Development and Demonstration of Autonomous Ships in Japan

5th November 2022

Capt. Taketoshi MORIOKA

Japan Marine Science Inc.

Digest Video of DFFAS project under MEGURI 2040

- Digest Version
  - https://www.youtube.com/watch?v=pnwgWmM3XHo&t=413s

- Full Version
  - https://www.youtube.com/watch?v=HpMuOBcs0Do

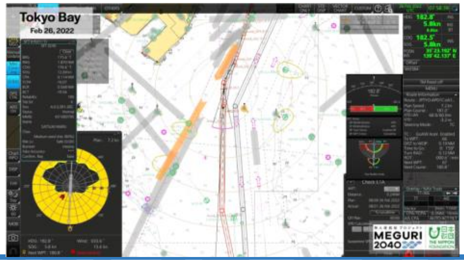
- Contact -> e-mail: taketoshi.morioka@jms-inc.jp

DFFAS system overview

DFFAS
Designing the Future of Full Autonomous Ship

DFFAS

Onboard system (autonomous functions)



DFFAS

MEGURI 2040

Telecommunication system
(3 satellite and 1 terestrial communication lines, information management & control)

Land-based system
(land-based support functions)

Integrated Display Block

(ship information collection, monitoring & analysis)

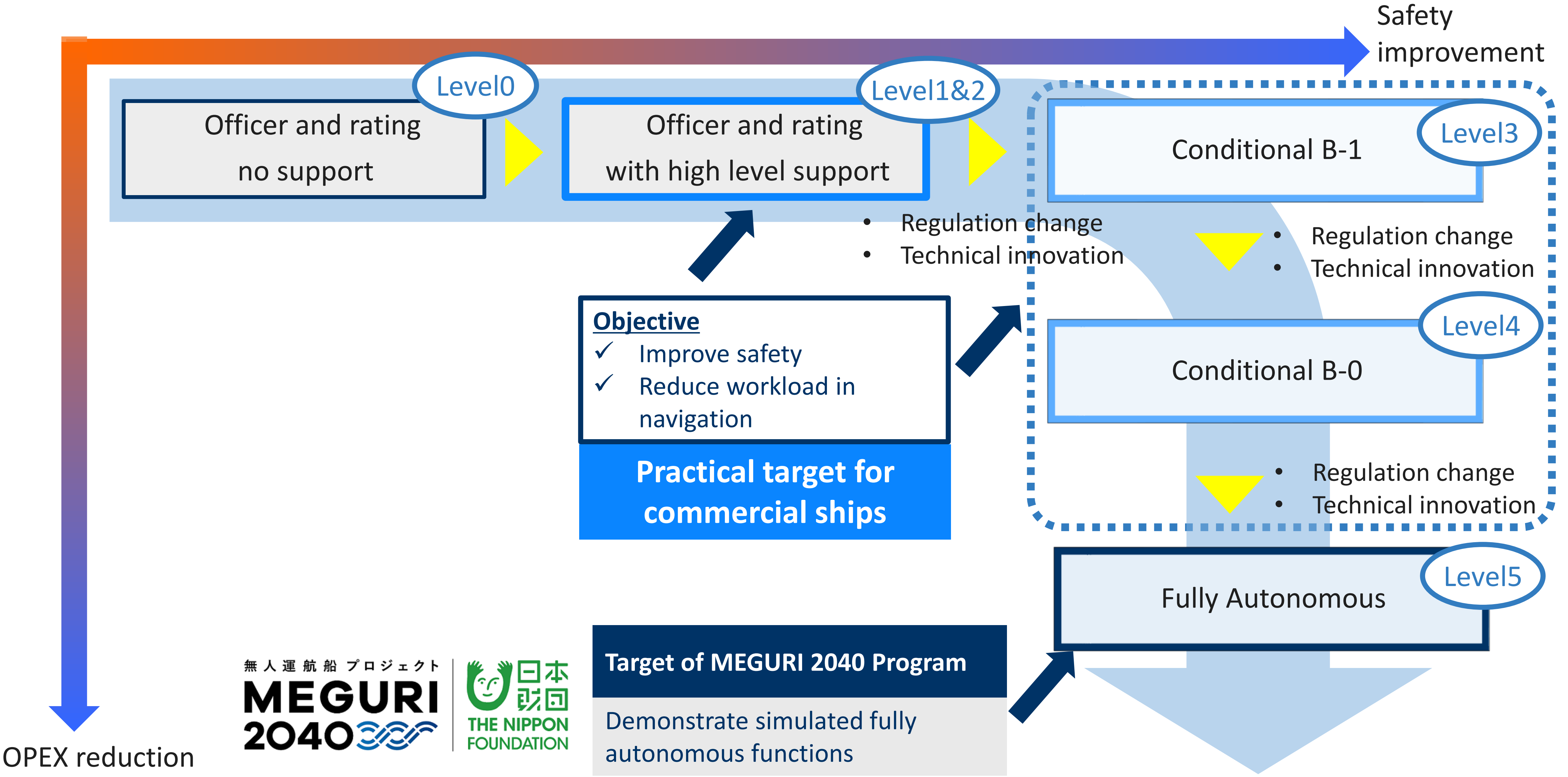
(engine remote monitoring, control & anomality detection)

Emergency Response Block
(remote operation function)

Outline

1. **Introduction of DFFAS Project**
2. System overview
3. System design and development process
4. Demonstration
5. Summary

Our view of autonomous ship roadmap and MEGURI 2040 program



* Level 0-5, ONE SEA White Paper, Autonomous Ships Terms of Reference for Rule Development, 2022

DFFAS Project (Designing the Future of Full Autonomous Ship)

Designing the Future of Full Autonomous Ship

Target

- Demonstrate fully autonomous ship navigation functions under MEGURI 2040 program in Mar 2022

DFFAS consortium members & partners

- Consortium: 30 organizations (domestic)
- Total: 60+ organizations (including global partners)

