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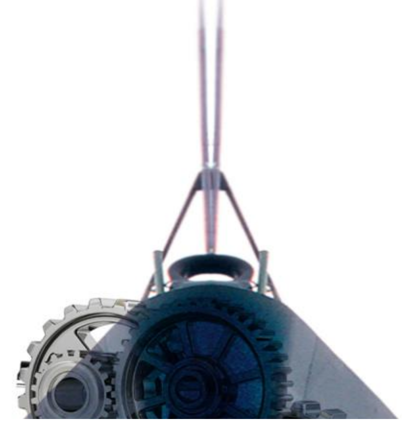

On the development of verification procedures of autonomous navigation system and test scenarios for ensuring reliability

2024. 5. 14.

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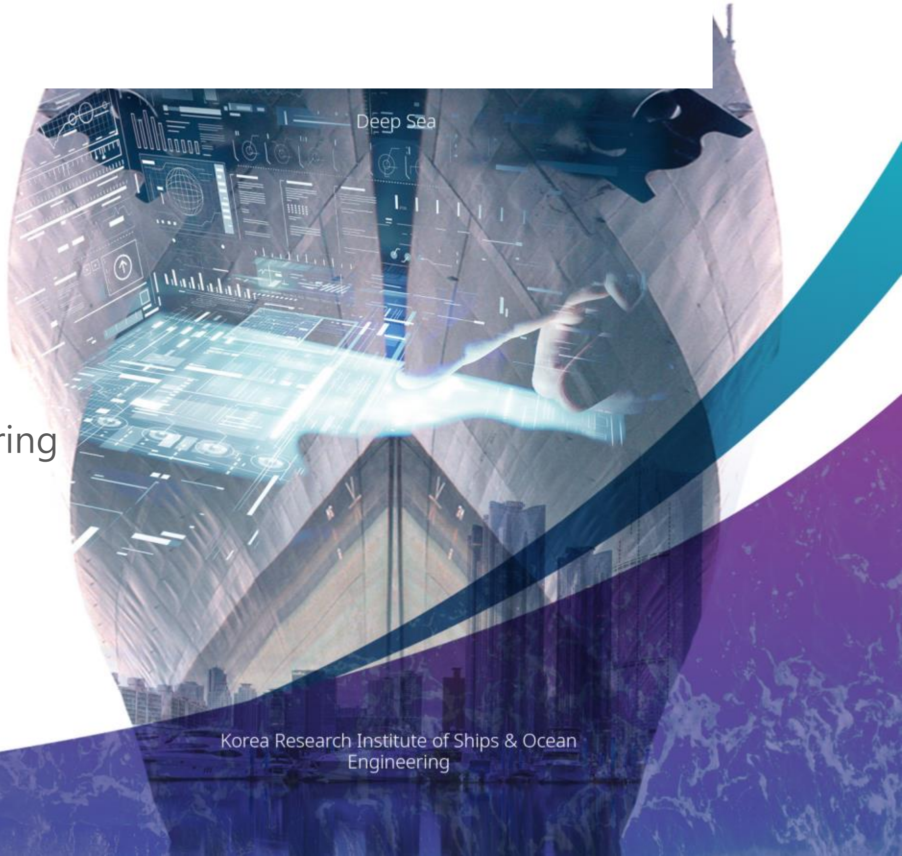

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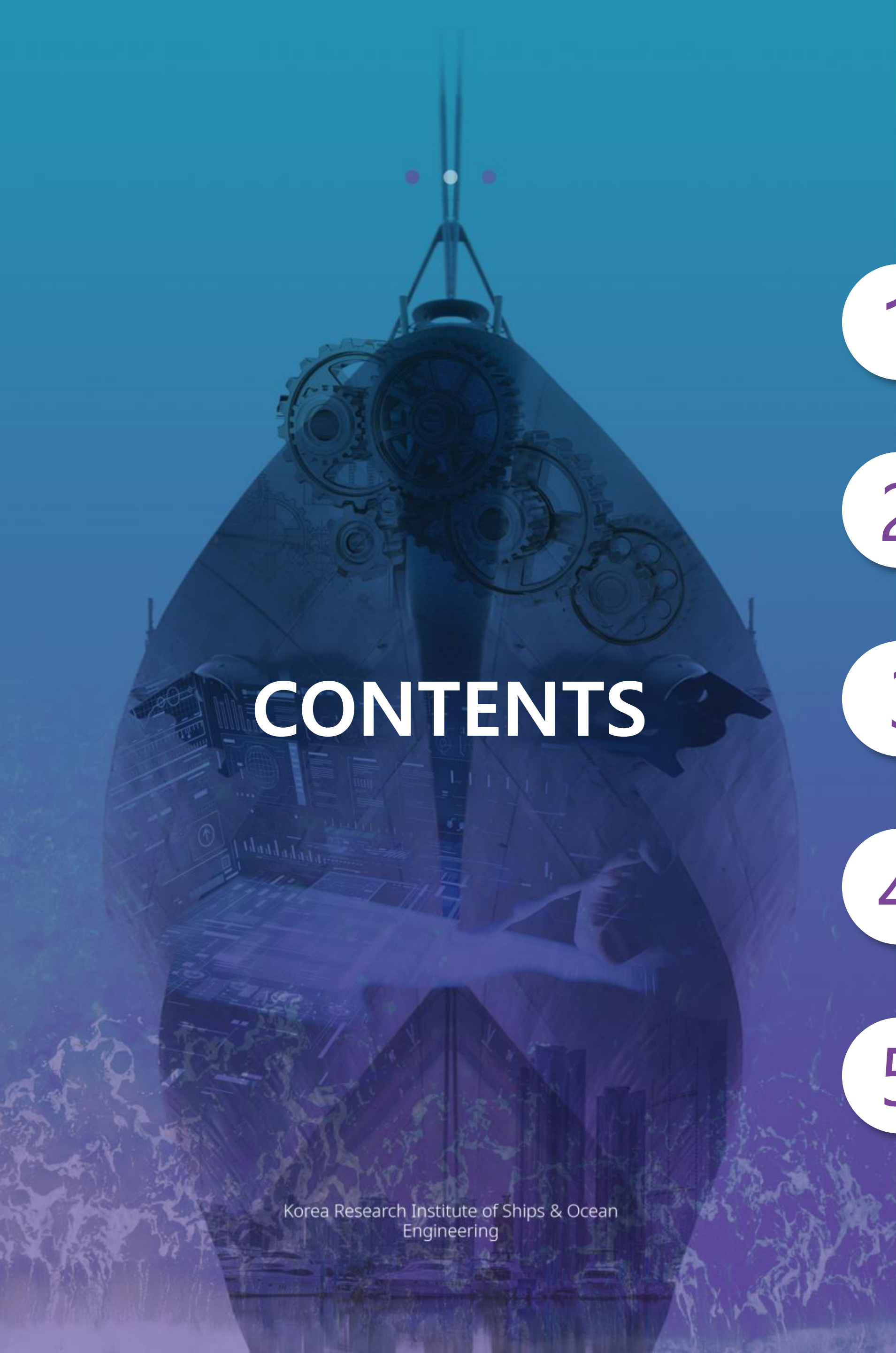

