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Scalable full-cycle marine litter remediation in the Mediterranean: Robotic and participatory solutions

SeaClear2.0

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D5.3
Report on tender USV autonomous operation
WP5 — Control Overhaul

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[1] R = Document, report, DEM = demonstrator, OTHER: Software, technical diagram, etc. DMP = Data Management Plan

[2] PU = Public, C-UE/EU-C = EU Confidential under Decision 2015/444, SEN = Sensitive

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Definitions

- **Beneficiary:** A legal entity that is signatory of the EC Grant Agreement no. 101093822.
- **Consortium:** The SeaClear2.0 Consortium, comprising the below-mentioned list of beneficiaries.
- **Consortium Agreement:** Agreement concluded amongst SeaClear2.0 Beneficiaries for the implementation of the Grant Agreement.
- **Grant Agreement:** The agreement signed between the beneficiaries and the EC for the undertaking of the SeaClear 2.0 project (Grant Agreement no. 101093822).

Beneficiaries of the SeaClear2.0 Consortium are referred to herein according to the following abbreviations:

- **TU Delft:** TECHNISCHE UNIVERSITEIT DELFT
- **DUNEA:** REGIONALNA AGENCIJA DUNEA
- **Fraunhofer:** FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV
- **HPA:** HAMBURG PORT AUTHORITY
- **ISOTECH**: ISOTECH LTD
- **MDanchor**: M. DANCHOR LTD
- **Subsea Tech:** SUBSEA TECH SAS
- **TECNOSUB**: TÉCNICAS Y OBRAS SUBACUÁTICAS, SLU
- **TUM**: TECHNISCHE UNIVERSITAET MUENCHEN
- **UNIDU:** SVEUCILISTE U DUBROVNIKU
- **UTC**: UNIVERSITATEA TEHNICA CLUJ-NAPOCA
- **VEO**: VEOLIA PROPRETE
- **VLPF**: VENICE LAGOON PLASTIC FREE

Abbreviations

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Executive summary

This deliverable documents the design, development, and validation of the shuttle tender Uncrewed Surface Vehicle (USV) within the SeaClear2.0 project. The shuttle tender USV is engineered to support the collection, transport, and offloading of underwater litter, working in coordination with other robotic assets such as the SeaCat 2 USV and the Smart Grapple.

The report details the operational modes of the shuttle tender USV, including path following, docking, and station keeping. The software architecture is developed around a custom navigation stack, NJORDIQ navigation stack for USVs (NJORDIQ), integrating perception, navigation, guidance, control, and communication modules, leveraging Robot Operating System 2 (ROS2) framework. The guidance module employs global path planning to ensure safe and efficient navigation, while the perception module enables real-time obstacle detection using advanced Light Detection and Ranging (LiDAR)-based 3D object detection techniques.

A comprehensive simulation environment based on Gazebo and Virtual RobotX was developed to test and validate the USV's behaviour under realistic marine conditions, reducing the need for extensive sea trials. System integration was verified through sea trials in controlled environments, demonstrating reliable USV-USV communication, precise docking maneuvers, and effective litter transboarding operations.

Key results include successful autonomous navigation and docking, robust communication between system components, and effective litter offloading and transportation to shore. The deliverable concludes with considerations for future enhancements, including deeper integration of perception and guidance modules, improved control algorithms, and streamlined coordination with the Smart Grapple system to fully integrate of the shuttle tender USV in the robotic solution and to increase overall autonomy of the SeaClear2.0 system.

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1 Introduction

1.1 SeaClear2.0 project objectives

The SeaClear2.0 project will develop an integrated approach to address the entire cycle of marine litter. The project focuses on reducing marine pollution, specifically from marine litter, in the Mediterranean. This will be achieved by using teams of autonomous, intelligent robots to monitor and collect marine seafloor and surface litter, and through participatory practices to identify site-specific measures for marine litter prevention and reduction. By identifying ways to valorise litter and extend policy-making, SeaClear2.0 will provide innovative solutions for effective marine litter management, further promoting the health of oceans, seas, and water bodies.

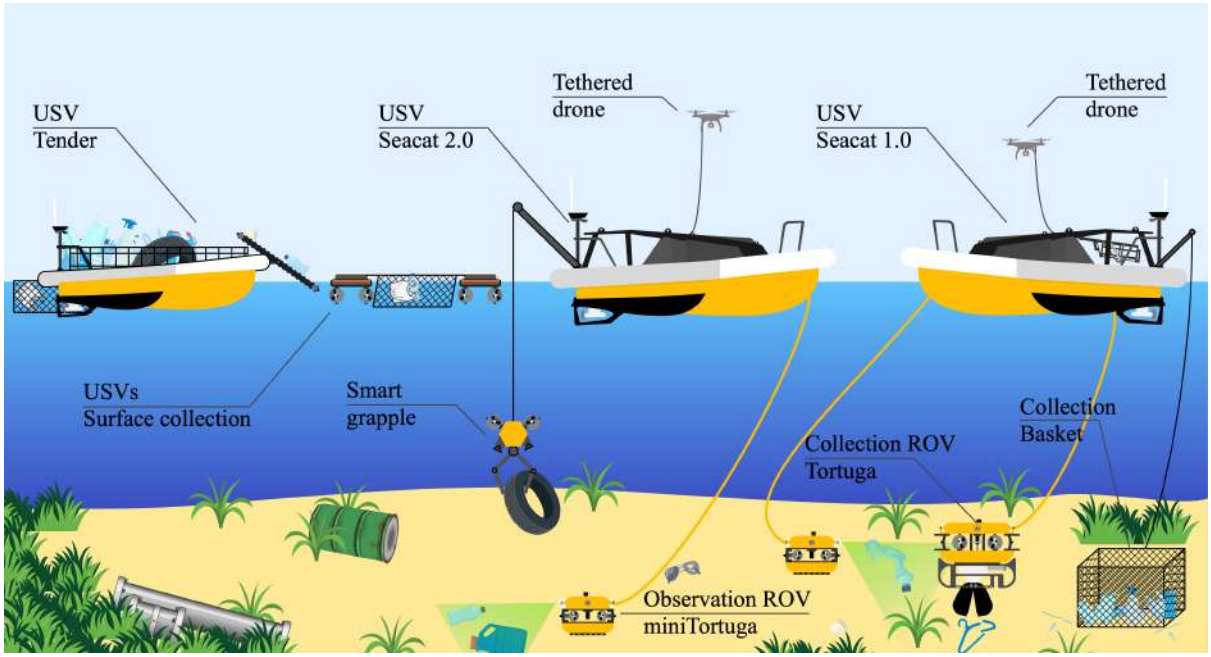


Figure 1: The SeaClear2.0 system concept shown alongside the original SeaClear system. The original system is composed of SeaCat1.0, the Collection ROV and Collection Basket. The Observation ROV and the Tethered drone are used in both systems.

The main objective of this report is to document the describe the software architecture, including the Guidance Navigation and Control (GNC) modules enabling the autonomous docking procedure of the shuttle tender USV, the vessel used within the SeaClear2.0 robotic system to store the collected underwater litter. In addition, the simulation experiments and the actual sea trials are documented.

The goal of SeaClear2.0 is to make a contribution to all of the expected outcomes of the call *"Mediterranean sea basin lighthouse – Prevent and eliminate pollution of our ocean, seas and waters"*. In order to accomplish this objective and demonstrate the benefits of the SeaClear2.0 system, as well as to identify any challenges, a correlation of the project use cases with the qualitative descriptors of the Marine Strategy Framework Directive (MSFD) was synthesized in [1]. This analysis also highlights how Good Environmental Status (GES) can be achieved, along with a direct contribution to MSFD.

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Sea debris poses environmental, economic, health, aesthetic, and cultural threats, with huge degradation consequences for marine and coastal habitats and ecosystems that incur socioeconomic losses in marine-based sectors. It can be observed everywhere in the oceans, with the Mediterranean Sea being drastically impacted because of its specific geographical and oceanographic setting. Debris enter oceans from both land and water sources and can travel long distances before depositing on the shores, surface and seafloor. A clear example of great magnitude of the distances travelled by marine litter is the Great Pacific Garbage Patch [2], which is estimated to accumulate from $1.15\,\mathrm{Mt}$ to $2.41\,\mathrm{Mt}$ of litter entering from the rivers flowing into the PacificOcean, [3]. SeaClear2.0 system will be challenged with various fractions of marine litter and site conditions. The continuous removal of marine debris is a key factor in fighting this enormous environmental problem, where innovative solutions such as the robotic system SeaClear2.0, depicted in Figure 1, play a crucial role in solving the problem and mitigating the consequences of further accumulation of garbage in our seas, specifically at depths that are difficult for human divers to reach.

1.2 Marine litter uncrewed collection phase

The process of collecting underwater litter commences with the deployment of a ROV for the purpose of locating and mapping submerged debris. Subsequently, a submersible grapple is deployed to retrieve the identified litter. Both robots (ROV and grapple) are operated using tether cables. The introduction of an additional basket, akin to the smaller SeaClear1.0 system, presents several concerns. These include increasing the risk for entanglements, limitations on the maximum feasible payload due to vessel constraints and the requisite torques for lifting from the seafloor as well as increased vulnerability of the USV to grounding incidents. Furthermore, using a basket would prolong operation duration as additional trips from the collection area to the shore would be required and increase probability of requiring remapping efforts as well as amplifying the total energy consumption throughout the operation. In order to improve efficiency, mitigate risks, and conserve energy, an additional shuttle tender USV is integrated into the original operational configuration. The shuttle tender USV is the in-house developed SeaDragon USV (see Figure 2), which is a $6.5\,\mathrm{m}$ x $2.2\,\mathrm{m}$ catamaran, having $350\,\mathrm{kg}$ payload and capable of developing up to $7\,\mathrm{kn}$ speed. The USV actuation system consists of a twin-azimuth propeller, capable of controlling the lateral drifts (on sway axis) and developing $6\,\mathrm{kW}$ power.

The proposed collection phase begins after retrieval of the ROV and generation of the underwater litter map. The latter is a 3D map, having the bathymetric scan of the analyzed area as base, onto which the identified litter objects are added. The underwater litter map serves as operational area for the grapple.

When the Smart Grapple is launched from the SeaCat 2 USV, the shuttle tender USV begins sailing to the former and approaching it, while keeping a safe distance of around $100\,\mathrm{m}$ until the litter element has been retrieved from water. Further on, the shuttle tender USV prepares for docking after the grapple has been retrieved from water and having a collected item within its claws. After the docking procedure is completed, the collected litter is transported into the litter bay, onboard the shuttle tender USV. Depending on whether the payload is reached or not, the shuttle tender USV will sail back to shore for discharging the litter bay, that can be done by manually removing the collected items, either with the litter bay being on the vessel or after it being craned on shore. If this is not the case, then the vessel will be kept at the same safe distance of $100\,\mathrm{m}$, until the next docking procedure begins.

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Figure 2: SeaDragon shuttle tender USV, catamaran used for validating the *Guidance* module

1.3 Deliverable structure

The structure of this deliverable is as follows. Section 2 provides a comprehensive overview of the software architecture for the shuttle tender USV, detailing its operational modes, the guidance, navigation, and control (GNC) stack, and the underlying communication framework. Section 3 outlines the simulation environment and the implementation of the digital twin, which are employed for the verification and validation of the software architecture. Section 4 addresses the system integration and validation processes, with particular emphasis on the USV-USV communication with the other components of the robotic system and the docking procedure setup. Finally, Section 5 presents the results of the sea trials and discusses the performance and further developments of the system.