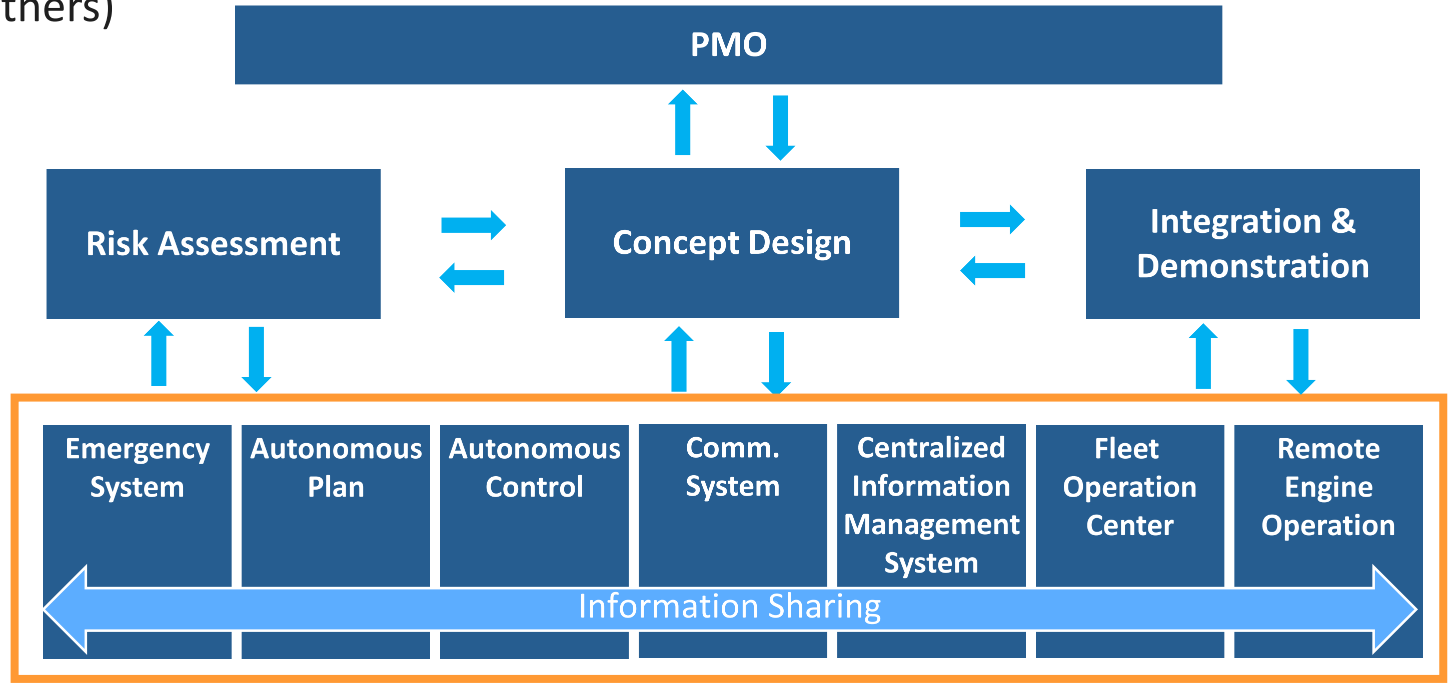
Schedule

- Feb 2020 – Mar 2022 (abt. 2 years)

Target ship and route	Container ship "Suzaku", 749GT Tokyo bay – Ise bay

Project Director
Capt. Satoru Kuwahara

Organization of DFFAS Project



Background target: Develop open architecture & open process for autonomous ship design, development, construction, commission and operation for to realize social implementation of autonomous ships for all autonomous levels.

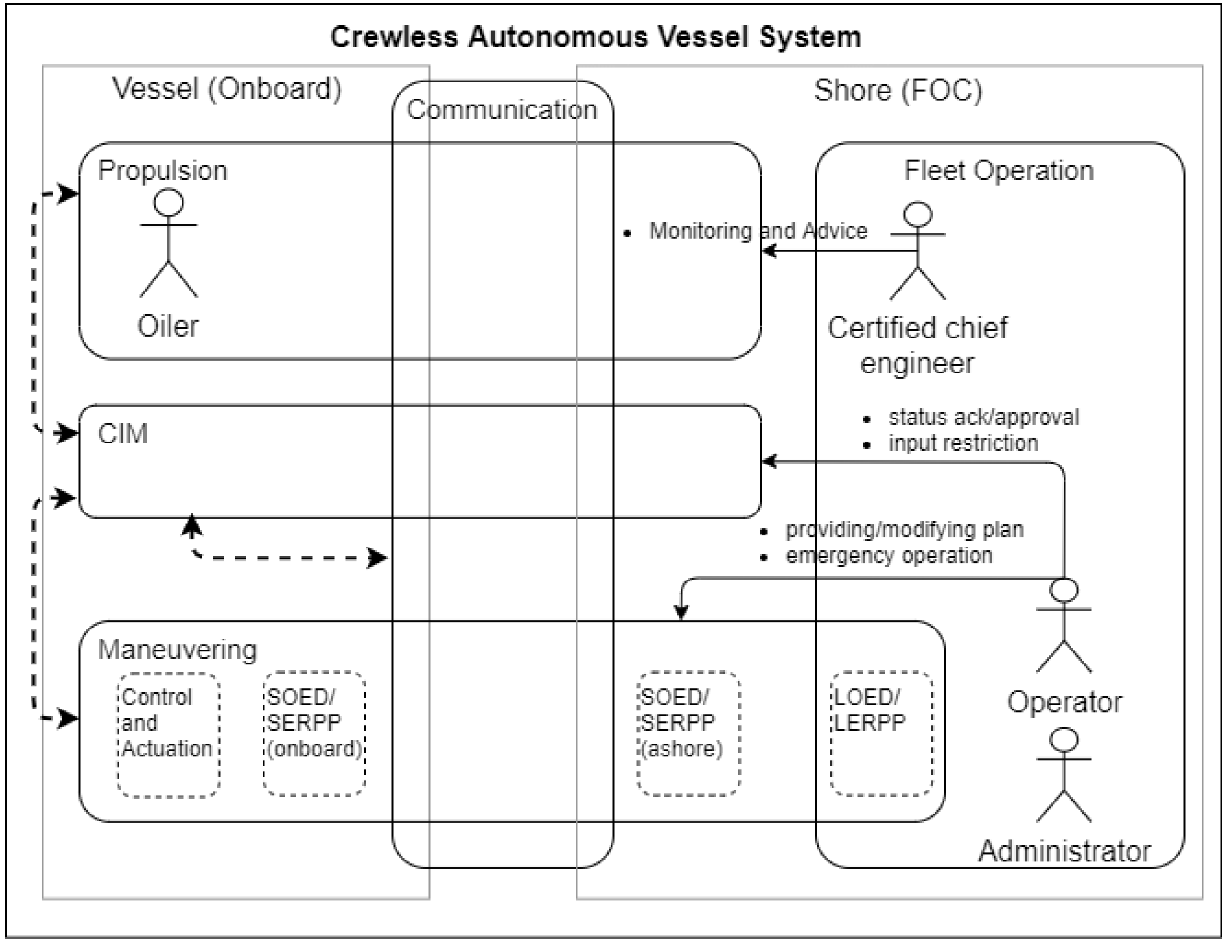
Outline

1. Introduction of DFFAS Project
2. **System overview**
3. System design and development process
4. Demonstration
5. Summary

Definition of system requirements with deep domain knowledge

To formulate the conceptual design of an autonomous navigation system, two deep knowledge domains, the master mariners' and chief engineers' knowledge of the operational domain and the manufacturers' knowledge of the technical domain, were essential,

- Master mariners and chief engineers, who are well versed in ship operations, lead the project, define the concept of operations (ConOps), design autonomous ship navigation system and iterate risk assessment, for eliciting system requirements together with engineers of manufactures and system specialists by using **Model-Based Systems Engineering (MBSE)** approach.