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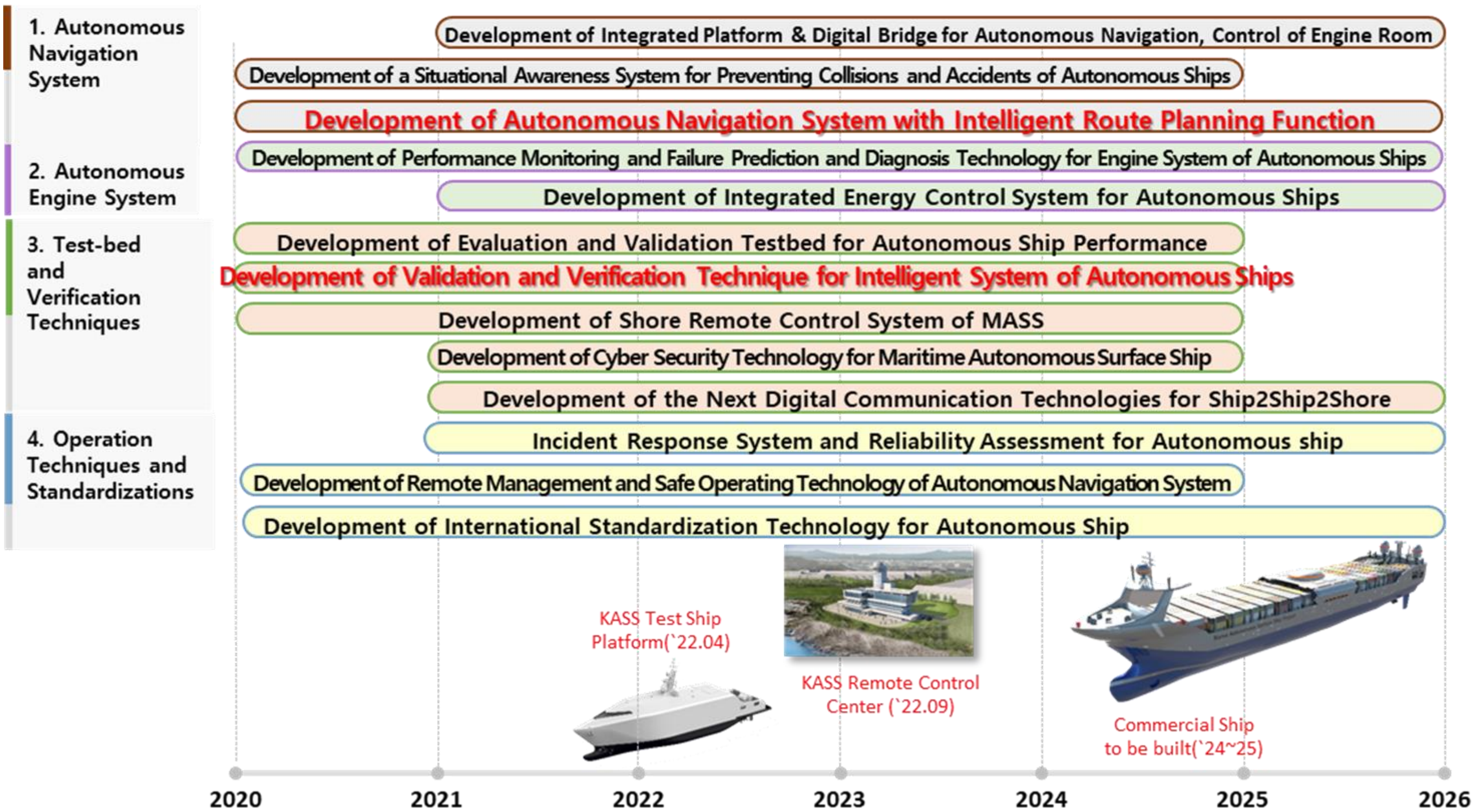
1

Introduction

Korea Research Institute of Ships &
Ocean Engineering

KASS Project

Korea Autonomous Surface Ship (KASS) Project (2020~)



Development of Verification Procedures

Purpose

- ☑ To check if the target system can be fully functional in the design domain
- ☑ Deliver overall performance expectation of a system of interest to whom it may concern
- ☑ Make consensus on the system of interest among stakeholders (developers, users, ship owners, harbor authority, VTS officers, police, etc.)
- ☑ Helping development of highly safe and reliable intelligent system of MASS

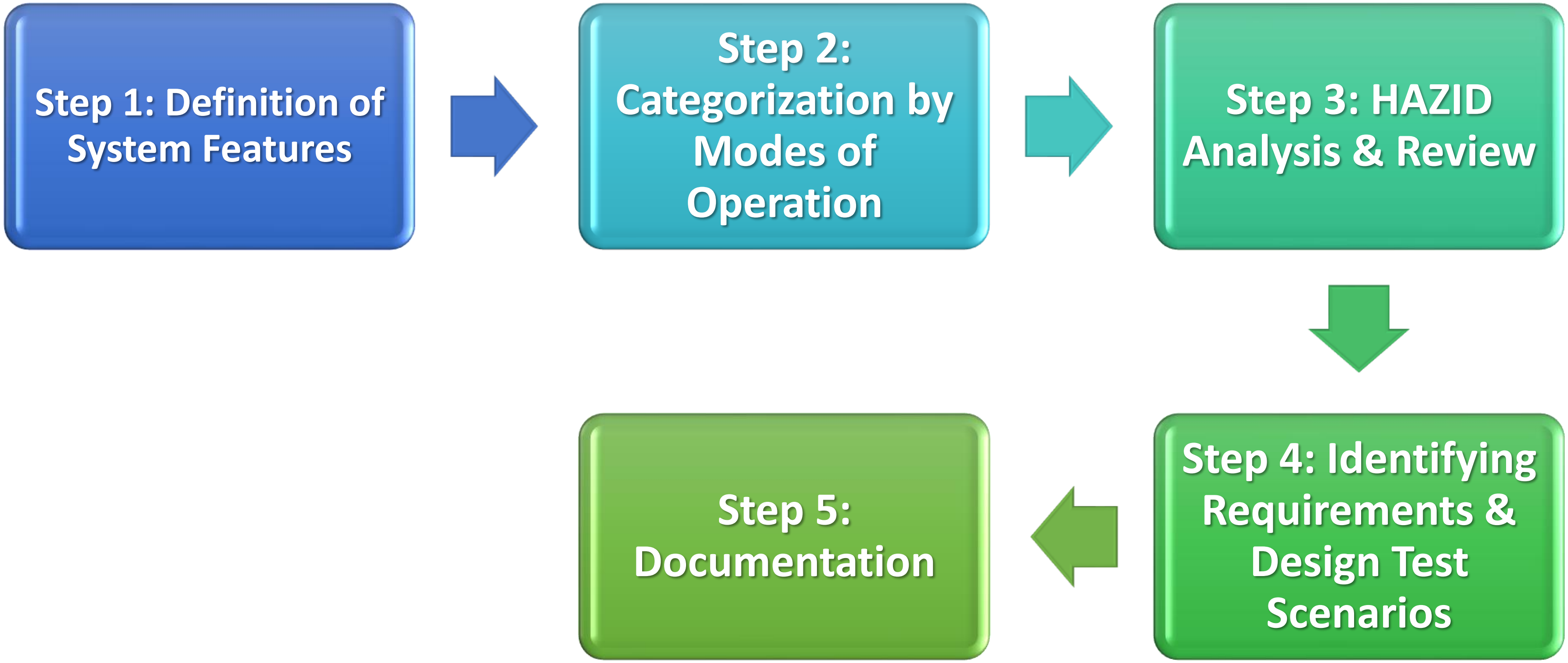
Systems of interest

- ☑ Systems related to autonomous navigation
    - ☑ **Intelligent navigation system**
    - ☑ Situational awareness system
    - ☑ Remote control system including monitoring function
- ☑ Important for navigational safety
- ☑ Highly related with MASS level of autonomy and overall performance