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2 Software Architecture

2.1 Mode of operation

Given the aforementioned marine litter uncrewed collection phase description, the mode of operation of the shuttle tender USV can be formulated.

Initially, the shuttle tender USV will be kept in an `idle` state until the marine litter phase is being commenced. Then, knowing the position of the SeaCat USV and having a priori information about the surrounding area via nautical chart data, a path will be planned. Depending on the vessel traffic, anchored ships, or other infrastructural elements not available in the nautical chart data, the path will be adapted "on the fly" during navigation. During navigation, the shuttle tender USV will be in the `path following` mode, or state, where the control objective of the autopilot is to steer the USV to converge to the series of waypoints with the final one, being placed next to the SeaCat USV's position. If the latter drifts from the initially recorded position, then the path will be adapted "on the fly", similar to when an unmapped obstacle is encountered.

Upon reaching the destination, the state will change to the `docking` mode, in which the reference points of the stern of the SeaCat 2 USV will be used to define a target pose relative to it, which can be regarded as safe for proceeding to the litter transboarding phase. In that sense existing guides, such as ones depicted in Figure 3, can be used for positioning the shuttle tender USV relative to the SeaCat 2 USV.

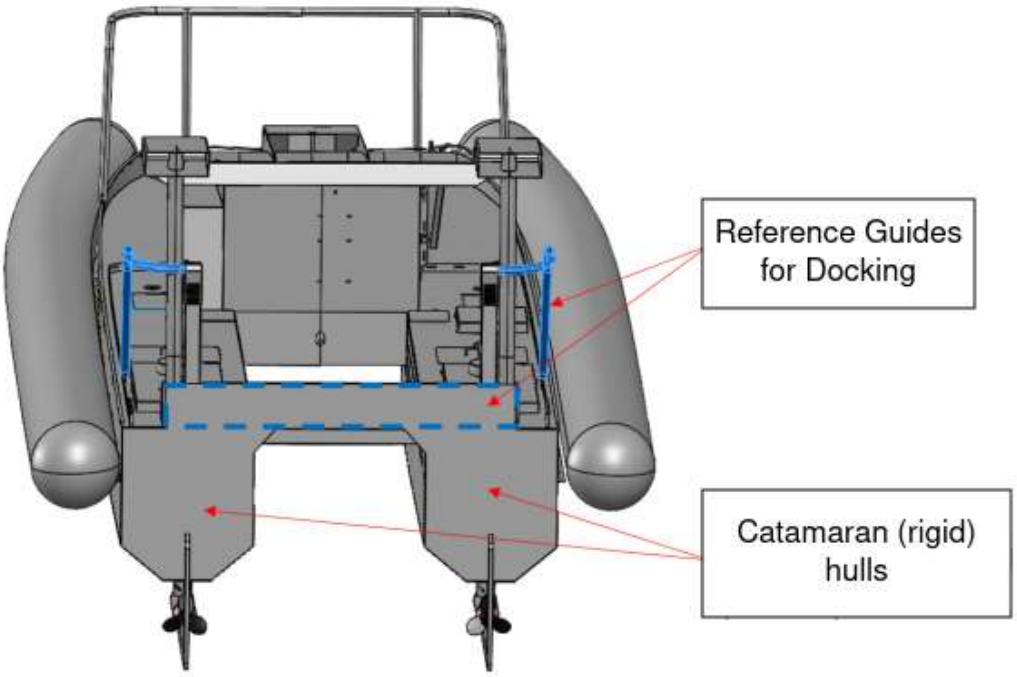


Figure 3: The stern of the SeaCat 2 USV has some reference guides for the stern-to-stern docking of the shuttle tender USV, which allow around $20\,\mathrm{cm}$ lateral tolerance (source SST)

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Shortly after entering the litter transboarding phase, the shuttle tender USV will enter a `station keeping` state, which minimises all drifts from the pose (position and orientation) and gently pushes against the stern of the SeaCat 2 USV. If there is a critical threshold distance relative to the SeaCat USV passed, the shuttle tender USV re-enters the `docking` state and attempts to approach the former again. During the litter transboarding procedure, however, this operation will not be permitted, as the shuttle tender USV needs to ensure a stable pose and avoid adding additional disturbances to the process.

After completing the litter transboarding from the SeaCat USV to the shuttle tender USV, another path will be generated to reach the shore and discharge the litter. The complete set of states and transitions within the shuttle tender USV's mode of operation are depicted in Figure 4.

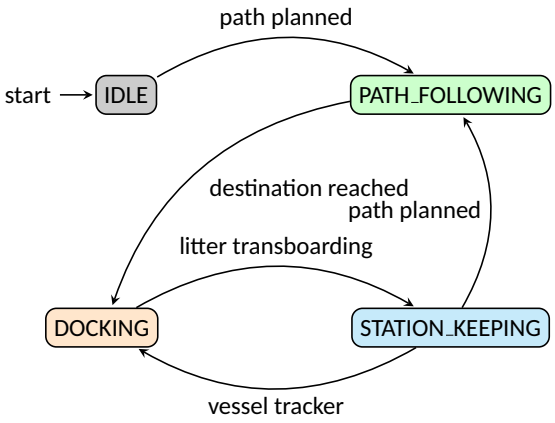


Figure 4: Operational states of the shuttle tender USV

For completeness, after discharging the litter at shore, the shuttle tender USV will plan a path to return to a predefined waiting area, where it will enter the `idle` state again, until being called for another marine litter collection mission.

At the software logic level, the transitions between the different states will be managed by a state machine, which will ensure that the vessel operates in a safe and efficient manner. The state machine will be responsible for monitoring the vessel's status, receiving high-level commands from the operator, and transitioning between states based on predefined conditions.

The state machine logic of the shuttle tender USV is illustrated in Figure 5 and follows the storyline described above. The various states are colour-coded based on their function: grey for idle, green for active navigation, orange for docking procedures, and cyan for station keeping procedures (offloading and dynamic positioning). The reason for adding an *offloading* mode within station keeping state is because the loose coupling between the two USVs must be kept also in case of some drifts of the whole tandem from the rendezvous position. In this mode a constant slight backwards thrust is exerted by the shuttle tender USV against SeaCat 2 USV, while the latter is having the complementary response, but at a slightly lower magnitude and frequency. The transitions between these states are triggered by specific events or conditions, such as the completion of path following, docking, or offloading operations, as well as the detection of new payload readiness or loss of pose publishing from either the home base or target ship.

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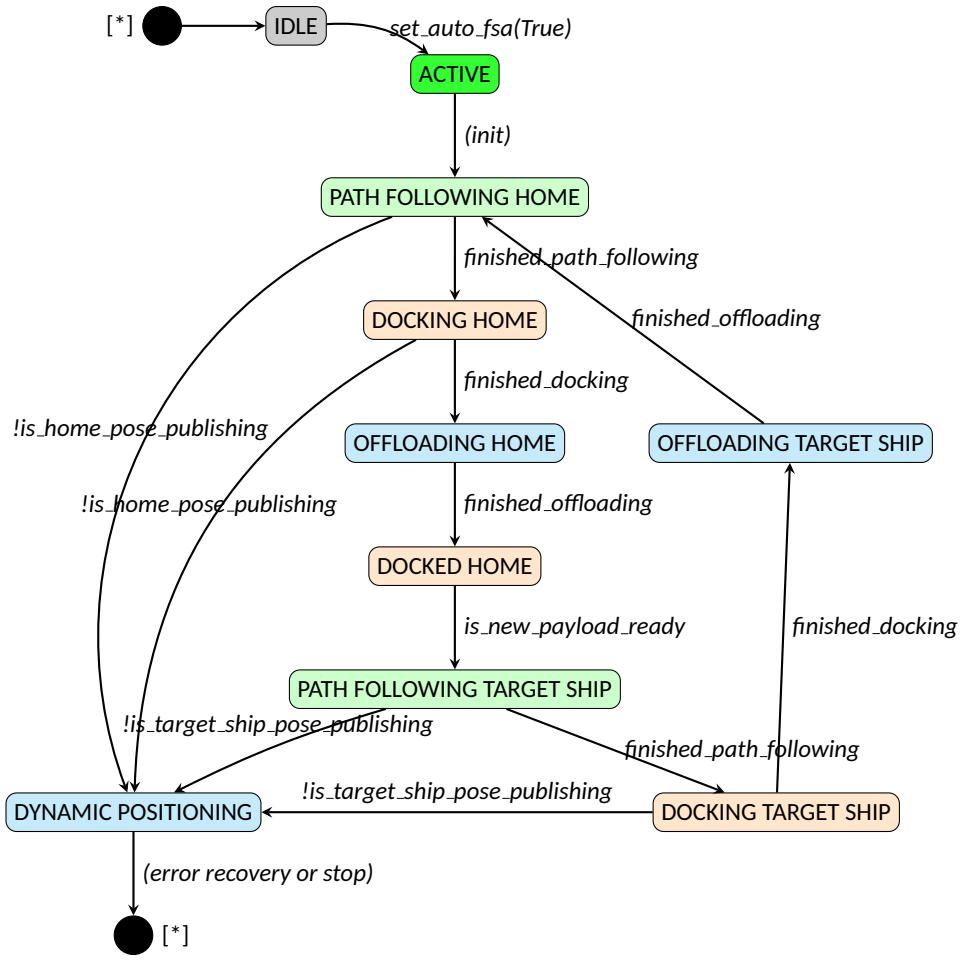


Figure 5: State machine diagram for the shuttle tender USV's mode of operation

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2.2 NJORDIQ navigation stack

The in-house developed NJORDIQ stack, having its main components depicted in Figure 6, is a modular and flexible framework designed to support various USV applications. The navigation stack has been developed to address the autonomous tasks envisioned within the project and beyond it. The navigation stack contains the full GNC architecture for USVs and includes components for perception, navigation, control, and communication, allowing for efficient integration of different sensors and algorithms. The *Navigation* module is responsible for providing the necessary information about the vessel's position, velocity, and pose, which is used by the other two modules.

Within the scope of detecting vessels in the vicinity of the USV's sailing path, a LiDAR-based object detection pipeline using a Point–Voxel Feature Set Abstraction for 3D Object Detection (PV-RCNN) model with raw pointcloud data, has been developed. A deep learning model (PV-RCNN), implemented within the 3D object detection method box, transforms the input data into output predictions, represented by 3D bounding boxes around detected objects within the point clouds. PV-RCNN is a two-stage 3D object detection framework that integrates the advantages from point-based and voxel-based feature learning methods to achieve high accuracy [4]. The full details of the implementation have been published in [5].

The *Control* module is responsible for generating the control commands to the thrusters based on the reference provided by the *Guidance* module. The *Guidance* module is responsible for generating this reference, in form of a vector containing the desired values of the vessel's states, calculated based on the current position of the vessel and the desired path to be followed. Finally, the Human-Machine Interface (HMI) module represents the abstracted interface rendering user input and visualising the navigation data. For current work, Foxglove Studio[1] has been chosen as the main HMI, due to its flexibility in using different plugins and due to it being the preferred visualisation tool for most of the SeaClear2.0 project members.