High level concept description by using use case diagram

Task category, Executor and Location

Table 3.1: Task category, executor and location

Task		Executor	Location
Situation awareness (Detection)	Long Term Object & Event Detection (LOED)	Machine, Human	Shore
	Short Term Object & Event Detection (SOED)	Machine	On board
Decision making (Integration/Analysis/Planning)	L-Event Response & Path Planning (LERPP)	Machine Human (including/restriction, approval)	Shore
	S-Event Response & Path Planning (SERPP)	Machine	On board Shore (status: AM/RFB)
		Human	Shore (status: AM/RFB)
	CIM	Machine	On board
		Human (operation for system status)	Shore
Execution (Control/Actuation)	DTC and propulsion	Machine	On board
(Independent) Fallback		Machine	On board

Ref) MTI, APExS-auto system overview, DFFAS PJ, MARCH 2022

CIM: Centralized Information Management
DTC: Drive Train Controller

DFFAS System - Composition and System Status Definition

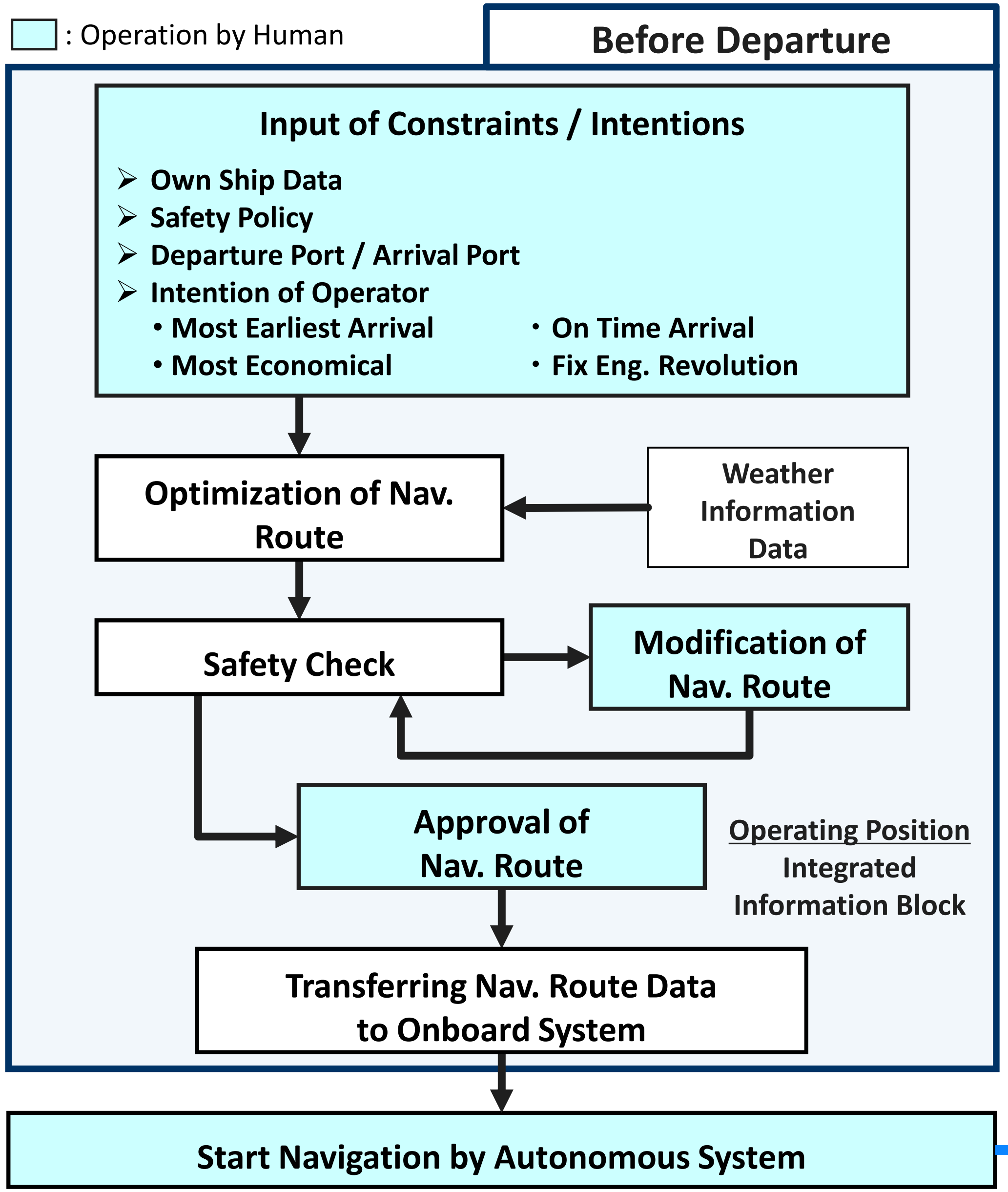
Subsystem	Main Functions	
Maneuvering	• Collect Information around own ship • Plan Short-Term Navigation (collision avoidance)	• Control actuator • Monitor & operate DFFAS System remotely
Propulsion	• Collect information of engine condition	• Monitor & operate engine & power plant remotely
Communication	• Achieve communication between ship & Fleet Operation Center (FOC)	• Monitor communication quality
Fleet Operation Center(FOC) System	• Collect wide variety of information for safe navigation (weather, traffic etc.)	• Plan a Long-Term Navigation (voyage planning)
Centralized Information Management System (CIM)	• Collect condition of other subsystems • Judge the status of DFFAS System	• Feedback the determined status of the whole DFFAS system to each subsystem

Status	Definition	
Normal	System is running without any intervention by crew or fallback from shore	Level4
Active Monitoring	System is running under the verification by operator at shore	Level3
Remote Fallback	System is running under fallback operations by operator at shore	Level1
Independent Fallback	System is running under fallback operations by system on vessel	Level0

Ref) OneSea definition

System status definition:
The definition of the whole system status is based on degree of engagement by human on shore and necessity of fallback operation.