2

Steps for Developing Verification Procedures

5 Steps for Developing Verification Procedures



Step 1: Definition of System Features

Safe navigation system

- A system that controls a vessel or assists a human in controlling a vessel so that the vessel can continue its voyage to its destination while securing safety from hazards that may occur during the voyage.
- …

Situation awareness system

- A system that automatically detects surrounding objects (traffic ships, floating objects, buoys, land obstacles, etc.) located in the vicinity of a navigating vessel, and provides it to the operator or vessel's system to assist for decision-making.
- …

Remote control system w/ monitoring function

- A system that is composed of a system installed in the onshore remote control center (Remote Operation Center; ROC) to control the target ship remotely and a system that receives signals from the ROC, judges the appropriateness of the signals, and implements them in the autonomous ship.
- …

Step 2: Categorization by Modes of Operation

Categories for discriminating operation modes of safe navigation system

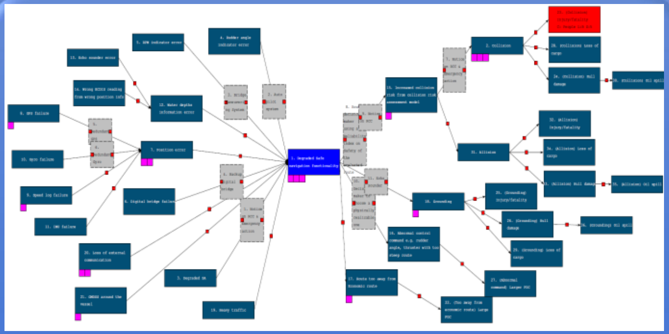
- ☑ Category A: Operational area (Complexity of traffic situation)
- ☑ Category B: Human location
- ☑ Category C: Degrees of human intervention

Category A - Operational Area	Cat. Code	Category B - Human location	Cat. Code	Category C - Human intervention	Cat. Code
Open Sea (Mid & Large Vessel, No-sail zone)	OS	On board	OB	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Remote	RM	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Fully autonomous	FA	System Controls All, Human Absent, intervention after accident	
Costal Area - Within 20 nautical miles of land, islands, or reefs (Small, Mid & Large Vessel, Towed vessel, Fishing trawler, low-UKC zone, Fishing nets, No-sail zone)	CA	On board	OB	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Remote	RM	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Fully autonomous	FA	System Controls All, Human Absent, intervention after accident	
Near Harbour - Within 12 nautical miles of land, islands, or reefs (Small, Mid & Large Vessel, Islands, AtoNs, Bridges, Towed vessel, Fishing trawler, low-UKC zone, Fishing nets, No-sail zone)	NH	On board	OB	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Remote	RM	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Fully autonomous	FA	System Controls All, Human Absent, intervention after accident	
Harbour (Small, Mid & Large Vessel, Islands, AtoNs, Bridges, Wave breakers, Towed vessel, (Un)Berthing vessels, No-sail zone)	HA	On board	OB	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Remote	RM	Human Controls, System Reference	HC
				Human Supervision, System Controls	SC
				System Controls All, Warning, No Human Supervision, takes control only when beyond system capability	SCA
		Fully autonomous	FA	System Controls All, Human Absent, intervention after accident	

Step 3: HAZID Analysis & Review – 1/2

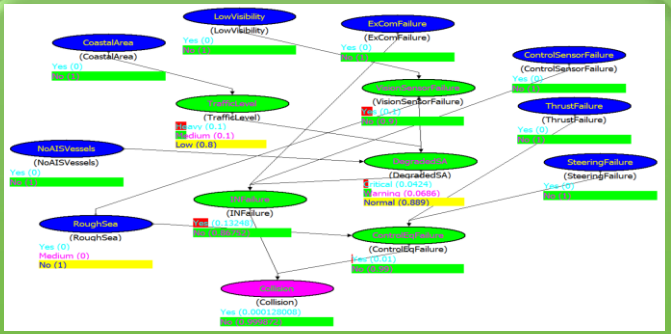
Purpose of HAZID

☑ Early identification of potential threats that could result in harm to personnel or to the environment, and forms the basis for major accident hazard management (ISO 17776:2002) ➔ Identification of functional requirements, fallbacks, minimum risk conditions, and important factors those should be considered thoroughly as test conditions



Identifying factors&barriers by Flex Bowtie diagram

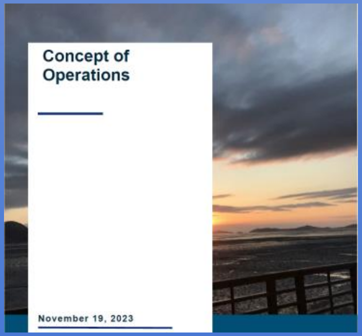
- System status: Regular, Degraded, Fail, Back-up
- Identifying factors those characterize operation status
- Identifying factors those degrade system operation, and, barriers for each factors, then draw relation diagr am



Analysis of major hazard factors and sensitivities

- Analyze major hazard factors, assume degrees, levels, and probabilities of those factors, and then identify rel ations among those factors. Finally, calculate accident probability (Bayesian Belief Network; BBN)

Step 3: HAZID Analysis & Review – 2/2



Identification of ConOps (Concept of Operations)

- Organize the conditions under which the system of interest operates, the functions it performs in each condition, and the functional elements to prepare for degradation and malfunction

ID	Hazard	Fallback	MRC	Recommendations
1	Too harsh weather beyond Operation scenario (Weather forecast failure)	ANS shall change the course to get out of the harsh weather.	Ensure a non-critical weather condition	A set of concrete and specific safe voyage condition should have been established, which may be subject to simulation-based test.
2	Too high level of congestion	Choose the operation that has the lowest level of collision risk including crash stop using emergency anchoring.	Maintain the collision risk as low as possible.	Evaluate necessity of an analysis whether a crash stop increases risk of collision.
3	Single failure in ANS (SA, IN or DB)	A fallback must be an alarm to ROC for it to assess the situation.	Failed system is isolated from ANS.	An FMEA is recommended to be performed to check failure effects of single failure and if a single failure may lead to total loss of ANS
4	Degraded performance of SA and/or IN	The fallback of ANS is to identify spurious information, inform ROC and reject it for SA & IN, the process of which should have been designed through relevant documentation.	MRC can be defined as Using only reliable information for SA and IN.	A test may be devised for a function that uses ship motion, weather information, complexity of the background image, etc. as a criterion for SA's reliability. Develop a method to identify spurious information to be rejected by SA & IN.
5	Complete loss of SA	At deep sea, MASS shall adjust the route to the nearest safe haven while manifesting clearly that MASS is in her emergency and can't perform a collision avoidance maneuver. ROC shall be notified to prepare an emergency response to recover the SA or to take control of the vessel. Around a coastal area, MASS shall slow down and stop with audio and visual signals informing that MASS is in her trouble and can't perform any collision avoidance.	MRC upon this hazard can be defined as Using only reliable information.	Two test scenarios can be considered: switch to a pre-determined safe haven at an open sea & slowing down and stop without altering the course.
6	Complete loss of IN	At open sea, having informed ROC of the status, MASS may keep the current route. This fallback can maintain the current level of risk temporarily. At coastal area, the duration during which the current level of risk can be maintained will be short and there is a collision risk with following vessels. The fallback would be to decrease the speed and stop while SA doesn't identify an object in the course. Emergency stop can be considered if there's no following vessel.	MRC is to put MASS under the control of ROC as soon as possible	

Review of Minimum Risk Condition; MRC

- Identify and organize Minimum Risk Conditions and key actions to achieve them to ensure the safety of autonomous ships in case of degradation and malfunction of system of interest.