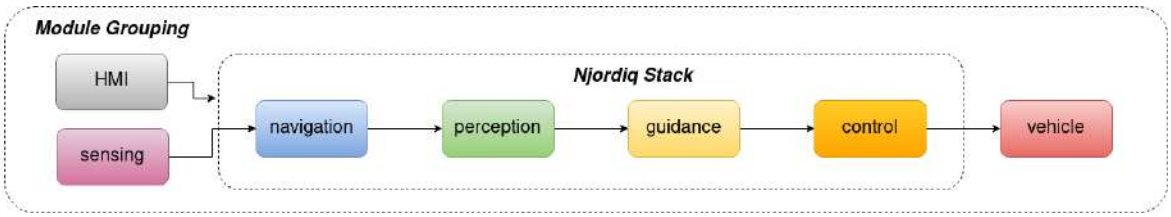


Figure 6: NJORDIQ stack - GNC architecture for USVs

The NJORDIQ stack is implemented using the ROS2 framework, which provides a robust and scalable platform for developing robotic applications. The stack is designed to be modular and flexible, allowing for easy integration of different sensors and algorithms.

2.2.1 Guidance

The primary focus is on the *Guidance* module, which is responsible for parsing the input itinerary (provided as a list of desired locations), generating an optimal path for the vessel to reach these locations in a specific sequence, and dynamically adjusting the active location to be followed based on the ves-

[1] https://foxglove.dev/product

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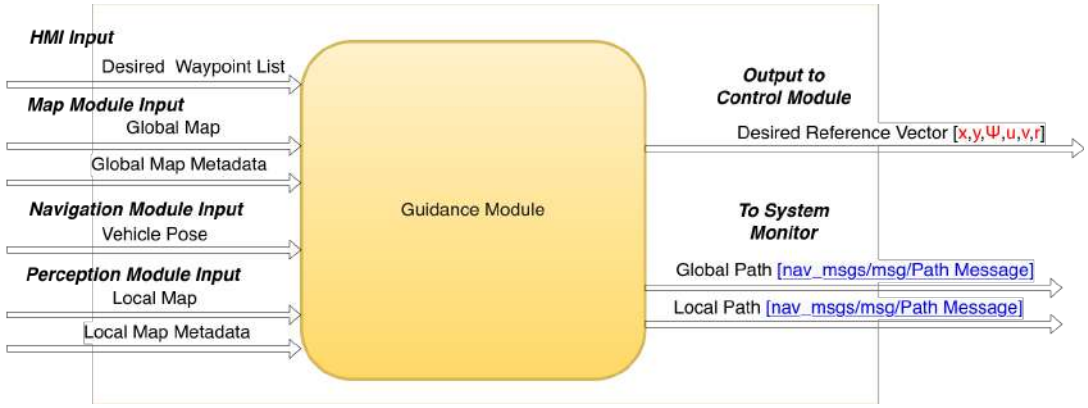


Figure 7: NJORDIQ stack - detailed *Guidance* module

sel's current position. While the onboard controllers are assumed to robustly handle environmental disturbances such as wind and waves, as well as compensate for sensory noise, the effects of these disturbances can be mitigated through effective planning. Proper planning minimises sharp heading changes, reduces sailing time under adverse conditions (e.g., side winds), and the overall time required to reach all objectives. The planning process is conducted at two levels: global and local. Global planning involves generating a path that accounts for a priori knowledge of the environment, such as waterways, piers, and restricted areas. Local planning, on the other hand, addresses dynamic elements such as wind, vessel traffic, and obstacles encountered in real-time. The current work focuses on the global planning aspect, while the local planning will be addressed separately.

The desired state vector $\mathbf{x}_d$ for the vessel is defined as follows:

$$\mathbf{x}_d = \begin{bmatrix} x_d \\ y_d \\ \psi_d \end{bmatrix} \tag{1}$$

where:

- x_d and y_d represent the desired position in the global coordinate frame
- ψ_d is the desired yaw angle (heading) of the vessel

All of them expressed using the North-East-Down (NED) convention, where the x-axis points North, the y-axis points East, and the z-axis points downwards.

In view of the envisioned operation briefly explained in Section 2.1, the USV receives a list of geographical locations, called waypoints, assumed to be the positions of the USVs collecting marine litter. Each location needs to be visited once for transboarding the collected waste into the litter bay, on-board the USV. As depicted in Figure 7,the list of waypoints are the input for the *Guidance* module, which, in turns, provides $\mathbf{x}_d$ output for the controller located in *Control* module.

The path planner is implemented initially by generating an occupancy grid map, where each cell in the occupancy grid has a value representing the cost for navigation through that cell, which range from -1

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to 100, with -1 being unknown cost. The higher the costs of a cell are, the higher probability that on the cell there is an obstacle or land or it in the vicinity of an obstacle or land. Values close to 0 represent a high probability that the cell is not occupied and obstacle free. The reason for not having binary values (such as occupied and free cells) is due to the planning algorithm, which can be tuned to avoid obstacles with a higher buffer zone. The map grid size was set at $1\,\mathrm{m}$, meaning that each cell of the occupancy grid map represented a $1 - by - 1\,\mathrm{m}$ space, which would have a non-zero value even if it was partially occupied by an obstacle. The obstacles referred to in this work are static (e.g landmass, piers, tonnes, mooring posts etc.) and are computed using sea chart information, [6]

This information will be fed to a global path planner consisting of Genetic Algorithm (GA) and A-star algorithm to find the optimal sequence of waypoints to be visited, as well as the shortest path between each waypoint. The first selects the optimal order of waypoints, while the second discretises and plans the route between each two waypoints. The global path planner aids the USV to avoid collision with static pre-known obstacles.The multi-waypoint problem is formulated as a Travelling Sales man Problem (TSP), in which the USV starts its itinerary from a depot point and needs to visit multiple waypoints, each being considered a chromosone by the GA algorithm. The fitness function of each chromosome is estimated cost function between each two pair of points is summed through the chromosome to provide the final fitness value for each chromosome as described by the following equation 2.

$$C^j_{fitnessvalue} = \sum_{0}^{k=C^j_{length+1}} A - star_{f(n))}(C^j_k, C^j_{k+1}) \tag{2}$$

where, C^j_k denotes the chromosome of the j^{th} order and the k^{th} gene in the population. $f_{(n)}$ is the A-star estimated cost function. For the current implementation, the elitism, crossover and mutation parameters are $10\,\%$, $80\,\%$ and $10\,\%$, besides 10 populations and 8 generations. The complete implementation of the GA algorithm has been published in [6].

For the envisioned operation, the path planner will be used twice: first, to plan the path from the home location to the target USV position for litter transboarding, and second, to plan the path from the target USV position back to the home location for litter offloading. The path planner maps the waypoints onto the occupancy grid map and computes an array of intermediary poses, each having a valid waypoint equivalent on the map. The array of intermediate poses generated by the path planner will be used by the *Guidance* module to compute the desired state vector $\mathbf{x}_d$ for the controller in the *Control* module.

In order to avoid unnecessary revisits of some intermediary poses, in the case that the vessel drifts from the planned path, a look-ahead distance is implemented. As depicted in Figure 8, this look-ahead distance defines a circular area around the vessel's current position, and only the intermediary poses outside this area are considered for computing the desired state vector $\mathbf{x}_d$, the others being discarded. In addition, the current path is constantly recomputed every $2\,\mathrm{s}$, in order to avoid forceful rejoining of the initial path, but rather adapt to the new conditions. Because the new path is using the same occupancy grid map, the newly generated poses will also be located in obstacle-free location. This approach ensures that the target poses are always ahead of the vessel and, in the edge case, when the vessel drifts significantly from the planned path, it can rejoin the path at the closest point ahead of its current position that will not require backtracking and that will guide the vessel towards its final target location and keep the track collision-free.

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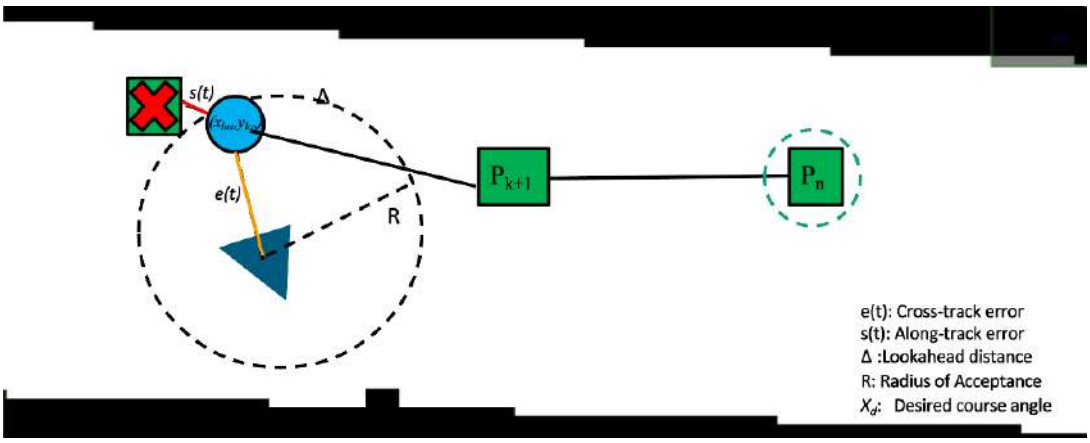


Figure 8: Caption

2.2.2 Navigation

The `Navigator` node is responsible for real-time navigation and localization of the USV. It integrates data from onboard Inertial Navigation Systems (INS), Doppler Velocity Logger (DVL) and dual-Global Navigation and Satellite System (GNSS) sensors and transforms positions between coordinate frames (East-North-Up (ENU), NED, geodetic), and publishes navigation states for the other modules. The module provides services for resetting the home position. The node outputs navigation messages such as odometry, home position, and course over ground, ensuring accurate and robust state estimation for autonomous guidance and control.

2.2.3 Perception

The perception module within the NJORDIQ stack is responsible for detecting and localizing both static and dynamic obstacles in the vicinity of the USV, as well as predicting their future positions. Its output consists of detected objects with associated positions, velocities, and predicted trajectories, which are provided to the guidance module's local path planner for real-time replanning to maintain collision-free operation. The perception module implemented on the USV comprises several components: data acquisition, data processing, and data visualization. The data acquisition component collects sensor data from the environment, while the data processing component applies algorithms for object detection and tracking. Integrating the perception module with the high-level control system, particularly the guidance module, presents several technical challenges. Real-time performance is critical, as the perception module must process LiDAR data, detect objects, and predict both static (e.g., length or beam) and dynamic parameters (e.g., course or velocity) within time constraints that allow the guidance module to replan the USV's path or trajectory effectively. Since most pleasure craft are not required to transmit their position via Automatic Identification System (AIS), ground truth data for validating perception performance is often unavailable. As a result, detection accuracy directly impacts the set of feasible maneuvers. Delayed or inaccurate detections can lead to suboptimal path planning, potentially resulting in conservative actions (e.g., station-keeping until the vessel is no longer in proximity) or even collisions with environmental objects. To address these issues, a predefined close-proximity safety zone around the USV is established, within which any detected objects are treated as higher collision risks,

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prompting conservative maneuvers [5]. Furthermore, the applicability of COLREG [7] rules to uncrewed vehicles remains unresolved. Adopting a conservative strategy, such as always yielding to other vessels, may be advantageous and would significantly influence the maneuvering decisions implemented by the *Guidance* module.

