If the operator does not veto the suggestion within a certain time, the system executes that suggestion.
6.5	The system presents one suggestion to the operator, and simultaneously executes that suggestion.
7	The system decides and executes all actions automatically and informs the operator of the actions taken.
8	The system decides and executes all actions automatically and informs the operator of the action taken if requested by the operator.
9	The system decides and executes all actions automatically. The actions executed are reported to the operator only if the system judges reporting to be necessary.
10	The system decides and executes all actions automatically.

It may be noted that Table 1 shows 11 automation levels 2), as level 6.5 was added by Inagaki et al. to soften the shock of automation.

Here, the levels where major changes occur in the relationship between the system and human operators are as follows.

(1) Between Levels 1 and 2: At Level 2, supporting information is provided as reference for policy decisions concerning control.

(2) Between Levels 4 and 5: Transition from execution of control by a human to control by the system.

(3) Between Levels 6 and 7: Means of human intervention are eliminated, and the system only reports the control results.

(4) Between Level 9 and Level 10: Even reporting to the human is stopped.

In terms of the control modes described above, Level 1 to Level 4 are the “Manual Control” mode, Levels 5 and 6 are the “Supervisory Control” mode, and the “Fully automated control” mode begins from Level 6.5.

These levels of automation proposed by Sheridan are used in study of the human factor in automation of the operation of aircraft and nuclear power plants, and have also been introduced as the most widely used classification method for automation systems, including study 3) of the human factor in the concept of automated driving at automation Levels 2 and 3 by the National Highway Traffic Safety Administration (NHTSA) in the United States. Thus, Sheridan’s automation levels cover the full spectrum from manual to fully automated control. Although little experience is currently available for unmanned ships, when setting the automation levels for unmanned ships, it is thought that Sheridan’s automation levels can contribute to study of the definitions of those automation levels and the items that should be considered when establishing those definitions.

3. AUTOMATION LEVELS OF OTHER INDUSTRIES OF TRANSPORTATION

As automation levels of transportation other than shipping industry, the following reports the Levels of Driving Automation and flight operation levels of drones.

3.1 Levels of Driving Automation

Driving automation levels were prepared independently by various organizations, including the German Federal Highway Research Institute (BASt) 4), the above-mentioned National Highway Traffic Safety Administration (NHTSA) 5) and the Society of Automotive Engineers (SAE) 6) from the beginning of the 2010s until around 2015.

In 2016, the NHTSA and the European Road Transport Research Advisory Council (ERTRAC) decided that the Levels of Driving Automation (LoDA) defined in SAE document SAE J3016 should be adopted, and following that decision, the SAE’s LoDA were also adopted worldwide as automation levels for automated driving systems.

3.1.1 SAE Levels of Driving Automation

The SAE’s initial Levels of Driving Automation (LoDA) for on-road motor vehicles were announced in 2014 as SAE J3016 (2014) 6).

The LoDA provide a classification method for driving automation systems, and are classified according to differences in the mutual roles of the human driver and the driving automation system. The LoDA in SAE J3016 (2014) 6) comprise the six levels in Table 2.

Table 2　Summary of levels of driving automation for on-road vehicles in 2014 Edition of SAE J3016

SAE Level	Definition
Human driver monitors the driving environment.	
LoDA 0 No Automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems
LoDA 1 Driver Assistance	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task
LoDA 2 Partial Automation	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.
Automated driving system monitors the driving environment.	
LoDA 3 Conditional Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene.
LoDA 4 High Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene.
LoDA 5 Full Automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

In this table, “driving mode” refers to types of driving scenarios such as expressway merging, high speed cruising, traffic jams and the like. Dynamic Driving Task (DDT) means all of the real-time functions required to operate a vehicle, for example, acceleration and deceleration, lane keeping, etc.

SAE J3016 has been revised twice in the past, and the 3rd Edition was released in April 2021. The main additions to date include the following.

- Addition of a fallback function (DDT Fallback) to the LoDA.
- Clarification of functions, including remote control of the Automated Driving System (ADS), which is an automation system.
- Introduction of the concept of Operational Design Domain (ODD) in order to incorporate the limits of the automation system and the response when those limits are exceeded into the automation system.
- Introduction of the concept of the subtask Object and Event Detection and Response (OEDR).
- Addition of detailed descriptions of the human driver or user (at levels where human driving is not assumed), the Automated Driving System, and the other vehicle components and systems, which are the “three primary actors” that play roles in driving.

Based on the added items, the conditions that differentiate the LoDA levels can be summarized as follows and have been incorporated in the SAE’s LoDA 7) in the revision of 2021, as shown in Table 3.

a) Whether the driving automation system performs either the longitudinal or the lateral vehicle motion control subtask of the DDT.
b) Whether the driving automation system performs both the longitudinal and the lateral vehicle motion control subtasks of the DDT simultaneously.
c) Whether the driving automation system also performs the OEDR subtask of the DDT.
d) Whether the driving automation system also performs DDT fallback.
e) Whether the driving automation system is limited by an ODD.

Table 3 Summary of levels of driving automation in 2021 Edition of SAE J3016

Level of driving automation	Definition
LoDA 0 No Driving Automation	The performance by the driver of the entire DDT, even when enhanced by active safety systems.
LoDA 1 Driver Assistance	The sustained and ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT.
LoDA 2 Partial Driving Automation	The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system.
LoDA 3 Conditional Driving Automation	The sustained and ODD-specific performance by an ADS of the entire DDT with the expectation that the DDT fallback- ready user is receptive to ADS- issued requests to intervene, as well as to DDT performance- relevant system failures in other vehicle systems, and will respond appropriately.
LoDA 4 High Driving Automation	The sustained and ODD-specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will need to intervene.
LoDA 5 Full Driving Automation	The sustained and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will need to intervene.

Although this classification concept includes items specific to self-driving cars, for example, items a) and b) above, it is nevertheless important for studying the automation levels of automated and autonomous ships, and has been incorporated in the guidelines of some classification societies.

3.2 Flight Operation Levels of Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles (UAVs) are a class of unmanned fixed-wing airplanes and rotorcraft which are capable of remotely operated or automatic flight. Accompanying the reduced cost and improved performance of UAVs, drones, a type of unmanned rotorcraft, are now used in an increasingly wide range of applications. For example, high expectations are placed on drones as a means of unmanned cargo transportation.

From the viewpoints of encouraging the use of drones and ensuring safety, the Public-Private Sector Conference on Improving the Environment for UAVs held in April 2016 set flight operation levels 8) for the automation levels for drones.

Figure 2 shows the flight operation levels of aerial unmanned vehicles (UAVs). The following three items may be mentioned as factors that determine the flight operation goals (level of full-scale operation) of UAVs.

(1) Control method: Remote control or Automated control?

(2) Visual range: Flight range within the visual line of sight (VLOS)? (If beyond VLOS, the flight range is also considered within visual range if an assistant is present.) Or beyond visual line of sight (BVLOS)?

(3) Populated areas: Is the flight zone a populated area? Or is it a less-populated area (areas with low possibility of entry by third parties, sea areas, rivers, lakes and marshes, forests, etc.)?

The following four flight operation levels for drones are set based on combinations of these three factors.

Level 1: Remotely piloted flight within VLOS
Level 2: Automatic or automation flight within VLOS
Level 3: BVLOS flight over less-populated areas (without deploying an assistant)
Level 4: BVLOS flight overpopulated areas above third parties (without deploying an assistant)

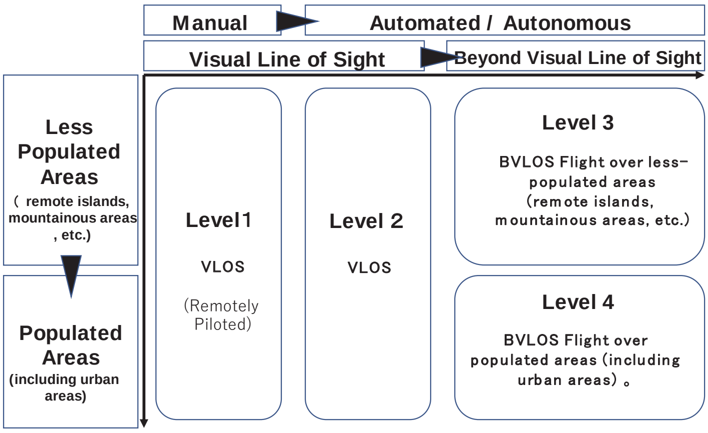

Figure 2 Flight operation levels of UAVs
(Source: Ministry of Land, Infrastructure, Transport and Tourism, Civil Aviation Bureau, Directions of New System for Realization of Level 4 UAVs)

At present (2021), it is necessary to take safety measures and obtain the approval of the Ministry of Land, Infrastructure, Transport and Tourism in order to fly drones in the following airspaces.

Airspace A: Airspace in skies around airports, etc.
Airspace B: Airspace with an altitude of 150 meters or more above the ground surface or water surface.
Airspace C: Skies above densely inhabited districts set based on the results of the National Census.

Although Level 4 flight in Airspace C is not currently approved, effective use of drones is desired in the future. Therefore, together with setting flight operation Level 4 as a high-risk flight category and encouraging the use of drones by rationalization and simplification of the existing approval and certification system for flights, creation of a drone certification and piloting license system for drone pilots, and establishment of common operation rules which must be observed by drone pilots are being promoted [9)].

The distinctive features of the flight operation levels of these UAVs are twofold: the distinction between remotely piloted operation and automatic and automation operation, and the distinction between flight operation levels depending on whether the range is within the visual line of sight (VLOS) or beyond VLOS (BVLOS). These concepts also provide suggestions for how remotely operated ships should be treated when considering the automation levels for automated and autonomous ships in the future.

4. AUTOMATION LEVELS OF SHIPS

The following presents an overview of the automation levels for ships and various types of ship equipment which are now being studied by several organizations.

4.1 International Maritime Organization

Considering the recent increase in projects for developing Maritime Automation Surface Ships (MASS), those are expected to improve safety and economy, the International Maritime Organization (IMO) began an IMO “Regulatory Scoping Exercise (RSE) for the use of Maritime Automation Surface Ships (MASS)” in 2018 in preparation for providing a clear and consistent regulatory framework to designers and owners of MASS and other interested parties. The outcome [10)] of the RSE was reported and approved in the 103rd session of the Maritime Safety Committee (MSC 103) held in 2021. Several levels of automation were proposed in this activity.

4.1.1 Degrees of Automation for IMO Regulatory Scoping Exercise (RSE)

In advance of the Regulatory Scoping Exercise for MASS, provisional definitions of “Maritime Automation Surface Ship (MASS)” and the degrees of automation were established so that the RSE could be carried out with consistency among the various organizations involved. The following are the definition of “Maritime Automation Surface Ship (MASS)” and the degrees of automation.

Provisional definition of "Maritime Automation Surface Ship (MASS)":

"Maritime Automation Surface Ship (MASS) is defined as a ship which, to a varying degree, can operate independent of human interaction."

Provisional definitions of degrees of automation:

Degree One

Ship with an automated process processing function and decision-making support function: Seafarers are on board to perform operation and control of the onboard system and functions.

Degree Two

Remotely controlled ship with seafarers on board: The ship is controlled and operated from another location. Seafarers are available on board for operation of the ship systems and functions.

Degree Three

Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.

Degree Four

Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself.

The following two items may be mentioned as factors that determine the degree of automation.

(1) Operation mode: Difference of manually operated ship, remotely operated ship and autonomous ship
(2) Presence of seafarers on board: Are there any seafarers on board the ship?

There was also a view that the above-mentioned degrees of automation should be improved by developing a more detailed system of degrees in order to study safe operation and regulation when conducting the RSE. However, these degrees of automation were used in their existing form in the RSE due to the time required to reach the conclusion of the exercise, and were then studied again after the completion of the RSE.

4.1.2 Other Proposed Automation Levels

In addition to the degrees of automation described in the previous section, several other automation levels were proposed in the RSE conducted by the IMO.

One was a proposal submitted by Australia and four other countries with the aim of strengthening the degrees of automation for the RSE [11). This proposal was based on the idea that, in order to be socially and ethically acceptable, control and responsibility for automated operation should ultimately rest with a human, even in automated ships, and asserted that an autonomous system should be supervisory control, limited to its operation under the supervision and responsibility of a suitably qualified human.

In this proposal, the factors that determine the level of automation are defined as the "Level of automation (technical)" and "Operational control" by humans, and the levels of autonomy and control are set on this basis. Concretely, the technical levels of automation are set in 4 levels and operational control by humans is set in 2 levels, as described below, and the levels of autonomy and operational control are defined by the combinations of these levels.

Level of autonomy (technical)

A0 – Manual: Manual operation and control of ship systems and functions, including automation at the individual system level for simple tasks and functions.

A1 – Delegated: The permission of a human operator is required for functions, decisions and actions, and the operator can override the system (intervene) at any stage.

A2 – Supervised: The permission of the operator is not required for functions, decisions and actions. The operator is always informed of all decisions taken by the system, and can override the system at any stage.

A3 – Autonomous: The system informs the operator in case of emergency or when ship systems are outside of defined parameters (outside ODD). The permission of the operator is not required for functions, decisions and actions. The operator can override the system at any stage.

Levels of operational control

B0 – No qualified operators on board

Exercise of meaningful human control and supervision is available remotely.

B1 – Qualified operators on board

Qualified operators who exercise meaningful human control/supervision are on board.

The levels of autonomy and control are arranged as a matrix of the technical level of autonomy and the level of operational control, as shown in Table 4.