Step 4: Identifying Requirements & Design Test Scenarios

Identification of requirements

- ☑ Functional requirements
  - Derived by system features
  - Derived by operational mode
  - Derived from safety features (fallback functions)
- ☑ Performance Requirements
  - Determined by operation mode
    - Traffic conditions
    - Environmental conditions

Test scenario design

- ☑ Traffic situations those can represent typical traffic condition of target operation mode

Step 5: Documentation

System Overview

- ☑ General definition of the system
- ☑ Categorization of system by modes of operation

Verification procedures

- ☑ Target system
  - Definition of the system of an operation mode (role & functions)
- ☑ Requirements
  - Functional requirements
    - Operational features
    - Safety features (fallback functions)
  - Performance requirements
    - Traffic conditions
    - Environmental conditions
- ☑ Test items
- ☑ Test procedures
  - Functional requirements tests
  - Scenario tests

3

Functional Requirements Tests & Scenario Tests

Functional Requirements Tests – 1/2

Ex.) Requirements - Near coast, human on-board, system controls, human supervise

- ☑ The system must be able to calculate the collision risk of other ships and fixed obstacles
- ☑ The system must be able to create action plans to avoid dangerous traffic situations, and keep sailing to the existing global path after avoiding dangerous traffic situations
- ☑ Thrust and rudder control commands generated by the system must be within the target ship's implementable control range
- ☑ The system must have up-to-date navigational chart data
- ☑ The system must be able to transfer control to the human who is authorized to operate the vessel through a proper process without flaws, if needed
- ☑ The system must be able to get the information related to safe navigation
- ☑ Ship’s navigational status data related to the system operation must be shown to the human who is authorized to operate the vessel, and must be logged

Functional Requirements Tests – 2/2

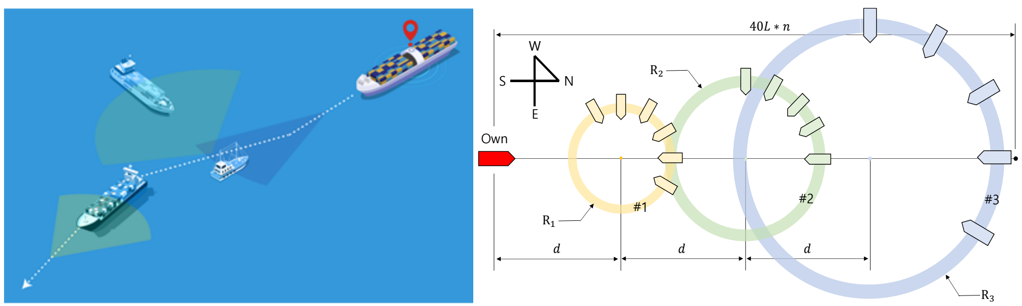
☑ To ensure safety, the system must have fallback functions to reach minimum risk conditions

- Risky status
  - Encounters dangerous traffic situation beyond the system's capacity
  - Abnormalities in the system's status, interfacing equipment, and sensors
  - Malfunctions of control systems
  - Malfunctions of safe navigation system
  - Change of operational domain
- Fallback functions
  - Send warnings, alarms, or emergency call to the person in charge of navigation
  - Collision avoidance control
  - Provide operation history data
  - Activate control transfer protocol
  - Activate emergency stopping protocol
- Minimum Risk Conditions
  - Continuing control by the system
  - Direct control of human who is authorized to operate the vessel
  - Emergency stop and spreading current situation

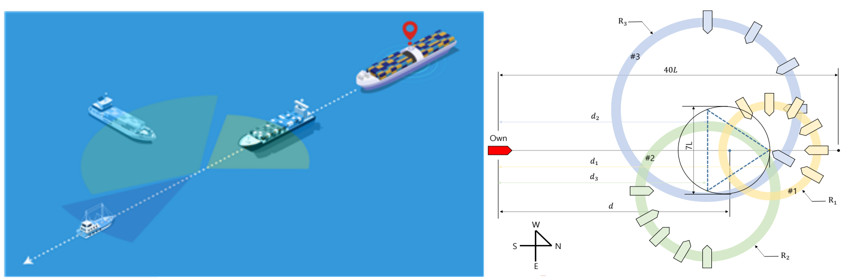
Scenario Tests

Simulations + Sea trial

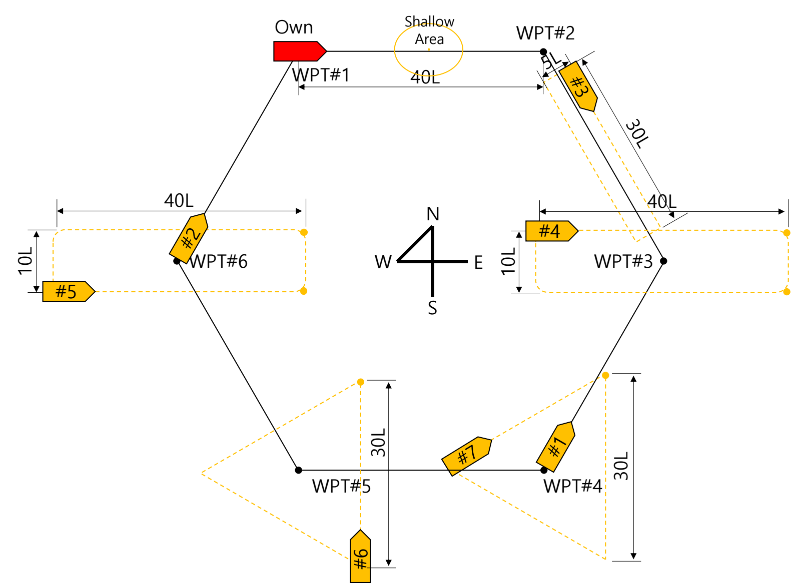
- ☑ Performance check
- ☑ Various areas/environment/fixed objects/traffic vessels/ownship conditions
- ☑ Traffic scenario
  - Single & Successive encounter (Open sea, coastal area, near coast)
  - Multiple simultaneous encounter, complex traffic (Coastal area, near coast)
  - Combined traffic (Near coast)



Successive encounter scenario (example)



Multiple simultaneous encounter scenario (example)