Point cloud-based 3D object detection pipelines start with data acquisition from the LiDAR sensor. The raw points are often transformed from polar to cartesian coordinates. The next pre-processing steps are ground removal and noise filtering to remove outlier points. The following step is data segmentation. The outputs are distinct grouped points to form candidate objects for classification and detection. Finally, objects are detected and recognised. Modern deep learning techniques use neural networks to automatically learn features from point cloud data. This approach improves accuracy and robustness, but they also have a high computational demand and are memory-intensive. Deep learning approaches have been applied to point cloud processing, inspired by image-based detections [8]. The following Figure 9 shows an overview of the pipeline for 3D object detection using a custom dataset. The object detection pipeline's has been used to identify vessels and for offering a pose estimation of the SeaCat USV, redundant to the GNSS-based pose. Both detection pipelines have been only tested offline, further integration being sought until the end of the project.

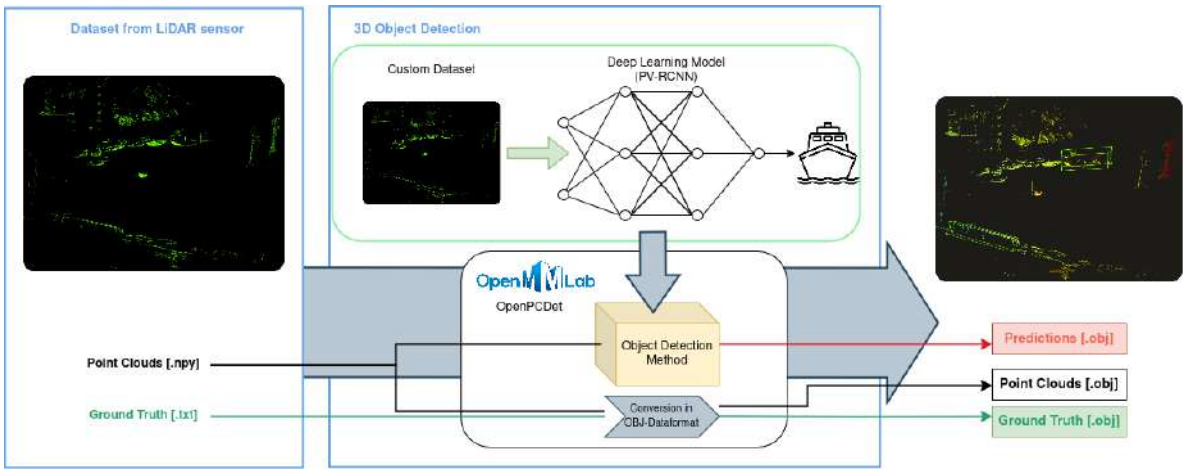


Figure 9: Workflow overview of point cloud-based object detection using custom dataset

2.2.4 Control

The *Control* module is responsible for generating the control commands to the thrusters based on the reference provided by the *Guidance* module. The *Control* module uses a combination of PID controllers and model-based control techniques to ensure that the vessel follows the desired path accurately.

The controllers are split for each phase, each carrying a different set of design objectives. The transition between controllers is done at the same state machine level explained in Section 2.1. The path planning controller is active from the start or depot position, until reaching the docking start pose next, situated $30\,\mathrm{m}$ from to the target USV. The docking controller is active from the docking pose until reaching the final docking position relative to the target USV, while the station keeping controller is active during the litter transboarding phase and when waiting for further information about the goal pose.

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From the start pose to the docking pose, the USV is controlled using a Line-of-Sight (LoS) guidance law combined with a PID controller for surge velocity and yaw rate control. Provided that the information about the landmases and water bodies are detailed enough, the global path planner ensures that there are no obstacles along the path. Uncharted or dynamic obstacles, such as marine traffic or temporary pontoons, are not considered in the planning. The LoS guidance law computes the desired heading angle ψ_d based on the current position of the vessel and the target pose. The desired surge velocity u_d is set to a constant value during path following, while the desired yaw rate r_d is computed based on the difference between the current heading angle ψ and the desired heading angle ψ_d. The PID controllers are then used to compute the control commands for the thrusters based on the errors between the desired and actual surge velocity and yaw rate.

The docking procedure is initiated when the shuttle tender USV is within a predefined threshold distance of $30\,\mathrm{m}$ from the SeaCat 2 USV. During the `docking` phase, the USV is controlled using position controller, which takes into account the vessel's dynamics and orientation constraints. The controller computes the optimal control inputs for the thrusters based on the current state of the vessel and the desired pose. The controller also considers the effects of environmental disturbances caused by the wind and adds a compensation factor on the three degrees of freedom to ensure that the vessel impedes unwanted drifts and keeps its desired orientation. The control law for the docking controller is expressed as follows:

$$
\begin{aligned}
e_x &= x_{\text{curr}} - x_{\text{des}} \\
e_y &= y_{\text{curr}} - y_{\text{des}} \\
e_\psi &= \arctan 2\big(\sin(\psi_{\text{curr}} - \psi_{\text{des}}),\ \cos(\psi_{\text{curr}} - \psi_{\text{des}})\big) \\
u_x &= K_{p,x} e_x + K_{i,x} \int e_x\, dt + K_{d,x} \frac{de_x}{dt} + u_{x,\text{wind}} \\
u_y &= K_{p,y} e_y + K_{i,y} \int e_y\, dt + K_{d,y} \frac{de_y}{dt} + u_{y,\text{wind}} \\
u_\psi &= K_{p,\psi} e_\psi + K_{i,\psi} \int e_\psi\, dt + K_{d,\psi} \frac{de_\psi}{dt}
\end{aligned}
\tag{3}
$$

Legend:

$x_{\text{curr}},\ y_{\text{curr}}$: Current vessel position (NED frame)
$x_{\text{des}},\ y_{\text{des}}$: Desired vessel position (NED frame)
ψ_{curr} : Current vessel heading (radians)
ψ_{des} : Desired vessel heading (radians)
$e_x,\ e_y$: Position errors in surge and sway
e_ψ : Heading (yaw) error (radians, wrapped to $[-\pi, \pi]$)
$u_x,\ u_y$: Commanded surge and sway thrusts
u_ψ : Commanded yaw moment
$K_{p,i},\ K_{i,i},\ K_{d,i}$: PID gains for axis $i \in \{x, y, \psi\}$
$u_{x,\text{wind}},\ u_{y,\text{wind}}$: Wind compensation thrusts (from wind controller)

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The docking orientation will always be 180° relative to the target USV's heading, in order to facilitate the litter transboarding procedure. During the docking procedure, the shuttle tender USV uses its docking controller to align itself with the stern of the SeaCat 2 USV and to compensate for drifts on the sway axis, while slowly approaching the SeaCat 2 USV. Once the error on the surge axis falls below $1\,\mathrm{m}$, the vessel enters `offloading_target_ship` state, where the physical contact to the stern of the SeaCat 2 USV is made, as depicted in Figure 19. At this point, the litter transboarding process can begin.

The dynamic positioning controller is used during the `station keeping` phase, which aims to maintain the vessel's position and orientation within a specified tolerance.

2.2.5 Control allocation

The control allocation logic determines how desired forces and moments are distributed among available actuators onboard the USV. Given desired surge, sway, and yaw forces, it allocates motor setpoint commands, which consist in thrust magnitude and azimuth angle for the shuttle tender USV equipped with twin-azimuth thrusters. The algorithm considers the physical positions of the thrusters, actuator limits, and previous command states to minimize abrupt changes. It uses geometric relationships and, when needed, numerical optimization to solve for thrust and angle combinations that best achieve the requested motion, while respecting hardware constraints and maximizing maneuverability.

The nonlinear optimisation problem can be expressed as follows:

$$
\begin{aligned}
\min_{F_{\text{port}},F_{\text{stbd}},\theta_{\text{port}},\theta_{\text{stbd}}} \quad & w_{\text{angle}} \left[(\theta_{\text{port}} - \theta_{\text{port,prev}})^2 + (\theta_{\text{stbd}} - \theta_{\text{stbd,prev}})^2\right] \\
& + w_{\text{reg}} \left[(F_{\text{port}} - F_{\text{port,prev}})^2 + (F_{\text{stbd}} - F_{\text{stbd,prev}})^2\right] \\
\text{subject to} \quad & \mathbf{A} \begin{bmatrix} \tilde{F}_{\text{port}} \\ \tilde{F}_{\text{stbd}} \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} \\
& F_{\text{port}}, F_{\text{stbd}} \in [-F_{\text{max}}, F_{\text{max}}] \\
& \theta_{\text{port}}, \theta_{\text{stbd}} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]
\end{aligned}
\tag{4}
$$

where:

- F_{port}, F_{stbd}: Forces generated by the port and starboard thrusters
- θ_{port}, θ_{stbd}: Azimuth angles of the port and starboard thrusters
- $F_{\text{port,prev}}$, $F_{\text{stbd,prev}}$: Previous thruster forces
- $\theta_{\text{port,prev}}$, $\theta_{\text{stbd,prev}}$: Previous thruster angles
- w_{angle}: Weighting factor for angle regularization
- w_{reg}: Weighting factor for thrust regularization
- F_x, F_y, M_z: Desired surge, sway, and yaw moment

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- $\mathbf{A}$: Mapping from thruster states to vessel forces/moments
- F_{max}: Maximum allowable thruster force

and the effective forces for each thruster is defined as:

$$\tilde{F}_i = \begin{cases} F_i, & F_i \geq 0 \\ \alpha_i F_i, & F_i < 0 \end{cases} \tag{5}$$

where $i \in \{\text{port}, \text{stbd}\}$ and $0 < \alpha_i < 1$ is the scaling factor for the reduced backwards thrust.

2.3 Communication architecture

The communication protocol underneath the ROS2 modules is Data Distribution Service (DDS) and not the default Simple Discovery Protocol (SDP). While the latter has the great advantage of out-of-the-box functionality, it does not scale efficiently, as the number of exchanged packets highly increases as new nodes are added and requires Multicasting capabilities that may not work reliably in some scenarios, e.g. WiFi. As an alternative, the Discovery Server can be used instead of SDP. The Discovery Server provides a Client-Server Architecture that allows the nodes to connect with each other using an intermediate server. Each node will work as a Client, sharing its info with the Discovery Server and receiving the discovery information from it. This means that the network traffic is highly reduced in big systems, and it does not require Multicasting. These Discovery Servers can be independent, duplicated or connected with each other in order to create redundancy over the network and avoid having a Single-Point-Of-Failure.

