Engineering For Social Change
A. Cooper et al. (Eds.)

doi:10.3233/ATDE240844

Multi-Layered Integration of System Models and Roadmaps for the Implementation of Autonomous Ships

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Abstract. Maritime transport is critical for global and Japanese transportation infrastructure, facing crew and driver limits. Although autonomous ships are expected as a solution to tackle these limitations, the enabling environment, such as regulations, governance, and social acceptance is essential for their implementation along with technology. Industrial roadmaps can guide the design of autonomous ships, aligning user needs with technology. This study proposes a multi-layered approach to clarify the relationship among industrial systems, navigation systems, and component system performance and to design the concept of autonomous vessels and industrial policies in an integrated manner. The industrial model explores the appropriate decision-making set for maritime stakeholders and presents possible introduction roadmaps. The navigation model evaluates the performance of subsystems to achieve safety goals. This comprehensive approach defines the necessary steps for technology realization and supports achieving broader social goals. Future work will focus on validating these models through interactive workshops with decision-makers and expanding simulation scenarios to enhance the realism and practicality of the simulations.

Keywords. Autonomous vessels, Industrial systems, Multi-layered model, Implementation scenario, Transdisciplinary engineering.

Introduction

The development of autonomous ships continues to advance with the expectation of addressing crew shortages, maintaining inland maritime transportation, reducing human errors, and cost reduction [1]. Previous research has identified remaining needs despite technological advancements, including further regulation, governance, and social acceptance for their implementation [2]. This gap is exacerbated by the complexity of autonomous ship systems, the diversity of architectures, and the involvement of various stakeholders, leading to disparate definition of use cases and implementation goals of this novel technology [3].

In this work, an industry-wide roadmap is considered as guide to appropriate goal-setting for implementation and adoption of autonomous ships. We suggest that a shared direction across industry will help to identify bottlenecks in technological development and to streamline R&D toward more targeted objectives. However, a roadmap for the

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adoption of autonomy, at least for coastal shipping in Japan, has yet to be generated. This absence may be due to difficulty in linking technological progress with implementation, confounded by factors such as uncertain marine transport demand, seafarer numbers, and infrastructure development. Furthermore, the societal impact of this technology depends on its integration into ship operations, the services provided, and other external uncertainties. Therefore, a useful roadmap should support step-by-step consideration of how technological development will affect operations, society, and the industry.

This paper introduces a transdisciplinary approach to the design of technological systems with societal implementation hurdles, taking autonomous ships as an example.

1. Background

1.1. Maritime Industry and Autonomous Ship

Maritime transportation accounts for more than 80% of global trade volume and 99.6% of Japan’s trade, serving as a critical societal infrastructure. Japanese domestic maritime transport, which handles 40% of the country's transport volume, faces crew shortages and challenges to maintain operation routes [4]. At the same time, starting in April 2024, Japan imposed limits on overtime work for truck drivers, potentially reducing transport capacity. In response, the government aims to double the transport volume and share of inland shipping (ferries, RORO ships) within a decade, highlighting the urgency of a “modal shift” [5]. However, the availability of crew remains a significant challenge, necessitating reforms in the shipping industry to manage the increased transport volume.

In this context, expectations for autonomous ship implementation are increasing. Apart from addressing crew shortages while maintaining societal infrastructure like routes to remote islands, autonomous ships promise reduction by up to 80% of maritime accidents caused by human errors. Additionally, autonomy can lower labor and equipment costs, thereby enhancing industrial competitiveness [1]. MEGURI2040, led by the Nippon Foundation, succeeded in demonstration of crewless operation of domestic ships in 2022 [6]. This initiative’s second phase has started, aiming for “50% of ships running domestically to be unmanned by 2040.”

