ICRA2026 Late Breaking Results Poster presented at
2026 IEEE International Conference on Robotics and Automation (ICRA 2026)
June 1-5, 2026. Vienna, Austria

Optimal Path Planning for USV-AUV Docking under Various Marine Environmental Conditions

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I. INTRODUCTION

The escalating demand for precision in maritime missions—ranging from resource exploration to tactical surveillance—has pushed the boundaries of autonomous systems. However, as mission profiles grow in complexity, the inherent limitations of single-vehicle deployments, such as finite battery capacity and communication latencies, become significant bottlenecks. To ensure mission persistence and operational flexibility, research has increasingly focused on heterogeneous multi-robot systems. In particular, the collaborative deployment of Autonomous Surface Vehicles (ASVs) and Autonomous Underwater Vehicles (AUVs) offers a synergistic solution; the ASV acts as a high-bandwidth communication relay and mobile recharging station, while the AUV performs high-resolution subsea mapping and monitoring [1].

Autonomous docking is the linchpin of this collaborative framework, allowing the AUV to use the ASV as a hub for data offloading and energy replenishment, thereby linking subsea operations with surface mission management. However, achieving reliable docking in the open ocean is notoriously difficult. A critical technical hurdle arises from the fact that both ASVs and AUVs are typically *underactuated systems*, possessing fewer independent control inputs than available degrees of freedom. This inherent underactuation makes the platforms highly susceptible to environmental loads; disturbances from currents and wind can lead to significant degradation in trajectory-tracking performance or involuntary heading shifts, ultimately compromising docking success.

Consequently, a strategy that explicitly accounts for the resultant force of these external disturbances is vital for generating feasible docking paths and control laws. In this paper, we address the complexities of docking underactuated heterogeneous maritime platforms by introducing a specialized simulation environment. Our framework evaluates docking success rates in real-time by analyzing measured wind and current vectors, allowing for the dynamic generation of optimal docking headings and trajectories. The proposed system was not only refined within a high-fidelity simulator but also validated through field trials in actual sea environments, demonstrating its robustness in real-world maritime conditions.

*This work was supported by KRISO under the major project "Development of HILS Core Technology for Hybrid Power Design of Underwater Unmanned Vehicles (PES5940)" and by the NRF of Korea, funded by MSIT, through the Unmanned Vehicle Advanced Core Technology Research and Development Program for "Development of Mission and Operation Technology for an Unmanned Surface Vehicle–Autonomous Underwater Vehicle Integrated System (PNS5780)" (No. 2020M3C1C1A02086303).

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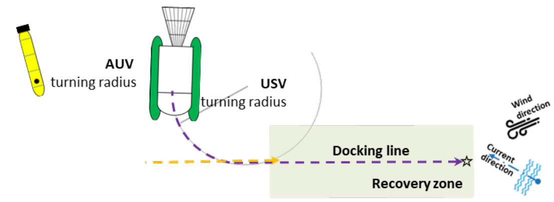
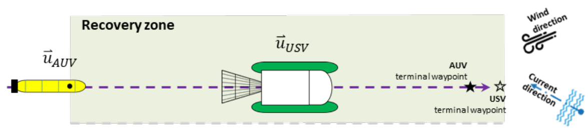
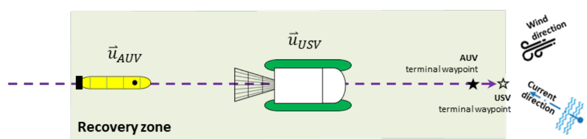


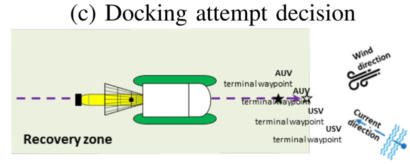
(a) Recovery environment assessment



(b) Guidance to the feasible recovery region



(c) Docking attempt decision



(d) Docking

Fig. 1: USV-AUV Docking Scheme.

II. SIMULATION FRAMEWORK

To evaluate collaborative maneuvers between heterogeneous platforms under realistic sea states, we developed a simulation environment utilizing a MATLAB-based Graphical User Interface (GUI). This framework encapsulates the dynamic properties of both the ASV and AUV by leveraging the 6-DOF equations of motion [2]. The architecture is specifically designed to isolate and integrate the complex effects of the marine environment, enabling high-fidelity emulation of vehicle performance across diverse maritime conditions.

