Co-Simulation Platform with AI-Based Decision Making for Digital Twins of Autonomous Vessels

Summary

The plan is the development of a co-simulation platform that integrates AI-based decision-making modules into the digital twins of autonomous vessels. The co-simulation platform will enable real-time interaction between AI models, environmental simulators, and vessel behavior models using standard communication protocols such as FMI and RESTful APIs. By replacing rule-based trajectory planning tools with machine learning models, the platform will support dynamic and context-aware decision-making. These AI models will be trained using simulation scenarios, historical maritime data, and behavior patterns to predict optimal navigation strategies in various situations. The digital twin will continuously update based on AI-driven decisions and environmental feedback, allowing it to adapt in real time. The co-simulation environment will validate the AI system through multiple scenarios, including collision avoidance, course keeping, and obstacle detection. By enabling modular integration of AI components, the platform will also support scalability and extensibility for diYerent vessel types and environments

Research field:	Environmental, marine and coastal technology
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Description

1. Motivation: What is the Problem?

The maritime industry is entering a new era of automation and digitization. With the growing push toward autonomous shipping, the need for vessels that can make intelligent, real-time decisions is more demanding than ever. These autonomous systems must be able to navigate safely, comply with international regulations like COLREG, and respond to dynamic changes in their environment. However, traditional rule-based navigation systems are rigid and often fall short in handling the complexity of real-world maritime operations. While simulation environments and digital twins have become useful tools for testing autonomous systems, they are still limited by static decision-making logic and lack integration with intelligent, adaptive algorithms. This results in digital twins that do not fully reflect the behavior of vessels in uncertain and changing conditions.

During my Master's thesis at Åbo Akademi University, I developed a modular co-simulation platform that connects external decision-making tools to maritime simulation environments using a client-server architecture. The platform was designed to allow dynamic waypoint updates and real-time interaction with vessel models. This foundational work demonstrated the feasibility and flexibility of building co-simulation environments that support real-time communication and control. However, the decision-making component in that system relied on a rule-based trajectory planner, which limited its ability to handle complex and unpredictable navigation scenarios.

Building on this foundation, my proposed PhD research seeks to extend this co-simulation platform by integrating AI-based decision-making modules, transforming the system into a truly intelligent digital twin framework for autonomous vessels. This advancement will allow the simulation platform not only to execute pre-planned behaviors but also to make informed, adaptive decisions in real-time. Such a system can better simulate real-world conditions and support testing and development of more reliable autonomous navigation solutions.

2. How to Solve It?

To address this problem, I propose the development of a co-simulation platform that integrates AI-based decision-making modules into the digital twins of autonomous vessels. The co-simulation platform will enable real-time interaction between AI models, environmental simulators, and vessel behavior models using standard communication protocols such as FMI and RESTful APIs. By replacing rule-based trajectory planning tools with machine learning models, the platform will support dynamic and context-aware decision-making. These AI models will be trained using simulation scenarios, historical maritime data, and behavior patterns to predict optimal navigation strategies in various situations. The digital twin will continuously update based on AI-driven decisions and environmental feedback, allowing it to adapt in real time. The co-simulation environment will validate the AI system through multiple scenarios, including collision avoidance, course keeping, and obstacle detection. By enabling modular integration of AI components, the platform will also support scalability and extensibility for different vessel types and environments.

3. Why is It Important?

This research is important because it bridges the gap between static digital twin models and intelligent real-world autonomous operations. By enabling AI-based decision-making within a co-simulation environment, it enhances the effectiveness of digital twins in maritime applications. Autonomous vessels require decision-making systems that can understand and respond to rapidly changing situations at sea, something traditional approaches struggle with. The proposed solution not only advances simulation technology but also supports the development of safer and more efficient autonomous maritime systems. This has significant implications for industries aiming to reduce human error, fuel consumption, and operational risks. Furthermore, this research aligns with the global trend of digital transformation and green shipping, providing a foundation for smarter and more sustainable marine operations. As regulations and demand for autonomous systems grow, the integration of AI with digital twins will become increasingly critical.

