LiDAR Co-Simulation for Maritime Assistance System V&V

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***Abstract*— Maritime Autonomous Surface Ships (MASS) increasingly rely on LiDAR-based perception systems for maneuver automation, collision avoidance, and berthing assistance. However, systematic V&V of these safety-critical, sensor-driven systems remain constrained by the lack of scalable, automated, and transparent simulation environments. While commercial maritime simulators offer high-fidelity traffic environments, they typically rely on proprietary, non-interchangeable sensor models. Research-oriented platforms, on the other hand, often operate offline and lack real-time integration with bridge systems, limiting their applicability for end-to-end testing.**

To address this gap, this paper presents a sensor-centric co-simulation framework that integrates a modular LiDAR simulation environment with S-100 maritime traffic data or real onboard bridge systems. The proposed approach supports data-driven scenario generation based on maritime standards, high-fidelity raycasting-based LiDAR simulation, and real-time coupling with both SiL and HiL testing workflows. An experiment using the research vessel *Sally* demonstrates the framework's ability to inject virtual LiDAR data into live operational scenarios, enabling systematic evaluation of assistance functions under realistic conditions. The results highlight the potential of sensor-centric co-simulation as a critical enabler for scalable, reproducible, and evidence-based V&V in the maritime domain.

Keywords—LiDAR simulation, maritime autonomy, scenario-based testing, V&V, co-simulation, sensor modeling, MASS

I. INTRODUCTION

Despite the growing importance of LiDAR sensors for autonomous vessels, the maritime domain still lacks an open, standardized, and automated simulation infrastructure for scenario-based verification and validation (V&V) of LiDAR-based assistance systems on Maritime Autonomous Surface Ships (MASS). This gap significantly hinders the systematic assurance of safety and reliability for these safety-critical, data-driven perception systems.

LiDAR sensors offer high-resolution, close-range environmental perception [1], making them increasingly relevant for maneuver automation in MASS. Key applications include collision avoidance [2,3], obstacle detection [4,5], and berthing assistance [6,7]. Given their deployment in real-time, safety-critical scenarios—such as avoiding collisions with vessels, obstacles, or port infrastructure—rigorous V&V is essential. However, real-world testing is costly and constrained by limited vessel maneuverability and variable environmental conditions, including tides, weather, and sensor-specific effects.

Current testing approaches rely on recorded LiDAR datasets [8] or manually constructed traffic scenarios [3,9], both of which offer limited realism, scalability, and parameterization. These limitations restrict their applicability for systematic V&V. In adjacent domains, such as automotive, scenario-based simulation has become a cornerstone of V&V, supported by standardized interfaces like the Open Simulation Interface (OSI) and synthetic sensor data generation [10,11]. A similar need is emerging in the maritime sector, where LiDAR and machine learning-based perception systems are increasingly used for vessel detection and collision avoidance [12].

While commercial maritime traffic simulators—such as those from Wärtsilä, Kongsberg, VSTEP NAUTIS, and ABB—offer high-fidelity environments and proprietary sensor models, they are primarily designed for training and lack open, modular interfaces [13–16]. Their internal models are typically non-replaceable, limiting automation, parameter variation, and independent testing of perception and assistance functions.

There is a clear need for a standardized, open, and modular co-simulation framework that supports scenario-based V&V of LiDAR-based maritime assistance systems. Such a framework should integrate seamlessly with existing maritime simulators via established data standards (e.g., AIS, NMEA, S-100), support realistic traffic and environmental modeling, and enable plug-and-play replacement of validated vessel dynamics, control models, and virtual sensor components. Developing this type of co-simulation environment would close a critical research and capability gap, enabling scalable, evidence-based V&V for autonomous LiDAR-based maritime assistance systems.

