Search, identification and collection of marine litter with autonomous robots

SeaClear

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D6.2

Economy-oriented demonstrator (port cleaning) with assessment.

WP6 –Demonstrations

Grant Agreement no. 871295

Lead beneficiary: name

Date: day/month/year
Type: [DEM]
Dissemination level: [PU]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 871295.

Document information

Grant agreement no.	871295
Acronym:	SeaClear
Full title:	Search, identification and collection of marine litter with autonomous robots
Start date of the project	01/01/2020
Duration of the project	48 months
Deliverable	D6.2: Economy-oriented demonstrator (port cleaning) with assessment
Work package	WP6: [Demonstrations]
Deliverable leader	UNIDU
Delivery date	Contractual: 31.12.2023 Actual: 29.12.2023
Status	Draft ☐ Final x
Type[1]	R ☐ DEM x DEC ☐ OTHER ☐ ETHICS ☐
Dissemination level[2]	PU x CO ☐ CI ☐
Authors (Partner)	[C. Hertel-ten Eikelder] [HPA]
Responsible Author	[C. Hertel-ten Eikelder, claudia.hertel-tenEikelder@hpa.hamburg.de, Tel: +49 40 42847-5708, HPA
Deliverable description	The overall system developed in WP3, WP4 and WP5 is tested in the Hamburg test site.

1 R = Document, report, DEM = demonstrator, DEC = Websites, patents filing, etc. OTHER: Software, technical diagram, etc. ETHICS = Ethics

2 PU=Public, CO=Confidential, only for members of the consortium (including the Commission Services), CI=Classified, as referred to in Commission Decision 2001/844/EC.

Document history

Name	Date	Version	Description
[C. Hertel-ten Eikelder]	18/12/2023	V[0.1]	First draft of demo report
[C. Hertel-ten Eikelder]	29/12/2023	V[1.0]	Final report

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Definitions

- **Beneficiary:** A legal entity that is signatory of the EC Grant Agreement no. 871295.
- **Consortium:** The SeaClear Consortium, comprising the below-mentioned list of beneficiaries.
- **Consortium Agreement:** Agreement concluded amongst SeaClear 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 project (Grant Agreement no. 871295).

Beneficiaries of the SeaClear Consortium are referred to herein according to the following codes:

- **TU Delft:** Delft University of Technology.
- **DUNEA:** Regional Development Agency Dubrovnik-Neretva County - DUNEA.
- **Fraunhofer:** Fraunhofer Center for Maritime Logistics.
- **HPA:** Hamburg Port Authority.
- **Subsea Tech:** Subsea Tech SAS.
- **UTC:** Technical University of Cluj-Napoca.
- **TUM:** Technical University of Munich.
- **UNIDU:** University of Dubrovnik.

Abbreviations

- **EC:** European Commission.
- **GA:** Grant Agreement.
- **ObsROV:** Mini Tortuga
- **ColROV:** Tortuga
- **LARS:** Launch and Recovery System
- **UAV**: Unmanned Aerial Vehicle
- **ROV**: Remotely operated vehicle
- **USV:** Unmanned Surface Vehicle

Executive summary

From 05. – 09. June 2023 the whole SeaClear consortium gathered in Hamburg, Germany for the final system demonstration focusing on the economy-oriented use case in an industrial port environment.

This document summarizes the project partners' accomplishments in hardware and software developments within work packages WP3, WP4, and WP5 towards creating an autonomous robotic system implementing a port cleaning mission.

1. Introduction

During the project duration a large number of trials was conducted to test the SeaClear system as part of the iterative development throughout the course of the project. While some tests focused on individual components and were implemented at the facilities of the respective partners working on it, some required integration of components and deployment in real-time environments. Those preparatory trial campaigns have been organized in Hamburg, Dubrovnik, and Marseille. Further developments and refinements afterwards finalized the design and functionality of the overall SeaClear System which was officially demonstrated in Hamburg in June 2023.

Due to the projects requirement and regulations for the deployment of unmanned systems in the industrial port of Hamburg, potential test locations were assessed within D2.1 Use Case concept. The locations were evaluated regarding suitability in meeting the project partners demands, as well as to the regulatory requirements from the permitting authorities.