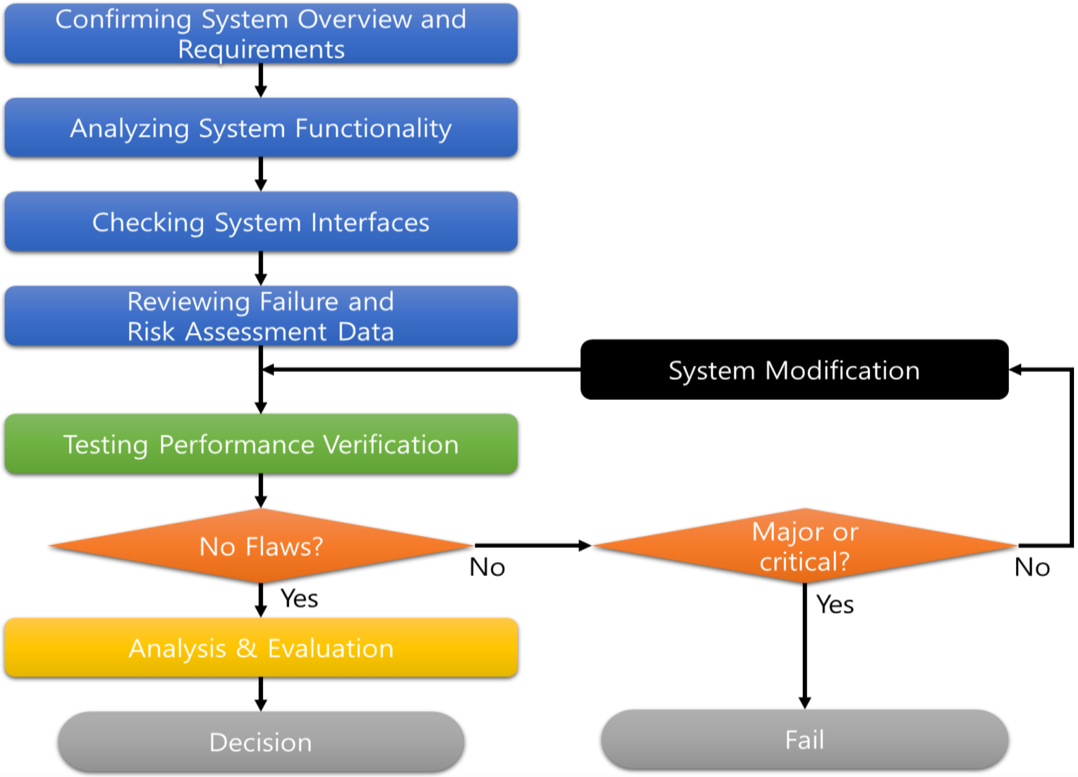


Combined/complex traffic scenario (example)

Verification Flows

Systematic verification of systems of interest

- ☑ Systematically assess various aspects of the system, from overview and functionality to failure and risk assessment.
- ☑ Determine system failures, need for fixes, or need for retesting based on different test scenarios for the system under verification



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Test Results of NEMO Intelligent Navigation System

Tests during Development

System development phase

Simulation Tests
- Setting parameters
- Simple/combined/complex traffic situations

Model Tests of Basic Conditions
- Basin model test (Disturbance can be controlled)
- Basic traffic situations (One or two vessel passage, head-on, crossing, overtaking, etc.)

Model Tests of Complex/Combined Conditions
- Inland water model tests
- Combined/complex traffic situations
- Augmented reality traffic situations

On-board system verification phase

Simulation Tests
- Various areas/environmental disturbances/fixed obstables /traffic vessels/ownship conditions
- Simple/combined/complex traffic situations

Sea Trials of Basic Conditions
- Sea-trials
- Basic traffic situations (One or two vessel passage, head-on, crossing, overtaking, etc.)
- Functional review including HMI, control transfer, fallback, etc. (Considering target category)

Sea Trials of Complex/Combined Conditions
- Sea-trials
- Combined/complex traffic situations
- Augmented reality traffic situations
- Functional review including HMI, degree of Integration with navigation system, control transfer, fallback, etc. (Considering target category)

Simulation Tests: Development Phase

NEMO(Navigation Expert for MASS Operation) simulation tests for algorithm performance check & complements

- ☑ Initial setting of algorithm parameters
- ☑ Checking massive traffic situation cases by simulation speed adjustment
- ☑ Checking feasibility of test scenarios

Model Tests of Basic Conditions

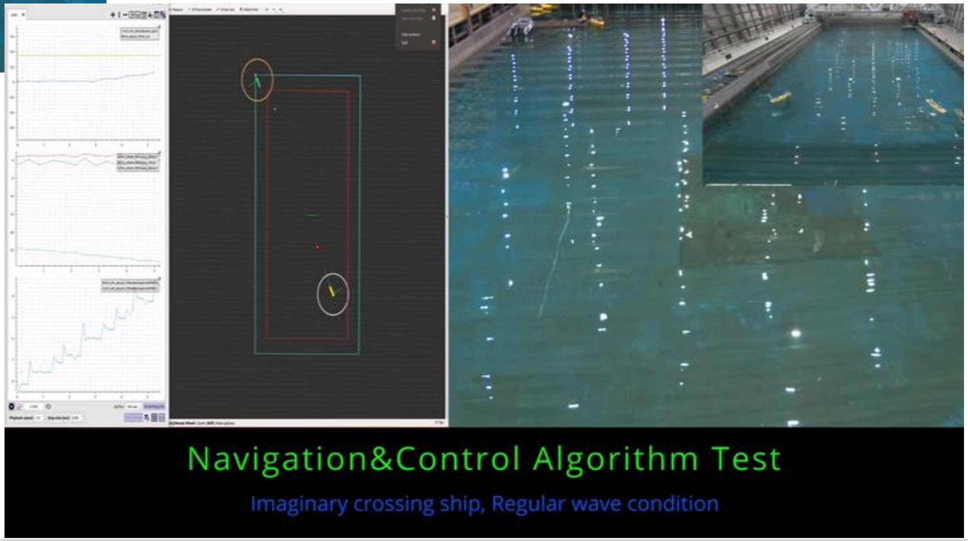
NEMO algorithm verification model tests – Basics & disturbance

☑ Basic traffic situation w/ disturbance control (wave condition)

- 1 physical traffic ship, head-on

- 1 imaginary traffic ship, crossing
- 1 observer ship

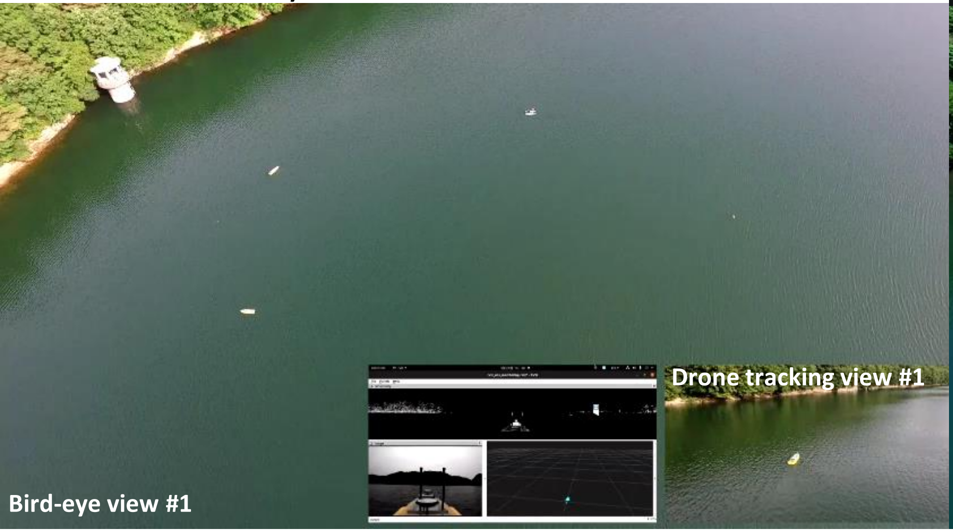
- 1 imaginary traffic ship, head-on
- 1 observer ship

