NYK’s Approach for Autonomous Navigation – Structure of Action Planning System and Demonstration Experiments

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Abstract. NYK Line and its group companies have been conducting research projects towards autonomous ship operation. This paper shows the structure of our Action Planning System (APS), which integrates several support functions with man-machine interface, targeted at supporting decision making for seafarers. By conducting risk assessment with reference to class guidelines for autonomous ships, the safety of APS is verified. This paper also introduces our demonstration experiment of this system, which will be conducted in FY2019.

1. Introduction

Technological development and demonstration projects for autonomous shipping are being conducted all over the world. In December 2018, Rolls-Royce and Finferries demonstrated a fully autonomous operating ferry [1], and ABB carried out the world's first test of remote control for a passenger ship [2].

In addition to the technological developments, efforts towards their social implementation are progressing. At the Maritime Safety Committee’s 100th session (MSC100) in December 2018, discussions began on a framework for the scoping exercise and trial guidelines for MASS operation. At MSC101 in June 2019, interim guidelines for MASS trials were agreed. Classification societies are also working on the creation of guidelines; DNV GL released a class guideline for autonomous and remotely controlled ships [3], and ClassNK issued a provisional version of "Guidelines for Concept Design of Automated Operation and Autonomous Operation of Ships" [4] in 2018.

To achieve efficient and safe operations and reduction of crew workloads, NYK Line and two Group companies, MTI Co. Ltd. and Japan Marine Science Inc. (JMS), have been conducting research projects towards autonomous ship operations, including a demonstration project utilizing ship manoeuvring support functions and remote control supported by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) [5].

We analysed the causes of navigational accidents from the internal database and found that human error accounts for 95 percent of all losses [6]. Also, based on our feasibility study, we concluded that “manned autonomous navigation” should at the current stage be aimed from safety and economic perspectives [6]. Manned autonomous navigation means that the machine systems support the cognitive and decision-making tasks of vessel crews. In particular, this will achieve one-man bridge operation (B1), which enables a more-efficient utilization of vessel crew and a reduction in fatigue.
This paper shows the structure of our Action Planning System (APS), which the NYK Group considers a core system for manned autonomous navigation, and for which we are aiming to obtain approvals in principle (AiPs) and/or concept approvals from classification societies. The APS integrates several support functions with human-machine interface, targeted at making decisions for the seafarers. With reference to the class guidelines, the paper describes target tasks, main roles and functions, operational design domain (ODD), and APS fallback mechanisms. Also, in order to verify this system has an equivalent level of safety, risk assessment was conducted.

2. Concept of Action Planning System

2.1 Premise

As the core system of manned autonomous navigation, the NYK Group designed the concept of Action Planning System (APS). APS aims to support crews’ decision making by analysing the situation surrounding the ship based on sensor information and presenting an action plan based on the analysis. After a verification and approval by humans, the plan is transferred to the control signals sent to the actuators. APS also has a potential to realize high-level autonomous navigation with additional sensors and reliable action-planning algorithms in the future.

Figure 1 shows a conceptual diagram of APS. The core part of this system is called Action Planning Unit (APU), which analyses surrounding situations and calculates optimized action plans. In addition, in our use case, APS information is also shared with an onshore support system, which provides additional information and advice to the crew. We call this onshore support system a Remote Concierge service. Based on the data-transmission requirements of each system [7], the transmission information between ship and land, the transmission frequency, and remote supporting menus, e.g., voyage planning based on the latest weather, are to be changed depending on the communication speed, which is continuously monitored from the shore support centre.

![Figure 1. Conceptual diagram of action planning system (APS).](image)

2.2 Elemental technologies

The NYK Group’s research and development for manned autonomous navigation can be categorized as situation-awareness support and risk-analysis and planning support. Remote support for each part can also be combined. System developments and several experiments for these support functions are being conducted.
As for situation-awareness support, image-processing technologies to detect surrounding ships and obstacles are being developed. For risk analysis, indices for collision-risk judgement that extracts the sense of expert seafarers are evaluated by navigation simulator experiments. For planning, collision-avoidance programs are being developed based on several approaches. One of them constantly calculates optimal routes from the collision-risk and economic preference. And from the viewpoint of communication cost, we are developing a concept of a shore support centre that monitors vessels and gives them additional information using an abundant information network and computing capacity.