4. What Are the Research Questions?

This research will address the following key questions:

1. How can AI-based decision-making be effectively integrated into co-simulation platforms for autonomous vessels?
2. What machine learning approaches are most suitable for dynamic trajectory planning under maritime constraints like COLREG?
3. How does the integration of AI influence the usefulness of digital twins in maritime simulation?
4. What are the key challenges in testing and validating AI-based navigation systems using simulation-based methods?

5. Major Research Activities

The project will begin with literature review and requirement analysis, focusing on existing research in co-simulation, digital twins, autonomous vessels, and AI-driven control systems. The review will identify gaps in adaptability, interoperability, and uncertainty handling in current maritime simulation platforms. This stage will also outline the key architectural requirements for enabling dynamic AI control in a modular simulation environment.

"Navigating the future: AI and Co-Simulation for Green Shipping" [1] explores how co-simulation and AI can work together to create more energy-efficient maritime systems. It highlights the importance of modular simulation environments and their role in developing sustainable shipping solutions.

"Maritime Digital Twin Architecture: A Concept for Holistic Digital Twin Application for Shipbuilding and Shipping" [2] outlines a comprehensive digital twin architecture relevant to ship behavior and simulation frameworks.

"Digital Twin for Autonomous Surface Vessels: Enabler for Safe Maritime Navigation" [3] proposes a level-based classification and application of digital twins for ASVs with real-time.

"Deep reinforcement learning based collision avoidance system for autonomous ships" [4] demonstrates the application of RL in COLREG-compliant ship navigation.

Following the review, the second major activity will involve the design of the co-simulation platform architecture. This includes defining communication protocols and modular interfaces between the AI module, digital twin, and simulation environment. Components will be designed to support asynchronous communication and real-time data flow, ensuring the system is scalable and flexible for future integration with physical testbeds or extended maritime environments.

The third activity will focus on the development of the AI-based decision-making system. Techniques such as deep reinforcement learning, probabilistic decision trees, and fuzzy control will be explored to create navigation strategies that can adapt to environmental uncertainty while maintaining COLREG compliance. These AI models will be developed and trained initially in isolation using controlled datasets, and then gradually integrated into the full simulation loop.

In parallel, the fourth activity involves building and integrating the digital twin of the autonomous vessel. The twin will replicate vessel state variables, environmental inputs, and sensor behaviors in real time. It will be connected to the AI module to allow continuous feedback, enabling the system to respond to environmental changes dynamically.

The fifth major activity is testing and evaluation through simulation-based experiments. A series of real-world inspired scenarios will be developed to test the performance of the full system in complex and uncertain maritime environments. A web-based interface will be developed for visualization and interaction with the co-simulation platform. Evaluation criteria will include decision-making latency, navigational accuracy, adaptability to uncertainty, and robustness in degraded data scenarios. Performance will also be benchmarked against existing rule-based systems to quantify the benefits of learning-based decision frameworks.

Finally, the sixth activity will be dedicated to validation and dissemination. This includes refining the platform based on experimental feedback, conducting final case study simulations, and publishing results in peer-reviewed journals and conferences. The platform will be prepared for potential open-source release with clear documentation and modular design to facilitate adoption and future development.

6. Time Division

The figure illustrates the timeline of my PhD research. The phase is divided into subphases as per years. Each year is structured to generate substantial outcomes, which will result in publication to be submitted to high-ranking conferences.

7. References

[1] Iancu, B., Lafond, S., & Rexha, H. (2024). *Navigating the future: AI and co-simulation for green shipping*. Port Technology International, (140), 42–45.
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[4] Wang, Y., Xu, H., Feng, H., He, J., Yang, H., Li, F., & Yang, Z. (2024). *Deep reinforcement learning based collision avoidance system for autonomous ships.* Ocean Engineering, 292, 116527.

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