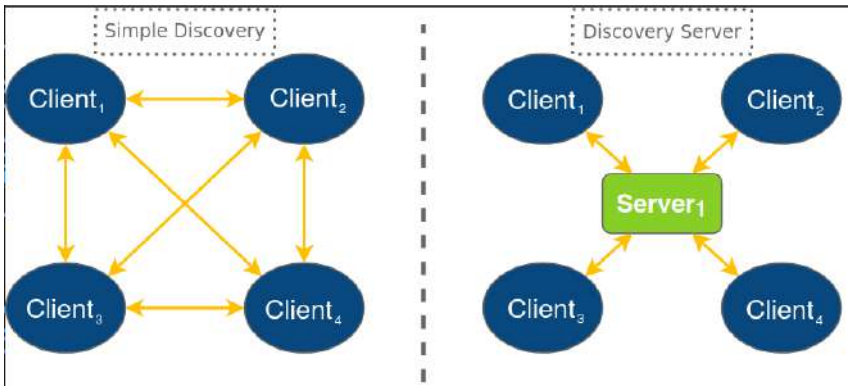


Figure 10: ROS2 communication architecture using DDS Discovery Server (source: eProsima)

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3 Simulation and digital twin

3.1 Simulation environment

The simulation environment for the shuttle tender USV is built using Gazebo, a popular open-source robotics simulator. The simulation environment includes a detailed model of the shuttle tender USV, as well as a realistic representation of the marine environment, including water currents, waves, and obstacles. The simulation environment also includes a virtual representation of the SeaCat 2 USV, which is used for testing the docking and litter transboarding procedures.

To address these requirements, the 'njordiq_gazebo' ROS2 package is substantially based on Virtual RobotX (VRX) [9], a Gazebo-based maritime vessel simulator. While VRX provides the necessary functionality, modifying its codebase presents significant challenges due to its complex structure. Consequently, the 'njordiq_gazebo'' package was redeveloped to incorporate custom vessel models and to integrate as many pre-existing plugins from VRX Simulation as feasible (e.g., hydrodynamics, wave plugins, etc.).

The package is modularly structured, as seen in Figure 11, allowing for the addition of new vessel models and environmental features as needed. The simulation environment is designed to be flexible and extensible, allowing for the testing of different scenarios and configurations.

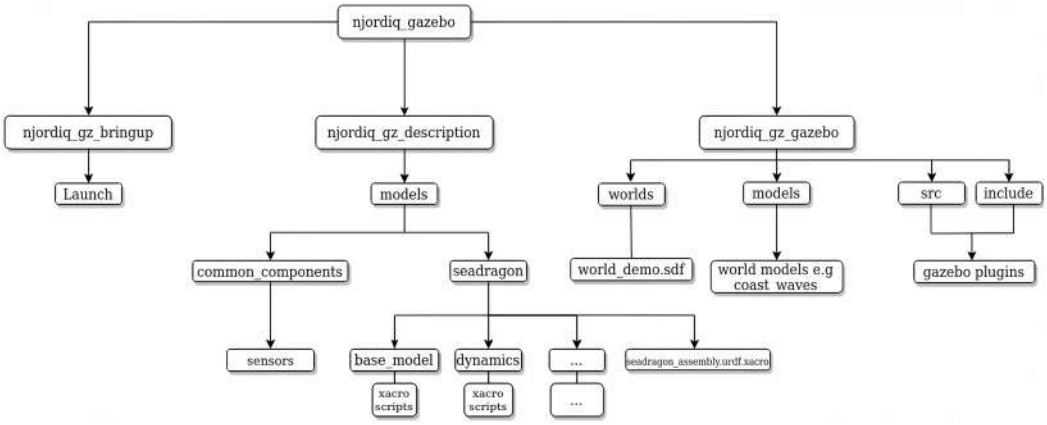


Figure 11: Simulation environment for the shuttle tender USV, including the SeaCat 2 USV for testing docking and litter transboarding procedures

Several scenarios have been developed within the simulation environment to test the various functionalities of the shuttle tender USV. These scenarios can be selected and extended in the interface which prompts the user when starting the simulation. The interface is depicted in Figure 12.

With the mathematical model of the shuttle tender USV being similar to the actual vessel, the simulation environment can replicate the dynamics and behaviour of the vessel in different conditions. The weights of the controllers and the parameters for transitioning to other states could be tuned first time without the need of a physical sea trial, thus reducing the time and risks associated with field testing. Nevertheless, the fine tuning of the weights and parameters, and the software pipeline validation still

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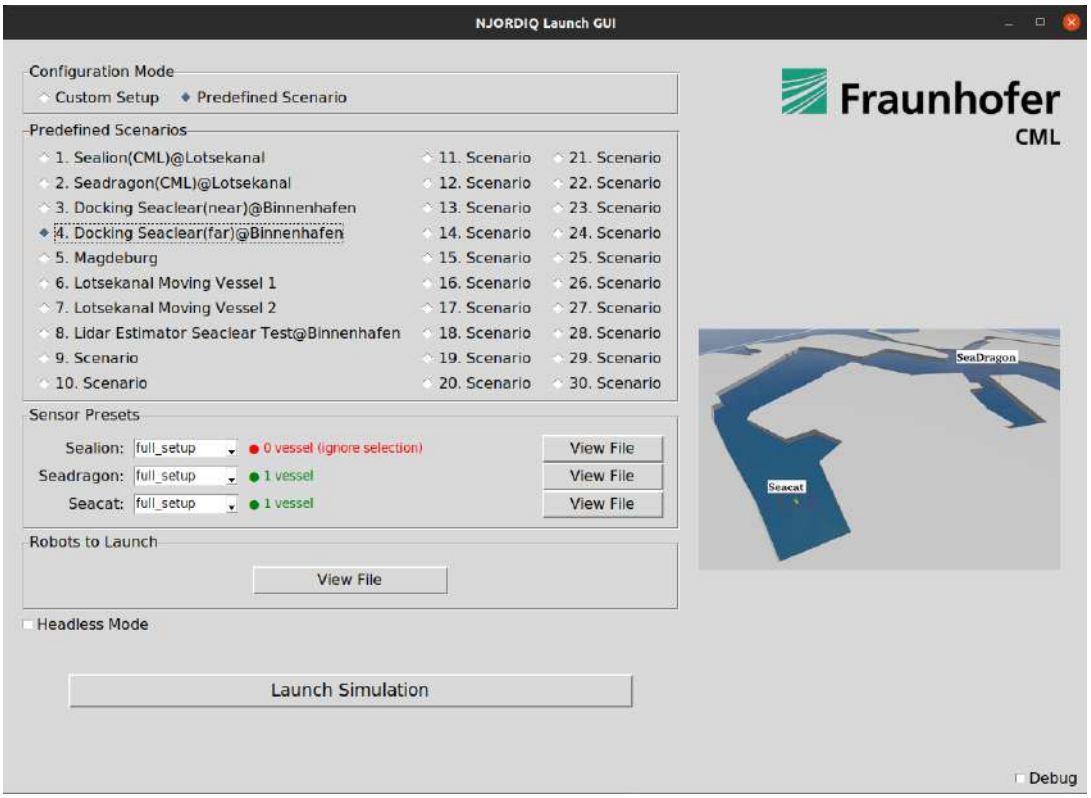


Figure 12: Simulation interface for selecting and extending scenarios for testing the shuttle tender USV

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required sea trials. And even if the visual representation of the vessel is not photorealistic, as it can be seen in Figure 13, these still give enough insight about the operation and for the possible limitations of the system.

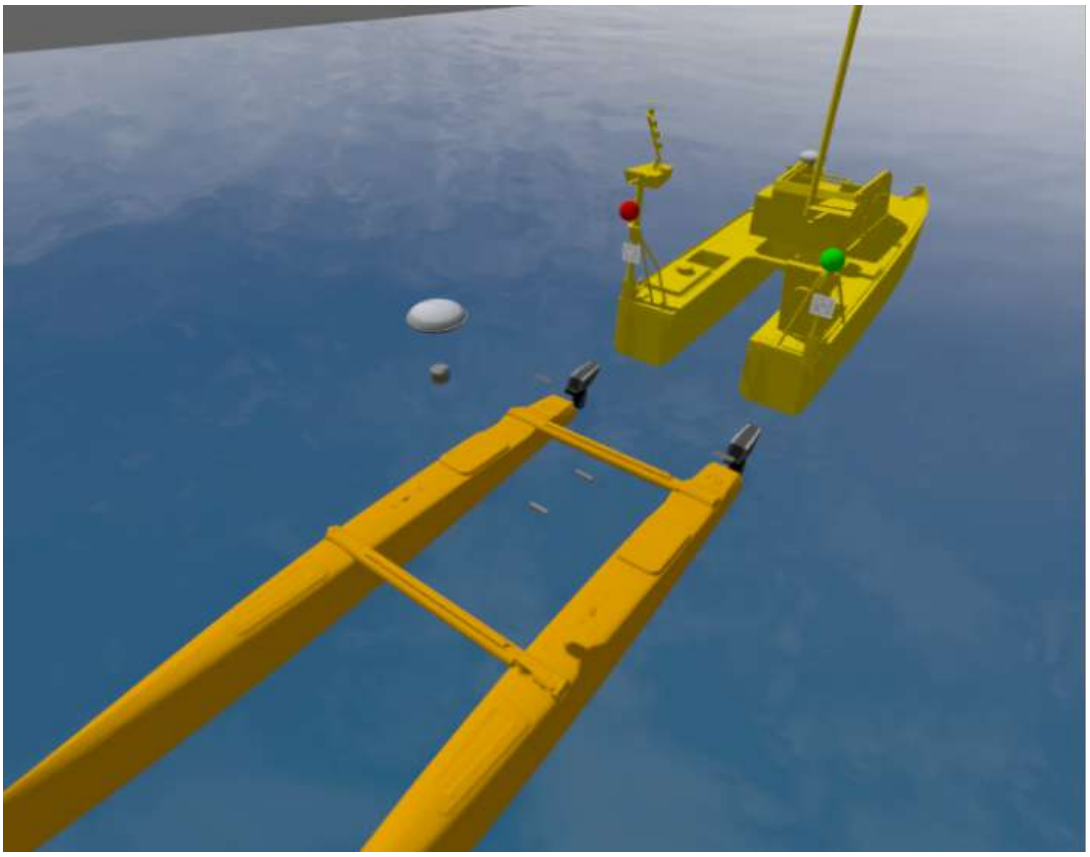


Figure 13: Docking procedure simulation between the shuttle tender USV and the SeaCat 2 USV within the Gazebo environment

3.2 Digital twin implementation

The digital twin of the shuttle tender USV is implemented using a combination of Gazebo and ROS2. The digital twin includes a detailed model of the shuttle tender USV, as well as a virtual representation of the marine environment. The digital twin is used for testing and validating the software architecture, including the guidance, navigation, and control modules, as well as the communication architecture. The digital twin also allows for testing the docking and litter transboarding procedures in a safe and controlled environment. As depicted in Figure 14, the digital twin is packaged within a Docker container, allowing for easy deployment and scalability. The digital twin can be then run alongside the rest of the NJORDIQ stack modules, which, in turns, are packaged within their own Docker containers.