2.3 Target task and mode
The APS targets the decision-making support necessary for seafarers to manoeuvre vessels and has the following three specific functions.

- Anti-collision and anti-aground support: formulate and present an action plan to prevent collision and aground during voyage. The parameters for the analysis can be different depending on the area (open ocean, coastal area, congested area, or waterway).
- Approach support: formulate and present an action plan for stopping and restarting the boat, e.g., anchoring, berthing, and mooring.
- Docking and undocking support: formulate and present an action plan for docking/undocking including position and attitude adjustment by using various actuators such as main engine, rudder, thruster, and tug’s support. This function is the same as the approach support mode for a ship with a docking and undocking capability of its own.

Tasks related to marine vessel decision-making can be divided into the following categories:

- Information acquisition: obtain information of own ship and other ships (position, heading, speed), geographical information, and weather information (wind direction and speed, wave direction and height, ocean current, etc.).
- Information integration: integrate and fuse the information sent from several sensors, considering their specification and accuracy.
- Risk analysis and action planning: based on the obtained information, grasp current and future situations of the own ship and accompanying risks to formulate appropriate action plans.
- Verification and approval: judge whether the action plan is appropriate and approve the action plan by making modifications as necessary.
- Execution and control: continuously converse the action plan to control orders to the actuator according to the approved plan.

2.4 Division of roles
Advanced collaboration between machines and humans is an important feature of APS. In the system design for automation, it is important to divide the roles between humans and the system clearly, i.e., to clarify who will conduct the tasks and/or subtasks. Regarding APS, basically, the system will lead the implementation except for the verification and approval parts, which greatly reduces the load of the crew.

Table 1 shows the division of roles between machine and human operator. In the case of the AP Normal 2 status (to be described later), part of the information acquisition and integration is replaced by a human being from the system (additional information input by a human being is necessary). In case of the AP Failed status, the risk-analysis and action-planning function will not operate.
Table 1. Division of roles between machine and human operator.

| Task No. | Task                                    | Main      | Sub   |
|----------|-----------------------------------------|-----------|-------|
| 1        | Information acquisition                 | Machine   | Human |
| 2        | Information integration                 | Machine   | Human |
| 3        | Risk analysis and action planning       | Machine   | NA    |
| 4        | Verification and approval               | Human     | NA    |
| 5        | Execution and control                   | Machine   | Human |

2.5 Operational Design Domain (ODD)

Operational Design Domain (ODD) means a design area where the system functions properly. It can be composed by traffic density, geographical restriction, weather conditions, availability of traffic system support, time zone (day and/or night), and so forth.

The ODD for APS is roughly defined as follows. Since onboard seafarers validate the action plan from the system, those who handle APS should be required to have appropriate competences.

- The geographic and weather condition are acceptable enough that ships can be controlled by the system, which refers to the standards for other navigation instruments, such as the Dynamic Positioning System [8], etc.
- The system behaves correctly, i.e., information is correctly displayed on the monitor, and the results are validated by human judgement.
- Integral and reliable information including human manual function can be obtained for situation assessment and action planning.

As for the integrity and reliability of information, we analyse the information from each piece of onboard equipment related to the subtasks of “information acquisition,” “information integration,” and “risk analysis and action planning” as shown in table 2.

Also, as shown in table 3 and figure 2, we classify the APS status of implementing the "situation analysis" and "action planning" tasks, which are the core function of APS. Of these, AP Normal 0-2 are in the ODD, and AP Failed is subject to “fallback” (to be described later). Figure 3 shows the criteria for determining the status.
### Table 2. Integrity and reliability of related equipment by subtask.

| No. | Task/Sub Task                                | Human Backup | Equipment       | Integrity | Reliability | Main | Num |
|-----|---------------------------------------------|--------------|-----------------|-----------|-------------|------|-----|
| 1   | Information Acquisition/Position Detection  | Available    | GNSS            | A         | B           | Main | 2   |
|     |                                             |              | GPS Compass     | A         | B           |      | 1   |
| 2   | Information Acquisition/Azimuth Measurement | Unavailable  | Gyro Compass    | A         | A           | Main | 2   |
|     |                                             |              | GPS Compass     | A         | B           |      | (1) |
| 3   | Information Acquisition/Speed Measurement   | Available    | Speed Log       | A         | B           | Main | 2   |
|     |                                             |              | GNSS            | A         | B           |      | 1   |
|     |                                             |              | GPS Compass     | A         | B           |      | (1) |
| 4   | Information Acquisition/Target Detection and Tracking | Available (only for confirmation of existence) | Radar | A         | B           | Main | 2   |
|     |                                             |              | AIS             | B         | B           |      | 1   |
| 5   | Information Acquisition/Geographic Information | Unavailable | ECDIS           | A         | A           | Main | 2   |
|     |                                             |              | User Chart      | C         | A           |      | 1   |
|     |                                             |              | Echo Sounder    | C         | B           |      | 1   |
| 6   | Information Integration                       | Unavailable  | APU             | A         | B           | Main | 1   |
| 7   | Risk Analysis & Action Planning              | Unavailable  | APU             | A         | B           | Main | 1   |