Table 4　Levels of autonomy and control

		Operational control	
		B0: No qualified operators on board	B1: Qualified operators on board
Technical level of autonomy	A0: Manual		A0-B1
	A1: Delegated	A1-B0	A1-B1
	A2: Supervised	A2-B0	A2-B1
	A3: Autonomous	A3-B0	A3-B1

For example, in this table, A2-B0 means the ship is operating at the Supervised level A2 under condition B0, in which the ship is operated remotely by a qualified operator.

These levels of autonomy and control were also used in setting the targets of study in “SAFEMASS Study of the risks and regulatory issues of specific cases of MASS” 12) by the European Marine Safety Agency (EMSA). That study examined the newly arising risks and regulatory issues for ships with autonomy and control levels of A3-B1 (Qualified operator on board operates with an Autonomous level system) and A2-B0 (Remote operation with a Supervised level system).

As one additional case, in the activities of the International Standardization Organization (ISO), the ISO is planning to establish an international standard for the basic terminology and concepts to provide a method of communicating the concepts, etc. related to autonomous ship systems. A general framework that can be used to compare various definitions of “degree of autonomy”13) was proposed in the 100th session of the Marine Safety Committee (MSC100) of the IMO, and mentioned “Operational complexity,” “Automation Level” and “Human Presence” as the three main factors of ship autonomy, and added “Human Responsible” (principle of human responsibility) and “Latency” (delay of timing in regaining control of an emerging problem) as “Additional factors.”

Although the details will be omitted here, it appears that this basic thinking follows SAE J3016 7), which is the most recent concept of driving automation levels for self-driving cars.

4.2　Automation Levels of Lloyd’s Register

Lloyd’s Register released guidance for autonomous ships, “Cyber Enabled Ships ShipRight Procedure Autonomous Ships Version 1.0, 14)” in 2016 before other classification societies, and this document included definitions of automation levels. In advance of this guidance for autonomous ships, Lloyd’s Register released guidance for cyber-enabled ships equipped with ICT and cyber systems, “Deploying Information and Communications Technology in Shipping – Lloyd’s Register’s Approach to Assurance,” proposing a comprehensive certification procedure for assuring safety, quality and reliability. Autonomous ships are positioned as one type of cyber-enabled ship. Furthermore, automation levels were created for autonomous ships, and are not limited to ship-handling but can also be applied to engine operation and various types of information services.

The 7 autonomy levels (AL) are shown below.

Autonomy levels

AL0: Manual – no autonomous function
- All action and decision making is performed manually by the operator.

AL1: On-ship decision support
- All actions at the ship level are taken by a human operator on board the vessel.
- A decision support tool can present options to the operator and influence the actions chosen.

AL2: On and off-ship decision support
- All actions at the ship level are taken by a human operator on board the vessel.

- A decision support tool can present options to the operator and influence the actions chosen.
- Data may be provided from on or off the ship.

AL3: 'Active' human in the loop

- Decisions and actions at the ship level are performed autonomously by the system under human supervision.
- It is possible for the operator to intervene and override high-impact decisions.
- Data may be provided from on or off the ship.

AL4: Human on the loop – supervisory control

- Decisions and actions are performed autonomously by the system under human supervision.
- It is possible for the operator to intervene and override high-impact decisions.

AL5: Fully autonomous (access possible)

- Operation in which decisions and actions are taken by the system with almost no human supervision.

AL6: Fully autonomous (access not possible)

- Operation in which decisions and actions are taken by the system completely without supervision.

The factors that differentiate these levels are as follows:

Whether a decision support system is provided or not (differentiating factor for AL0 and AL1 levels)
Availability of information from off the ship (AL1 and AL2)
Transition from a human operator executing actions to the system executing actions (AL2 and AL3)
Whether human intervention is possible or not (AL4 and AL5)
Whether human access to the system is possible or not (AL5 and AL6)

From the viewpoint of control modes, levels AL0 to AL2 are the "Manual Control" mode, AL3 and AL4 are the "Supervisory Control" mode and AL5 and AL6 are the "Fully Automated Control" mode.

4.3 Automation Levels of DNV

DNV released its Class guidelines: Autonomous and remotely operated ships 15) in 2018. This Guideline defines levels of autonomy. DNV thinks that the level of autonomy differs depending on the context in which automation is used, and therefore proposed guidelines for the levels of autonomy in ship-handling work ("navigation functions"), which requires a high order of observation, analysis and judgment, and the levels of autonomy in engine operation work ("engineering functions"), which can be divided into automatic support and automatic operation. The following introduces the levels of autonomy for navigation functions.

Based on the operational requirements and hazards to navigation set forward as part of the CONOPS / HAZID (Concept of Operations / Hazard Identification Study), the DNV guideline specifies the tasks which should be performed by a human operator and the location where the tasks, etc. are performed, and defines the "levels of autonomy for navigation functions" as follows.

Levels of autonomy for navigation functions

M: Manually operated functions

DS: System decision supported function

DSE: System decision supported function with conditional system execution capabilities

- Human acknowledgement is required before execution by the system.
- Referred to as "Human in the Loop."

SC: Self-controlled function

- The system will execute the function.
- The human is able to override the action.
- Referred to as "Human on the Loop."

A: Autonomous function

- The system will execute the function with no possibility for human intervention.

The following may be mentioned as factors that differentiate these levels of autonomy:

Whether a decision support system is provided or not (differentiating factor for M and DS levels)
Transition from mainly human execution of actions to execution by the system, and whether human approval is required for execution or not (DS and DSE)

Transition from human approval before execution of actions by the system to a human override capability (DSE and SC)

Whether human intervention is possible or not (SC and A)

In many cases, these distinctions overlap with the factors in the Lloyd's Register guidance.

The above-mentioned example of levels of autonomy for navigation functions was prepared in line with the content of the SAE guidelines for automobiles 7). While it was necessary to study the effect of the different characteristics of ships and self-driving cars, the fact that this study incorporated the content of the automotive guidelines 7) in the guidelines for autonomous ships is important.

4.4 Automation Levels of Bureau Veritas

Bureau Veritas released Guidelines for Autonomous Shipping 16) in 2019. The scope of the Guidelines includes systems used to enhance automation in shipping, ships equipped with automation systems capable, to varying degrees, of making decisions and performing actions, their associated remote control centers and surface propulsion systems. Because the environment in which these systems and equipment operate is expressed as including human interaction, the Guidelines define the three items "Degrees of automation," "Degrees of direct control" of the automation system, and "Degrees of remote control," and the condition of an automation system is characterized by the combination of those three degrees.

The content of the three items is described below.

Degrees of automation

A0: Human operated

- A human makes all decisions and controls all functions.
- The human is located aboard the ship (crew).
- The system or ship can perform information acquisition, but cannot analyze the information, make decisions or execute actions in place of the human.

A1: Human directed

- The human makes decisions and executes actions.
- The system or ship can perform information acquisition, analyze the information and suggest actions, but cannot make decisions or execute actions on behalf of the human.
- The human can be located aboard the ship (crew) or outside the ship at a remote call control center (operators).

A2: Human delegated

- The human can reject decisions made by the system.
- The system or ship can perform information acquisition and information analysis, and initiate actions, but confirmation by the human is necessary.
- The human can be located aboard the ship (crew) or outside the ship at a remote call control center (operators).

A3: Human supervised

- The human is always informed of decisions and actions, and can take control at any time.
- The system or ship can perform information acquisition and information analysis, and initiate actions under human supervision. Confirmation by the human is not necessary.
- The human can be located aboard the ship (crew) or outside the ship at a remote call control center (operators).

A4: Full automation

- The human can take control at any time.
- The system or ship can perform information acquisition and analysis, make decisions and execute operation without human intervention or supervision. The system invokes functions without informing the human, except in case of emergency.
- Supervision can be performed aboard the ship (crew) or outside the ship at a remote call control center (operators).

Degrees of direct control

DC0: No direct control

- There is no crew to monitor and control the system or ship, or to respond to system errors.

DC1: Available direct control

- The crew is onboard and can respond to alerts from the system, but may not be at the control station.

DC2: Discontinuous direct control

- The system or ship is monitored and controlled by the crew at the control station aboard. However, monitoring and control may be discontinuous for short periods.
- The crew is always available at the control station aboard, ready to take control in case of a warning or alert from the system.

DC3: Full direct control

- The system or ship is monitored and controlled at all times by the crew from the control station aboard.

Degrees of remote control

RC0: No remote control

- There are no operators in the remote control center outside the ship.

RC1: Available remote control

- Operators are available in the remote control center, and can respond to warnings from the system, etc.
- Operators may not be at the control station.

RC2: Discontinuous remote control

- The system or ship is monitored and controlled by operators from a remote control station outside the ship. However, monitoring and control may be discontinuous for short periods.
- Operators are always available at the remote control station, ready to take control in case of a warning from the system.

RC3: Full remote control

- The system or ship is monitored and controlled at all times by operators from a remote control station outside the ship.

In these Guidelines, the characterization of an automation system is expressed by the degrees of automation, which represent the relationship between the human and the system when performing tasks comprising information acquisition, information analysis, decision and action selection, and action implementation, and the degree of control, which is expressed in terms of whether operators or present on the ship or at a remote location or not, the control modes described in Chapter 2, and whether monitoring is performed continuously or not, etc.

The following are factors that differentiate the degrees of automation.

Whether a decision support system is provided or not
Whether human approval is required before execution of an action or not
Whether there is a human intervention function or not
Whether the system reports to the human operator or not

Many of these factors overlap with the factors in the Lloyd’s Register classification system.

The factors which differentiate the degree of control include the following, in addition to direct control and remote control.

Whether an operator is present or not
Whether there are time periods when a human is not present or not, and if so, the duration of the periods

Regarding continuous monitoring (“full control”) in the degrees of control, this was described clearly for the first time here. However, since temporary interruptions of continuous monitoring are also allowed in Level 3 automated driving of self-driving cars, it is thought that this should also be added to study of the automation levels of ships.

4.5 Automation Levels of Nippon Kaiji Kyokai (ClassNK)

ClassNK released Guidelines for Automated and Autonomous Operation on Ships Ver. 1.0 17) in 2020. These Guidelines are applicable to Automated Operation Systems (AOS) and Remote Operation Systems (ROS) which automatically operate some or all of the human decision-making processes of situational awareness, decision and action in shipboard work, and to ships equipped with such systems.

In order to categorize the AOS and ROS, the Guidelines use the following four indexes.

(1) Scope of automation
(2) Scope of remote operation
(3) Fallback Executor

(4) Contents of ODD

Of these, examples of categorization are provided for the three indexes (1) Scope of automation, (2) Scope of remote operation and (3) Fallback Executor, as shown below.

Scope of automation

Level 0:

- Humans execute all subtasks.
- The Fallback Executor of the subtasks is human.

Level I:

- Computer systems execute some decision-making subtasks.
- Fallback execution of the subtasks is shared between humans and computer systems.

Level II:

- Computer systems execute all decision-making subtasks.
- The Fallback Executor of the subtasks is a computer system.

Scope of remote control

Level 0:

- Crew onboard execute all subtasks.
- The Fallback Executor of the subtasks is the crew onboard.

Level I:

- Some decision-making subtasks are executed remotely.
- Fallback execution of the subtasks is shared between the crew onboard and the remote operators in a Remote Operation Center (ROC).

Level II:

- All decision subtasks are executed remotely.
- Fallback execution of the subtasks is the remote operators in a Remote Operation Center (ROC).

Fallback Executor

Level 0:

- A human executes Fallback.
- The Fallback Executor is a human.

Level I:

- Fallback execution is shared between humans and computer systems.
- Fallback Executor is a human and computer systems.

Level II:

- A computer system executes Fallback.
- The Fallback Executor is a computer system.

In these categories, the nature and Fallback Executors of the respective indexes are defined in the categories, and are used in classification of automation systems.

However, these categories are set individually in order to explain the elements in an easy-to-understand manner. Actual systems can be classified by combinations of the indexes of these three elements. For example, a system in which “Computer systems perform some decision-making processes, and a human executes Fallback” is as shown by the combination in Table 5.

Table 5　Example of combination of AOS, ROS and Fallback

Category			Executor of task				Executor of Fallback	
			Onboard		ROC			
AC	RC	FB	Human	CS	Human	CS	Human	CS
I	0	0	○	○			◎	
I	I	0	○			○	◎	
I	I	0		○	○		◎	

AC: Scope of automation
RC: Scope of remote control
FB: Fallback Executor
ROC: Remote Operation Center
CS: Computer system
◎: Executes all
○: Shared execution

As in the DNV Guidelines, from the standpoint that the levels of automation cannot be determined uniquely but will change depending on the task, circumstances, etc., the levels in the ClassNK Guidelines were shown as a basic method of categorization for an abstract object for the scope of automation, the scope of remote operation and the Fallback Executor. Therefore, the factors which differentiate the levels were not clearly specified.

Here, it may be noted that the addition of a “Fallback Executor” is a new concept in the expression of automation levels in the maritime field.

4.6　Automation Levels of American Bureau of Shipping (ABS)

The ABS released a Guide for Autonomous and Remote Control Functions $^{18)}$ in 2021. The Guide is applicable to all marine vessels and offshore units (referred to collectively as “vessels”). The autonomous functions covered by the Guide focus on functional capabilities that enable operation of marine vessels and offshore units, and do not imply unmanned operation.

The “Function Categories” which are the objects of application cover a diverse range: Navigation (NAV), Maneuvering (MNV), Mooring / Unmooring (MOR), Docking / Undocking (DOC), Propulsion (PRP), Auxiliary (AUX), Environmental Protection (ENV), Cargo Handling (CGH), Ballast and Trim (BAL) and Industrial Processes (IND). Levels of autonomy are applied to all of these functions. These functions have been codified and are used when describing the notations of the autonomous functions shown below.