II. RESEARCH GAP

Modern maritime simulation platforms fall into two broad categories: industrial full-mission bridge simulators and research-oriented/open simulation frameworks. The former (e.g., Kongsberg K-Sim, Wärtsilä NTPRO, VSTEP NAUTIS, ABB simulators) provide highly realistic ship-handling environments with integrated sensor outputs (radar, ECDIS, etc.) and are widely used for training, certification, and even evaluating new bridge systems [13–16]. These commercial simulators can simulate LiDAR-like sensors in a physically plausible way, but their sensor models are proprietary "black boxes"—they are built into the simulator and cannot be easily inspected or swapped out. Although such systems may allow some parameter tuning, they lack open interfaces and modularity. This means a developer cannot, for example, plug in a custom LiDAR model or vary the sensor physics in isolation; as a result, systematic testing and validation of collision avoidance algorithms at the sensor level is restricted. In short, today's full-mission simulators excel at high-fidelity vessel and environment modeling but assume a fixed sensor suite, which limits their applicability for developing and rigorously verifying autonomous navigation and collision-avoidance assistance systems.

In contrast, the research and open-source simulation platforms prioritize modular sensor and scenario modeling, often at the expense of seamless integration with actual bridge systems. Projects in robotics and academia have produced simulators that support physics-based LiDAR simulation (e.g., using ray-tracing) and customizable sensor models [17]. For instance, the Gazebo-based Virtual RobotX competition simulator provides a realistic environment for Uncrewed Surface Vehicles with support for LiDAR and camera plugins; similarly, Unity or Unreal Engine-based simulators (e.g., MARUS or SMaRC-Sim) offer configurable maritime sensors and environment physics [18–20]. These frameworks enable swapping or modifying sensor models and can generate synthetic point clouds with adjustable noise and weather effects—critical for AI training and perception testing. However, such research simulators typically run in isolation, producing sensor data offline without a human operator in the loop. They usually do not connect in real time to full bridge consoles or navigation systems. As a consequence, standard system-in-the-loop (SiL) or human-in-the-loop (HiL) testing with a realistic bridge context is not supported. The maritime domain currently lacks a unified platform that combines the strengths of both worlds: the fidelity and realism of industry-grade bridge simulators with the flexibility of interchangeable, high-fidelity LiDAR sensor models. This gap is evident in the absence of a standardized, scenario-based V&V framework analogous to what the automotive field has achieved (e.g., with ASAM OSI and OpenSCENARIO) [21,22]. DNV's Open Simulation Platform (OSP) offer a co-simulation architecture to link different maritime simulation components, but they still rely on whichever sensor models the integrated tools provide, and domain-specific LiDAR models remain scarce [23]. Other efforts, including the European Maritime Simulator Network (EMSN), primarily focus on training and vessel traffic management [24]. The VERA simulation framework incorporates sensor error models but is tailored to inland navigation scenarios [25], while HAGGIS supports system-of-systems simulation using an HLA-based architecture yet does not include a native LiDAR model [26].

The paper closes the gap by a sensor-centric real-time co-simulation framework that links industrial bridge simulators with a highly realistic LiDAR sensor simulation. The approach is based on a physics-driven ray-casting simulation that accounts for environmental influences and sensor-specific distortions, and it operates in synchronization with a full-mission bridge simulator. Standard maritime data interfaces (e.g., AIS, NMEA-0183/2000) enable real-time, bidirectional data exchange between the sensor and ship simulation models. This setup allows collision avoidance assistance systems to be tested under realistic operational conditions—with a human bridge crew in the loop if desired. The modular architecture enables LiDAR models to be exchanged, analyzed, or systematically varied. The framework supports both SiL and HiL scenarios and facilitates systematic investigation of system behavior under varying sensor parameters and environmental conditions. In doing so, the approach combines the strengths of commercial high-fidelity simulators with the openness and modularity of research-oriented platforms, providing a robust foundation for traceable and repeatable V&V of LiDAR-based maritime assistance systems.

III. Sensor-Centric Co-Simulation as a Missing Link in Maritime Scenario-Based V&V

The main contribution of this work is a sensor-centric co-simulation approach that addresses this gap by enabling live, scenario-based sensor simulation compliant with S-100 maritime traffic data, thereby allowing seamless interaction with real-world bridge systems and established simulators.