1.2. Challenges for implementation

Of course, the potential value of autonomous ships will be realized only when adopted and operated in the real world. Fonseca et al. state that most of the discussions have been solely focused on technical developments, thus overlooking the complex array of socio-economic and policy factors [2]. They show the technology adoption (“Tech-Ado”) model, which emphasizes the necessities of actions to enhance the enabling environment, such as regulations, governance, and social acceptance, along with technology, economy and human capital perspectives. For instance, crew employment concerns will need to be addressed with the introduction of autonomous ships. Moreover, amendments to international agreements led by the International Maritime Organization (IMO), the development of port and communication infrastructure, insurance systems, and other policies and subsidy programs will also influence the introduction of autonomous ships. Thus, in addition to the ships themselves, the surrounding infrastructure, regulations, and business environments must be addressed.

Systems engineering, widely used in aerospace and other complex product and service industries, is one approach to realize new complex technologies such as autonomous navigation systems [7]. In the design phase, a primary process is development of a Concept of Operations (ConOps) based on user needs, extracting system requirements, and then top-down refinement of requirements, behaviors, and architectures. Systems engineering methodologies are believed to be effective for the top-down design of autonomous ships, with several application cases available [8][9]. However, there is few research on the concept design of autonomous ship for future commercialization.

An industry-wide roadmap is one tool for guiding appropriate goal-setting for concept design. Roadmap is defined as “a structured visual chronology of strategic intent,” supporting communication, decision making, resource allocation, action, performance assurance, and capability development [10]. A roadmap can contribute to building a consensus between stakeholders and developing a concept that considers their implementation. It hopefully clarifies the relationship between user needs and technology, which naturally reveals technological development goals to be pursued by the entire industry. Designing the industrial strategy, operating rules, and product concept in an integrated manner can accelerate the implementation of automation.

2. Objectives

This study proposes an approach to address the design of autonomous ships considering implementation through multi-layered integration of models with different scales. Specifically, we utilize two simulations constructed from industrial and operational perspectives to quantify the relationships between industrial systems, operational systems, and product system performances. This approach allows for a top-down examination of system performance requirements and system design while concurrently evaluating decision-making by stakeholders external to the system (industrial policies and operational rules) to support consensus-building for implementation.

3. Methodology

We propose a multi-layered industry and technology roadmap design methodology using industrial and navigation simulators to simulate the implementation of autonomous ships in the industry and the service operation, as shown in Figure 1. We define performance metrics (Figure of Merit: FOM) for systems at different layers and clarify the relationships between these metrics. The industrial simulator quantifies the relationship between industrial and operational systems, while the navigation simulator quantifies the relationship between operational and product systems.

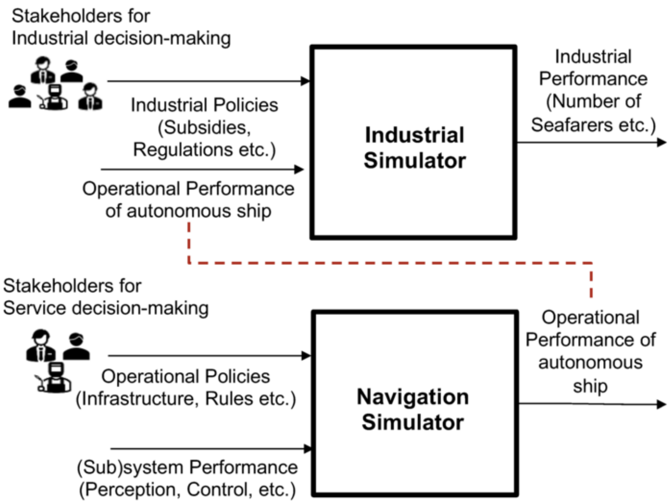

Figure 1. Conceptual diagram of the methodology.

3.1. Figure of merit

Considering the industrial transformation by implementing autonomous technology, we first assume the FOM for the maritime industrial system, which is a system of systems consisting of various independently operated stakeholders (Table 1). These indicators are extracted based on existing literature discussing the benefits of autonomous ships [1] and the Nippon Foundation's implementation goals.

Table 1. Figure of Merit for the maritime industry system (SoS).