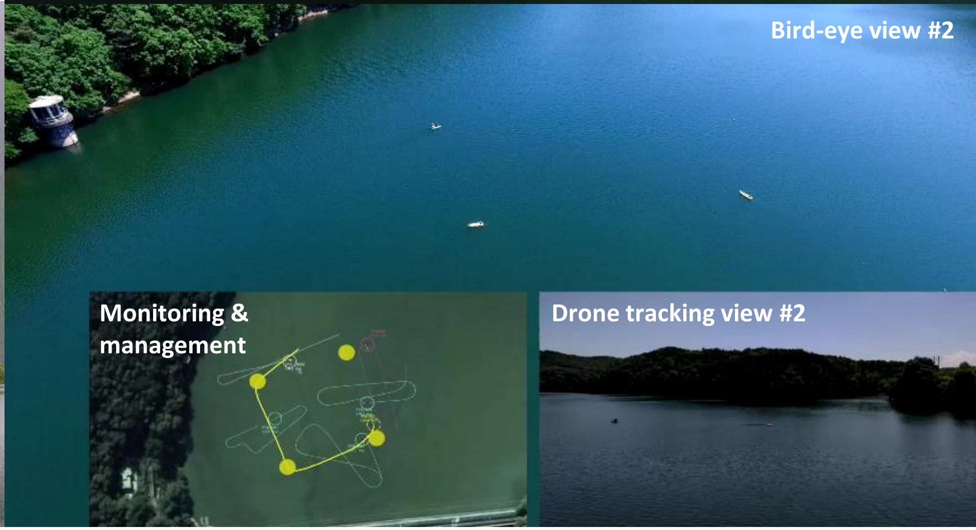


Model Tests of Complex Conditions

NEMO algorithm verification model tests – Costal area

- ☑ Checking overall performance
- ☑ 2 physical traffic ships + 3 imaginary traffic ships & α
- ☑ 1.5 hours duration with no human intervention/1 test
- ☑ About 1,000 times of different encountering situations
- ☑ Remotely monitored by DTB/E monitoring mirror system in KRISO





Model Tests of Complex/Combined Conditions

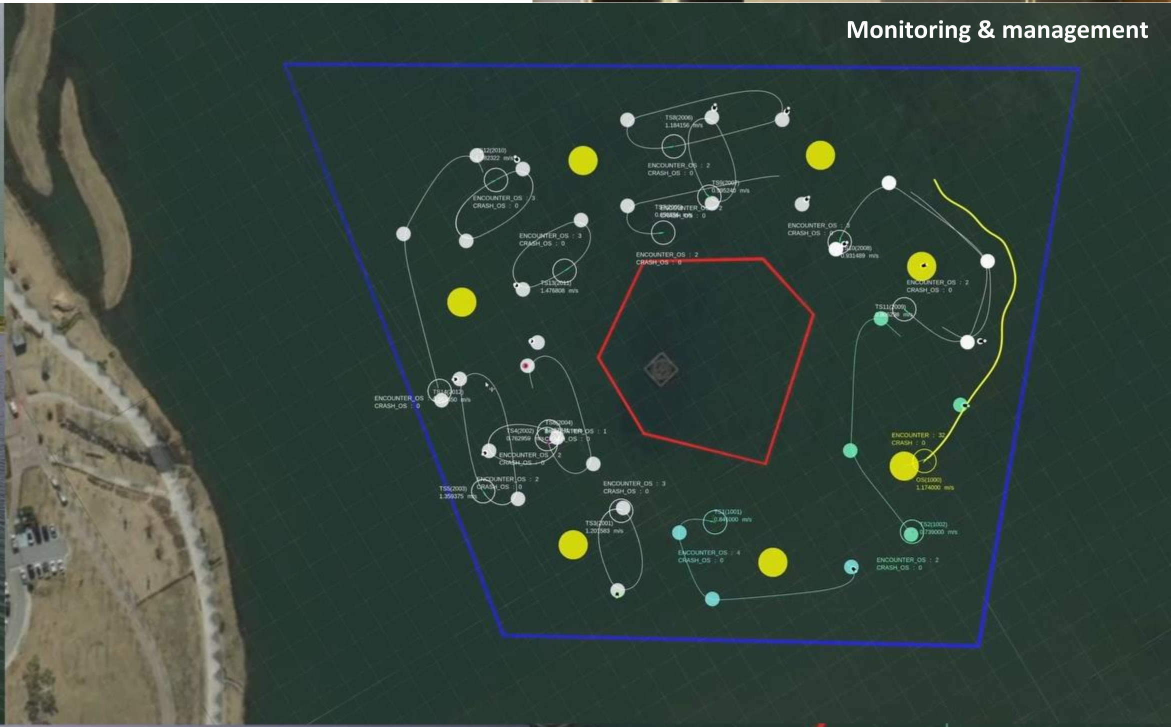
NEMO algorithm verification model tests – Near coast

- ☑ 3 physical traffic ships + 11 imaginary traffic ships with imaginary boundaries, no-sail zones


Remote monitoring (KRISO)

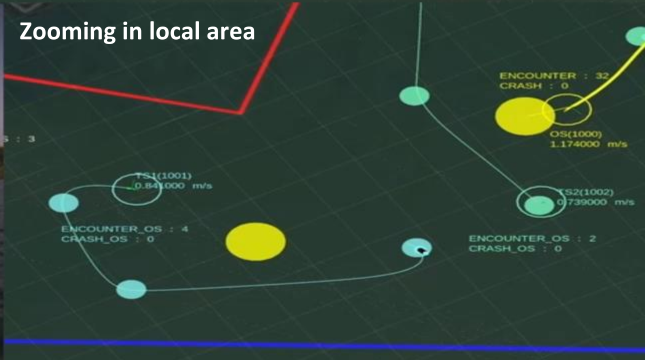

Bird-eye view #1


Bird-eye view #2


Monitoring & management


Traffic ship #2


Ownship

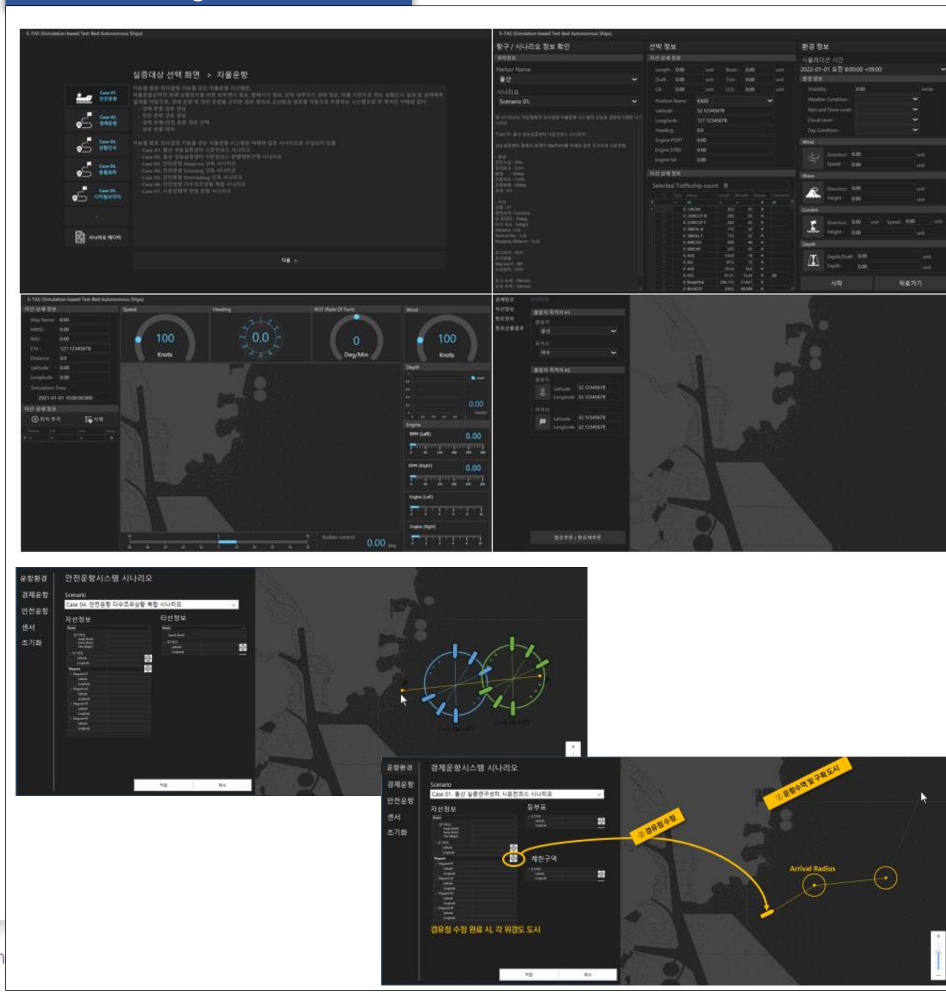

Zooming in local area

Simulation Tests: System Verification Phase

S-TAS (Simulation-based Testbed for Autonomous Ship)