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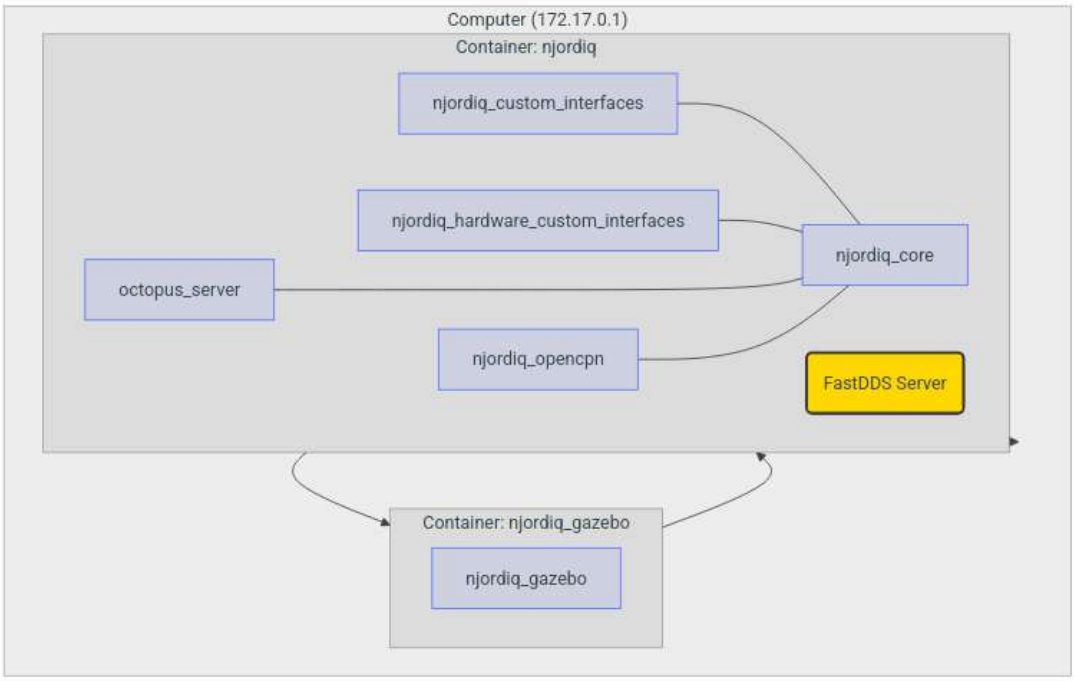


Figure 14: Simulation environment for the shuttle tender USV, including the SeaCat 2 USV for testing docking and litter transboarding procedures

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4 System integration and validation

4.1 USV-USV communication

Pose of SeaCat 2 USV is shared with the shuttle tender USV via a computer that subscribes to both Fast-DDS servers within the same Local Area Network (LAN). SeaCat 2 USV is also equipped with an Real-Time Kinematics (RTK)-enabled dual-GNSS sensory system that provides accurate positioning information, which is then transmitted to the shuttle tender USV. The shuttle tender USV converts the geographical position into a pose and uses this information to plan its path and approach the SeaCat 2 USV for docking and litter transboarding.

The smart Grapple onboard the SeaCat 2 USV is also connected to the same LAN and can share its status with the shuttle tender USV in a similar way as the SeaCat 2 USV shares it position. This allows the shuttle tender USV to know when the Grapple has successfully collected litter and is ready for transboarding.

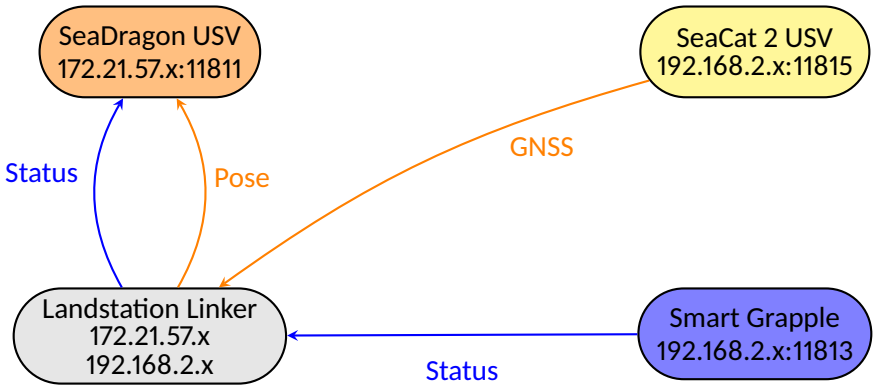


Figure 15: Network architecture: Three FastDDS servers (SeaDragon USV:11811, SeaCat 2 USV:11815, Smart Grapple:11813) linked by Landstation. Landstation reads GNSS and Grapple status, republishes to SeaDragon USV.

4.2 Experiment setup

For validating the shuttle tender USV's software architecture and docking procedure, a series of sea trials needed to be conducted, For the validation procedure to be relevant, it will be repeated multiple times to ensure the reliability and robustness of the shuttle tender USV's operations. The tests will involve the following steps:

- **Pre-test preparations:** Ensure that both USVs are fully operational, with all sensors and communication systems functioning correctly. Calibrate the docking offsets as described in the previous section.
- **Initial approach:** The shuttle tender USV will navigate to a safe distance of $30\,\mathrm{m}$ from the SeaCat 2 USV using the global path planner.

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- **Docking procedure:** The shuttle tender USV will initiate the docking procedure, using the pose information received from the SeaCat 2 USV. The alignment accuracy on the sway axis will be measured to ensure it falls within the specified tolerance.
- **Litter transboarding:** Once docked, the litter transboarding process will be conducted, and the weight of the transboarded litter will be recorded.

For reaching the capacity and volume requirements of the litter bay onboard the shuttle tender USV, a custom litter bay was designed and built, as depicted in Figure 16. The litter bay is made from a fiberglass structure, which is lightweight and durable, and is designed to fit within the available space on the shuttle tender USV. The litter bay has a capacity of $1.5\,\mathrm{m}^3$ and is equipped with a drainage system to allow for the water captured in the litter to be drained out. The maximum payload has not been determined experimentally yet, but it has been tested at $350\,\mathrm{kg}$ with a static load, which is the shuttle tender USV's payload capacity.

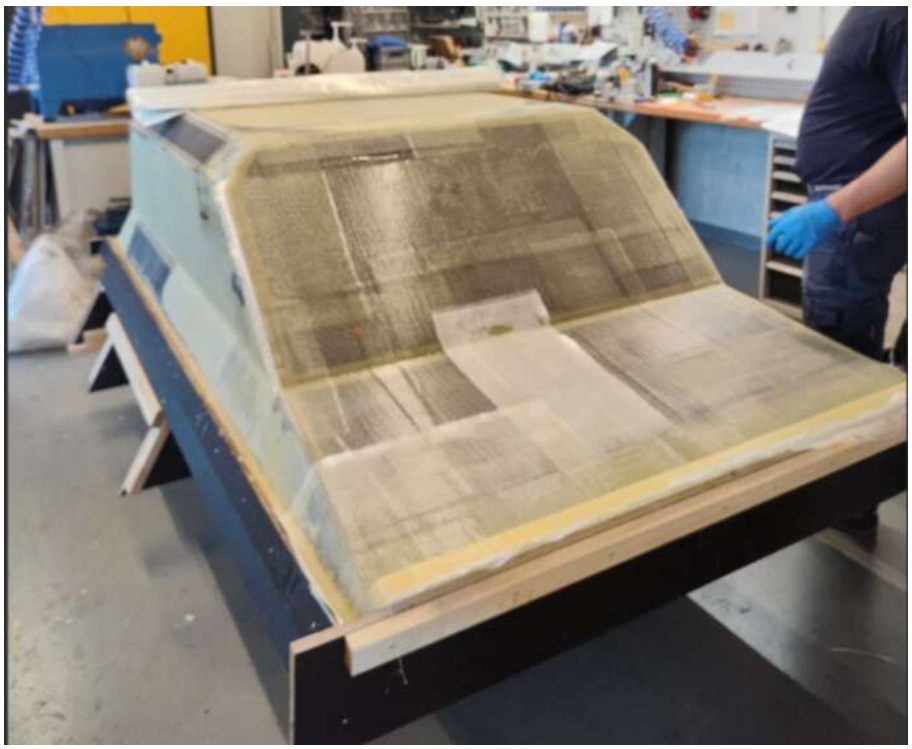


Figure 16: Custom litter bay designed and built for the shuttle tender USV. The litter bay has a capacity of 1.5 cubic meters and is equipped with a drainage system to allow for water drainage

Because the presence of the SeaCat 2 USV is essential for the testing but couldn't be guaranteed at all times, a mock target USV was also designed and built to simulate the presence of the SeaCat 2 USV during the tests. The mock target USV is equipped with a GNSS system to provide positioning information, which is then transmitted to the shuttle tender USV in the same way as the SeaCat 2 USV. The mock target USV, depicted in Figure 17, also has a physical structure that mimics the stern of the SeaCat 2 USV, allowing for realistic docking tests.

Due to its lack of actuation and impossibility to anchor in the test sites, the mock target USV is towed by

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Figure 17: Mock target USV used for simulating the presence of the SeaCat 2 USV during docking tests. The mock target USV is equipped with a GNSS system and has a physical structure that mimics the stern of the SeaCat 2 USV

a crewed vessel during the tests, in this case a Rigid Inflatable Boat (RIB), ensuring it remains stationary during the docking procedure. The RIB tightly binds the mock target USV to one of its inflatables, while it being positioned next to the quay wall, in order mimic the same damping characteristics as the SeaCat 2 USV. The experiments with the mock target USV are depicted in Figure 18. The main difference to the SeaCat 2 USV is the absence of the inflatables, which, on one hand, limits the possibility of side drifting when the vessels are docked, but, on the other hand, allow the sway error to be compensated even in the last centimeters before reaching the final docking position. As the inflatables on the Seacat 2 USV extend around $25\,\mathrm{cm}$ outwards, the sway error needs to be within the tolerance before encountering them.

Prior to the docking procedure between the two USVs, the shuttle tender USV approaches the SeaCat 2 USV to a safe distance of $30\,\mathrm{m}$. From this position, the shuttle tender USV uses the pose information received from the SeaCat 2 USV to plan its final approach for docking. The docking procedure is initiated when the shuttle tender USV is within a predefined threshold distance of $30\,\mathrm{m}$ from the SeaCat 2 USV. The position transmitted by the SeaCat 2 USV is within its centre of gravity, so the shuttle tender USV needs to account for this offset when planning its approach. The offsets are determined using the dimensions of the SeaCat 2 USV, which are known a priori. In addition, the same procedure has to be accounted for the shuttle tender USV pose , as the transmitted position is also within its centre of gravity. For refining the two sets of offsets, an initial calibration procedure is performed with both USVs manually docked together by their operators, measuring the relative distance between their centres of gravity and the physical contact point during docking. As the allowed tolerance for the alignment on the sway axis is very small (in the order of $\pm 0.2\,\mathrm{m}$), the calibration procedure needs to be very accurate. Once the physical contact in between the two inflatables on the stern of the SeaCat 2 USV is made, as depicted in Figure 19, the litter transboarding process can begin.

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Figure 18: Experiments with the mock target USV being towed by a crewed vessel in the Pilot's Channel. The shuttle tender USV approaches the mock target USV for docking tests



Figure 19: Docking procedure for litter transboarding between the SeaCat 2 USV and the shuttle tender USV. The shuttle tender USV approaches the stern of the SeaCat 2 USV and aligns within the two inflatables onboard the latter.

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4.3 Validation sites

The validation of the shuttle tender USV's software architecture and docking procedure has been conducted through a series of sea trials in a controlled marine environment, such as the Pilot's Channel in Hamburg, Germany, depicted in Figure 20.