Figure of Merit (FOM)	**Description (Main Stakeholders)**
Route maintenance (MT・NM)	Administration, Public
Required crew size (people)	Crew, Shipowners, Administration
Estimated accident (cases)	Crew, Shipowners, Classification societies, Administration
Industry profit (USD)	Shipowners, Shipyards, Manufacturers
Autonomous ship adoption rate (%)	Administration

Table 2 shows the FOM for the technical product system for autonomous navigation. We discuss four subsystems: own-ship perception, other-ship perception, planning, and vessel control. The performance or accuracy of these subsystems will have impacts on the navigation service improvement and eventually reduction in crew tasks.

Table 2. Figure of Merit for autonomous ship product system.

Figure of Merit (FOM)	**Description (Main Equipment)**
Own-ship perception accuracy (m)	GNSS, etc.
Other-ship perception accuracy (deg)	Integrated cognition subsystem incl. RADAR, LiDAR, Visible light/IR camera, etc.

Figure of Merit (FOM)	Description (Main Equipment)
Planning performance (-)	Action planning system
Vessel control accuracy (e.g. cross-track distance) (m)	Speed and heading control subsystem incl. TCS/HCS, DPS, etc.

It seems difficult to define how much product system-level FOMs are needed to achieve industry-level FOMs. As a link between these FOMs, we set the operational-level FOMs for the autonomous navigation system as Table 3. As it's directly linked to the OPEX and CAPEX, and human errors, crew task reduction rate can be the most crucial factor for economic and social benefits, as shown in Kretschmann et al. [11]

Table 3. Figure of Merit for the autonomous navigation service system.

Figure of Merit (FOM)	Description
Crew task reduction rate (%)	Described in Figure 2.
Safety (-)	Equivalent safety will be assured based on [9].
Cost Efficiency (%)	Fuel efficiency due to optimized routing etc. [11]

These metrics vary depending on the target tasks and level of automation. Figure 2 shows the structured model calculating an autonomous ship's crew task reduction rate. The area represents the rate of task reduction for each automation task, expressed as a product of the degree of autonomy and the condition coverage. This study categorizes tasks to be automated into berthing, navigation, and monitoring. Condition coverage is the Operational Design Domain (ODD) coverage ratio to the Target Operational Domain (TOD). While the ODD defines of the operating conditions that the autonomous system is designed to operate in, the TOD is the area where the system will be deployed (expected to operate in). These concepts are defined in ISO34503 [12], indicating the degree to which the task can be automated out of the events encountered during operation. By setting this, it is possible to evaluate the performance of the autonomous system from the viewpoint of how much ODD can be covered while ensuring safety. By setting this for each task, it is possible to simply evaluate the NPV of various types of autonomous vessels.

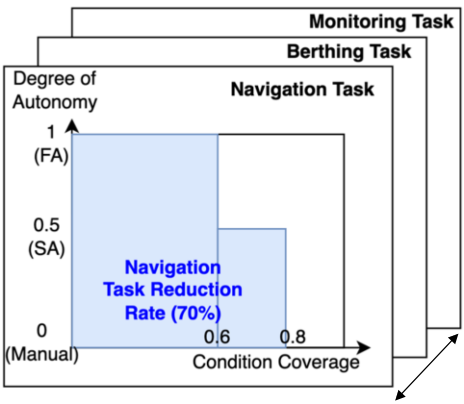

Figure 2. Structural image of crew task reduction rate of autonomous ship.

3.2. Industrial Simulator

To clarify the relationship between the industrial FOMs and service FOMs, we utilize an industrial simulator adapted for inland vessels based on [3]. The overview of the simulator is presented in Figure 3. It aims to outline a roadmap for automation over the next few decades while accommodating changes in decisions made by ship companies, shipyards, manufacturers, policymakers, and others. Architectural decisions (ADs) to be evaluated include;

- government subsidy strategies (AD1),
- regulatory relaxations (AD2),
- purchasing strategies and knowledge sharing ratio by shipowners (AD3), and
- a premium setting of the insurance companies (AD4).