The ABS Guide defines “Smart-to-Autonomy” levels by the three levels of “Smart,” “Semi-Autonomy” and “Full Autonomy,” and the notation is also set on this basis. The definitions of these levels of autonomy are presented below.

Smart-to-Autonomy levels

Autonomy level 1 – Smart: System augmentation of human functions.

- The system provides passive decision support, such as system anomaly detection, diagnostics, prognostics, decision/action alternatives, etc.
- Notation: SMART

Autonomy level 2 – Semi-Autonomy: Human augmentation of system functions.

- The system builds on a smart foundation and is governed by a combination of system and human decisions and actions.
- Notation: AUTONOMOUS

Autonomy level 3 – Full Autonomy: No human involvement in system functions.

- The system makes decisions and takes actions autonomously.
- Humans only perform a supervisory function. An override function enables intervention in the system.
- Notation: AUTONOMOUS

In order to clarify the roles of humans, the Guide also defines “Operations supervision levels.” For the operations supervision levels, two “Operator locations” (onboard vessel or remote location) and three “Required attention levels” are defined, and the operations supervision level is then defined by combinations of the two.

The required attention levels are shown below, followed the operations supervision levels, which are shown in Table 6.

Required attention levels

Required attention level 1: Continuous supervision

- Throughout the operation of the function, continuous (uninterrupted) supervision by the operator is required.

Required attention level 2: Periodic supervision

- Throughout the operation of the function, supervision by the operator is required at set intervals. The length of the interval and means of ensuring supervision by the operator are determined by the vessel operator and documented in the Concept of Operations (ConOps) document.

Required attention level 3: As needed basis (as required by system notification or the operational mode)

- Throughout the operation of the function, supervision by the operator is required on an as needed basis only. Details are determined by the vessel operator and documented in the Concept of Operations document.

Table 6 Operations supervision levels

Operations supervision level and its code	Required attention level	Operator location
OP1	**Required attention level 1**: Continuous supervision	Onboard vessel
OP2	**Required attention level 2**: Periodic supervision	Onboard vessel
OP3	**Required attention level 3**: As needed basis	Onboard vessel
RO1	**Required attention level 1**: Continuous supervision	Remote location
RO2	**Required attention level 2**: Periodic supervision	Remote location
RO3	**Required attention level 3**: As needed basis	Remote location

Both the required attention levels and the object functions are attribute values of the class notation AUTONOMOUS. For example, the notation AUTONOMOUS (NAV, OP1, RO1) indicates that an Autonomous Function related to navigation of the vessel is operated under continuous supervision by operators located both onboard the vessel and at a remote location.

In addition to the levels of autonomy, the ABS Guide also describes the roles of humans and the system by combinations of required attention levels and operator work locations (onboard the vessel or remote location).

The levels of autonomy provide a comparatively simple system of notation, and the required attention levels correspond to the degrees of direct and remote control in the BV Guidelines. This provides a graduated scale of the condition of continuous monitoring by humans, which is an important study item when considering automated and autonomous ships, and thus is an important issue for study.

5. FACTORS IN CLASSIFICATION OF AUTOMATION LEVELS

As an overview of the automation levels discussed here, in many proposed automation level classification schemes, the automation system is perceived as a system that supports or acts in place of operational work in which the respective tasks of information acquisition, situational awareness, decision and action are performed as a loop, and the level of automation is set based on the extent to which the automation system supports or replaces those human tasks.

Moreover, the levels of automation range from manual control to fully automated control. Concretely, many automation level classification schemes were established based on four levels of control modes, that is, manual, delegated, supervised and full automatic (fully autonomous). The divisions of these levels correspond to the transition from manual control to supervisory control and then fully automatic control in the control modes proposed by Sheridan. Even comparatively complex systems can be explained convincingly by using these control modes. In particular, because the roles that humans play and the level where the entity that executes control changes can be expressed in easily understood terms, this is a good index for appropriately understanding the outline of automation system operation.

The following may be mentioned as factors for classifying automation levels based on these control modes.

- Presence/absence of a function that provides information support
- Requirement for human approval prior to action
- Transition from human to system as the entity executing control
- Presence/absence of a means of intervention
- Reporting of control results to a human

Next, the following factors that classify the automation level other than the items related to the control mode are as follows.:

- Requirement of continuous supervision
- Presence or absence of operators, and their location

Where continuous supervision is concerned, Level 3 automation of self-driving cars allows cases where continuous supervision is not required, for example, such as the short use of a mobile phone during driving a car. This is also described clearly in the guidelines of classification societies, which were released relatively later. As one example, the ABS Guide classifies operations supervision levels as continuous supervision, periodic supervision or as needed basis.

One further factor is the presence or absence of operators and their location. The locations of operators include the cases where operators are onboard, not onboard, at a remote control center, and not at a center. A total of four cases is possible based on the combinations of these cases. The automation level schemes of many classification societies use the factor of operator location in combination with the degree of supervision by the operator. Moreover, although there is currently no mention of whether remote control of ships is limited to within the visual line of sight, it will also be necessary to add this as an issue for study in the future, particularly when considering unmanned small craft.

Finally, the automation levels for self-driving cars include the concepts of the dynamic driving task (DDT) and the operational design domain (ODD), and the concept of object and event detection and response (OEDR), etc. as subtasks. These concepts are described in the ConOps document, which is necessary when creating an automation system, as shown in Table 3. Many classification societies have also followed this conceptual framework. Although consideration of the cost of incorporating this kind of concept is considered necessary, this concept must also be included as a factor in classification of automation levels.

6. CONCLUSIONS

This report has examined the contents of past studies on automated and autonomous ships and the relationship between humans and the functions of the various types of automation systems that realize such vessels, and the definitions of automation levels which have been proposed in order to obtain a common understanding. The report has also presented an overview of automation levels for automobiles, a sector where automation is progressing, and unmanned aerial vehicles (drones), together with the automation levels established to date by various maritime-related organizations and several classification societies. The factors for classifying automation levels were also summarized. These factors clarify the differences in the relationship between humans and the respective system, and have also clarified the tasks in which humans are required, such as continuous supervision and intervention during abnormalities, etc.

This study has clarified the history of efforts to create automation levels up to the present and the functions of automation systems defined in terms of automation levels were clarified, and has arranged the factors which are effective when describing automation systems.

As can be seen in the automation levels for self-driving cars, it can be thought that diverse factors will also be added to the automation levels of automated ships and evolve as automation systems evolve. From this viewpoint, the author hopes that the contents of this survey will be used in future studies of the automation levels of ships.

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Initiatives for Ship Fire Safety Measures

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1. INTRODUCTION

Fire safety measures for ships are provided in the SOLAS Convention and have been revised repeatedly up to the present. The provisions related to the increasingly large-scale container carriers of recent years have also been revised, but because multiple fire accidents resulting in serious damage have occurred, a review will be conducted in the IMO to further improve safety. In addition to the fire safety measures for roll-on/roll-off (RORO) passenger ships which are currently under discussion, issues related to fire safety requirements for vehicles which are equipped with lithium ion batteries or use new fuels such as hydrogen, natural gas, methanol and ethanol have also been raised in the IMO, and study is planned in the future. Separate from those issues, fire accidents have also been reported in large vehicle carriers, which mainly transport gasoline-fueled vehicles, and a study on safety measures for these vessels was carried out by a working group in Japan led by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), which compiled “Measures for effective use of fixed foam fire-extinguishing systems.”

This paper provides an overview of the trends in fire safety measures for container carriers and vehicle carriers under discussion in the IMO, and introduces the ClassNK initiatives in response to the additional fire safety measures voluntarily being taken by ship owners and ship management companies which operate container carriers, and the above-mentioned fire safety measures developed by the working group in Japan in advance of future revisions of the SOLAS Convention.

2. FIRE SAFETY MEASURES FOR CONTAINER CARRIERS

2.1 Trends in the IMO

While the SOLAS Convention has been revised repeatedly in the IMO up to the present to secure and improve the fire safety of the increasingly large size of container carriers, fire accidents still occur and further enhancement of the fire safety measures is being discussed at IMO. Specifically, a group composed of the Marshall Islands, Singapore, the World Shipping Council (WSC) and the International Association of Classification Societies (IACS) and another group composed of the Bahamas, Germany, the International Union of Marine Insurance (IUMI) and the Baltic and International Maritime Council (BIMCO), both submitted joint proposals for new work plans to develop new requirements for fire safety measures for container carriers.

These proposals were approved as new outputs for fire safety measures for container carriers at the 103rd session of the MSC (MSC103) held in May 2021 with a view to having concrete discussions on safety measures for the cargo holds and on-deck cargo areas of container carriers from the 8th session of the Sub-Committee on Ship Systems and Equipment (SSE8), which is to be held in March 2022. Under this plan, discussions on revisions of SOLAS Chapter II-2 and the International Code for Fire Safety Systems (FSS Code) are to be completed by 2025 with the aim of its entry into force in January 2028.

2.2 Fire Safety Measures in Cargo Areas of Container Carriers

Following are the brief of problems raised at the IMO in connection with fire safety measures for container, which are planned to be focused on in the IMO discussion.

(1) Fixed fire-extinguishing systems of cargo holds

There are some cases where, even with their proper operation, fixed carbon dioxide gas fire-extinguishing systems installed in cargo holds fail to extinguish the fire due to the nature of the cargo and there needs to fill the affected hold with water. For these cases, secondary means such as a fixed fire-extinguishing device or an alternative fire-extinguishing system is needed.

Figure 1　Container carrier

(2)　Fire-extinguishing equipment for on-deck cargo areas

For fires in containers stacked on the exposed weather deck, at least one water mist lance and two or four mobile water monitors are required on ships constructed on or after January 1, 2016. However, currently, there are no established performance standards for water mist lances that penetrate through the container wall for spraying water into the container and the materials and penetration methods vary among devices. Thus, standards that ensure a certain level of effectiveness in water mist lances are necessary. Even in mobile water monitors, for which standards exist, the required number and the effective positioning requirement may be insufficient. In addition to these problems, installation of remotely operated water-type fire-extinguishing devices may be necessary.

(3)　Communication equipment for fire-fighter

All ships are required to provide some means of communication for fire-fighters by the first periodical survey on or after July 1, 2018. However, there are no requirements for them in respect of the communication range or a hands-free function to enable effective firefighting.

(4)　Fire detection

Sample extraction smoke detectors (devices which detect smoke) in cargo holds required under current SOLAS are not able to detect the transmission of heat in the stage where a fire is spreading inside a container, therefore, fires are detected at the point when the smoke has generated in the cargo hold consequential to deformation or destruction of the container wall. Moreover, it is difficult for such devices to identify the exact position of the container where a fire has occurred. For earlier discovery of fires, further consideration, for example, on requirements for supplementary heat detection devices is needed.

(5)　Container cargos

Particularly in case of dangerous cargos, heat may trigger a chemical reaction that causes a fire or explosion. To prevent these situations, correct information on the cargos in containers must be provided and the containers must be stacked appropriately onboard based on a proper understanding of the types of cargos, etc. On the other hand, inaccurate information on the cargo may cause a fire to start or spread. Additional discussion on the handling of container cargos, including their identification and packing information sharing, etc. is necessary.

2.3　ClassNK Initiatives

As described above, discussion of fire safety measures for container carriers in the IMO will begin shortly. In advance of this, some ship owners and ship management companies that operate container carriers have shown an intention to respond voluntarily, and in fact, there have also been the moves to implement additional fire safety measures independently.

The IUMI, which presented the results of an analysis of fire accidents on container carriers to the IMO, has proposed an original concept of measures to strengthen fire safety (see Fig. 2). For details, please refer to the IUMI Position Paper “Firefighting systems on board container vessels” released in 2017. Some of large container carriers have already been constructed based on a design concept close to the IUMI concept.

In line with these trends, there have been requests for evaluation of fire safety measures which were taken voluntarily. To respond to these requests, ClassNK is considering a revision of its rules to add notations to the ship’s character of classification for evaluating ships on which additional fire safety measures have been implemented. The following presents several examples.

(1) Additional fire detection devices for cargo holds

For example, for ships equipped with, in addition to the conventional sample extraction smoke detectors, heat detection systems utilizing thermographic cameras, optical imaging, or temperature monitoring devices to detect a container in which a fire has occurred, notation showing such additional devices would be provided.

(2) Additional water-spraying devices

For ships installed with water-spraying fire-extinguishing system arranged with nozzles in cargo holds, the end walls of the deckhouse, end walls of the engine casing, container lashing bridges and the like, notation indicating installation of that equipment would be added (see Fig. 3).

(3) Water-flooding to cargo holds

For ships that provide a means of water-flooding to the cargo holds, and verify that there will be no problems with hull strength or stability in case of water flooding is carried out, the notation that the said additional action can be implemented would be added.