Integrity: Functional integrity for each Task  
A: Full  
B: Partial  
C: Low (Only supplemental information)  
Reliability: Information Reliability  
A: High  
B: Intermediate (available for action planning)  
C: Low (Unavailable for action planning)

### Table 3. Definition of APS status.

| Status     | Target                        | Definition                                                                                                                                 |
|------------|-------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| AP Normal 0| Fully autonomous navigation  | It has highly reliable information and planning algorithms to carry out all tasks. Human approval can be skipped in usual situations. It does not apply to the current APS, but it is assumed to be available for achieving automation only with machines in the future. |
| AP Normal 1| Manned autonomous navigation | It has reliable information to carry out tasks till action planning. Human intervention and additional actions other than verification and approval of navigation plans are unnecessary. |
| AP Normal 2| Manned autonomous navigation | To maintain all tasks to be executed with high accuracy, part of the input information is missing, or some tasks depend on the manual inputs by human only. |
| AP Failed  | NA                            | A state in which some or all the information sources of tasks are missing, and it is impossible to present an appropriate analysis and action plan even if a human adds and/or modifies information. |
2.6 Fallback

Fallback means the alternative action to ensure Minimum Risk Condition (MRC) when the automation system does not operate properly. Basically, MRC for APS (other than AP Normal 0) is guaranteed by the crews’ backup; therefore, it is necessary to have appropriate alert mechanisms.

Figure 3 shows the state transition of APS with ODD and fallback. The status of the APS needs to be properly displayed on the interface for the seafarers and remote operators to understand its system reliability.

In order to confirm whether fallback mechanisms are safe and reliable, we conduct fallback assessments considering external conditions, internal conditions, and ODD. A time-and-distance allowance for the necessary action is assumed by each fallback mechanism.

Figure 2. Criteria for determining APS status.

Figure 3. APS status transition.
2.7 Safety verification by risk assessment

Risk assessments were conducted to verify whether APS has a proper human-machine interface, and whether appropriate measures are taken to ensure cybersecurity and computer system reliability.

We conducted comprehensive risk assessment with reference to Systems Theoretic Process Analysis (STPA), which is a hazard-identification model based on the Systems-Theoretic Accident Model and Processes (STAMP), and useful especially for novel and/or complicated systems [16][17]. We went back and forth between the risk analysis and the concept, including task and mode, division of roles, ODD, and fallback, mentioned in 2.3, 2.4, 0, and 2.6, with reference to the guidelines from DNV GL and ClassNK [3][4]. By this goal-based approach, the goal and subgoals for each task can be identified [9][17].

In the hazard identification (HAZID) phase, we first assumed “collision,” “allision,” and/or “critical machine failure” as the critical effects of possible incidents due to APS. Then hazards, failures, and scenarios that lead to the critical effects were assumed as comprehensively as possible, using “What-if” analysis and fishbone diagrams. In addition, possible human-failure events were also identified by this process, with reference to Ramos et al. (2018) assuming a human-machine interaction scheme and possible operator decisions for each task [10].