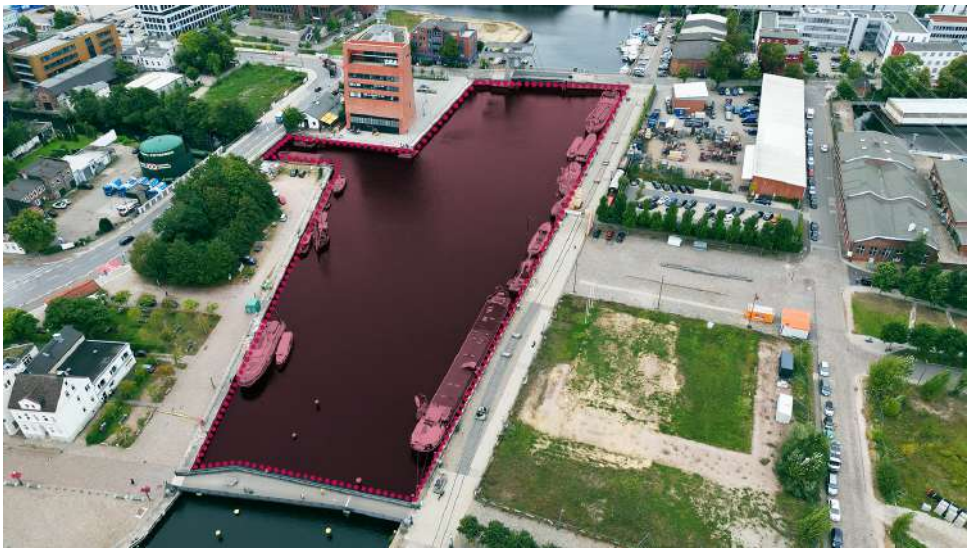


Figure 20: The Lotsekanal (Pilot's Channel), situated in the Port of Hamburg, has been chosen for conducting the sea trials. The designed area, marked with dark-red colour, is approximately $200\,\mathrm{m}$ long and $65\,\mathrm{m}$ wide in its broadest point

In addition, the validation procedure benefited from further testing conducted in May 2025 at the Harburger Werfthafen, part of the Port of Hamburg. This location provided a suitable environment for testing the shuttle tender USV's capabilities in a real-world setting, allowing for the assessment of its performance in terms of navigation, docking, and litter transboarding operations. The Harburger Werfthafen offered a controlled area with minimal traffic, ensuring safety during the trials while still presenting realistic challenges moderate wind conditions, with gusts up to $35\,\mathrm{km}$ during the testing. Prior to the deployment of any of the underwater vehicles of the SeaClear2.0 a bathymetric scan of the test area needs to be completed. This task is completed by the SeaCat USV. Nevertheless, due to validation site's proximity from the Fraunhofer CML headquaters and to the integration of a multibeam echosounder on the shuttle tender USV, done beyond the project's scope, a detailed bathymetric scan of the test site could be completed. As the test site being the first ever where the full SeaClear2.0 system has been tested and due to the challenging visibility conditions within the Elbe river, a bathymetric survey was requested by the project partners. The bathymetric survey conducted with the shuttle tender USV, depicted in Figure 21, revealed a plethora of possible marine litter objects and, thus, saved operation time by knowing a priori the litter hotspot areas.

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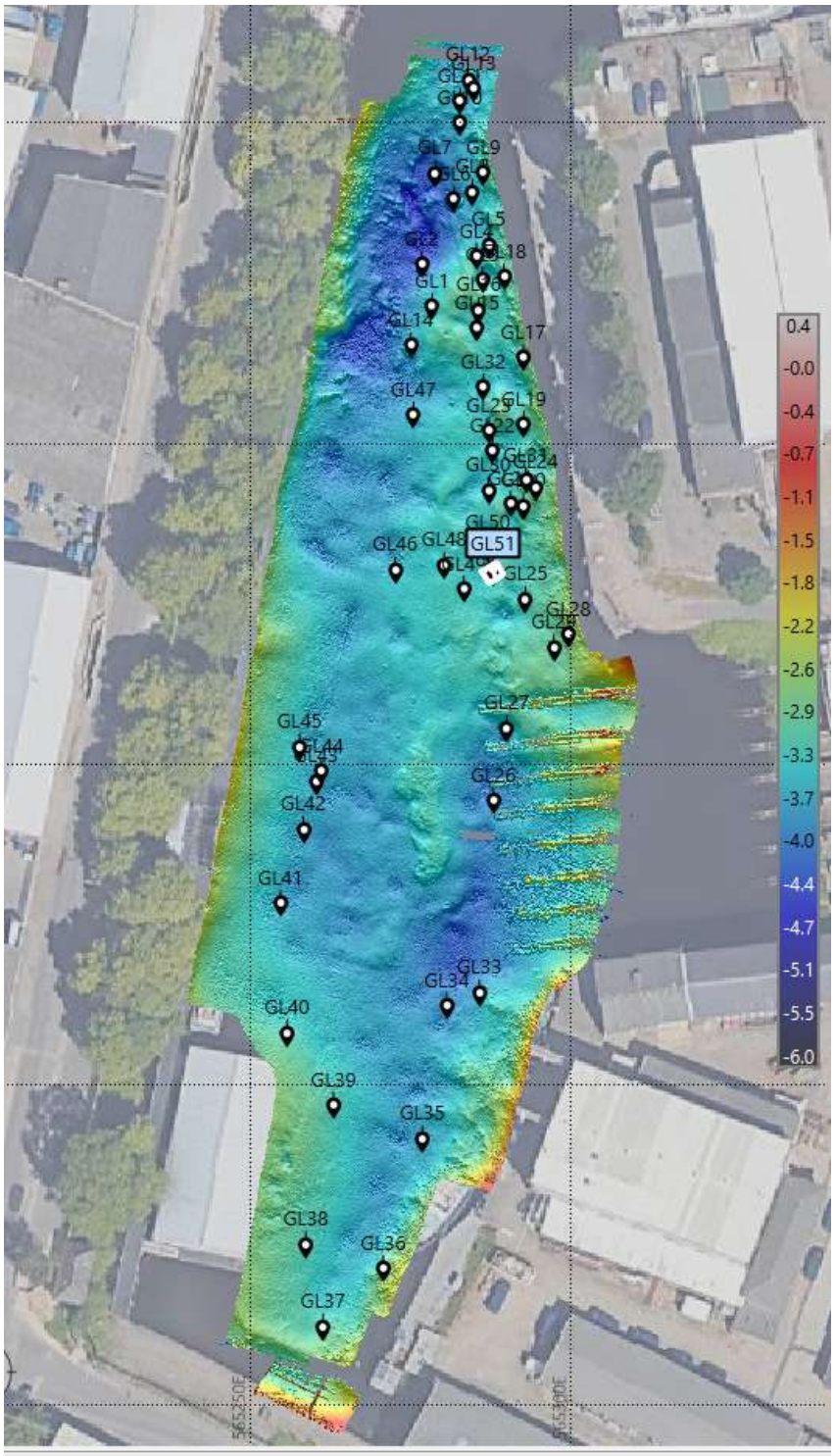


Figure 21: Bathymetric scan of the Harburger Werfthafen, part of the Port of Hamburg, served as an additional validation site for testing the shuttle tender USV's capabilities in a real-world setting

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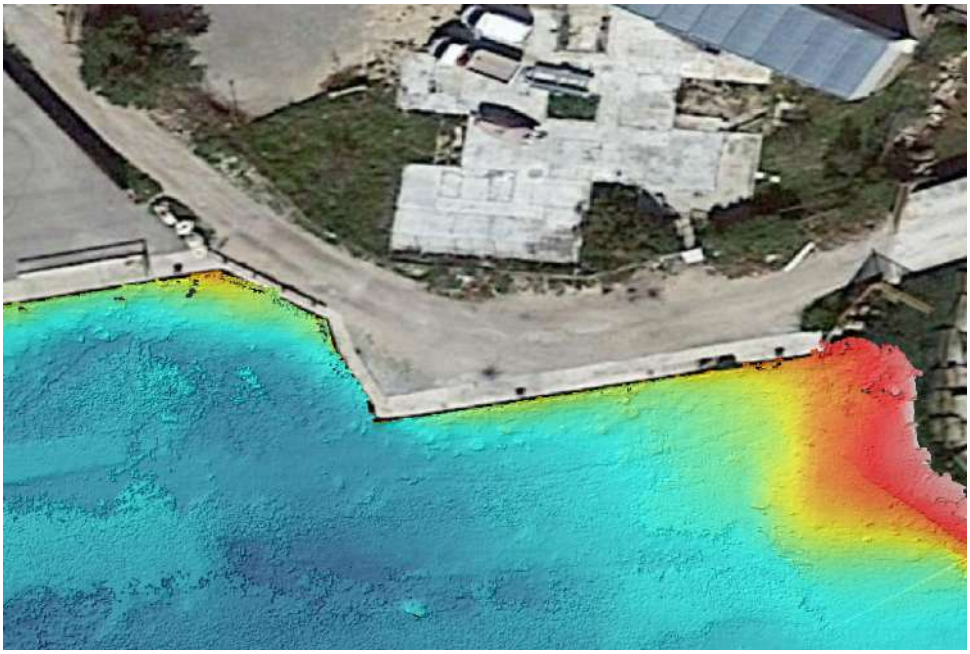


Figure 22: L'Estaque Marina in Marseille, France, provided a challenging environment for testing the shuttle tender USV's performance under varying tidal conditions and vessel traffic

Finally, the shuttle tender USV underwent further sea trials in September 2025 at the L'Estaque Marina in Marseille, France, depicted in Figure 22. This location of the first demonstration site within the SeaClear2.0 project provided a more challenging environment for testing the shuttle tender USV's performance, with varying wind direction and intensity and more vessel traffic. The trials at the L'Estaque Marina allowed for a comprehensive evaluation of the shuttle tender USV's capabilities in terms of navigation, docking, and litter transboarding operations under more demanding conditions.

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5 Results and discussion

5.1 Sea trials results

The sea trials for the shuttle tender USV were conducted in a controlled marine environment to validate the software architecture and docking procedure. The trials involved multiple test runs, each consisting of the steps outlined in the validation procedure. The results are based on the data recorded in both test sites described in Section 4.3. A total of 5 full system runs have been conducted, 2 for the test site in Hamburg, 3 for the one in Marseille. It is important to note that only the full system runs have been quantified, that included all steps from the detection to the litter collection phases. The separate tests that have been conducted before or after the full system runs have not being considered in the statistics. The results of the sea trials are summarised as in the following lines.

Navigation accuracy: The shuttle tender USV successfully navigated to the docking start pose, situated at a distance of $30\,\mathrm{m}$ from the SeaCat 2 USV in 5 full system test runs. The docking procedure was successfully completed in 4 of the 5 full system test runs. The alignment accuracy on the sway axis was within the specified tolerance of $\pm 0.2\,\mathrm{m}$, with an average alignment error of $0.12\,\mathrm{m}$ across the 4 successful dockings.

Vessel tracking: The shuttle tender USV effectively detected traffic vessels around the test sites and tracked the pose of the SeaCat 2 USV using two mounted markers on the stern of the vessel, that can be seen in Figure 23. The pose estimation was accurate only from certain angles of approach, as occlusions could happen from other vessels or objects in the environment. Hence, the pose estimation was based on the GNSS data transmitted from the SeaCat 2 USV, while the LiDAR-based perception module was used for offline obstacle detection.