DFFAS System - Operation Flow



* FOC: Fleet Operation Center

During Navigation

Monitoring Navigation Control & Emergency Response Operation

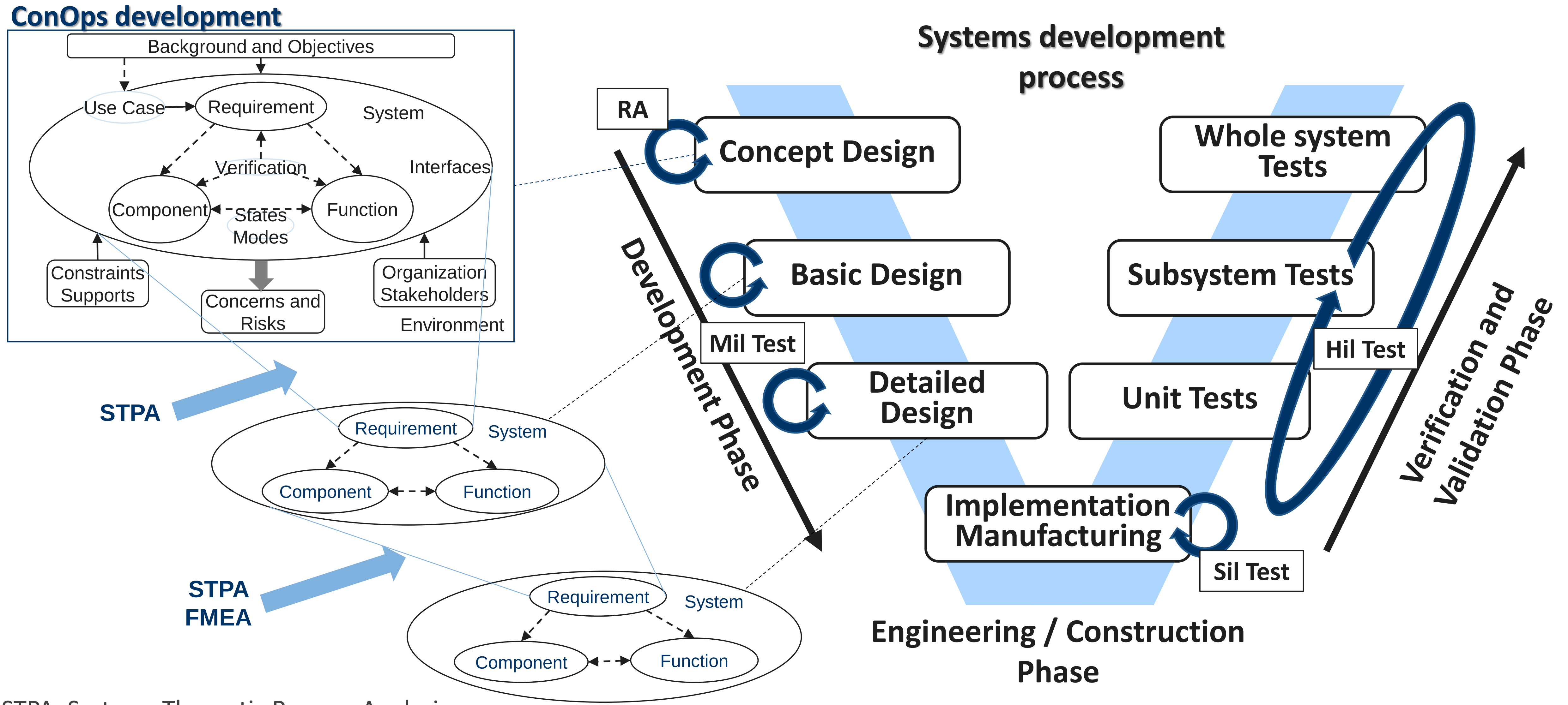
Status	Control	Operator Position
Normal	Autonomous System (Onboard)	Integrated Display Block
Active Monitoring		Emergency Response Block
Remote Fallback	**Remote Operator (@FOC*)** • Modification of Avoiding Route • Input Heading Course & Speed to Onboard System	
Independent Fallback	**Onboard Captain (@Bridge)** (Normal Navigation)	

Finish Navigation by Autonomous System

Outline

1. Introduction of DFFAS Project
2. System overview
3. **System design and development process**
4. Demonstration
5. Summary

Methodology – V Process



STPA: Systems Theoretic Process Analysis

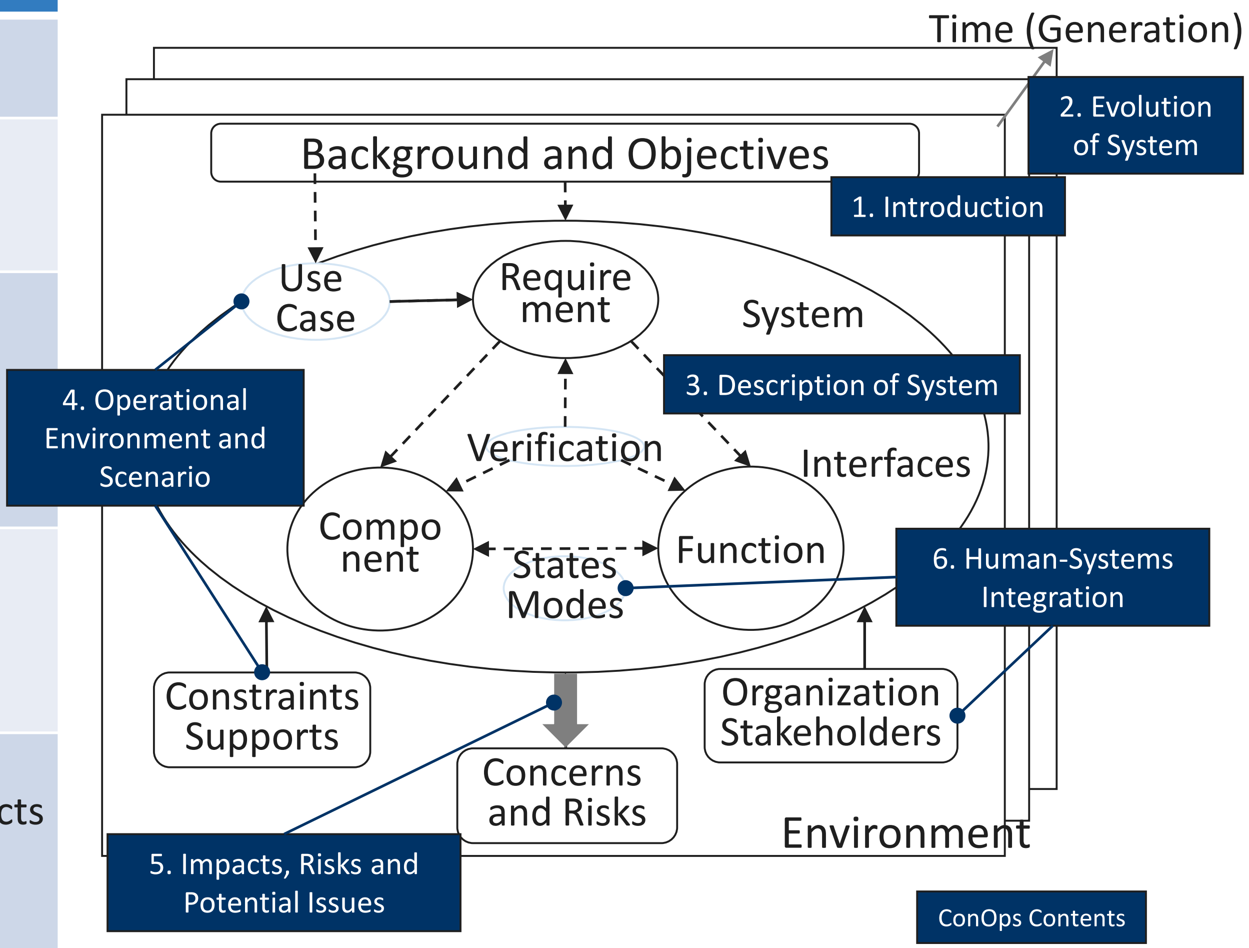
FMEA: Failure Mode and Effects Analysis

Concept of Operation (ConOps)

ConOps contents for autonomous system

Contents	Description
1. Introduction	• Background • System Scope, Assumption & Constraints
2. Evolution of System	• Justification for changes • Future Roadmap and Status of the envisioned system
3. Description of System	• Needs, Goals & Objectives of the system • Overview Architecture incl. Interfaces (Major System elements & interconnections) • Modes of Operation • Basic Functions (Proposed Capabilities)
4. Operational Environment and Scenario	• Use Cases (Nominal, Off nominal) • Actors/Stakeholders • Operational Scenario • Data flow (input & output of the system)
5. Impacts and Potential Issues	• Operational impacts, Environmental Impacts, Organizational Impacts, Scientific/Technical Impacts • Regulatory Compliance, How to Implement the system
6. Human-Systems Integration	• Human-in-the-loop involvement • Human-machine interface etc.
Appendix	• Glossary, Acronyms, Reference Documents