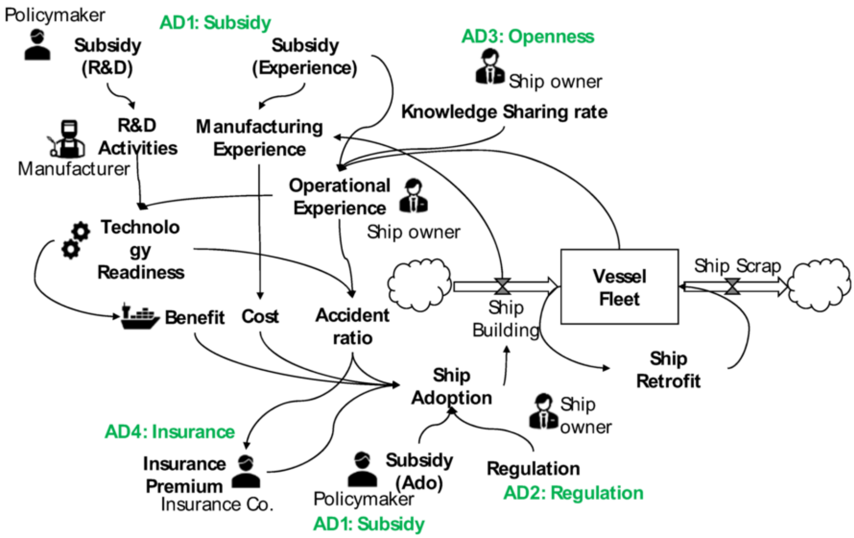

Figure 3. Schematic Model of Industrial Simulator.

The combination of these decision parameters is the input, and the output is directly related to industrial FOMs, such as the number of autonomous vessels of different types to be deployed and the associated number of crew members required. External uncertainties, such as changes in marine transportation demand, are also considered in the simulation to determine the appropriate decision options.

Figure 4 shows a sample result of a simulation run with uncertainty parameters. In this case, we set the decision-making sets as shown in Table 4. Figure 4 evaluates part of the Industrial FOMs: with the first introduction year on the horizontal axis and the introduction ratio at 2040 on the vertical axis.

Table 4. Decision making sets of sample simulation.

#	Description	Option1	Option2	Option3	Option4
D1	Subsidy (Policy maker)	For R&D activities	Adoption	Experience	Experience &Adoption

#	Description	Option1	Option2	Option3	Option4
D2	Regulation (Policy maker)	As-is	Relaxation		
D3	Openness (Ship Operator)	Close	Open		
D4	Insurance Rate (Insurance Co.)	Resisted	Considered		

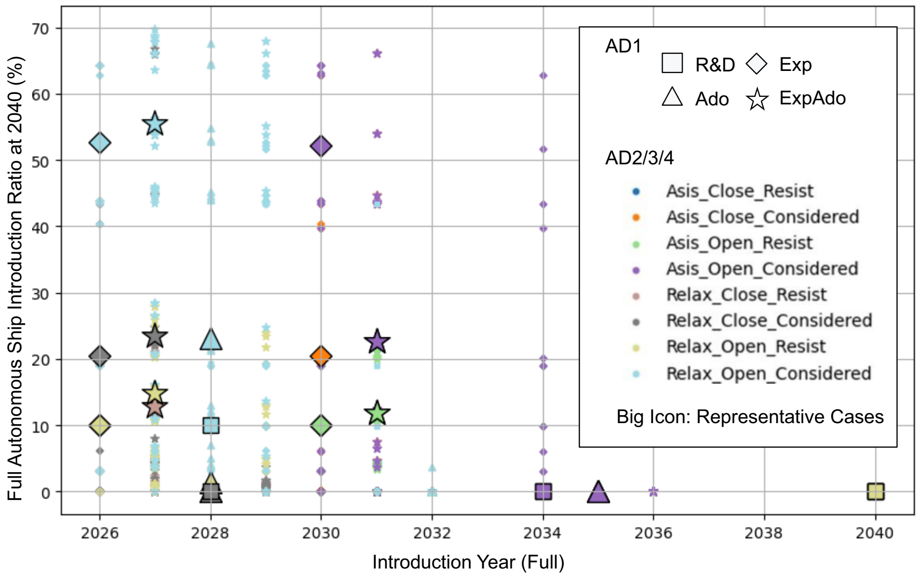

Figure 4. Sample simulation results of industrial simulator comparing several decision-making sets.