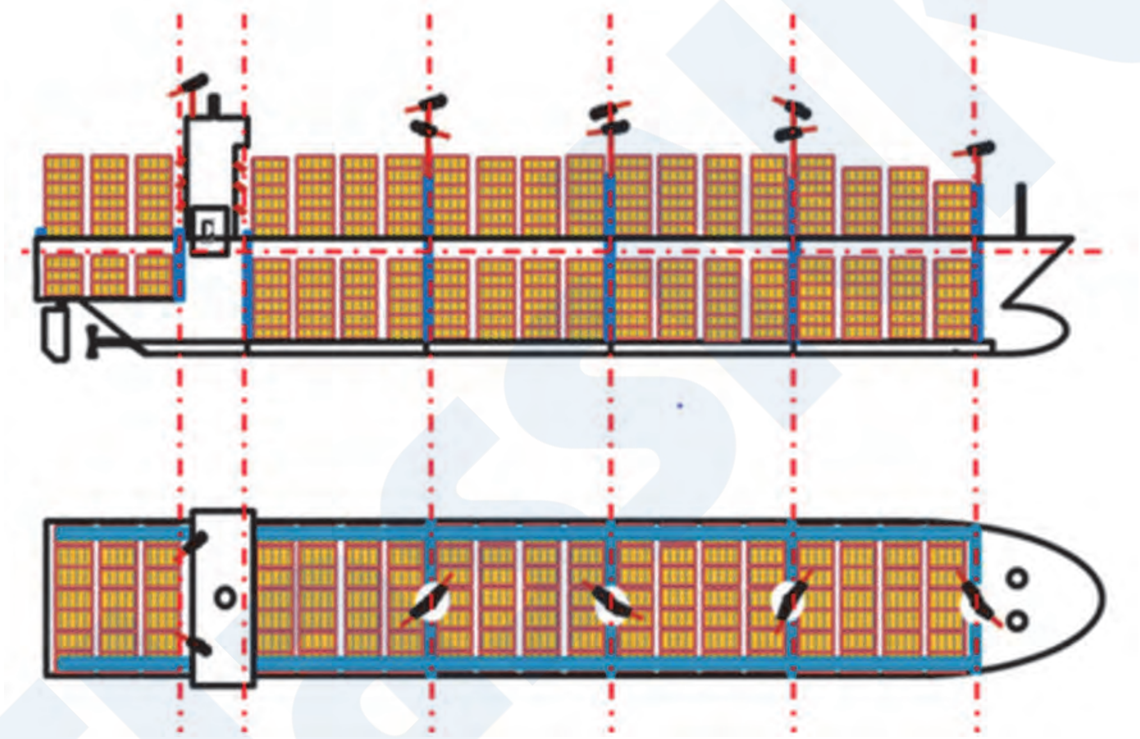

Figure 2 Image of water-spraying system on deck (proposed by IUMI)

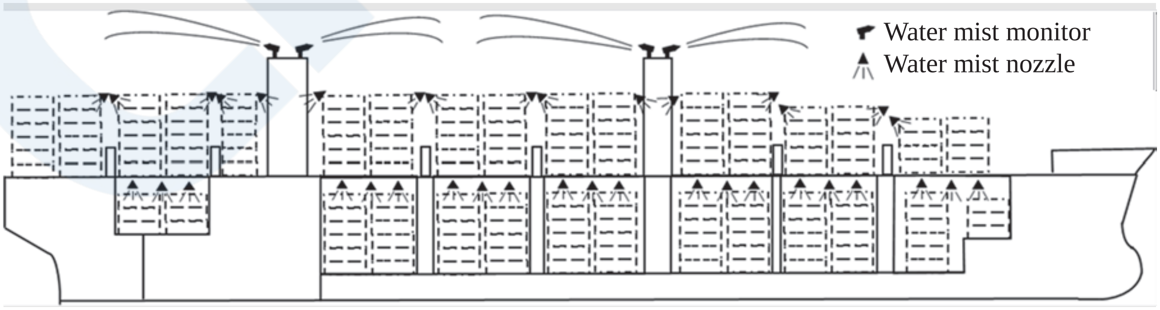

Figure 3 Image of water-spraying system

Figure 4　Large vehicle carrier

3.　FIRE SAFETY MEASURES FOR LARGE VEHICLE CARRIERS

3.1　Trends in the IMO

In the IMO, the development of safety requirements for fires involving vehicles equipped with lithium ion batteries was proposed in the 7th session of the Sub-Committee on Ship Systems and Equipment (SSE7) held in March 2020.

However, it was concluded that a wide-ranging study of this issue is necessary, including not only vehicles using lithium ion batteries, but also other types of new energy vehicles. As of this writing, the future work plan is scheduled to be discussed at the 104th session of the Maritime Safety Committee (MSC104) to be held in October 2021. It will be necessary to keep eyes on future developments in this connection, as a focus may not be limited to only the problem of RORO passenger vessels, which are currently under discussion, but may be on all ships that carry new energy vehicles and are subject to the application of the SOLAS Convention.

3.2　Study of Safety Measures in Japan

3.2.1　Study of Response When a Fire Occurs

Discussion on vehicle areas and RORO ships that are loaded with new energy vehicles in the IMO are scheduled to begin shortly. On the other hand, multiple fire accidents have also occurred in recent years in the vehicle loading areas of large vehicle carriers in service mainly transport gasoline-fueled vehicles. Based on this situation, a study of safety measures to reduce the damage of this type of accidents was initiated by Japan’s Ministry of Land, Infrastructure, Transport and Tourism.

While discussions on the fire safety of new energy vehicles (vehicles equipped with lithium ion batteries, etc.) are scheduled to begin in the IMO, based on the facts that the new energy vehicles are not yet a high percentage of the cargo, gasoline-fueled vehicles have accounted for the majority of cargos in the reported fire accidents, and that vehicles have the highest heating value in the vehicle loading area, even though the ignition source is unclear, the aforementioned study in Japan was conducted on the assumption that conventional gasoline-fueled vehicles are the ignition source.

Concretely, in December 2019, the “Working Group on Prevention of Recurrence of Fire Accidents on Vehicle Carriers” (hereinafter, “working group”) was organized with the Japan Ship Technology Research Association (JSTRA) as the Secretariat and related Japanese parties (shipping companies, shipyards, manufacturers of fire extinguishing/detection systems, national research and development agencies, universities, national government agencies, etc.) for a study of the above-mentioned safety measures. ClassNK also participated in the working group as a member.

First, the working group collected information on actual fire accidents, verified scenarios of fire spread and extinguishment and extracted issues for reducing the damage caused by such accidents. The group then conducted experiments and investigations of these results and established concrete improvement methods. The experiments conducted by the group consisted of two types: experiments on fire detection performance to investigate the effect of the distinctive deck back structure of vehicle carriers on smoke detection, and vehicle fire experiments to identify the mechanism of vehicle fires and fire spread in the vehicle areas of vehicle carriers, where the height between the decks is low and cars are tightly parked, as can be seen in

Figs. 5 and 6, which show the condition of vehicle fire experiments.

Figure 5　Photograph of a vehicle fire experiment: Condition of horizontal arrangement

Figure 6　Photograph of vehicle fire experiment: Condition of vertical arrangement

The working group compiled the results as “Improvement measures for effective use of fixed foam fire-extinguishing systems.” The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) then issued a request dated June 10, 2021, to the Japanese Shipowners’ Association to make further voluntary efforts for improvement of the safety of ships of large vehicle carriers by utilizing the improvement measures, and notified this to the registered ship classification societies, including ClassNK.

This Society released ClassNK Technical Information TEC-1239 on June 11, 2021, taking into account its active contribution to the working group from the standpoint of securing safe operation as a ship classification society and requested for ship owners and management companies involved in the operation of large vehicle carriers to consider introducing these improvement measures.

3.2.2　Improvement Measures for Reducing Damage

The purpose of the above-mentioned “Improvement measures for effective use of fixed foam fire-extinguishing systems” is to reduce the damage in fire accidents through more effective use of the fixed foam fire-extinguishing systems which are now commonly installed in the vehicle loading areas of large vehicle carriers. These measures summarize concrete safety measures based on the new knowledge obtained by the vehicle fire tests used gasoline-fueled vehicles. Here, the content of the measures will be introduced.

In cases where fire that happened in vehicle loading areas cannot be extinguished by the initial fire-fighting action, the fire will spread from vehicle to vehicle. However, if the scale of the fire expands beyond a certain size as a result of the fire spreading, it will be impossible to stop the spread with the fixed fire-extinguishing system installed in the ship. The purpose of the measures mentioned below is to enable more effective functioning of the fixed fire-extinguishing systems required by the SOLAS Convention and FSS Code.

(1) Target ships

The target is large size vehicle carriers that use fixed foam fire-extinguishing systems in vehicle loading areas. Here, it is assumed that the loading condition is full-load and a ship with a gross tonnage of approximately 60,000.

(2) Basic policy

Based on the knowledge obtained by the above-mentioned working group, the target time for activating the fixed foam fire-extinguishing system is set to enable more effective use of the system, and measures are implemented in both the “intangible” and “tangible” aspects in order to achieve this.

- The target time is set in the “Procedure to activate foam fire-extinguishing systems,” which is part of the “Procedure for fire extinguishing” related to the Safety Management System (SMS) based on the International Safety Management Code (ISM Code). The procedure sets a target time (standard time: 14 minutes) from the alarm is given to press the button to activate the fixed foam fire-extinguishing system, and states that the target time should be announced to the crew.

  The above-mentioned “standard time” of 14 minutes is a guideline, and the actual target time is set by the ship owner or shipper, etc. themselves based on the specifications and structure of each ship, the type of cargo, the cargo loading condition and other relevant considerations. For vessels other than the 60,000 gross tonnages the improvement measures can be applied in a similar manner by appropriately setting the time required for on-site confirmation of the fire, considering the size of the vessel concerned, etc.

  The 14 minutes mentioned here is the total time, premised on implementation of all the measures in Table 1 and based on the speed of the spread of fires involving vehicles obtained from the results of vehicle fire experiments, and consists of 10 minutes for the crew to move to the lowest cargo level furthest from the bridge after an alarm is given and confirm the condition of the fire on the spot, 1 minute to issue instructions to the firefighting department, and 3 minutes to call over the crew.
- The measures in Table 1 should be implemented to achieve the target time for activating fixed foam fire-extinguishing. The measures may be applied to both new building and existing ships by establishing and/or modifying the fire extinguishing policy, procedure etc.
- The operation matters (e.g. Omission of the fire extinguishing action using fire hoses and hydrants etc.) should be specified in “Procedure for fire extinguishing”.

Table 1 List of measures for effective use of fixed foam fire-extinguishing systems

Item	Content
The measures to be implement	The automatic (remote) start of generators (To secure the required electrical power rapidly for the use of fire-extinguishing system) *1
	Normally-open or automatic ventilators (To shorten the starting time of the fire extinguisher) *1
	Omission of the fire fighting action using fire hoses and hydrants *2
The measures recommended to implement (Option)	Remote monitoring of cargo holds using CCTV (To detect the fire rapidly)
	Securing the safety of crews with RFID tugs etc. (To shorten the time to roll-call)
	Installation of one smoke detection to each frame spaces of car deck ceiling (To detect the fire certainly)
	Installation of the additional boundaries to prevent the spread of the fire in cargo holds (To prevent the spread of fire and to remove the psychological obstacles to activate the fire extinguisher) *3

*1 Alternatively, activation of generators and operation of ventilators can be manually done by each team(s) formed by crews, provided that there is no adverse effect for achieving the target time (standard time: 14min) for activation of fixed foam fire-extinguishing systems.

*2 Except for cases where the fire may be certainly extinguished by fire hoses and hydrants such as: the fire in the vicinity of wheelhouse, the fire happened to be discovered by crew during fire patrol. In this case, if the enough number of crews onboard are forming multiple firefighting teams, firefighting by hoses and hydrants can be tried provided that the fire is being monitored onsite in parallel. However, there should be no adverse effect for achieving the target time (standard time: 14min) for activation of fixed foam fire-extinguishing systems.

*3 This measure is supposed to be applied only to newly built ships.

4. CONCLUSIONS

This paper has introduced the current status of activities in IMO related to container carriers and vehicle carriers, the activities and initiatives by ClassNK in connection with container carriers, and the fire safety measures for vehicle carriers proposed by the Japanese working group.

In the future, discussions on new requirements for fire safety measures for container carriers and vehicle carriers will be held in the IMO, but several years will be necessary to complete that work. ClassNK is to continuously keep eyes on the work and to consider safety measures, either by itself or jointly with the maritime industry as necessary.

We will also announce newly established fire safety measures through ClassNK guidelines, etc. so as to contribute to the industry.

Estimation of Stress on Ship Structures Using Full-Scale Measurement Data and Machine Learning

Hideki MIYAJIMA[*]

1. INTRODUCTION

In the full-scale measurement project, various data such as navigation data (main engine speed, ship speed, heading, etc.), weather data (wind, waves, etc.), and ship motion data (acceleration, stresses on ship structure, etc.) are obtained and accumulated to understand the state of the ship during navigation. These data are used to assess structural strength, estimate life by fatigue strength assessment, and provide feedback for design 1-3). From the viewpoint of ensuring the safety of ships, it is important to understand the history of the stresses generated on ship structures.

One of the problems of stress measurement in full-scale is that installation and maintenance of sensors are costly. Since it is difficult to measure all the measurement points that are in demand, it is desirable to have a method to grasp the stress of the whole ship with fewer measurement points. As an approach to understand the stress history, which is different from the full-scale measurement, research on “load and structural consistent analysis” has been conducted to estimate the stress generated on ship structure by incorporating structural analysis. However, since there is no established method for stress estimation, there is room to consider new approaches.

If the estimation of stress generated on ship structure is considered as a regression problem, an approach using machine learning, which has been developed in recent years, is considered to be effective. Since machine learning can make estimations considering various factors related to the problem, the stresses generated on the ship structure can be estimated by using the stress-related data obtained from full-scale measurements.

The data obtained from full-scale measurements include data that are affected by the natural environment such as wind, waves, and currents. It is difficult to grasp the weather and ocean conditions accurately, and the full-scale measurement data contains many uncertain measurement values. In the field of machine learning, Natural Gradient Boosting (NGBoost) 4), a method for estimating probability distributions, has been proposed as an effective method for making numerical estimations based on such data. By using NGBoost, it is expected to make reasonable numerical estimations considering probability distributions. Therefore, in order to confirm the feasibility of stress estimation using a new approach, research on stress estimation on ship structures using full-scale measurement data and NGBoost has been conducted. In this paper, the contents of our research is introduced.