Required elements for system description

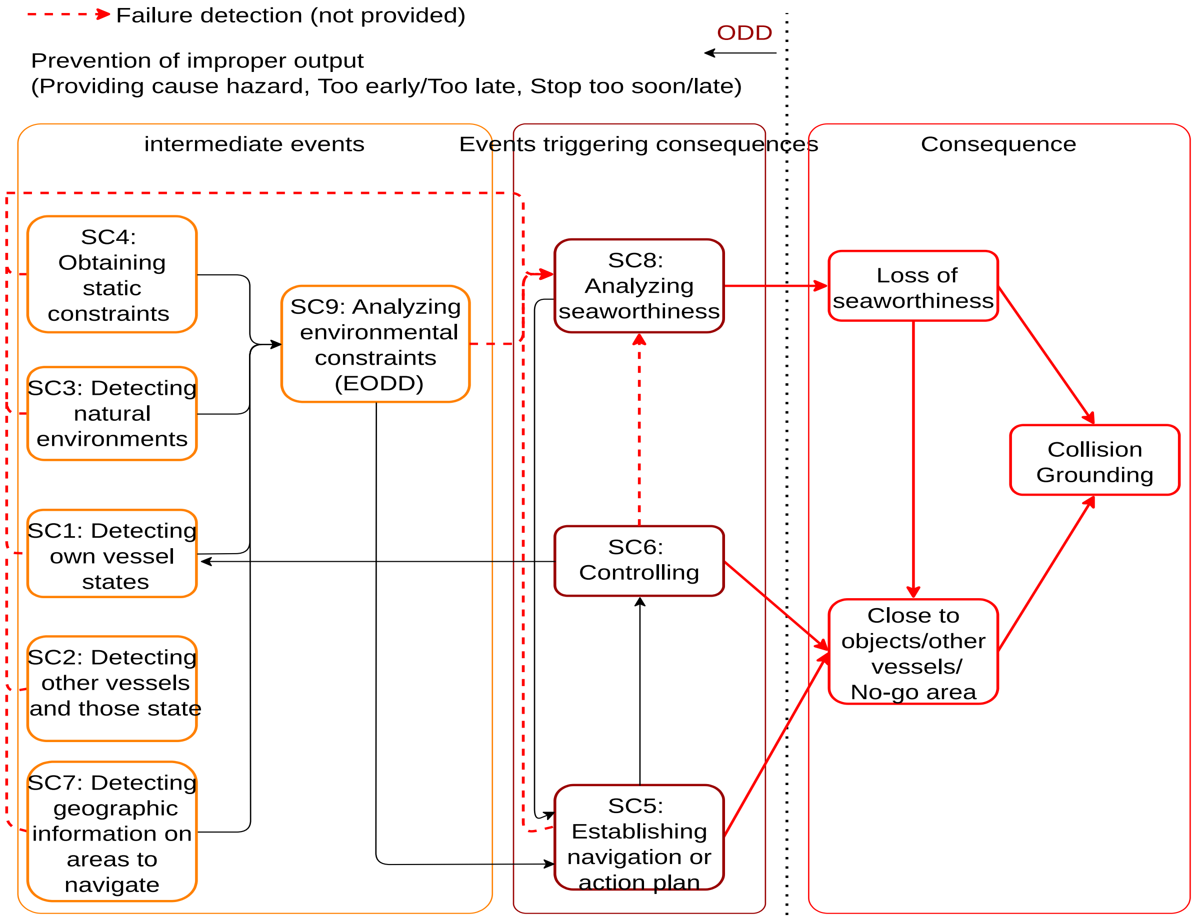


Ref. INCOSE Systems Engineering Handbook

Safety Constraints (SC)

- Safety Constraints (SC) are considered as the sub-goals to achieve the goal, safety autonomous navigation.
- SC violations are defined as hazardous events, which should be avoided.
- Basically, we tried to prove safety equivalence of autonomous ship operations to conventional operations at each SC.

SC	Description
SC1	Own vessel states must be detected: system conditions and sensor-detected values etc.
SC2	Other vessels and those states must be detected: existence and course, heading, speed and positions.
SC3	Natural environments which affect the system must be detected: wind, wave, tidal stream, temperature, etc.
SC4	Static constraints which are essential to achieve voyage must be obtained.
SC5	Navigation and/or action plan must be established.
SC6	Control signal must be calculated based on navigation/action plan.
SC7	Geographic information to navigate must be detected.
SC8	Seaworthiness including condition of equipment and hull must be analysed and actions must be selected based on own status and surrounding environment.
SC9	Dynamic constraints must be analysed based on static constraints and internal/external environment (e.g., short stopping distance, Turning circle).



The autonomous system concept design, APExS-auto, received AiP from ClassNK and BV in March 2022

Risk assessment and management

Bow-tie risk analysis

- SC violations are considered as incident, which is the top event of fault trees placed at the center of bow-tie diagram and should be protected by appropriate barriers.
- Barriers are placed to block propagation of threats.
- Threats are extracted by STPA analysis of the target system as UCAs(Unsafe Control Actions).
- Of the barrier categories, those related to system design are functional requirements.
- Barrier effects values are used for quantitative risk assessment.

Requirement detailed function (Lower layer)

Anomaly of SOED(nature environment detection)/
SC3 violation - Detecting natural environments which affects system (wind, wave, tidal stream, temperature, etc.)