The proposed approach introduces a modular LiDAR sensor simulation environment that can be integrated into co-simulation setups used for maritime assistance system testing. The sensor simulation is treated as an explicit part of the test environment, distinct from the system under test (SuT), enabling systematic variation of sensor parameters, scenario conditions, and environmental effects.

Fig. 1 shows the overall architecture of the proposed sensor-centric co-simulation framework. The system integrates traffic simulation based on AIS data and environmental models (e.g., weather and tide effects) as input to a LiDAR sensor simulation module. The sensor simulation generates time-synchronized point cloud data, which is provided to the SuT for evaluation. The SuT is further connected to a bridge system and a HiL interface, enabling testing under realistic operational conditions. This architecture highlights the separation between sensor simulation and the SuT, while enabling consistent data flow from scenario generation to system evaluation.

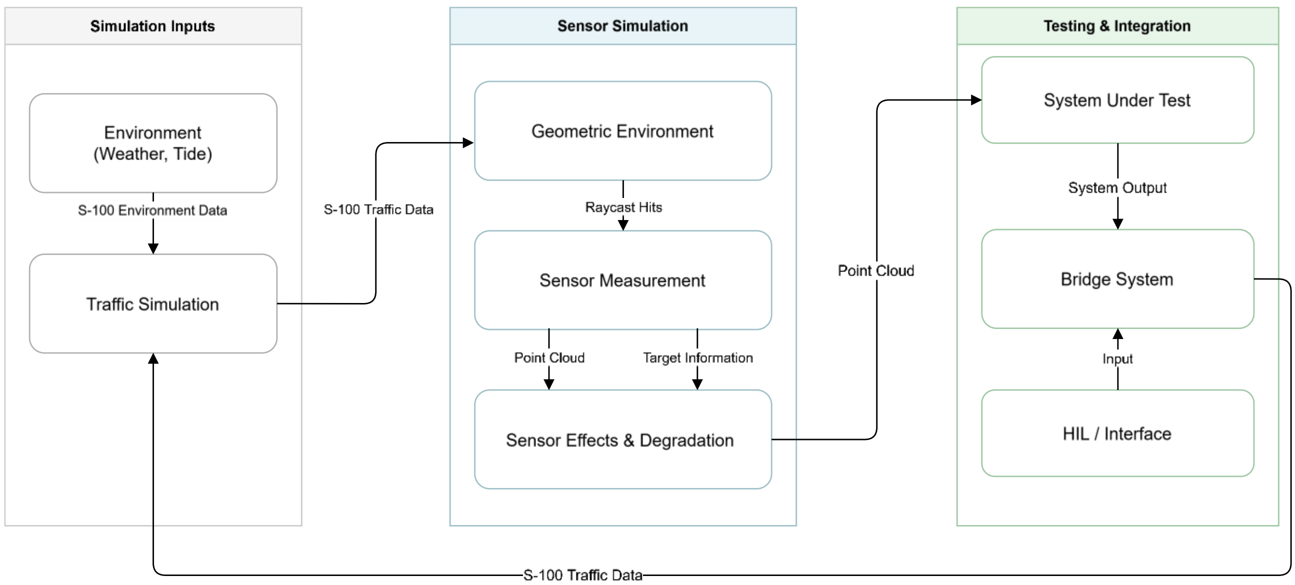

Fig. 1. Sensor-centric co-simulation architecture showing the integration of traffic and environmental simulation with LiDAR-based sensor modeling and real-time system evaluation via the SUT and bridge interface.

A. Scenario Generation from Real-World Maritime Data

To support automated and scalable scenario-based testing, dynamic traffic participant behavior and environmental conditions are generated using real-world maritime data sources. Vessel behavior is derived from Automatic Identification System (AIS) data, enabling realistic traffic patterns and encounter situations. Environmental dynamics, such as tidal effects, are incorporated through tide data passed to the simulation environment. This data-driven approach enables the automated generation of logical and concrete scenarios, ensuring relevance to real operational conditions while maintaining reproducibility and parameter control.