Figure 5 shows the results of a case that combines relaxation of regulations, open knowledge sharing scheme, and changes in insurance premium settings; light-blue star case in Figure 4. The results include vessel configuration transition (left) and TRL transition for each autonomous technology (right) over time. The colors in the left figure show the different types of autonomous ships, combining three autonomous technologies—berthing, navigation, and vessel monitoring—and levels of automation. This gradual change of fleet replicates the step-by-step introduction of autonomous technology. The simulator can also visualize the number of required crews, subsidies spent, and estimated accident occurrences. These can provide insights into potential employment changes in the maritime industry and technology development goals to achieve the industrial goal. Thus, we can see the possible roadmap for technology adoption, the changes in human resources, and the milestones in technological maturity, which is equal to the discretization of the operational performance of the autonomous vessel in this study (TRL9 means the crew task reduction rate is 1).

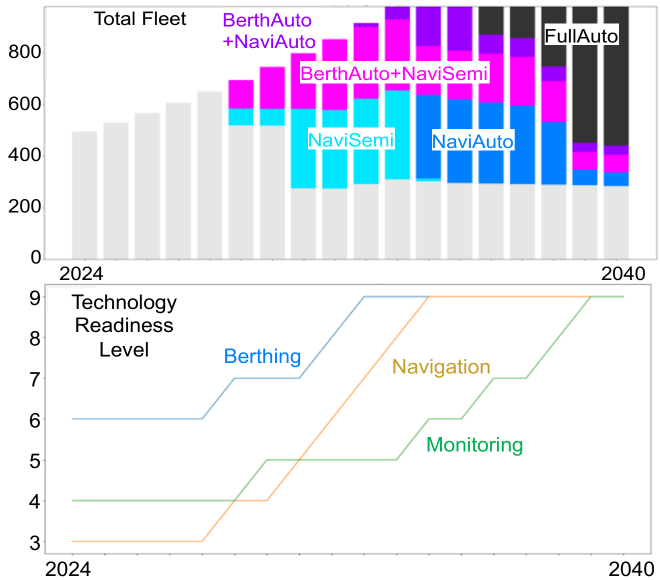

Figure 5. An Example of simulation results: vessel configuration transition (top) and progression of Technology Readiness Levels (TRL) for each technology (bottom) of a selected scenario in a sample simulation.

3.3. Navigation Simulator

The industrial simulator visualizes operational systems milestones necessary to achieve industrial goals. The navigation simulator, on the other hand, connects operational system performance with product system performance; it evaluates the required product performance to achieve the navigation automation milestone extracted by the industrial simulator. Results mentioned in the previous section indicate that TRL9 for autonomous navigation technology shall be achieved by 2035 to reach the goal of "50% introduction by 2040" (referred to Figure 5).

In this study, TRL9 means the crew task reduction rate is 1. We evaluated whether the autonomous operation could cover the whole TOD safely. Although there are several factors considered in ODD and TOD, e.g., geography, communication, and environmental conditions, the situation of encountering another vessel in a calm, open sea was assumed in this primitive study. The position, speed, and course of the other vessel's appearance were considered an ODD component, and the speed and course angle were used as input variables as we fixed the distance from the point of collision. We set the estimated speed as [0-12] knots and the angle as [67.5-292.5] degrees as TOD, assuming a head-on and crossing situation.

As the collision avoidance algorithm of the own ship, the rule-based model, which considers the preference of navigation officers and risks calculated by the Closest Point of Approach (CPA) [15] is assumed in this study. The controller is assumed to be a PID control algorithm, and vessel movements are calculated using the KT model [16].