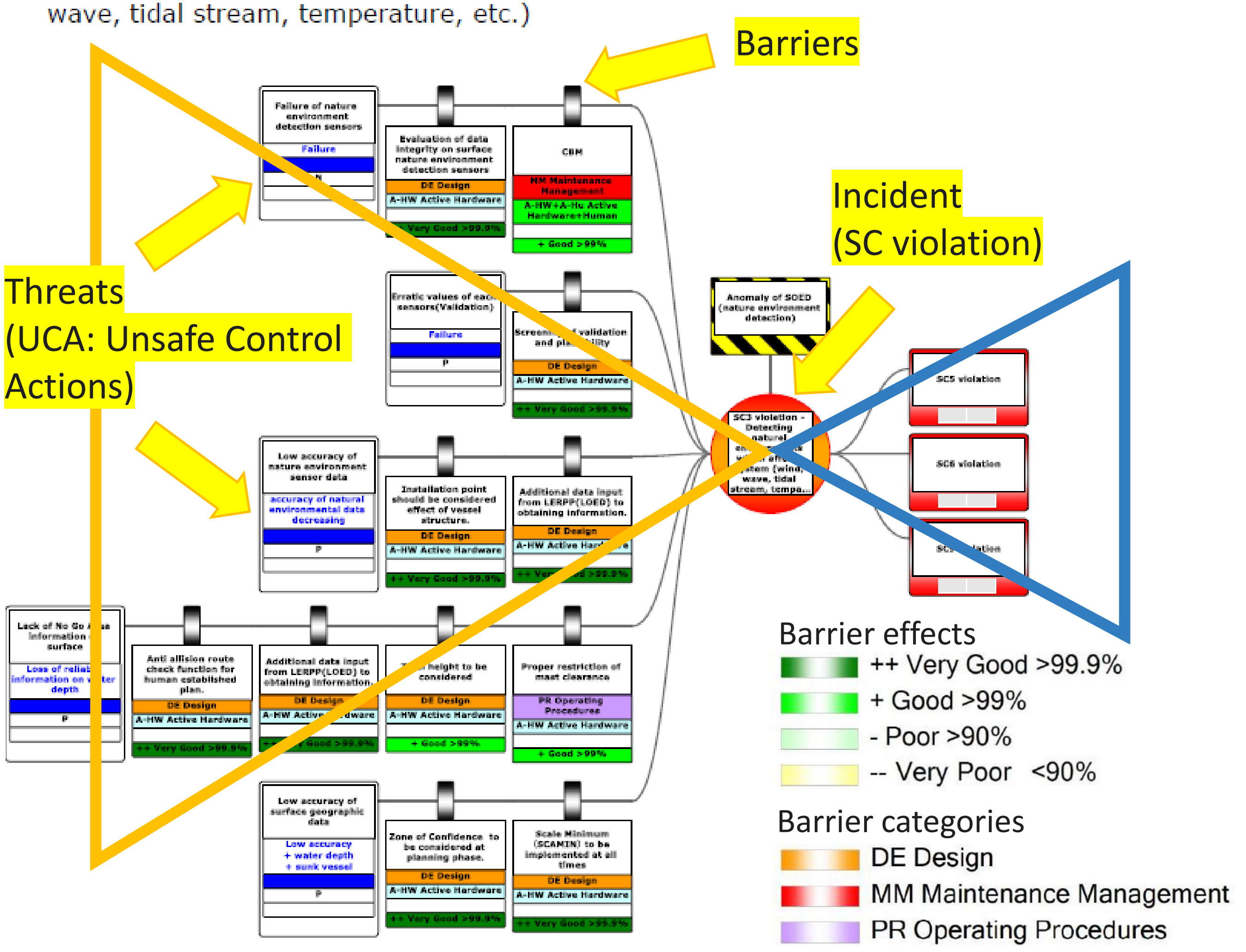


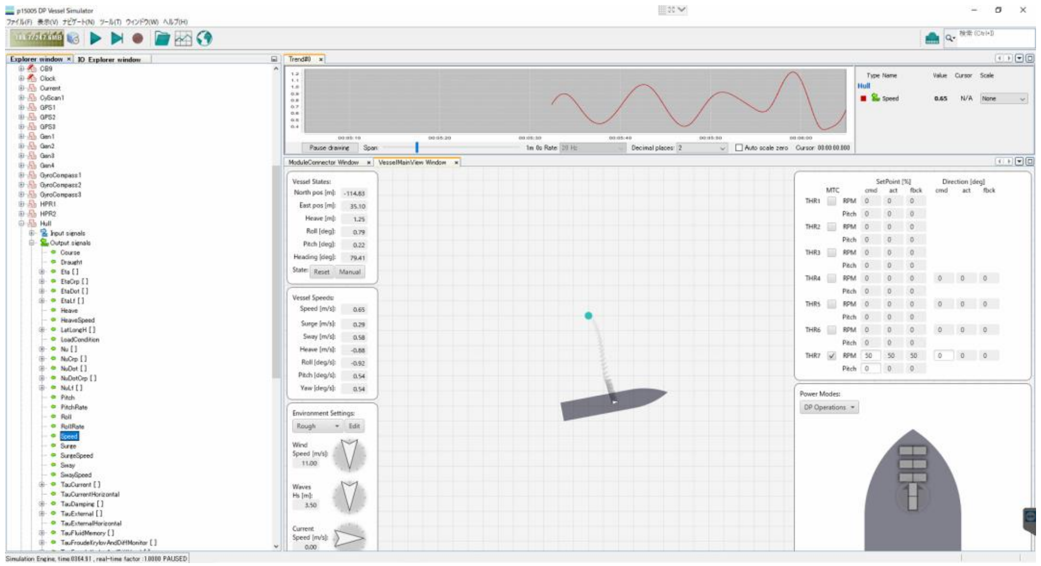
Figure: BowTie Diagram – SOED/SC3 violation

Model-based development (MBD) – simulation tests

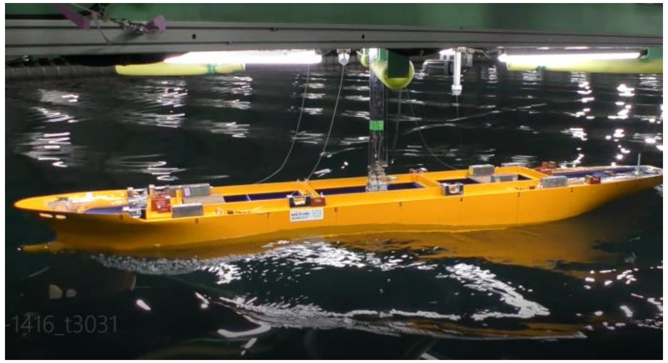
- Simulation tests are utilized for unit test and system integration test.
  - MIL(Model-In-the-loop)
  - HIL(Hardware-In-the-loop)

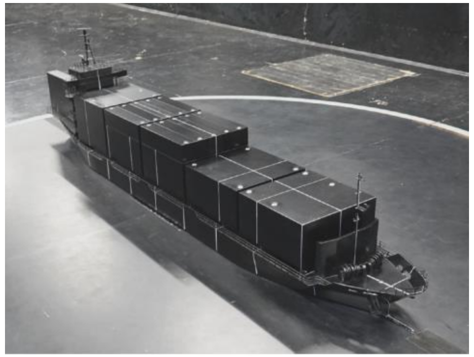
- Vessel dynamic models built as FMU (Functional Mockup Unit)

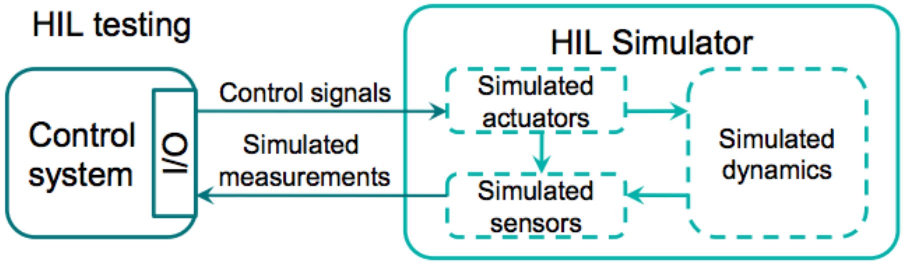
- FMU parameters of hull, thruster & rudder are calibrated based on model test results and actual ship data at sea trials to have necessary fidelity to test control system.



Simulation test platform CyberSea (DNV)







Ref) DNV Marine Cybernetics Advisory
https://www.dnvgl.com/services/hil-testing-concept-explanation--83385

System integration test @ FOC (Jun – Aug 2021)

- System integration tests were conducted to identify issues before actual installation of the system on the target vessel
- All the system/equipment except for some sensors (e.g. radar) are integrated and tested with a virtual ship on CyberSea simulator.
- Normal/abnormal situations are tested for coastal navigation, berthing and unberthing scenario
  - Normal … 75 sequence
  - Abnormal … 34 sequence
  - Through voyage … 8 voyages

Snapshot of system integration test
@ Fleet Operation Center (FOC)

→ 30 items, not detected at early stages, were found and corrected prior to loading the system on the vessel.