2. OVERVIEW OF FULL-SCALE MEASUREMENT

In this study, from the viewpoint of the measurement items and the number of data, the data for about two years obtained in the full-scale measurement project on the 8,600 TEU container ship is used. Table 1 shows the main particulars of the ship and Table 2 shows the measurement items of the ship.

The Sensors to measure acceleration and stress are installed on the ship. The locations of the sensors are shown in Fig. 1. The Optical Strand Monitoring System (OSMOS) sensors, which uses optical fiber to measure the strain of structural members, was used to measure the stress. And OSMOS sensors were installed in 12 locations, four in each of the three cross sections of the ship. Three-axis (x, y, z) accelerometers were used to measure acceleration, and were installed in three locations: fore part, midship part, and aft part. ERA-5 wave hindcast data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) is used for the wave data. Note that the ship's regular route was changed during the measurement period.

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Table 1 Main particulars of the ship

Length overall (L_{OA})	Abt. 334.5 m
Breadth	45.6 m
Depth	24.4 m
Design draft	14.0 m
Gross tonnage	Abt. 97,000 GT

Table 2 Measurement items

Data	Contents
Navigation	Ship's speed (through water, over the ground), Course over ground, Main engine speed, Power of main engine
Weather	Wind direction, Wind speed
Acceleration	3-axis (x, y, z) for fore, midship and aft part
Stress	Hull girder stress
Wave	Wave height, Wave direction, Wave period, Directional width of wave, Kurtosis of wave, Relative width of wave frequency spectrum, Water depth

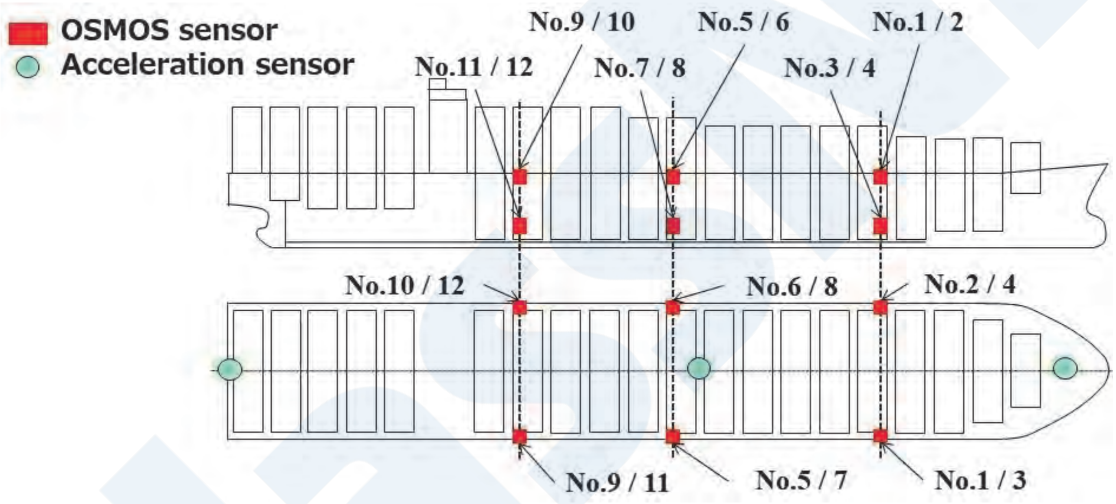


Figure 1 The positions of OSMOS sensors and acceleration sensors

3. STRESS ESTIMATION METHOD

3.1 Estimation Target

It is important to estimate the stress generated on the upper structure because container ships have large openings that cause high stress in the ship structure. In addition, the midship part of the ship is important because the stress is relatively high among the measurement points. Therefore, in this study, the stress measured at the midship part and on the port side of the deck (No. 6 in Fig. 1) is used as the estimation target.

3.2 NGBoost

In this study, considering the uncertainty of the full-scale measurement data, NGBoost, which is a method that can estimate the probability distribution, is used to estimate the stress generated on the ship structure. NGBoost is a regression model adapted gradient boosting for estimation of probability distributions. Gradient boosting is a type of ensemble learning method that creates one learner by combining multiple weak learners with low estimation accuracy. A feature of NGBoost is that it uses natural gradients [5] to improve the learning efficiency of the weak learner in order to estimate the multiple parameters of probability distributions simultaneously.

In this study, the log-likelihood $L(\theta, y)$ shown in Equation (1) is used as the loss function which is optimized in the training phase of NGBoost. The natural gradient $\tilde{\nabla} L(\theta, y)$ is shown in Equation (2). Here, the parameters of the probability distribution are θ, the correct answer label is y, and the probability distribution P, and $I_L(\theta)$ is the Fisher Information matrix. The normal distribution is used as the probability distribution, and the decision tree is used as the weak learner.

$$L(\theta, y) = -logP_\theta(y) \tag{1}$$

$$\tilde{\nabla} L(\theta, y) \propto -I_L(\theta)^{-1} L(\theta, y) \tag{2}$$

4. STATISTICAL PROCESSING OF FULL-SCALE MEASUREMENT DATA

In this study, using the full-scale measurement data processed as hourly statistics, the data set for stress estimation was created. The processing of each data and the data set created are described in this chapter.

4.1 Navigational Data, Weather Data, Wave Data

Navigational data and weather data were processed as hourly averages. For wave data, hourly wave hindcast data were used. The data representing the angle of wave direction, wind direction, etc., takes the value of 360 degrees clockwise with the bow direction as 0 degrees. Therefore, the amount of change in angle from the bow direction was added as the variables.

4.2 Stress Data

The stresses in the ship structure can be separated into two major components by frequency analysis: wave response component and elastic response component, with peaks around 0.1 Hz and 0.5 Hz, respectively. In this study, the wave response component from 1/60 to 0.3 Hz, the elastic response component from 0.3 Hz to 1.0 Hz, and the wave and elastic response component from 1/60 to 1.0 Hz were separated from the hourly stress time series data. Then the stress range per wave was calculated by the zero-up crossing method, and the standard deviation was calculated.

4.3 Acceleration Data

Frequency analysis showed peaks at around 0.1Hz and 0.6~0.8Hz. These components are wave response component and mainly elastic response component, respectively 2). In this study, the wave response component from 1/60 to 0.3 Hz, the elastic response component from 0.3 Hz to 1.0 Hz, and the wave and elastic response component from 1/60 to 1.0 Hz were separated to include the peaks, and the maximum values and standard deviations for each hour were calculated and used as variables. The maximum value and standard deviation for each hour were used as the features.

4.4 Data Set for Stress Estimation

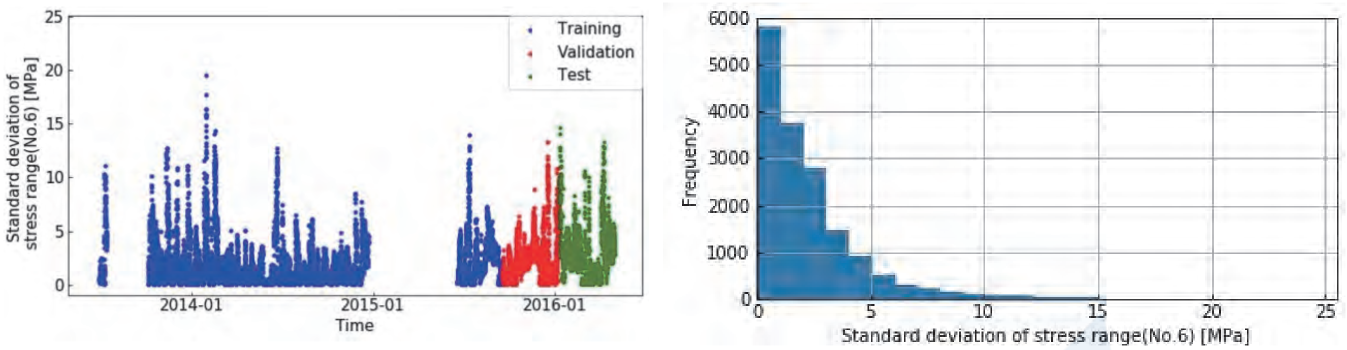
After the above process, the data set consisting of one objective variable (the measured value of stress at No. 6) and 108 explanatory variables was created. Table 3 shows the number of data points, and Fig. 2 shows the time series plot and histogram of the objective variable.

From Fig. 2 (b), it was confirmed that there were few data where high stress was measured. In the case of machine learning using such imbalanced data, there is a concern that the accuracy of estimation model will decrease in the areas where the number of data is small. Therefore, in order to compensate for the bias of the imbalance data, oversampling using SMOTE 6), a method of oversampling that increases the data with a small number of samples, is conducted.

SMOTE is a method of increasing data using the k-nearest neighbor method, which interpolates new data using specific data belonging to a minority group and randomly selected data from k of its neighbors. In this study, a threshold was set for the stress as the objective variable, and the data were labeled as above and below the threshold, and oversampling was performed so that the majority and minority groups had the same number of data.

4.5 Stress Estimation Model

In this study, two estimation models were developed, one using all explanatory variables (Case 1) and the other using only navigation, weather, and wave data (Case 2), as shown in Table 4. Note that, in Case 2, oversampling was not performed because it tended to reduce the estimation accuracy. The number of explanatory variables in Case 2 is smaller than in Case 1. Therefore, the pattern of data included in the training data decreased, and the number of similar data increased, which may have caused this problem.



(a) Time series plot (b) Histogram

Figure 2 Time series plot and histogram of the stress at No. 6

Table 3 Number of data in the data set

	Number of data
Training data	11,435
Validation data	2,614
Test data	2,288
Total	16,337

Table 4 Explanatory variables to use

Data	Case 1	Case 2
Navigation	○	○
Weather	○	○
Acceleration	○	○
Stress	○	—
Wave	○	—

5. ESTIMATION RESULTS

5.1 Comparison of Estimation Results in Case 1 and Case 2

Figure 3 and Fig. 4 show the results of stress estimation for the test data in Case 1 and Case 2, respectively. The mean of the normal distribution is plotted with the x-axis as the measured value and the y-axis as the estimated value. When the measured and estimated values of stress are equal, they are plotted on a reference line drawn diagonally. The 2σ confidence interval of the estimated normal distribution is also shown. Table 5 shows the mean squared error and correlation coefficient of the measured and estimated values, and the mean value of the estimated standard deviation.

For Case 1, Fig. 3 shows that the plots of the estimation results are distributed along the reference line, and the value of the correlation coefficient is about 0.99. Therefore, the measured values and estimated values are considered to be in good agreement with each other.

For Case 2, Fig. 4 shows that the plots are distributed near the reference line. On the other hand, from Table 5, it is confirmed that the value of the correlation coefficient decreased, and the value of the mean squared error and standard deviation increased in Case 2 compared to Case 1, which means that the estimation accuracy decreased. In Case2, the estimated value tended to be lower than the measured value in the high stress areas. From the viewpoint of the strength of the ship structure, it is not desirable for the estimated values to underestimate the stress, so it is also important to improve the estimation accuracy in the high stress areas.

The reason for the lower estimation accuracy in the high stress areas of Case 2 may be due to the lack of data measuring the high stress. The frequency of measuring high stress in full-scale measurements is low, and the weather and sea conditions that ships encounter vary depending on the route. In order to improve the estimation accuracy of high stress areas using only navigation, weather and wave data, it may be effective to collect measurement data for a longer period of time, and to create estimation model for each route.

5.2 Calculating the Importance of Explanatory Variables

When using decision tree-based machine learning methods, the importance of each explanatory variable to the estimation results of the created estimation model can be calculated. Since the stress estimation model using NGBoost outputs the mean and standard deviation, which are parameters of the normal distribution, as estimation results, the importance can be calculated for each of them. As part of the importance of the explanatory variables, Table 6 and Table 7 show the top five in Case 1 and Case 2, respectively.

In Case 1, the importance of stresses at No. 1, No. 5, No. 9, and No. 10, which were measured near the objective variable (stress at No. 6) or at the upper part of the ship, were high. On the other hand, the importance of the stresses at No.3, No.4, and No.7, which are located in the lower part of the ship and bow side, was lower than other measurement points. In this study, the measurement point No. 6 was targeted. The accumulation of knowledge on other measurement points and on ships for estimation is expected to lead to the clarification of measurement points necessary for stress estimation and to the accurate estimation of stress at multiple points with a small number of measurement points.

In Case 2, the importance of wave height, wave period, and wave direction related to wave load increased. In particular, the wave height has a linear relationship with the stress at the measurement location No. 6, as shown in Fig. 5, and is considered to contribute significantly to the estimation.