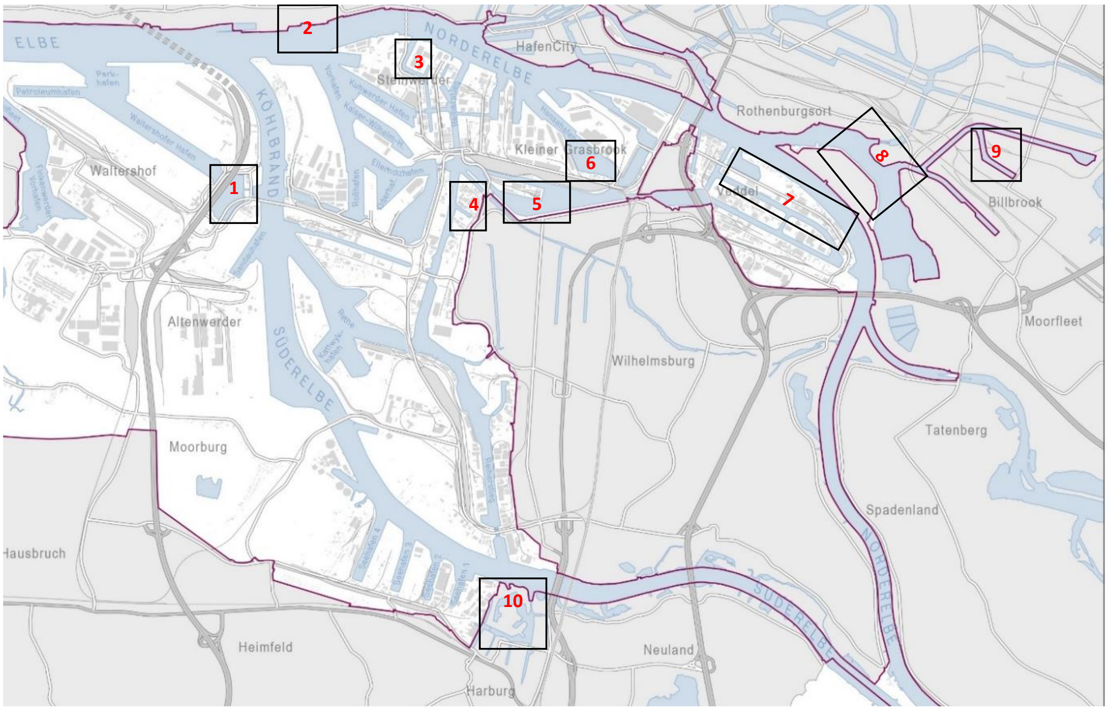

Figure 1: Potential test locations in the port of Hamburg.

Test sites used throughout the project are number 3 - Fährkanal and number 6 - Lübecker Ufer shown in Figure 1. The first trial in April 2021 was conducted at location number 3. All the following campaigns, as well as the final demonstration, were realized at the Lübecker Ufer as the overall facilities highlighted in Figure 2 proved to be better.

Figure 2: Aerial view of the Lübecker Ufer with detailed description.

The Lübecker Ufer area is part of an operational port with restricted access but offering all the amenities needed for the implementation of the SeaClear test demo.

Various workshops for metal and wood works, a canteen, a gas station, office space and parking are available to the project, together with crane lifting capacities for the deployment of materials and waterborne vehicles. Access to the water side is given through a jetty which additionally hosts a small container to set up and store equipment.

Figure 3: Jetty with container office and workshop space.

2. Final Demo

For the final demo a full week from June was scheduled to allow for system set up and preliminary trials before the actual demo day on June 8, 2023, took place. The schedule comprised a total of 3 days dedicated to preliminary tests, with a fourth day entirely devoted to a full system demonstration. The tidal impact changing water levels of up to 3,6 m affected the schedule, shifting the tests in the second half of the week to early in the morning, when sufficient water depth was available.

Table 1: Schedule of the final demo week in Hamburg from June 5-9, 2023.

	Mo 5th June 2023		Tu 6th June 2023		We 7th June 2023		Th 8th June 2023	
07:30 - 08:00 -	Arrival at Hansa Port		Arrival at Hansa Port		Arrival at Hansa Port		Arrival at Hansa Port	
09:00 - 10:00	Stage 1 Testing	- SeaCat craned in water with MBES and SBL attached; - SeaCat path following using Operator App; - MBES map generation; - litter hotspot mapping	Stage 1 Testing	- litter hotspot mapping - obsROV lawnmover using litter hotspot data	Stage 1 Testing	- litter hotspot mapping - obsROV lawnmover using litter hotspot data	Demo for EC	
10:00 - 11:00 11:00 - 12:00 -			Stage 2 Testing	- colROV path planning using underwater litter map - colROV manual grasping - colROV basket approach	Stage 2 Testing	- colROV path planning using underwater litter map - colROV manual grasping - colROV basket approach		
	Lunch		Lunch		Lunch		Lunch	
13:00 - 14:00 14:00 -	Stage 2 Testing	- obsROV lawnmower using litter hotspot data - obsROV underwater litter mapping and refinement - colROV path planning using underwater litter map - colROV manual grasping - colROV basket approach	Stage 1 Testing	- litter hotspot mapping - obsROV lawnmover using litter hotspot data	Stage 1 Testing	- litter hotspot mapping - obsROV lawnmover using litter hotspot data	Public Demo	
15:00 - 16:00 16:00 - 17:00			Stage 2 Testing	- colROV path planning using underwater litter map - colROV manual grasping - colROV basket approach	Stage 2 Testing	- colROV path planning using underwater litter map - colROV manual grasping - colROV basket approach		
17:00 - 18:00 -	Anchoring&Debrief Session		Anchoring&Debrief Session		Anchoring&Debrief Session		Packing Up &Anchoring	
19:00 - 20:00 - NA							Dinner @Altes Mädchen	

