Development and Demonstration of Autonomous Ships in Japan

IMO Seminar on Development of a Regulatory Framework for Maritime Autonomous Surface Ships (MASS)
5th and 6th September 2022

Hideyuki Ando
MTI (NYK Group)
Please check DFFAS short movie (8 mins) on Youtube

https://youtu.be/oWy0l15OzmA
DFFAS system overview

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

Integrated Display Block
(ship information collection, monitoring & analysis)
(engine remote monitoring, control & anomaly detection)

Emergency Response Block
(remote operation function)

Onboard system (autonomous functions)

Land-based system
(land-based support functions)

MEGURI 2040
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

Officer and rating with high level support

Level 1 & 2

Conditional B-1

Level 3

Conditional B-0

Level 4

Fully Autonomous

Level 5

Objective

✓ Improve safety
✓ Reduce workload in navigation

Practical target for commercial ships

Target of MEGURI 2040 Program

Demonstrate simulated fully autonomous functions

Safety improvement

OPEX reduction

Regulation change

Technical innovation

Officer and rating no support

Level 0

Operator no support

Level 0

Officer and rating no support

Level 0

Officer and rating with high level support

Level 1 & 2

Conditional B-1

Level 3

Conditional B-0

Level 4

Fully Autonomous

Level 5

Target of MEGURI 2040 Program

Demonstrate simulated fully autonomous functions

Safety improvement

OPEX reduction

Regulation change

Technical innovation

* 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)**

**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)

**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
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.

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,
### Task category, Executor and Location

<table>
<thead>
<tr>
<th>Task</th>
<th>Executor</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Situation awareness (Detection)</td>
<td>Long Term Object &amp; Event Detection (LOED)</td>
<td>Machine, Human</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shore</td>
</tr>
<tr>
<td></td>
<td>Short Term Object &amp; Event Detection (SOED)</td>
<td>Machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On board</td>
</tr>
<tr>
<td>Decision making (Integration/Analysis/Planning)</td>
<td>L-Event Response &amp; Path Planning (LERPP)</td>
<td>Machine, Human</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shore</td>
</tr>
<tr>
<td></td>
<td>S-Event Response &amp; Path Planning (SERPP)</td>
<td>Machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On board</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shore (status: AM/RFB)</td>
</tr>
<tr>
<td></td>
<td>CIM</td>
<td>Machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On board</td>
</tr>
<tr>
<td>Execution (Control/Actuation)</td>
<td>DTC and propulsion</td>
<td>Machine</td>
</tr>
<tr>
<td>(Independent) Fallback</td>
<td></td>
<td>On board</td>
</tr>
</tbody>
</table>

CIM: Centralized Information Management
DTC: Drive Train Controller

Ref) MTI, APEXs-auto system overview, DFFAS PJ, MARCH 2022
## 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  
**Active Monitoring** | System is running under the verification by operator at shore  
**Remote Fallback** | System is running under fallback operations by operator at shore  
**Independent Fallback** | System is running under fallback operations by system on vessel

**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.

Ref) OneSea definition
### DFFAS System - Operation Flow

#### Before Departure

- Input of Constraints / Intentions
  - Own Ship Data
  - Safety Policy
  - Departure Port / Arrival Port
  - Intention of Operator
    - Most Earliest Arrival
    - Most Economical

- Optimization of Nav. Route

- Safety Check

- Approval of Nav. Route

- Transferring Nav. Route Data to Onboard System

#### During Navigation

- Monitoring Navigation Control & Emergency Response Operation

<table>
<thead>
<tr>
<th>Status</th>
<th>Control</th>
<th>Operator Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Autonomous System (Onboard)</td>
<td>Integrated Display Block</td>
</tr>
<tr>
<td>Active</td>
<td>Remote Operator (@FOC*)</td>
<td>Emergency Response Block</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Remote Fallback (Onboard)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Modification of Avoiding Route</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Input Heading Course &amp; Speed to Onboard</td>
<td></td>
</tr>
<tr>
<td></td>
<td>System</td>
<td></td>
</tr>
<tr>
<td>Independent</td>
<td>Onboard Captain (@Bridge)</td>
<td></td>
</tr>
<tr>
<td>Fallback</td>
<td>(Normal Navigation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Modification of Avoiding Route</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>System</td>
<td></td>
</tr>
</tbody>
</table>

- Safety Check

- Modification of Nav. Route

- Operating Position
  - Integrated Display Block

- Emergency Response Block

#### After Navigation

- Start Navigation by Autonomous System

- Finish Navigation by Autonomous System

* FOC: Fleet Operation Center

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1. Introduction of DFFAS Project

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Methodology – V Process

ConOps development

Background and Objectives

Use Case → Requirement → System

Component → Function → Verifications

States → Modes → Interfaces

Constraints → Supports

Concerns and Risks → Organization → Stakeholders

Environment

Requirements

Function

Component

STPA

STPA FMEA

Systems development process

Concept Design

Mil Test

Basic Design

Subsystem Tests

Detailed Design

RA

Unit Tests

Whole system Tests

Implementation Manufacturing

Engineering / Construction Phase

Verifications and Validation Phase

ConOps development

RA

Mil Test

Sil Test

Hil Test

FMEA

STPA: Systems Theoretic Process Analysis
FMEA: Failure Mode and Effects Analysis

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### Concept of Operation (ConOps)

#### ConOps contents for autonomous system

<table>
<thead>
<tr>
<th>Contents</th>
<th>Description</th>
</tr>
</thead>
</table>
| **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

- **Background and Objectives**
- **Use Case**
- **Requirement**
- **System**
- **Component**
- **States**
- **Modes**
- **Function**
- **Verification**
- **Interfaces**
- **Constraints**
- **Supports**
- **Concerns and Risks**
- **Organization Stakeholders**
- **Environment**

Ref. INCOSE Systems Engineering Handbook
Safety Constraints (SC)

- Safety Constraints (SC) are considered as the sub-goals to achieve 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.

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

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.
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

30 items, not detected at early stages, were found and corrected prior to loading the system on the vessel.
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Demonstration voyages in Feb & Mar 2022

Port of Tokyo
Incl. Uraga Straight traffic route

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

Round trip
424 NM (790km)

26-27 Feb 2022
28 Feb – 1 Mar 2022

Demonstration of simulated actual fully autonomous operations on congested routes

Containership "Suzaku", 749GT with fully autonomous functions

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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.
Results of demonstration voyages

1. Westbound (26-27\textsuperscript{th} 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

2. Eastbound (28\textsuperscript{th} Feb.-1\textsuperscript{st} 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

97.4%

99.7%
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With the support of the Nippon Foundation, the NYK Group is working 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.
Thank you for your listening.

Source: DFFAS CONSORTIUM