A defining feature of this simulator is its ability to parameterize environmental disturbances as initial conditions. External forces such as currents, wind, and waves are initially defined within a global reference frame. The system then performs a coordinate transformation from the inertial frame to the vehicle's body-fixed frame to calculate the relative velocities. These calculated velocities are subsequently converted into equivalent hydrodynamic forces and moments, which are integrated as external force terms into the 6-DOF equations of motion. This systematic approach ensures that the platform captures the real-time dynamic responses of unmanned vehicles to stochastic environmental loads with high precision, providing a robust foundation for analyzing docking success rates.

III. Performance Analysis and Heading Optimization

We evaluated docking robustness by integrating stochastic marine disturbances into 6-DOF dynamic models. Our analysis reveals that current alignment is a primary determinant of success; while head and tail currents maintain positional stability, lateral currents exert significant transverse hydrodynamic forces that degrade trajectory tracking. Wind impact exhibits a distinct disparity between platforms: the submerged AUV remains largely immune to windage, whereas the USV suffers from lateral drift under crosswinds, necessitating precise heading compensation to avoid orientation misalignment.

To quantify these multi-variable interactions, we employed a scoring framework incorporating the Continuous Ranked Probability Score (CRPS) and time-weighted success rates. This metric allowed us to identify optimal docking headings (e.g., 90° and 180°) where environmental forces are either minimized or exhibit a "force-offsetting" effect. Specifically, when wind and current act from opposing lateral directions, their resultant forces partially cancel out, stabilizing the USV's maneuvering envelope and ensuring a more reliable docking sequence than in additive disturbance scenarios.

IV. Docking Path Generation via Vehicle Characteristics

Effective docking paths must transcend geometric simplicity to remain kinematically feasible. Neglecting non-holonomic properties often triggers "limit cycle" instabilities or missed waypoints during the final approach. To ensure physical consistency, we integrated minimum turning radii—15m for the USV and 20m for the AUV—into the trajectory planning logic. Furthermore, temporal synchronization is maintained via Estimated Time of Arrival (ETA) calculations at each waypoint. This sequencing ensures the USV is "on station" before the AUV initiates its final glide, thereby preventing rendezvous failures.

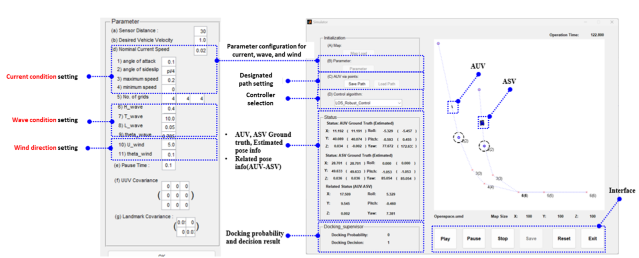


Fig. 2: USV-AUV Docking Simulator.

Fig. 3: Experimental Validation in Real Sea Condition.

V. Experimental Validation

The proposed algorithm was implemented in C++ within the ROS2 framework. Validation was conducted through two distinct scenarios to evaluate kinematic feasibility and disturbance compensation.

1) Scenario 1: Stationary Docking Validation: To isolate the AUV's kinematic constraints, the USV was kept stationary at a pier. The planner successfully generated approach trajectories that strictly respect the AUV's minimum turning radius. This prevents waypoint overshoot and ensures a smooth, collision-free transition into the docking zone, confirming the algorithm's adherence to non-holonomic vehicle dynamics.

2) Scenario 2: Collaborative Docking under Disturbances: This scenario involved simultaneous USV-AUV operations under stochastic wind and current loads. By applying the CRPS-optimized docking headings, the system demonstrated robust environmental compensation. The results confirm that aligning the docking axis with the calculated optimal direction allows the vehicles to maintain stable relative positioning and precise orientation, even when subjected to complex, time-varying external forces.

VI. Conclusion

This study presented an optimal docking path generation framework by analyzing success rates under various marine disturbances and incorporating vehicle dynamics. By utilizing CRPS-based quantitative scoring, we determined the most robust docking headings, specifically finding that success rates are maximized when wind and current forces partially offset each other. The proposed algorithm, which accounts for the non-holonomic constraints and time synchronization of the USV and AUV, was successfully validated through ROS2-based simulations and stationary experiments. Future work will involve conducting real-world sea trials to evaluate the algorithm's performance in unpredictable environments and refining the simulation models using gathered field data.

References

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