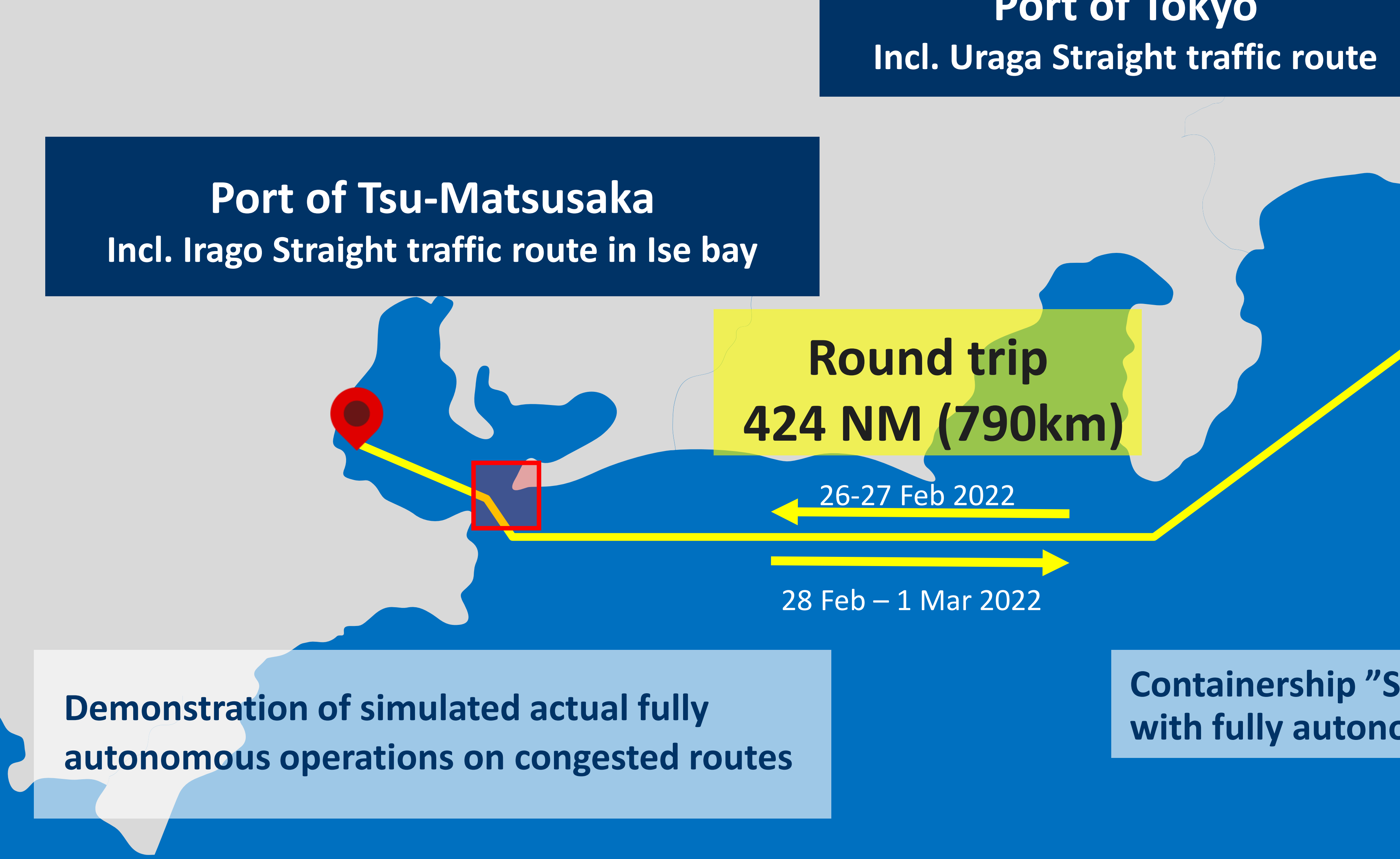
Outline

Demonstration voyages in Feb & Mar 2022

FOC Makuhari

Port of Tokyo
Incl. Uraga Straight traffic route

Port of Tsu-Matsusaka
Incl. Irago Straight traffic route in Ise bay



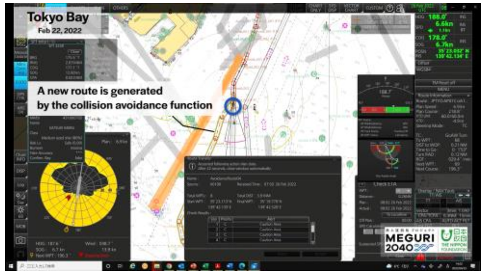
Demonstration of simulated actual fully autonomous operations on congested routes

Containership ”Suzaku”, 749GT with fully autonomous functions

An example case of collision avoidance in Tokyo bay on 26 Feb 2022

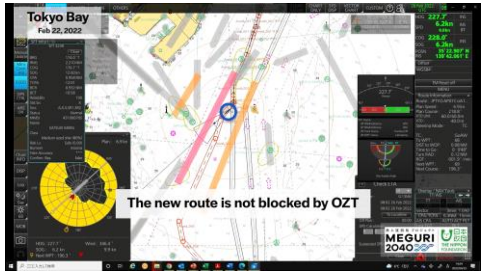
7:59:16 AM

- The planned route is blocked by Obstacle Zone of Target (OZT) of other surrounding ships.



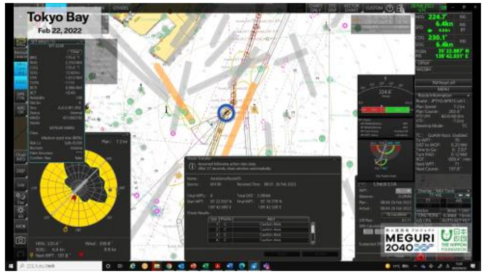
8:00:04 AM

- A new route is generated by the collision avoidance function
- The new route is automatically approved by the system under supervision by shore captain.