In this case, the coverage (ODD/TOD) of fully autonomous navigation is defined as the coverage area within the assumed ranges of these two variables, where the distance from other vessels is above the threshold, set as 0.25km in this case. Specifically, we sampled simulation inputs from the variable ranges, and a response surface was created using simulation results by Gaussian process regression (GPR). The area where the lower 0.5th percentile value was above the threshold was calculated as the task coverage.

The necessary accuracy of each ship's localization and situation awareness can be evaluated. This study sets the accuracy of the detection angle σ degrees of the target vessel as a standard deviation of a normal distribution. As shown in Figure 6, if we set σ to 0.0, then most of TOD was covered in this case. By doing this, we can calculate the necessary FOMs to achieve system-level and, eventually, social-level FOMs.

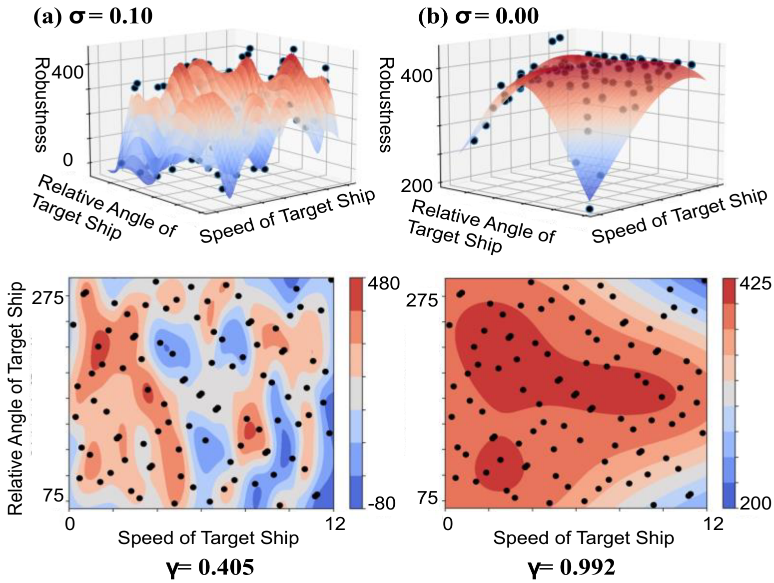

Figure 6. Mean GPR surface (upper) and Lower 0.5th percentile (lower) of robustness score in the TOD range with different cognition performance.

4. Conclusion

This paper proposes a transdisciplinary roadmapping approach for implementing autonomous ships using multi-layered simulations of different scales. This approach, when combined with stakeholder decisions made at the industry level, provides a transition towards autonomous ship implementation and accompanies technology development milestones. The navigation simulator allows for evaluating product system performance requirements, thereby contributing to realizing these technology development milestones and, ultimately, achieving our social goals.

As this study just showed the concept of social and technical integrated design processes, many future works remain. First, the industrial simulators need to be verified and validated. When modeling such industrial and social systems, several uncertain factors exist in the causal relationships, decision-making models, and scenario parameters. Since the simulator reproduces future events, it is necessary to improve the model's feasibility through workshops involving decision-makers interactively. While the roadmap can be valuable for communication, the main value lies in the process of road mapping and the communication and consensus building among stakeholders [10]. In addition, as the scenario tested in the navigation simulator was a simple case, it is necessary to push the boundaries of this scenario and consider other ODD factors, such as geographical conditions, weather, and the conditions of other vessels. This comprehensive approach will expand the scenario and make the simulation more realistic and practical. Additionally, it is desirable to develop simulators for estimating ODD coverage for Berthing and Monitoring, in addition to Navigation, to further enhance the simulator's capabilities.

Acknowledgement

We thank the members of the Autonomous Ship Team of MTI Co. Ltd., Maritime and Ocean Digital Engineering Laboratory (MODE Lab), Global Team Lab (GTL) and Laboratory of Intelligent Systems Design (LISD) of The University of Tokyo for their advice in conducting this research.

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