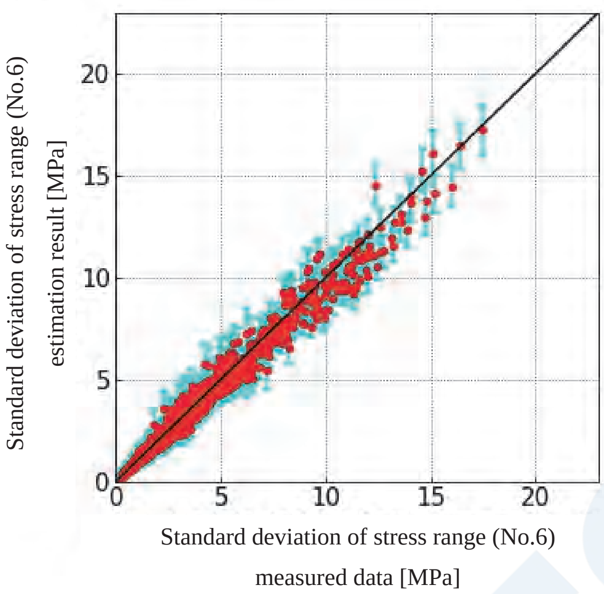


Figure 3　Measured value and estimated value: Case 1

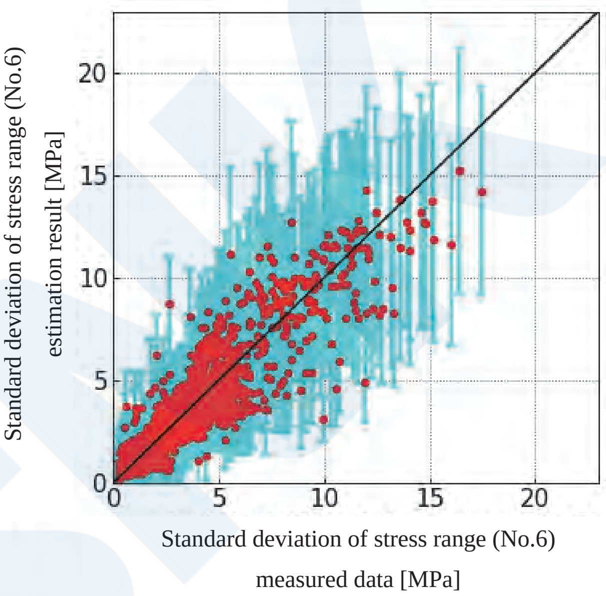


Figure 4　Measured value and estimated value: Case 2

Table 5　Summary of estimation results

	Case 1	Case 2
Mean squared error	0.13	1.10
Correlation coefficient	0.99	0.91
Standard deviation (mean)	0.19	0.74

Table 6　Importance of explanatory variables: Case 1

	Mean	Standard deviation
1	Stress (No.5) wave and elastic response component	Stress (No.5) wave response component
2	Stress (No.1) wave and elastic response component	Stress (No.5) wave and elastic response component
3	Stress (No.9) wave and elastic response component	Stress (No.10) wave and elastic response component
4	Stress (No.10) wave and elastic response component	Stress (No.12) wave and elastic response component
5	Stress (No.10) wave response component	Stress (No.9) wave and elastic response component

Table 7　Importance of explanatory variables: Case 2

	Mean	Standard deviation
1	Wave height	Wave height
2	Wave period	Wind speed
3	Wind speed	Wave direction
4	Ship’s speed through water	Main engine speed
5	Power of main engine	Ship’s speed through water

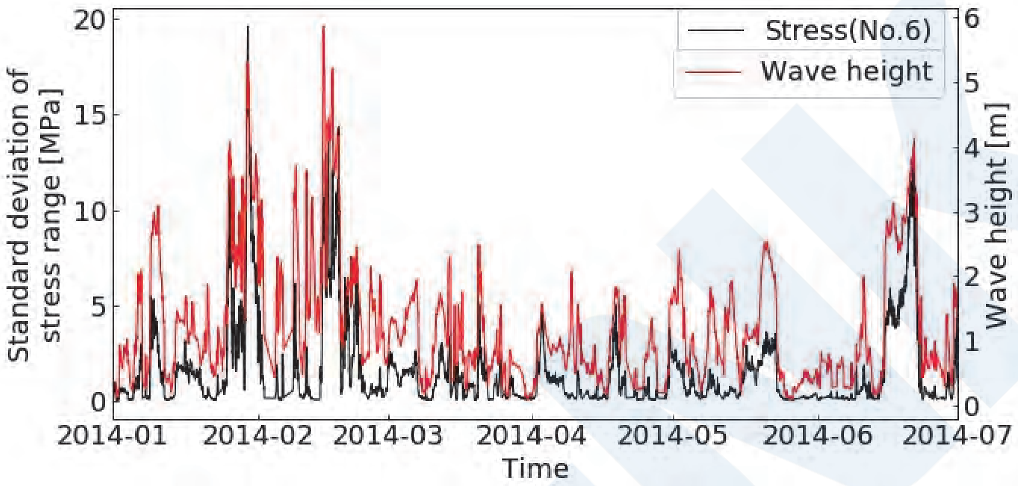


Figure 5　Time series data of the stress at No. 6 and wave height

6.　CONCLUSION

In this paper, research on estimation of stress generated on ship structures using full-scale measurement data and machine learning.

Since this study was conducted for one specific ship, it is necessary to confirm the effectiveness and versatility of this method through comparison and verification with the stress estimation results when this method is applied to other ships. In addition, through such efforts, it is expected to obtain knowledge about the number of data required to secure a certain estimation accuracy and the explanatory variables that are effective in improving the estimation accuracy.

In this study, stress estimation was conducted for the point where stress was measured in full-scale measurement, using the measured values as the correct data. On the other hand, there are many areas where there is a need to estimate stress generated on the ship structure, and it is difficult to install sensors in all points and obtain the measured values. Therefore, as a future work, it will be worthwhile to establish a method to estimate the stress history accurately without relying on direct measurement.

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Consideration of Utilization of Autonomous Drone for Ship Surveys/Inspections

― Demonstration Experiment in Non-GNSS and Dark Environments ―

Junji TOKUNAGA*

1. INTRODUCTION

1.1 Background

In recent years, the application of robotics technologies, such as drones, has become increasingly active in various fields. This trend is also occurring in the maritime industry, and expectations are rising for the effective utilization of these latest technologies in surveys by classification surveyors and in inspections by crew. For this reason, the classification societies were quick to revise IACS UR Z17 in January 2018 to allow the use of Remote Inspection Techniques (RIT) for the inspection of hull structures. Considering this situation, ClassNK also issued the “Guidelines for Use of Drones in Class Surveys” (hereinafter referred to as “the guidelines”), in April 2018 1). The guidelines summarize the applicable range and procedures for applying drones to class surveys, the technical considerations for safe operation and the requirements for drone service suppliers. The use of drones for surveys in high places, narrow places, and dark environments such as cargo holds is expected to improve the safety, efficiency, and quality of surveys.

There are two types of drone operation methods. One is “manual flight,” in which the operator operates the drone manually, and the other is “autonomous flight,” in which the drone flies autonomously by sensing the surrounding environment and estimating self-localization and direction. In the guidelines, the former method of drone operation is covered. This is because the use of autonomous drones onboard a ship requires technologies such as SLAM (Simultaneous Localization and Mapping), but at the time the guidelines were issued, the technology was still in the development stage and it was considered difficult to use them for ship surveys. In recent years, however, technological developments have led to the emergence of drones that can fly autonomously even inside the building 2) 3). In other industries, the utilization of such drones for infrastructure inspection and patrol security are being considered 4) 5).

1.2 Research Objective

Currently, in an environment surrounded by steel plates such as cargo holds, GNSS do not penetrate and the geomagnetic field is not stable, so ship surveys/inspections by manual flight require operators with advanced piloting skills. On the other hand, autonomous drone can be operated without depending on the skill of the operator. However, as mentioned above, the guidelines do not cover autonomous drones, so technical requirements for the use of autonomous drones for ship surveys need to be developed.

The inside of a ship is a non-GNSS environment and has many dark sections. Therefore, in addition to the technical requirements for autonomous flight, it is important requirement to be able to perform surveys/inspections even in dark environments where no lighting is provided. Therefore, it is important to install lighting, select a camera, and tune the camera so that it can photograph images of sufficient quality even in dark environments.

In recent years, there has also been progress in the development of technology to make effective utilization of the images photographed by the camera. For example, the technology to process camera images into 3D point cloud data and orthophoto has already been established, and the effective utilization of such technology is expected to improve the efficiency and quality of surveys/inspections.

In order to maximize the benefits of using autonomous drones, it is important to use them flexibly without sticking to the existing survey/inspection scheme. Therefore, the Society has been extracting technical requirements for drones that can fly autonomously and stably in non-GNSS and dark environments such as cargo holds and has been studying survey/inspection schemes suitable for ship survey when using autonomous drones.

In this paper, we describe the results of flight experiments conducted in inside of building where is non-GNSS and dark

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environment as same as ship inside environment, whose aim is to validate the automatic flight performance and photographic quality of the drone in non-GNSS and dark environments. An autonomous drone that has Visual SLAM is used, which simultaneously estimates 3D information about the environment and the position and direction of the drones from images photographed by a camera instead of GNSS (see Photo 1).

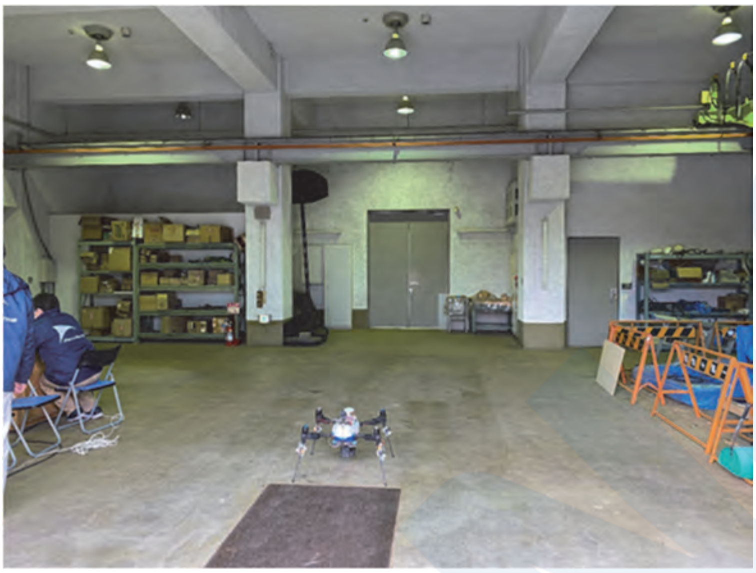

Photo 1 Exterior view of the materials storage area

2. EXPERIMENT SUMMARY

2.1 Equipment and Experimental Environment

In general, there are three methods of recognizing self-localization without depending on GNSS [6].

① Using vision sensors which recognize from images

② A method using a laser ranging system such as LiDAR

③ A method of sending location information to the drone through external sensing.

The advantages and disadvantages of each method are shown in Table 1.

Table 1 Types of sensors for autonomous flight and their advantages and disadvantages [6]

	Advantage	Disadvantage
①Vision Sensor	・Low cost ・Small size / light weight (miniaturization is possible) ・Location can be determined even on a flat surface if there are features.	・Accuracy tends to drop at long distances ・Difficult to detect flat surfaces and water ・Weak in dark environments
②LiDAR	・Capable of ranging even on featureless flat surfaces (in the case of large size) ・High accuracy even over long distances ・Capable of acquiring 3D information in all directions	・High cost ・Large size/weight (difficult to miniaturize) ・Difficult to acquire position information on a continuous plane
③External sensing	・Acquire information with high accuracy according to the environment	・High cost of installation ・Disconnection of communication with the drone can be dangerous

Drones that use LiDAR can achieve autonomous flight even in environments such as cargo holds. However, LiDAR is expensive, making it difficult to adopt in situations where cost effectiveness is not readily apparent. Therefore, in this experiment, we used the drone equipped with a Visual SLAM using a stereo camera as a vision sensor that can be developed more inexpensively than LiDAR (see Photo 2). The drone recognizes its own position and direction by simultaneously estimating the 3D information of the environment and the self-localization and direction of the drone by capturing feature points from the images acquired by the stereo cameras in multiple directions.

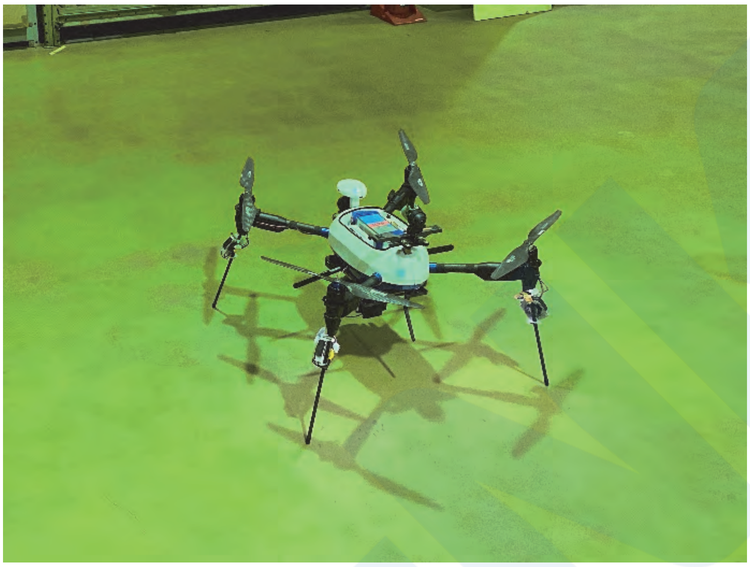

Photo 2　Autonomous drone equipped with vision sensor

Since the vision sensor does not work appropriately in the dark environments, a 100W lighting system was installed under the propeller to provide the necessary amount of light for the vision sensor. Photo 3 shows the scene before and after the lighting.

(a)　Before turning on the light　　(b)　After turning on the light

Photo 3　Experimental environment

2.2　Validation of Automatic Flight Performance of the Drone

As mentioned earlier, the vision sensor does not work appropriately in the dark environments, so it is necessary to equip the drone with an appropriate lighting system so that it can capture the surrounding feature points. Therefore, we actually flew the drone equipped with a 100W lighting system in a dark inside environment to validate whether the vision sensor was working appropriately.