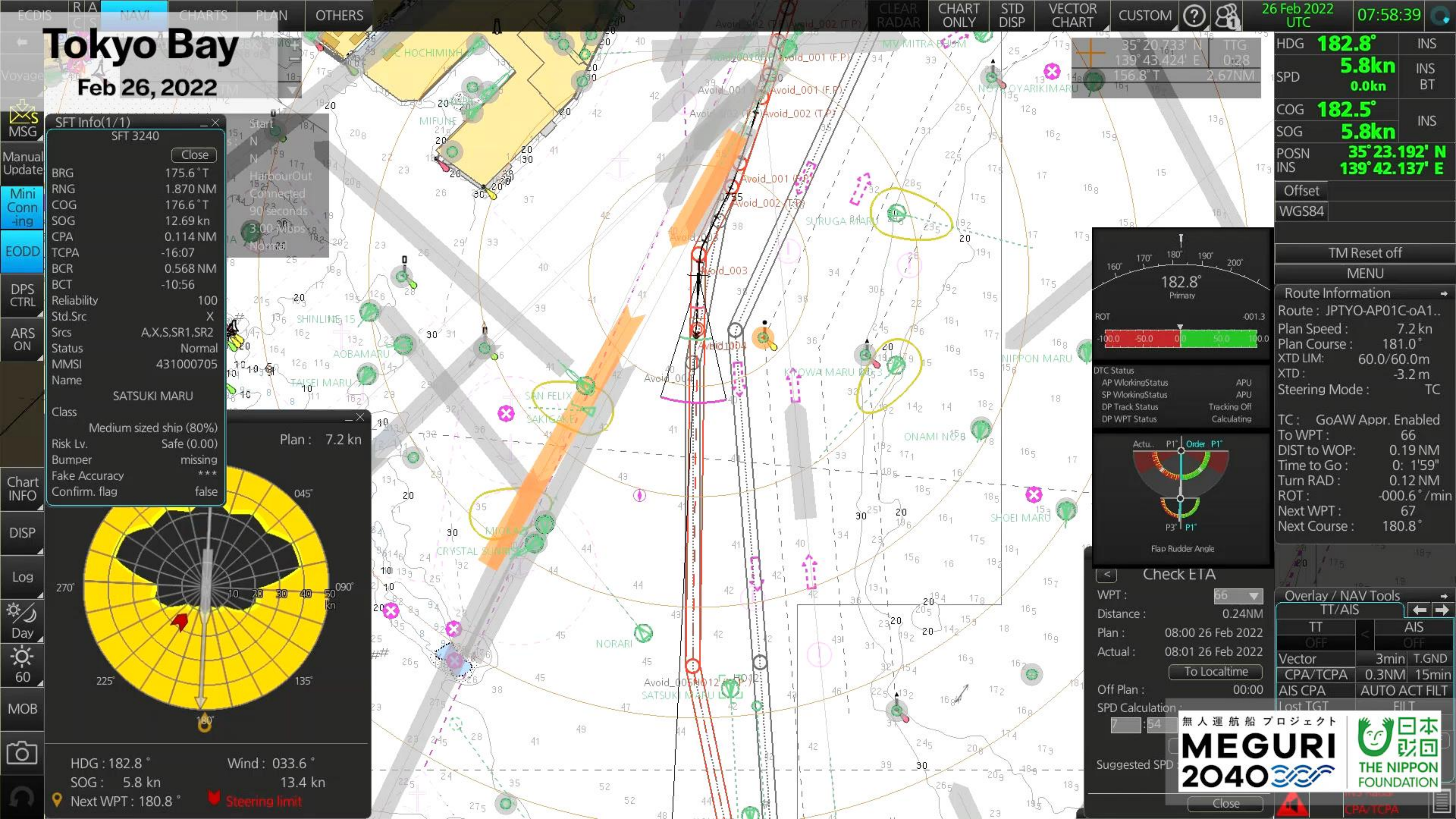
8:01:09 AM

- The new route is not blocked by OZTs and the vessel automatically track the new route.



8:01:53 AM

- The collision avoidance function generates a slightly modified new route due to occurrence of another OZT
- The new route is automatically approved by the system under supervision by shore captain.


Tokyo Bay
Feb 26, 2022
ECDIS
NAVI
CHARTS
PLAN
OTHERS
CLEAR RADAR
CHART ONLY
STD DISP
VECTOR CHART
CUSTOM
26 Feb 2022 UTC
07:58:39
HDG 182.8° INS
SPD 5.8kn 0.0kn INS BT
COG 182.5° INS
SOG 5.8kn
POSN INS 35°23.192' N 139°42.137' E
Offset
WGS84
TM Reset off
MENU
Route Information
Route : JPTYO-AP01C-oA1..
Plan Speed : 7.2 kn
Plan Course : 181.0°
XTD LIM: 60.0/60.0m
XTD : -3.2 m
Steering Mode : TC
TC : GoAW Appr. Enabled
To WPT : 66
DIST to WOP: 0.19 NM
Time to Go : 0: 1'59"
Turn RAD : 0.12 NM
ROT : -000.6°/min
Next WPT : 67
Next Course : 180.8°
Overlay / NAV Tools
TT/AIS
TT
AIS
Vector 3min T.GND
CPA/TCPA 0.3NM 15min
AIS CPA AUTO ACT FILT
MSG
Manual Update
Mini Conn -ing
EODD
DPS CTRL
ARS ON
Chart INFO
DISP
Log
Day
60
MOB
SFT Info(1/1)
SFT 3240
Close
BRG 175.6°T
RNG 1.870 NM
COG 176.6°T
SOG 12.69 kn
CPA 0.114 NM
TCPA -16:07
BCR 0.568 NM
BCT -10:56
Reliability 100
Std.Src X
Srcs A,X,S,SR1,SR2
Status Normal
MMSI 431000705
Name
SATSUKI MARU
Class
Medium sized ship (80%)
Risk Lv. Safe (0.00)
Bumper missing
Fake Accuracy ***
Confirm. flag false
Plan : 7.2 kn
045°
090°
135°
180°
225°
270°
HDG : 182.8°
SOG : 5.8 kn
Next WPT : 180.8°
Wind : 033.6°
13.4 kn
Steering limit
182.8°
Primary
ROT
DTC Status
AP WorkingStatus APU
SP WorkingStatus APU
DP Track Status Tracking Off
DP WPT Status Calculating
Flap Rudder Angle
Check ETA
WPT : 66
Distance : 0.24NM
Plan : 08:00 26 Feb 2022
Actual : 08:01 26 Feb 2022
To Localtime
Off Plan : 00:00
SPD Calculation
Suggested SPD
Close
35°20.733' N 139°43.424' E
156.8° T
TTG 0:28
2.67NM
Avoid_001
Avoid_002
Avoid_003
Avoid_004
SURUGA MARU
SAN FELIX
SAKIGAKE
NIPPON MARU
KYOWA MARU
ONAMI NO.8
SHOEI MARU
NORARI
SATSUKI MARU
CRYSTAL SUNRISE
SHINLINE 15
AOBAMARU
TAISEI MARU
MIFUNE
無人運航船プロジェクト
MEGURI 2040
日本財団
THE NIPPON FOUNDATION

Results of demonstration voyages

1. Westbound (26-27th Feb. 2022)
Port of Tokyo → Port of Tsu-Matsusaka off

Distance: 207.5NM (384.3KM)
Sailing time: 20h10m
Hours of autonomous operation: 19h39m
Ave. Speed: 10.3kt
Actions for collision avoidance: 107 times
* Number of avoiding ships were not countable

Percentage of autonomous operation

97.4%

2. Eastbound (28thFeb.-1st Mar. 2022)
Port of Tsu-Matsusaka off → Port of Tokyo

Distance: 216.4NM (400.8KM)
Sailing time: 19h38m
Hours of autonomous operation: 19h34m
Ave. Speed: 11.0kt
Actions for collision avoidance: 34 times
* Number of avoiding ships were not countable

Percentage of autonomous operation

99.7%

Outline

Summary

- Under MEGURI 2040 project which fully supported by Nippon Foundation, worked on the Designing the Future of Fully Autonomous Ship Project (DFFAS Project) with the cooperation of more than 60 partners.

- During the demonstration voyage in February and March 2022, we successfully conducted the first in the world fully autonomous demonstrated operation of long-distance voyages including congested areas. The success ratio of fully autonomous operation was 98.5% in total.

- To develop safety of the complex autonomous navigation system, we were using a modern engineering methodology, so called V-process, which includes ConOps, model-based systems engineering (MBSE) and model-based development (MBD).

- 9 Safety Constraints(SC) were considered as sub-goals in the system design. Functional requirements to the system were extracted as barriers to prevent propagation of threats to SC violation in bow-tie risk assessment.

Source: DFFAS CONSORTIUM

DFFAS

Designing the Future of Full Autonomous Ship

Thank you for your listening.

無人運航船プロジェクト

MEGURI 2040

日本財団

THE NIPPON FOUNDATION

n any for

f NYK Lin