- ☑ Overcoming the limitations of sea-trial tests
- ☑ Various areas/environmental disturbances/floating&fixed obstacles/traffic vessels/ownship conditions

Scenario Manager of S-TAS



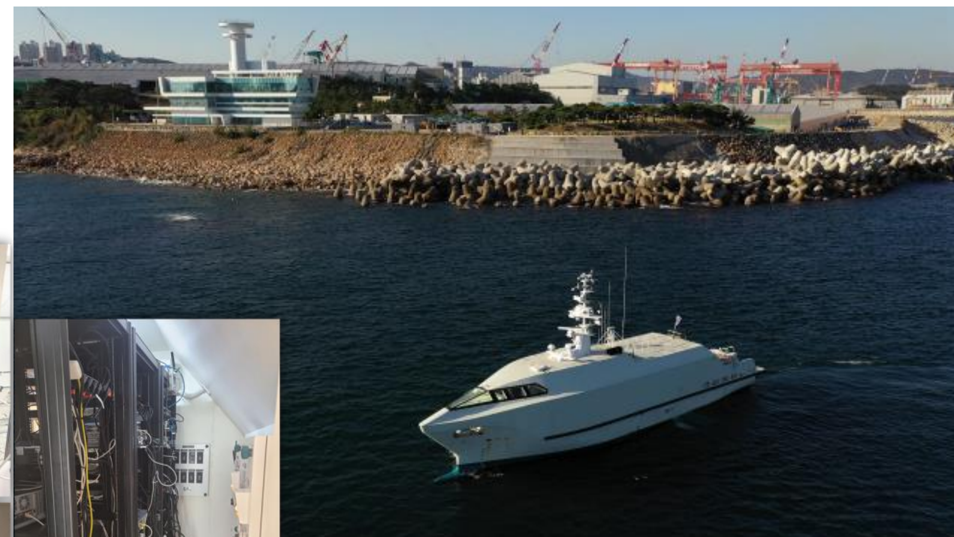
Integration of NEMO System & Sea-trial Tests

25m Testbed Vessel (Haeyang-nuri)

- ☑ 2nd half of 2023~2025
- ☑ Hybrid tests (Sea-trial tests w/ augmented reality (virtual data))

Demonstration Vessel

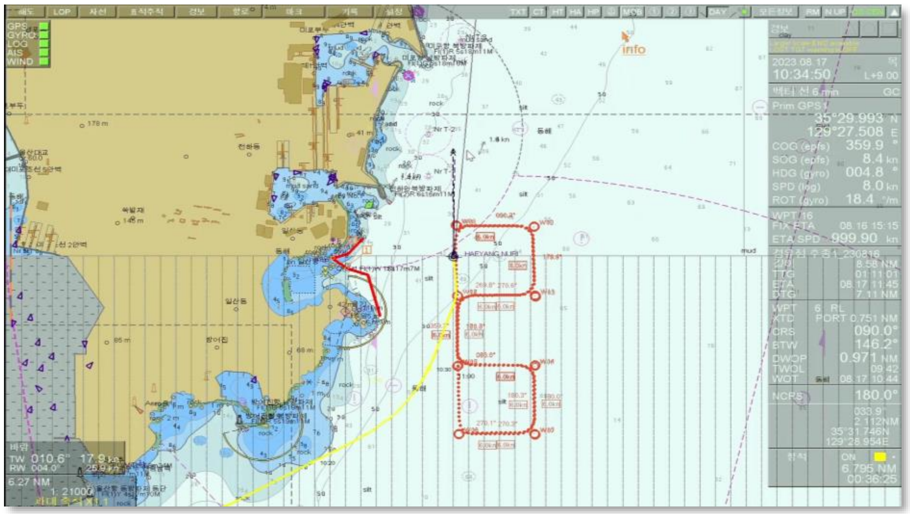
- ☑ 1,800 TEU container (POS SINGAPORE)
- ☑ NEMO system integrated early 2024
- ☑ Tests scheduled 2nd half of 2024~2025
- ☑ Hybrid tests

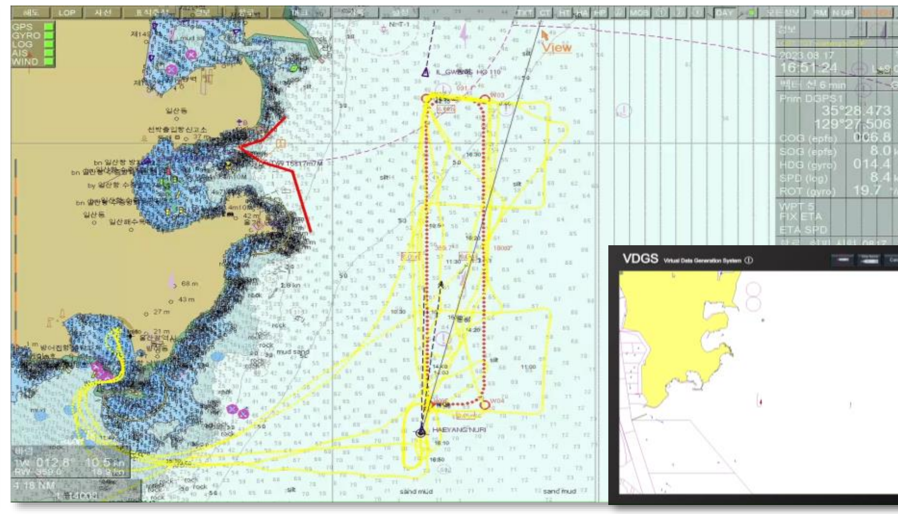


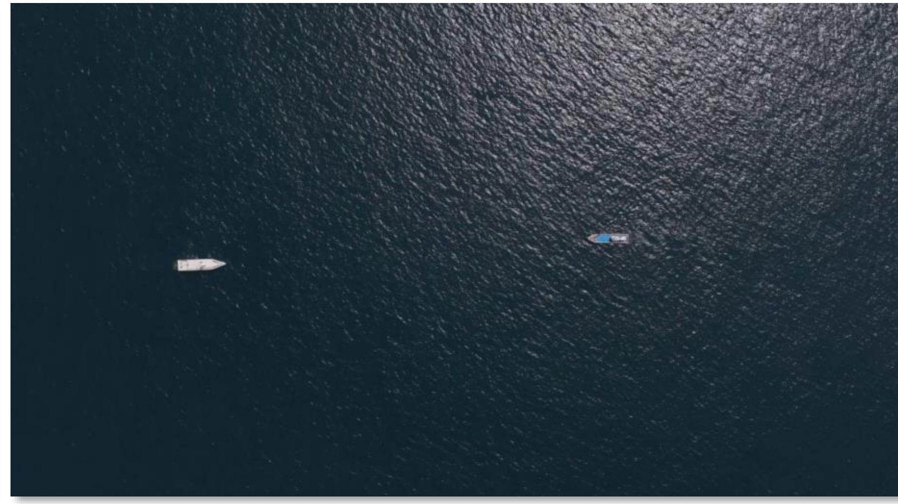
Installation of NEMO prototype on Haeyang-nuri testbed vessel and integration tests checking data communication

Sea-trial tests: Basic Conditions

Way-point tracking, Single & Successive encounter tests (2023. 8.16.~17.)