This drone can automatically fly along its path by setting waypoints. In this experiment, two flight paths were planned, as shown in Fig. 1. The distance to the detection target of vision sensor was set to 3m for the flight path of the solid line and 8m for the flight path of the dashed line.

Photo 4 shows the automatic flights of the drone. In the situation where this experiment was conducted, it was confirmed that the drone flew stably and automatically along the flight plan as the vision sensor worked appropriately with the lighting system, even in a non-GNSS and dark environments [7].

Figure 1　Flight plan

Photo 4　State of automatic flight

2.3　Validation of the Quality of Video Taken by the Drone

In this experiment, a 20 megapixels camera which is called Sony UMC-R10 [8] was used as the inspection camera. The images taken during the automatic flights are shown in Photo 5. The cracks at the locations indicated by arrows can be sufficiently identified.

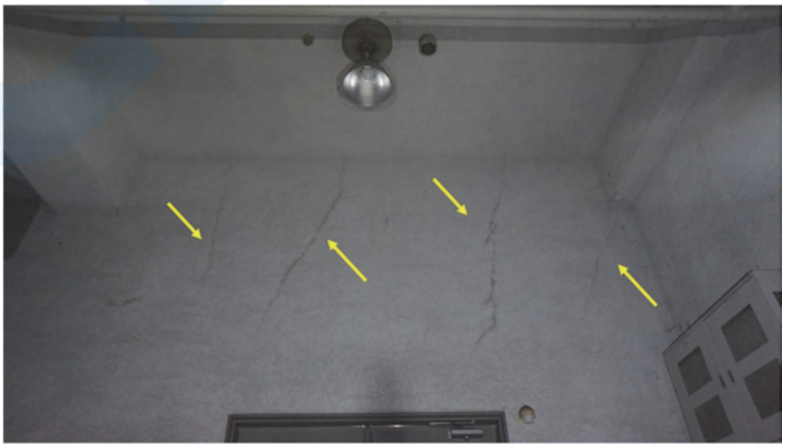

Photo 5　The images taken during the automatic flights

In this experiment, as shown in Photos 6~9, the distance from the photo location was increased to a maximum of 10 meters, and the cracks were confirmed in all cases. In a dark environment such as this experiment, the lighting attached to the drone is the only light source, and the amount of light hitting the photo location decreases as the distance increases. Therefore, as the distance increased, the ISO sensitivity increased, and the noise tended to be amplified.

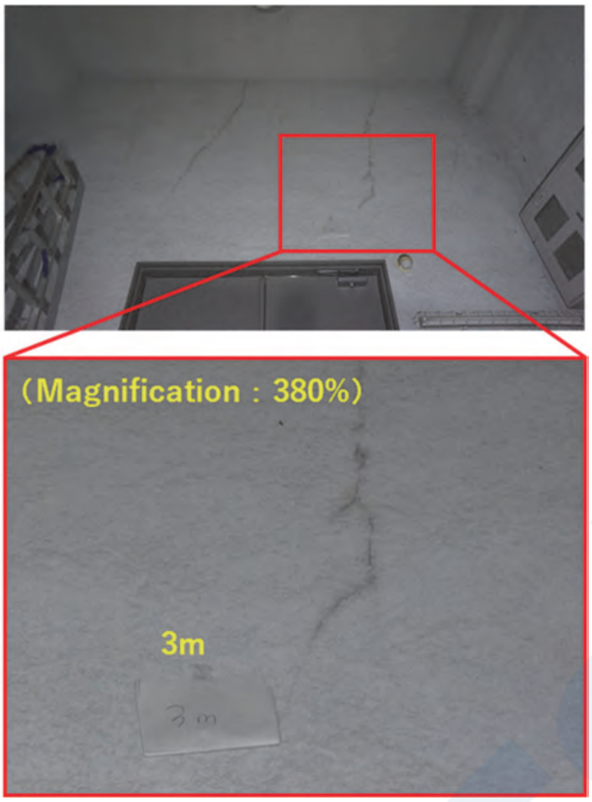

Photo 6　Image taken from a distance of 3m

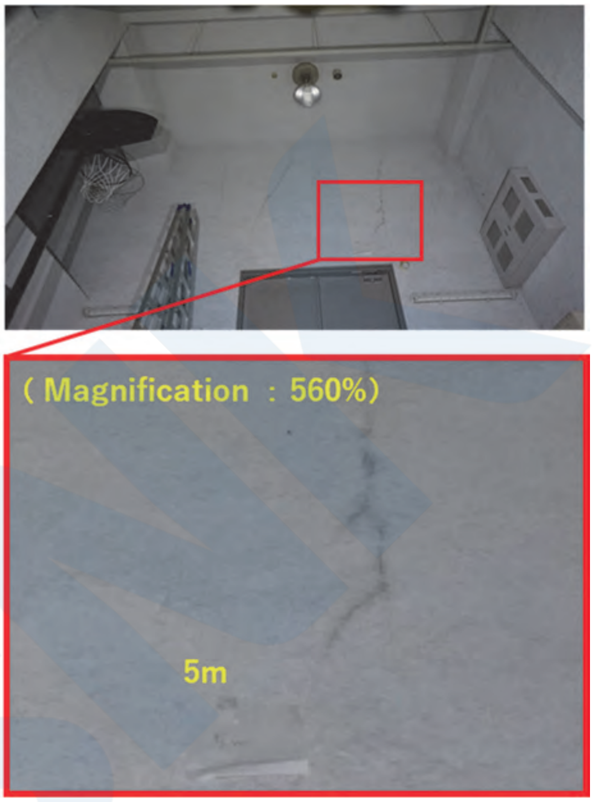

Photo 7　Image taken from a distance of 5m

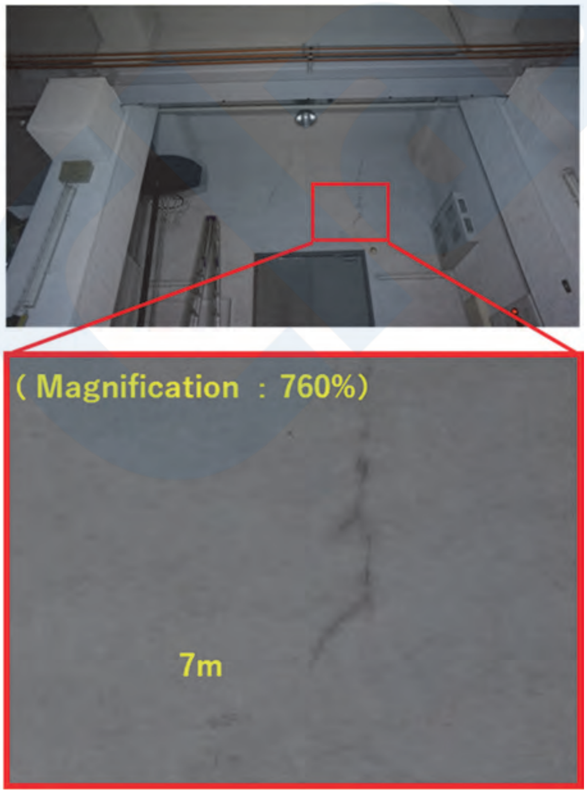

Photo 8　Image taken from a distance of 7m

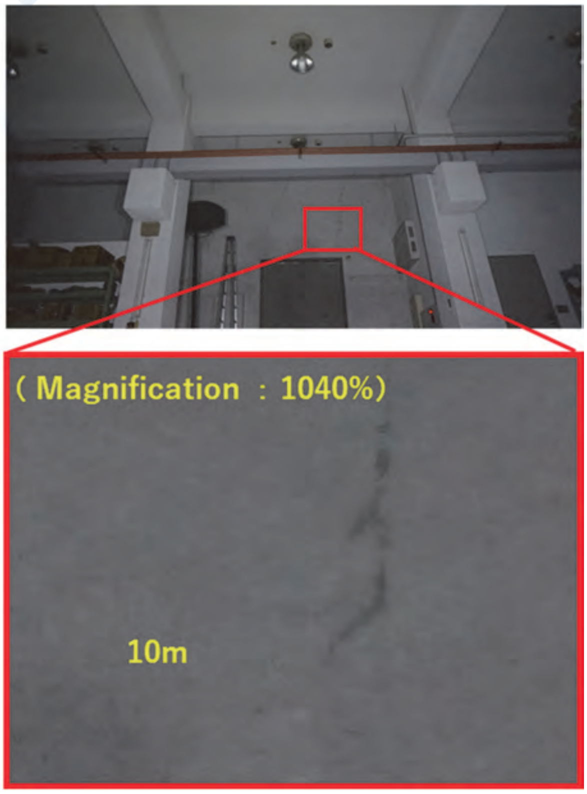

Photo 9　Image taken from a distance of 10m

2.4 Study of the Effective Utilization of Images Photographed by Drones

2.4.1 Processing into 3D Point Cloud Data and Orthophotos

If autonomous drones can be operated with simple operations, the information necessary for surveys/inspections can be easily obtained. For example, if crew can use an autonomous drone, they can take images of the inside of cargo holds during the time when the ship is waiting to enter port. The recorded images can then be used as effective advance information. In addition, technology has already been developed to generate 3D data from the recorded images, and by using this technology, it will be possible to efficiently grasp the situation inside the cargo holds.

SfM processing were performed to generate a 3D model using the images taken during automatic flights. SfM processing is a technique that estimates the positions of multiple images taken by a camera and generates a 3D model of the entire object from the disparity of each image to the same point [9]. The accuracy of the generated 3D model requires a sufficient overlap ratio (the ratio of overlapping parts in a series of images taken by a drone in automatic flight), because it depends on the overlap ratio of the images. In this experiment, the images necessary for SfM processing were acquired by continuously shooting at regular intervals during automatic flight and setting the overlap ratio to be more than 70%. The 3D model is output as 3D point cloud data consisting of many point clouds. The 3D point cloud data can also be processed and orthorectified to obtain orthophotos, which are 2D models. In this experiment, we generated 3D point cloud data and orthophoto from images taken from the two flight paths shown in Fig. 1.

2.4.2 Validation of Effectiveness of 3D Point Cloud Data

Figure 2 shows the generated 3D point cloud data. It shows that the data taken from two different flight paths were successfully combined into one 3D point cloud data, and the object can be confirmed from various angles.

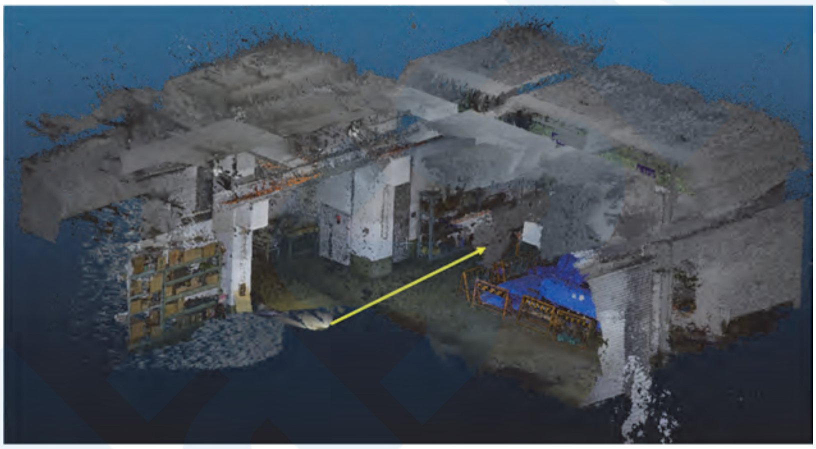

Figure 2 Composite view of 3D point cloud data

Figure 3 is an enlarged view of a portion of the 3D point cloud data when viewed from the direction of the arrow in Fig. 2. When the details are checked, the point clouds become sparse as shown in the lower part of Fig. 3, due to the data has been processed to point clouds.

Thus, while the 3D model makes it easier to grasp the situation intuitively, the image quality itself is degraded. In the ship survey, 3D point cloud data can be useful for understanding the general condition of the inspection area/section. However, it is needed to check in more detail from the photographed images individually to check the suspected areas.

Since the 3D model contains location information, it can also be used for length measurement. We compared the actual measurements with the 3D point cloud data at the three locations indicated by the lines in Fig. 4. Table 2 shows the measurement results.

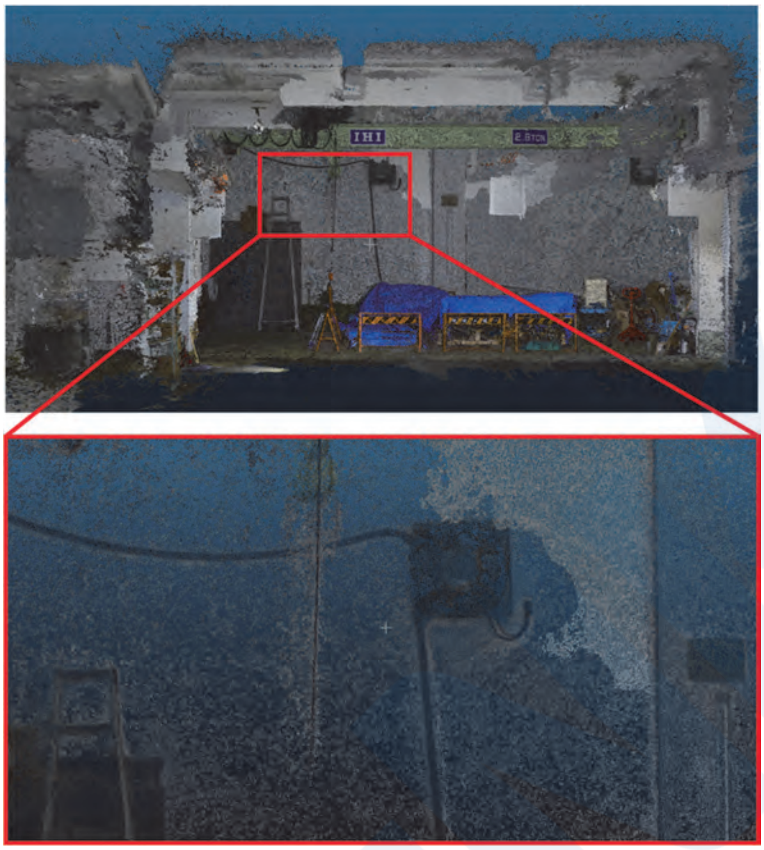

Figure 3　Magnified view of 3D point cloud data

Figure 4　Measured location

Table 2　Comparison of measurement results

	Result of length measurement with 3D point cloud data[cm]	Measured results[cm]	Accuracy[%]
①shelf	209	206	1.46
②Fire hydrant	110	105	4.76
③Barricade	119	121	1.65

Although there is an error in centimeters, it may be useful for measuring the crack length and roughly calculating the extent of damage.