B. LiDAR Sensor Simulation Methodology

The LiDAR sensor simulation is based on an established ray-casting approach to model the measurement process within the simulated maritime environment. Using the scene representation provided by the traffic and environment simulation, beams are propagated in to compute intersections with vessels, infrastructure, and environmental surfaces.

This method allows the sensor model to capture key perception-relevant effects, including:

- geometric visibility and occlusions caused by vessels and infrastructure (e.g., bridges),
- relative motion between sensor platform and observed objects,
- sensor-specific characteristics such as field of view, angular resolution, and range limits.
- By generating sensor-level data instead of idealized object lists, the approach enables realistic evaluation of perception algorithms and downstream assistance functions within scenario-based V&V campaigns.

C. Integration into Scenario-Based V&V Workflows

The sensor simulation is integrated into a time-synchronized co-simulation environment that supports real-time execution and interaction with other simulation components. This enables both open-loop testing of perception functions and closed-loop SiL or HiL testing, where assistance system outputs influence vessel behavior within the scenario.

This enables consistent mapping between:

- scenario definitions (traffic, environment, sensor configuration),
- test execution within a simulation-based test environment,
- quantitative evaluation against known ground truth.

D. Impact on Maritime V&V Practice

By combining data-driven scenario generation, high-fidelity LiDAR sensor simulation, and live co-simulation capability, this work provides a missing building block for maritime assistance system V&V. The approach bridges the gap between industrial bridge simulators and research sensor models, enabling transparent, reproducible, and scalable sensor-centric V&V under conditions aligned with current approval and certification practices.

IV. Experiment

To demonstrate the applicability of the proposed sensor-centric co-simulation framework under realistic operational conditions, a trial was conducted using a real vessel system in combination with a virtual automation island. The main objective of the experiment is to evaluate whether the simulation framework can be integrated into real bridge system outputs while maintaining a temporally consistent virtual sensor representation. The experimental setup is based on the research vessel *Sally*, which was equipped with differential GPS and navigated through the Jarßum port area.

Fig. 2. Test scenario track of the research vessel Sally during a lock transit maneuver in the port of Emden, serving as the basis for real-time co-simulation and sensor data generation. Chart Source: OpenStreetMap

The track is shown in Fig.2, the selected test scenario focuses on a lock transit maneuver, in which the vessel enters and exits the Emden lock under real operational conditions. This scenario represents a safety-critical close-range situation with high relevance for infrastructure-based assistance systems.

Two virtual land-based LiDAR sensors were positioned at the lock entrance, representing a shore-based sensing infrastructure forming a virtual automation island.

A. Real-Time Integration

A central aspect of the experiment is the integration of the co-simulation framework into real onboard system data streams. The onboard navigation data of the *Sally* is used as input to the simulation environment, allowing the virtual LiDAR sensors to generate measurements corresponding to the actual vessel motion. This setup allows the generation of a virtual automation island in real-time that reflects the real-world situation during the maneuver.

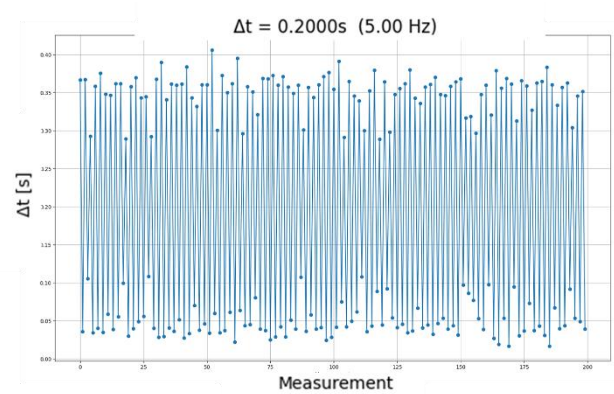

Fig 3. Temporal distribution of simulated LiDAR measurements demonstrating stable sensor update behavior and consistent synchronization with vessel motion at a frequency of 5 Hz.