Their causes, which can be acts or conditions, were pointed out and categorized with reference to MSCAT [11], a tool to investigate the cause of loss events proposed by DNV GL. Then we analyzed the frequency and severity of each hazard and plot them on the risk matrix shown in figure 5. Failure mode, effects and criticality analysis (FMECA) is used for the risk analysis of machine failure. Incident severity was ranked by the matrix shown in figure 5, with reference to Marine Injury Reporting Guidelines [12] and so forth. Finally, possible risk-mitigation measures were considered, and the mitigated risks were calculated. In this assessment, newly appeared hazards by the installation of APS, and hazards with gaps between conventional ships and autonomous ships with APS were assessed.

| Frequency          | Negligible                                      | Minor             | Moderately serious | Serious            | Major                          | Exceptional |
|--------------------|------------------------------------------------|-------------------|--------------------|--------------------|--------------------------------|-------------|
| Severity           | Extremely remote                               | Very remote       | Remote             | Seldom             | Reasonably probable            | Probable    | Frequently |
|                    | Likely to occur once per 20 years of 500 ships | Likely to occur once per ten years on 1,000 ships | Likely to occur once per year on 1,000 ships | Likely to occur once per year on 100 ships | Likely to occur once per year on 70 ships | Likely to occur once per year on one ship | Likely to occur once per month on one ship |
| Severity           | Negligible                                      | Minor             | Moderately serious | Serious            | Major                          | Exceptional |
|                    | Extremely remote                               | Very remote       | Remote             | Seldom             | Reasonably probable            | Probable    | Frequently |
|                    | Likely to occur once per 20 years of 500 ships | Likely to occur once per ten years on 1,000 ships | Likely to occur once per year on 1,000 ships | Likely to occur once per year on 100 ships | Likely to occur once per year on 70 ships | Likely to occur once per year on one ship | Likely to occur once per month on one ship |

**Figure 4. Risk matrix.**

| Severity       | Negligible                                      | Minor             | Moderately serious | Serious            | Major                          | Exceptional |
|----------------|------------------------------------------------|-------------------|--------------------|--------------------|--------------------------------|-------------|
| Scale          | Extremely remote                               | Very remote       | Remote             | Seldom             | Reasonably probable            | Probable    | Frequently |
|                | Likely to occur once per 20 years of 500 ships | Likely to occur once per ten years on 1,000 ships | Likely to occur once per year on 1,000 ships | Likely to occur once per year on 100 ships | Likely to occur once per year on 70 ships | Likely to occur once per year on one ship | Likely to occur once per month on one ship |

**Figure 5. Incident severity matrix.**
The identified hazards are shown in table 4, and the risk-assessment results are plotted in figure 6. This indicates that this system with risk-mitigation measures has a much higher safety level than current navigation systems.

Regarding cybersecurity, guidelines created by BIMCO (Baltic and International Maritime Council) et al. [13] and by ABS (American Bureau of Shipping) [14], and a framework proposed by NIST (National Institute of Standards and Technology) [15] are referred to in considering countermeasures to avoid and reduce risks. Basically, it is assumed that execution and control functions should be completely isolated from the external network to eliminate external threats and take effective countermeasures.

### Table 4. List of identified hazards.

| No. | Category I                  | Category II       | Hazard/Failure/Scenario                                                                 |
|-----|-----------------------------|-------------------|----------------------------------------------------------------------------------------|
| A1.1| System-Automated task       | Planning          | Improper input or no input of navigation plan                                         |
| A1.2| System-Automated task       | Planning          | Improper output of action plan                                                         |
| A2.1| System-Automated task       | Hardware          | APU failure due to environmental condition                                              |
| A2.2| System-Automated task       | Hardware          | APU failure affecting other equipment (e.g., ECDIS)                                     |
| A3.1| System-Automated task       | Information integration | Different input data from several sensors for the same function                  |
| A3.2| System-Automated task       | Information acquisition | Improper input (out of validation range) or no input of sensor data            |
| A3.3| System-Automated task       | Information integration | Deterioration accuracy of GNSS data                                                  |
| A4.1| System-Automated task       | Information acquisition | Erratic AIS data caused by sender                                                   |
| A4.2| System-Automated task       | Information acquisition | Erratic target tracking data due to noise and/or false echo                       |
| A4.3| System-Automated task       | Information integration | Detection failure of small objects (e.g., small boats, buoys) by system            |
| A4.4| System-Automated task       | Action and control | Deviation from the plan due to actuator failure                                    |
| B1.1| System-Manual task          | Information acquisition | No human response on manual input data of information integration                 |
| B1.2| System-Manual task          | Information acquisition | Incorrect data input by human                                                             |
| B2.1| System-Manual task          | Verification      | Human failure in verification of action plan                                          |
| B2.2| System-Manual task          | Verification      | Human failure in verification of alert                                                |
| B2.3| System-Manual task          | Verification      | Human failure in verification of working condition of systems                       |
| B3.1| System-Manual task          | Action and control | Human failure in manual operation to execute action plan                             |
| B3.2| System-Manual task          | Action and control | Human failure in reviewing execution of action plan                                |
| C1.1| Manual task                 | Motivation         | Failure in keeping navigation watch                                                    |
| C1.2| Manual task                 | Motivation         | Failure in decision making and/or human tasks due to physical stress                 |
| C1.3| Manual task                 | Motivation         | Failure in decision making and/or human tasks due to psychological stress           |
| C1.4| Manual task                 | Motivation         | Failure in decision making and/or human tasks due to improper motivation             |
| C1.5| Manual task                 | Motivation         | Failure in decision making due to over reliance on APS                               |
| C2.1| Manual task                 | Skill              | Failure in decision making and/or human tasks due to lack of skills and/or knowledge |
| C3.1| Manual task                 | Communication      | Failure in decision making and/or human tasks due to communication breakdown        |
| C3.2| Manual task                 | Communication      | Communication failure between the commander and others                              |
| D1.1| Environment                 | Heavy traffic      | Improper man-machine I/F to understand data coverage of action plan                  |
| D1.2| Environment                 | Heavy traffic      | Sudden change of traffic situation due to other vessels                              |
| D1.3| Environment                 | Heavy traffic      | Human failure in understanding situation due to large number of other vessels        |
| D2.1| Environment                 | Narrow channel     | Failure in execution of action plan due to environmental condition                  |
D3.1 Environment Restricted visibility Failure of target detection by human due to restricted visibility.