The quality of the LiDAR-based perception module was satisfactory during the sea trials, as it was able to detect and track nearby vessels effectively. An example of the detected vessels around the shuttle tender USV during the sea trials is shown in Figure 24, where the bounding boxes highlight the detected objects in the LiDAR point cloud data.

The detection models with different datasets and hyperparameters were evaluated on the validation set using KITTI metrics. Key evaluation metrics comprise Recall at various Intersection over Union (IoU) thresholds (0.3, 0.5, 0.7) and 3D detection performance (IoU=0.50/0.70) for bird's-eye view (BEV), 3D object detection (3D), orientation similarity (AOS), and bounding box (bbox) tasks. The separate reporting of performance for the Region-of-Interest (ROI) and (Region-based Convolutional Neural Network (RCNN)) stages provides detailed insights into the contributions of both the feature extraction backbone and the refinement stage. Table 1 presents the Recall values for different IoU thresholds. Further details and analysis of the results can be found in [5].

Litter transboarding weight: All collected litter could be successfully transboarded from the SeaCat 2 USV to the shuttle tender USV. The weights of various objects collected and deposited in the litter bay during sea trials are summarised in Table 2.

Communication reliability: The communication between the two USVs via the Fast-DDS servers was reliable throughout the trials. There were no instances of data loss or significant delays in the transmission of pose and status information.

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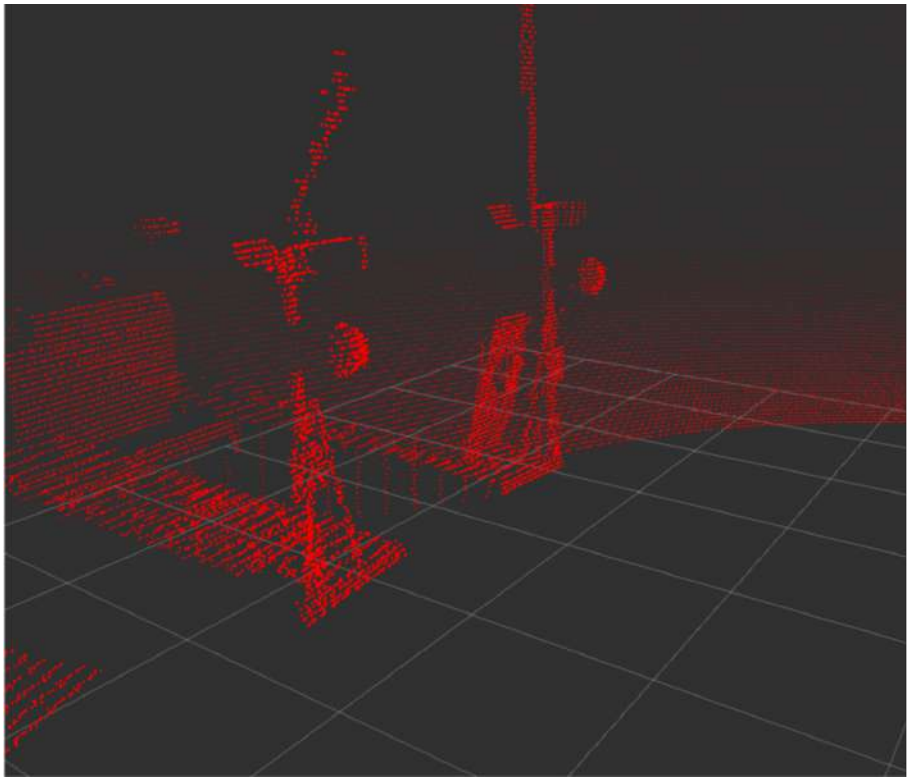


Figure 23: LiDAR point cloud data showing the stern of the SeaCat 2 USV during docking procedure in sea trials

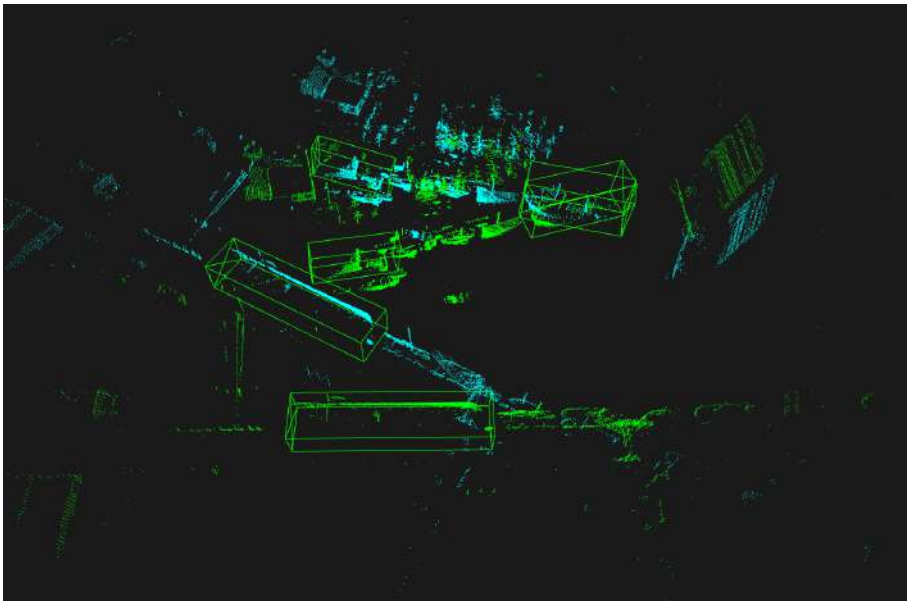


Figure 24: LiDAR point cloud data showing detected vessels (highlighted with bounding boxes) around the shuttle tender USV during sea trials in the Port of Hamburg. It also shows an augmented point cloud frame with z-rotation and used for training.

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Table 1: Recall at thresholds 0.3, 0.5, and 0.7 for ROI and RCNN Stage

Dataset (Epoch)	ROI @ 0.3	ROI @ 0.5	ROI @ 0.7	RCNN @ 0.3	RCNN @ 0.5	RCNN @ 0.7
Base (40)	0.9291	0.9134	0.7165	0.9291	0.8976	0.6929
Base + 10° (40)	0.9863	0.9726	0.8571	0.9863	0.9746	0.9217
Base + 30° (40)	0.9911	0.9788	0.7929	0.9911	0.9833	0.8842
Base (80)	0.9764	0.8976	0.0079	0.9764	0.9685	0.1417
Base + 10° (80)	0.9980	0.9765	0.9022	0.9961	0.9804	0.9374
Base + 30° (80)	1.0000	0.9396	0.0039	1.0000	0.9981	0.1657

Object	**Weight (USV Force Sensor Reading)**	**Dry Weight (Only Object)**
Chair (1)	—	24 kg
Tire	—	6 kg
Car Seat	185 kg (all together)	45 kg
Fences ($\times 2$)	156 kg (everything / force sensor)	14 kg

Table 2: Weights of various objects collected and deposited in the litter bay during sea trials

Overall, the sea trials demonstrated the effectiveness of the shuttle tender USV's software architecture and docking procedure. The results indicate that the USV is capable of autonomously navigating to and docking with the SeaCat 2 USV for litter transboarding operations.

5.2 Limitations

The shuttle tender USV is designed to carry a maximum payload of $350\,\mathrm{kg}$, which includes the weight of the litter collected from the SeaCat 2 USV. The litter bay onboard the shuttle tender USV has a volume capacity of $1.5\,\mathrm{m}^3$, allowing for efficient storage and transport of marine litter. The design of the litter bay takes into account the need for easy access during the transboarding process, as well as the ability to securely contain the litter during transit back to the home location for offloading.

While it was initially planned to have a volume capacity of $6\,\mathrm{m}^3$ for the litter bay onboard the shuttle tender USV, practical considerations during the design and construction phase led to a reduction in this capacity to $1.5\,\mathrm{m}^3$. The primary reason for this adjustment was the need to maintain the overall stability and manoeuvrability of the USV, as a larger litter bay would have significantly increased the vessel's surface exposed to wind, potentially impacting its performance in various sea conditions. Additionally, the maximum height of the Smart Grapple was $\leq 1.5\,\mathrm{m}$, which limited the vertical space available for the litter bay. Nevertheless, the current volume capacity of $1.5\,\mathrm{m}^3$ is deemed sufficient for the intended litter transboarding operations, as the maximum volume not being even closely reached during the sea trials.

As seen in the Table 2, the weights of various objects collected during the sea trials varied significantly, with some objects being relatively light (e.g., a tire weighing $6\,\mathrm{kg}$) and others being considerably heav-

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ier (e.g., a car seat weighing $45\,\mathrm{kg}$). Nevertheless, the total weight of litter collected at once during the trials was well within the maximum payload capacity of the shuttle tender USV. Nevertheless, the maximum payload capacity of $350\,\mathrm{kg}$ has been tested with static loads within the litter bay. Moreover, the shuttle tender USV was sailed with four adults onboard, reaching a total weight of approximately $350\,\mathrm{kg}$, with the main concern not being the freeboard or the resistance of the litter bay, but the increased drag on the litter bay's bottom surface. In order to have sufficient volume, while keeping the height of the contact point between the Smart Grapple and the litter bay as low as possible, the litter bay was designed with a sloped bottom, which has almost $0\,\mathrm{cm}$ clearance from the waterline when the payload is over $150\,\mathrm{kg}$, or even less, when considering swell.

5.3 Conclusions

The development and validation of the shuttle tender USV has demonstrated its capability to autonomously navigate, dock with the SeaCat 2 USV, and transboard collected marine litter. The NJORDIQ software architecture, based on ROS2, has proven effective in managing the various modules required for autonomous operations. The communication architecture utilising Fast-DDS servers has ensured reliable data exchange between the two USVs, facilitating coordinated operations.

The sea trials conducted in controlled marine environments have validated the shuttle tender USV's performance in terms of navigation accuracy, vessel tracking, litter transboarding weight, and communication reliability. The results indicate that the shuttle tender USV is capable of effectively supporting the SeaCat 2 USV in its litter collection missions, with some limitations in payload and volume capacity that have been addressed through design considerations.

5.4 Further developments

Integration of the perception module into the high-level control system, particularly the guidance module, is foreseen as a future enhancement beyond the originally planned scope of this deliverable. This additional development will enable the shuttle tender USV to detect and avoid obstacles in real-time during navigation and docking procedures. By providing the guidance module with information about the positions and trajectories of nearby objects, the perception module will allow for dynamic path replanning to ensure safe operations. Furthermore, further improvements to the control algorithms will be explored to enhance the robustness and responsiveness of the USV under varying environmental conditions.

In addition, the seamless integration with the Smart Grapple system onboard the SeaCat 2 USV will be a key focus area. This integration will enable automated coordination between the two USVs during the litter transboarding process, enhancing operational efficiency and reducing the need for manual intervention. The shuttle tender USV will be able to receive real-time status updates from the Smart Grapple, allowing it to adjust its operations based on the readiness of the Grapple for litter transfer. This will facilitate a more streamlined and effective litter collection process, contributing to the overall mission of marine litter removal.

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