2.4.3　Validation of Effectiveness of Orthophotos

Figure 5 is the orthophoto generated from the images taken in the flight path of the solid line on the left side in Fig. 1, and

Fig. 6 is the orthophoto generated from the images taken in the flight path of the dashed line on the other side.

Figure 5　Orthophoto of the flight path of the solid line

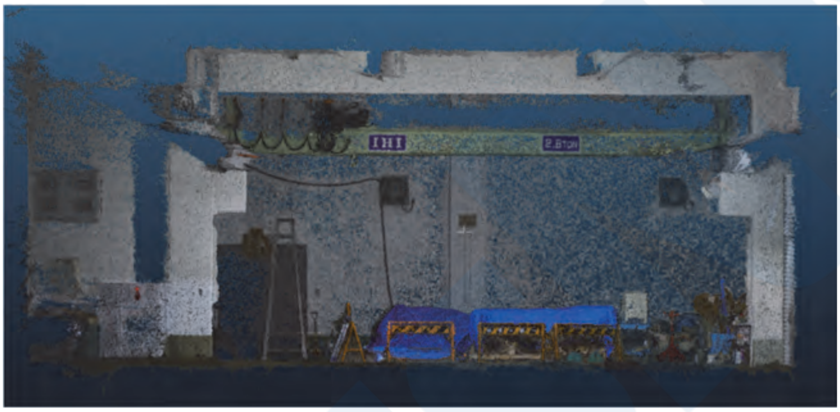

Figure 6　Orthophoto of the flight path of the dashed line

The quality of the orthophoto is close to that of the photographic image, although the image returns from 3D to 2D. Orthophoto cannot capture the situation in three-dimensionally like 3D point cloud data, but the visual information in a plane is improved. Therefore, orthophotos may be more suitable for understanding, for example, the painting condition.

On the other hand, images that show hidden parts of a component from an angle will be lost in the ortho image even though it is reflected in the image taken by the drone since orthophotos are generated by combining photos taken from the front. In this sense, there are advantages and disadvantages.

In addition, there were some parts (black parts) that are not output in the orthophoto. This may be because the orthorectifying is processed on the premise that it is projected onto a single plane, the distortion will be large, when the shape seen from the camera direction is complicated as in this experimental environment, and some parts were failed to convert. As a countermeasure, it is possible to reduce the distortion by generating separate data for each area with different depths.

2.4.4　Considerations

At this stage, it is difficult to determine whether 3D point cloud data or orthophotos are more suitable for ship surveys/inspections. We will continue to study the utilization of 3D point cloud data in combination with orthophotos, while increasing the number of validation cases, after understanding the characteristics of each. For example, if the aging of the entire area/section can be confirmed by comparing chronological order of 3D point cloud data and orthophotos, it can be expected to be effectively utilized for ship surveys/inspections.

Moreover, it is a great advantage to be able to obtain following three types of data from a single camera:

a) An image for survey.
b) A recording images for later confirmation.
c) A 3D model by post-processing the image.

It will become increasingly important for classification societies to make effective utilization of the data obtained. I would like to continue to study how to utilize the data acquired by the drone.

2.5 Summary

In this experiment, the following was confirmed.

- In a dark inside environment with an approximate volume (D x W x H) of 14 x 15 x 5 (m), we were able to confirm that the drone flew stably and automatically along the planned flight path even in a non-GNSS and dark environments as the vision sensor worked appropriately with the lighting system.
- It was confirmed that images that could sufficiently distinguish the cracks could be taken even in the dark environment. However, the quality of the images taken in dark environment varies depending on the distance between the drone and the photo location due to the illuminance. Therefore, it is necessary to take from an appropriate distance according to the performance of the camera and the illumination level.
- 3D point cloud data and orthophotos were obtained by SfM processing of the images taken by the drone.
- In 3D point cloud data, the 3D model makes it easier to grasp the situation intuitively.
- The image quality itself is degraded by processing into the 3D point cloud data. Therefore, In the ship survey, 3D point cloud data can be useful for understanding the general condition of the inspection area/section. However, it is needed to check in more detail from the photographed images individually to check the suspected areas.
- The length measurement from 3D point cloud data has an error of centimeters. It can be used to grasp the rough crack length and to calculate the extent of damage.
- In the orthophoto, visual information on a large area of a flat surface could be confirmed with a quality close to the photographic image. It may be possible to grasp the painting condition on ships. On the other hand, images that show hidden parts of a component from an angle may be lost in the orthophoto, even though it is reflected in the image taken by the drone.

3. CONCLUSION

In this experiment, we used a drone equipped with a vision sensor and confirmed that stable automatic flight was possible in an inside enclosed area without external lighting. However, since the vision sensor recognizes self-localization based on the feature points of the images captured by the camera, it is necessary to continue to validate whether the sensor can work appropriately in a larger space than this experimental environment. We would like to conduct a demonstration experiment inside a ship to validate the system under conditions closer to actual operation.

ClassNK will engage in relevant study to ensure that the ship surveys/inspections are carried out efficiently and rationally.

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Recent Topics at IMO

— Outline of Discussion at IMO Committees —

External Affairs Department, ClassNK

1. INTRODUCTION

This article introduces recent topics discussed at IMO (International Maritime Organization). At the previous issue, a summary of the topics discussed at 103rd Maritime Safety Committee (MSC 103) held in May of 2021 was provided.

This article provides a summary of the decisions taken at 76th Marine Environment Protection Committee (MEPC 76) held from 10 to 17 June 2021 as below. MEPC 76 was held remotely in lieu of physical session at the headquarters of IMO, due to COVID-19 situation. Please bear in your mind that, since time constraints due to remote meeting, a number of proposals and comment papers were not considered at MEPC 76 and thus postponed to MEPC 77 to be held in November.

2. OUTCOMES OF MEPC 76

2.1 Greenhouse Gases (GHG) Emission Reduction Measures

Measures to reduce GHG emissions from international shipping have been deliberated at IMO and the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP) and the Data Collection System for fuel oil consumption of ships (DCS) have been introduced so far. Further, the Initial IMO Strategy on reduction of GHG emissions from ships, was adopted at MEPC 72 held in 2018, which includes the emission reduction targets and candidate measures to reduce GHG emissions from maritime.

2.1.1 Short-Term Measures for Reduction of GHG

Initial IMO Strategy on reduction of GHG emissions from ships, adopted at MEPC 72, specifies short-term target by 2030 and mid/long-term target by 2050.

At this session, amendments to MARPOL Annex VI were adopted to implement (1) Energy Efficiency Existing Ship Index (EEXI), as a technical approach, and (2) Carbon Intensity Indicator (CII), as an operational approach, to achieve the short-term target for improvement of transportation efficiency at least 40% compared to 2008.

(1) Energy Efficiency Existing Ship Index (EEXI)

EEXI is regulations for existing ships to require the same level of energy efficiency as new ships and applied to all ships[*1] of 400 GT and above engaged in international voyage. Verification for EEXI shall take place at the first annual, intermediate or renewal survey of IAPP Certificate on or after 2023.

Attained EEXI for each existing ship should be calculated using the similar formula to EEDI, and is required to satisfy a required EEXI, which is calculated based on EEDI reference lines for each category of ships by multiplying reduction factor stipulated by ship size.

If the attained EEXI value cannot satisfy the required EEXI, the ship should implement a measurement to improve energy efficiency, such as shaft/engine power limitation etc, to satisfy the required EEXI.

For ships already applied EEDI requirements and, if the attained EEDI value also complies with the required EEXI, the attained EEDI value as indicated in IEE Certificate or EEDI technical file can be used as an alternative to the attained EEXI

(2) Operational Carbon Intensity Indicator (CII)

Operational Carbon Intensity Indicator is rating mechanism for ships based on the operational fuel consumption data. Each ship[*2] of 5,000 GT and above engaged in international voyage should calculate attained CII every year, based on the data

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[*1] Bulk carrier, Gas carrier (LPG carrier), Tanker, Containership, General cargo ship, Refrigerated cargo carrier, Combination carrier, Ro-ro cargo ships (Vehicle carrier), Ro-ro cargo ship, Ro-ro passenger ship, LNG carrier and non-conventional propelled Cruise passenger ship (Except ships which have non-conventional propulsion such as diesel electric, turbine or hybrid propulsion system, but in this context, except LNG carrier and cruise passenger ship)

[*2] Bulk carrier, Gas carrier (LPG carrier), Tanker, Containership, General cargo ship, Refrigerated cargo carrier, Combination carrier, Ro-ro cargo ships (Vehicle carrier), Ro-ro cargo ship, Ro-ro passenger ship, LNG carrier and Cruise passenger ship

of annual fuel consumption and annual distance travelled, which are collected under the Data Collection System for fuel oil consumption of ships (DCS). By the end of 2022, each ship should indicate on SEEMP, the calculation method of annual CII from 2023 calendar year and reporting procedure of CII.

Required CII is calculated using CII reference lines for each category of ships by multiplying reduction factor. Comparing the attained CII with the required CII, ships are rated as A to E, based on the gap between the attained CII and the required CII. If a ship is rated as D for three consecutive years or rated as E, the ship should develop a plan of corrective actions, such as speed reduction or optimal routing etc.

The reduction factor to be used for calculating the required CII will be enhanced every year as below. Reduction factor means reduction rates from CII reference lines, which is a curve representing the average CII for each category of ships in year of 2019.

Table 1 Reduction factor of CII

Year	Reduction factor
2023	5%
2024	7%
2025	9%
2026	11%
2027-2030	To be decided later

2.1.2 Other Measures for Reduction of GHG

(1) Work plan for mid/long-term measures

MEPC 76 developed work plan for development of mid/long-term measures, as a follow up of the initial IMO strategy on reduction of GHG emissions from ships. A summary of work plan is as follows:

Table 2 Work plan for development of mid/long-term measures

Phases	Work item	Timeline
Phase I	Collation and initial consideration of proposals for measures	2021-2022
Phase II	Assessment and selection of measures to further develop	2022-2023
Phase III	Development of measures for statutory requirements	2023-

(2) IMRF and IMRB

At MEPC 75 held in November 2020, it was proposed to establish International Maritime Research Fund (IMRF). MEPC 76 agreed to continuously consider this proposal at future session.

2.1.3 Requirements of Minimum Propulsion Power and EEDI

It is required to keep sufficient propulsion power for operations in adverse weather conditions, although the Energy Efficiency Design Index (EEDI) can be easily improved by a cutdown of main engine powers. At MEPC 65, Interim Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions (MEPC.232(65)) were developed to avoid construction of extremely under-powered ships. At MEPC 71, it was agreed to extend the application period of the Interim Guidelines towards phase 2 of EEDI regulation. The application date of Phase 3 is approaching, and finalisation of the Guidelines was the urgent matter.

At this session, amendments to Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions were adopted to incorporate the results of SHOPERA and JASNAOE projects.

MEPC 76 also agreed to further consider the concept of shaft/engine power limitation as measures to comply with both EEDI and minimum propulsion power requirements at MEPC 77.

2.2 Others (Underwater Noise)

Concerns on effects of underwater noise on marine mammals have been risen, since a number of marine mammal stranding were reported. MEPC 66, held in 2014, adopted non-mandatory Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (MEPC.1/Circ.833).

At this session, it was agreed to establish new work program to undertake a review of the Guidelines. The review will be started at SDC Sub-Committee next year.

2.3 Amendments to Mandatory Instruments

MEPC 76 adopted amendments to mandatory instruments as follows:

(1) Short-term measures for reduction of GHG: EEXI and CII

As the above 2.1.1, amendments to MARPOL Annex VI to implement EEXI and CII regulations to achieve short-term target by 2030, -i.e. 40 % improvement of energy efficiency of international shipping, were adopted.

(2) Heavy fuel oil in Arctic waters

Amendments to MARPOL Annex I to prohibit the use, and carriage for use as fuel of heavy fuel oil by ships in Arctic waters were adopted. This prohibition will be applied on or after 1 July 2024. For ships to which regulation 12A of this Annex or regulation 1.2.1 of chapter 1 of part II-A of the Polar Code applies, the application date is on or after 1 July 2029. The carriage of heavy fuel oil as cargo will not subject to the prohibition.

(3) Application of MARPOL Annex I, IV and VI for UNSP barges

Amendments to MARPOL Annex I, IV and VI for the exemption of unmanned non-self-propelled (UNSP) barges were adopted.

(4) Control of Harmful Anti-fouling Systems on Ships (AFS Convention)

Amendments to AFS Convention to prohibit the use of anti-fouling paints that contains cybutryne were adopted.

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