D4.1 Environment Night time navigation Failure of target detection by human due to restricted brightness at night.

E1.1 Emergency response Rescue Rescue operation of man overboard or other vessels

E2.1 Emergency response Fire Fire (affecting ship maneuverability and seaworthiness)

E2.2 Emergency response Fire Fire (not affecting ship maneuverability and seaworthiness)

E3.1 Emergency response Flooding Flooding (affecting ship maneuverability and seaworthiness)

E3.2 Emergency response Flooding Flooding (not affecting ship maneuverability and seaworthiness)

E4.1 Emergency response Power failure Short-time power failure which is easy to recover

F1.1 Cyber attack Planning Failure of APU due to cracking or infection of malware

F1.2 Cyber attack Information acquisition Failure of GNSS due to cracking or spoofing

F1.3 Cyber attack Information acquisition Failure of AIS due to cracking, or false data due to spoofing

F1.4 Cyber attack Information acquisition Failure of RADAR due to jamming

F1.5 Cyber attack Action and Control False output data due to infection of malware

F1.6 Cyber attack Communication Failure of network communication due to cracking or infection of malware

Figure 6. Result of risk assessment for conventional operation and autonomous operation with APS with mitigation measures.

2.8 Future Developments
Although the APS proposed in this paper is assumed to be used for manned autonomous navigation, it can also be utilized as a basic system for remote control or fully autonomous navigation in the future. In case of remote control, it is necessary for the remote operator to acquire information including visibility from the bridge by providing additional sensors, cameras, and a large-scale communication infrastructure. In addition, it is necessary to have redundancy and fallback mechanisms mainly for communication failure. As for fully autonomous navigation, it is necessary to guarantee that the available information, through additional sensors and cameras, be enough to conduct holistic judgment without human assistance.

3. Demonstration of APS
The NYK Group has been selected by MLIT to participate in a demonstration project utilizing ship maneuvering support functions and remote control. During this project, NYK aims to make use of APS in actual sea conditions. The demonstration test will be carried out on a tugboat in the latter half of FY2019.

Several APS functions are going to be verified in this test. Specifically, in order to support ship maneuvering and reduce the workload of human beings on board, a voyage plan will be prepared at a remote location and presented to the vessel, and after verification and approval by the vessel crew, the system will conduct navigation according to the plan. If there is a need to navigate against the voyage plan, such as to avoid the risk of collision with surrounding vessels, the vessel crew will override the system as appropriate. As the test system will not verify all APS functions shown above, additional demonstrations or simulations will be conducted in the near future.

4. Conclusion
This paper introduced the concept of Action Planning System (APS), which is being developed and demonstrated as a core technology of manned autonomous navigation by the NYK Group. According to the risk assessment we conducted with reference to class guidelines for autonomous ship, APS with risk-mitigation measures has a much higher safety level than current navigation systems. This system will be verified by the demonstration in actual sea conditions in FY2019.

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