Attention is given to temporal synchronization. The co-simulation framework maintains a consistent sensor update frequency of 5 Hz, ensuring that the simulated LiDAR measurements remain time-aligned with the real vessel motion throughout the scenario, as illustrated in Fig. 3.

B. Point cloud Generation

The co-simulation framework successfully generates time-synchronized LiDAR point clouds based on real vessel motion and simulated environmental conditions. The resulting point clouds provide a spatially consistent representation of the vessel and surrounding infrastructure, capturing geometry, occlusions, and relative positioning within the lock environment, as illustrated in Fig. 4.

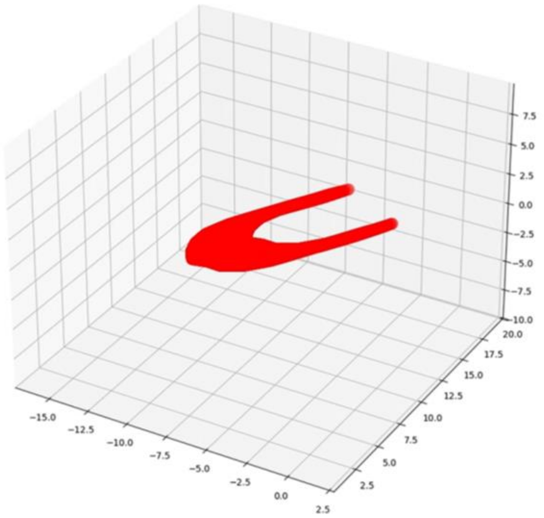

Fig 4.. Generated LiDAR point cloud representing the vessel geometry within the simulated environment, highlighting the realism and spatial consistency of the sensor simulation.

The generated data reflects key characteristics of LiDAR-based perception, including structural outlines of the vessel and proximity to infrastructure elements, thereby enabling realistic downstream processing by assistance systems. This demonstrates that the framework can produce sensor-level data suitable for scenario-based testing.

C. Assistance System Integration

Based on the simulated sensor inputs, the assistance system performs two main functions. First, it visualizes the filtered point cloud of the vessel within the lock environment. Second, it provides distance information relative to both sides of the lock's inner head, representing a safety-critical application in constrained maneuvering scenarios.

Fig 5. Assistance system output visualizing distance measurements between the vessel and lock infrastructure based on simulated LiDAR data, illustrating real-time support for constrained maneuvering.
Chart Source: LGLN OpenGeoData

This demonstrates the full processing chain from real onboard system data, via virtual sensor generation, to assistance-level outputs, as illustrated in Fig. 5. The experiment thus validates the integration of a simulated sensor infrastructure into an SuT assistance system context.

V. Conclusion

This work introduced a sensor-centric co-simulation framework designed to close a critical gap in the V&V of LiDAR-based maritime assistance systems. By enabling modular, transparent, and real-time sensor simulation tightly coupled with maritime traffic and infrastructure models, the approach bridges the divide between industrial bridge systems and simulators isolated virtual sensor models.

The experimental validation using the research vessel *Sally* demonstrated the framework's ability to seamlessly inject virtual sensor data derived from onboard measurements into replay and live co-simulation setups. This capability enables comprehensive SiL and HiL testing—onboard, in laboratory environments, or with virtual agents—while maintaining consistency with real-world conditions.

With the ongoing development of the IMO's Maritime Autonomous Surface Ships (MASS) Code the presented co-simulation framework provides a timely contribution to the emerging regulatory landscape for autonomous maritime systems. By enabling transparent, modular, and reproducible sensor-level testing, the proposed approach directly supports the evidence-based evaluation and risk-informed design practices envisioned by the MASS Code's goal-based framework for ensuring the safe and secure operation of remotely operated and fully autonomous vessels.

Moreover, the applicability of the co-simulation framework to other sensor modalities remains a topic for future research. While this work focuses on LiDAR as a representative high-resolution sensor, it needs to be investigated to what extent the proposed approach can be extended to radar, camera, or other perception systems. This would enable multi-sensor scenario-based V&V and further strengthen the practical relevance of the framework for maritime assistance and autonomous systems.

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