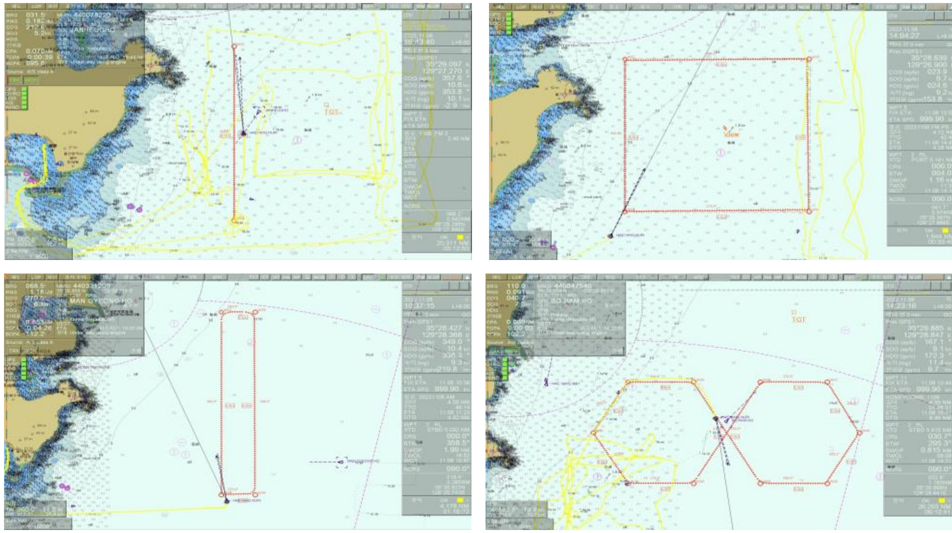


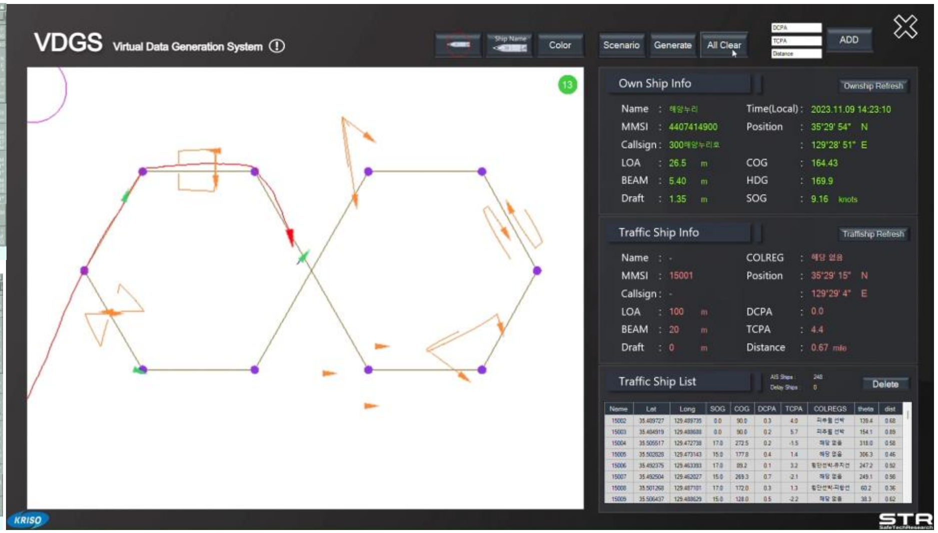


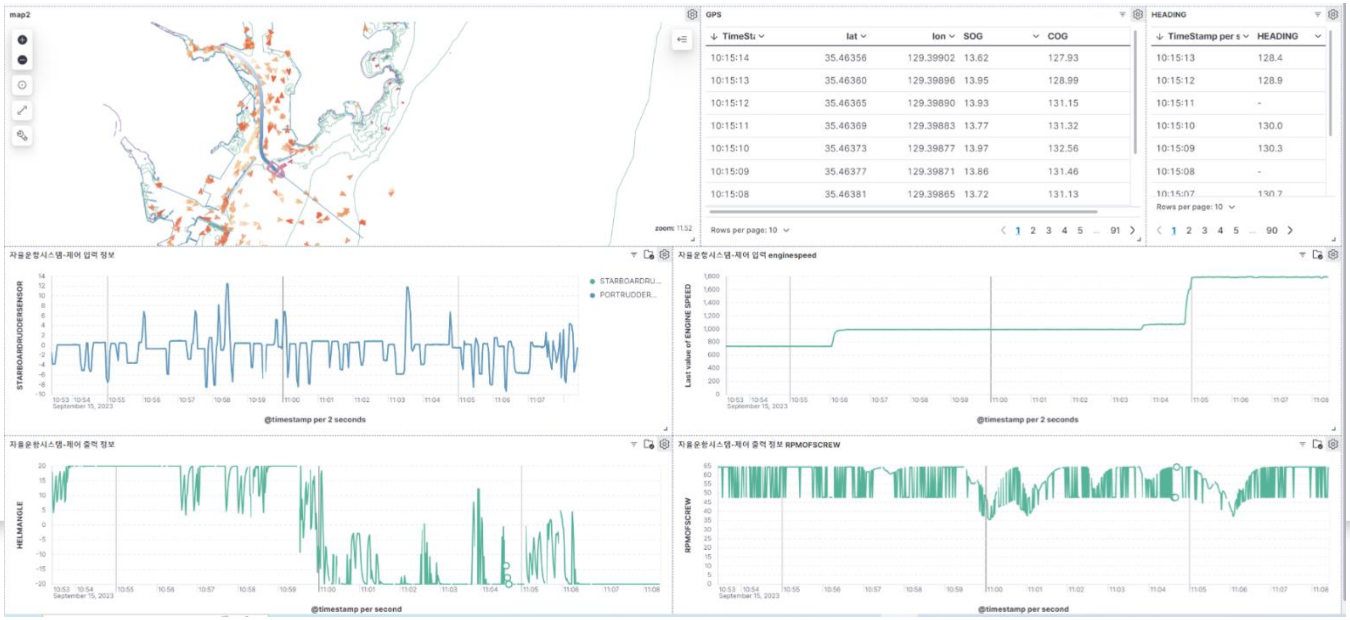
Sea-trial tests: Complex Conditions

Complex encounter tests (2023. 11. 6.~10.)

: Haeyang-nuri : Traffic vessel (Real) : Traffic vessel (Imaginary)







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Summary & Remark

Summary & Remark

Development of verification procedures

- ☑ Steps for development of verification procedures
  - Definition of system features, categorization by modes of operation, HAZID analysis & review, identifying requirements & design test scenarios by referring HAZID results, and documentation
- ☑ Functional requirement tests & scenario tests
- ☑ Serve as a guide for future development of verification procedures
- ☑ Helping development of highly safe and reliable intelligent system

Through and rigorous tests have been conducted during whole development of NEMO intelligent navigation system

- ☑ Expecting NEMO ensures high safety and reliability

Thank You

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