High Tide
Low Tide

The stages mentioned in Table 1 comprised a series of tasks which are further described in the following table.

Table 2: Task overview breaking down the technology, project partner involved and linking them to the projects KPIs.

Scenario	Mode	KPIs	Technology	To check/confirm	Status
Stage 1					
Trajectory/path generation for the SeaCat	autonomous	4.2	Path planning in 2D for non-holonomic vehicle (SeaCat)	CML	check the pipeline through CML GUI with hardware-in.the-loop
USV trajectory/path following	autonomous	4.3	Control of non-holonomic vehicle (SeaCat)	SST	check/confirm the performance
MBES map generation	autonomous	1.2		SST	offline
Litter mapping on the MBES data	manual	1.3, 1.4, 3.1, 3.2, 2.1		TUD/UTC	implementing the pipeline for litter tag on the online MBES map
Path planning for obsROV from MBES map	autonomous	4.2	Path planning in 3D for holonomic vehicle with the cable (obsROV)	CML/UTC	check the pipleline with hardware-in.the-loop
obsROV path following	autonomous	4.3	Control of holonomic vehicle (obsROV)	SST	check/confirm the performance
			Pose estimation EKF+SBL/UAV(Tortuga ROV)	UTC/UNIDU/CML	
Stage 2		4.1			
Litter mapping on sonar data	manual/autonomous	1.3, 1.4, 3.1, 3.2		TUD/TUM/UTC	implementing the pipeline for litter tag on the online sonar stream
obsROV map refinement on sonar data	autonomous	2.1	Pose estimation (Tortuga ROV) & Litter detection	UTC/TUD	
Path planning for obsROV return to SeaCat	autonomous		Path planning in 3D for holonomic vehicle with the cable (Tortuga ROV)	CML/UTC	automatic pulling of the tether cable
obsROV return path following to SeaCat	autonomous	4.3	Control of holonomic vehicle (Tortuga ROV)	SST	check/confirm the performance
			Pose estimation EKF+SBL/UAV(Tortuga ROV)	UTC/UNIDU/CML	
Path planning for colROV from obsROV map	autonomous		Path planning in 3D for holonomic vehicle with the cable (Tortuga ROV)	CML/UTC	
colROV path following	autonomous	4.3	Control of holonomic vehicle (Tortuga ROV)	SST	
			Pose estimation EKF+SBL/UAV(Tortuga ROV)	UTC/UNIDU/CML	
colROV station keeping control	autonomous	4.3		TUM	
			Local pose estimation - visual servoing (with litter detection)	TUM	
grasping stage	shared-control	1.5, 5.1, 5.3		TUM	
			Local pose estimation - visual servoing (with litter detection)	TUM	
drop-off stage	shared-control	1.5, 5.1, 5.3		TUM	
			Local pose estimation - visual servoing (with basket detection)	TUM	manual visual servoing

2.1 Litter set up

Since the existence of litter in the demo location was unclear, samples have been placed according to environmental regulations imposed by the authority. In order to fulfil the need of pre-existing litter, suitable for collection with the SeaClear system, a litter concept was developed in close coordination with the site operator and environmental authority.

Figure 4: Litter trays from sheet metal with samples tied to them and placed on the seabed during low tide.

The concept included the spread of a white 10m x 10m tarp on the ground as shown in figure 4 on which litter trays were placed at low tide. A limited number of different litter types was fastened to the trays with small ropes to enable collection attempts with the collection robot during tests while the area was fully under water upon the rising tide. This set up ensured, that no litter would be lost due to tidal movements or currents. For the final demo the ropes on the litter trays were cut and hence, the litter free to be collected by the ROV for demonstration purposes. The process was closely monitored by divers, who would have collected litter in case of loss by the ROV and recovered remaining litter samples after this part of the demo was completed. This proved to be the only solution for providing litter material for the system demonstration under the regulatory circumstances.

Additional preparations included the mounting of all SeaClear vessels and craning them to water, assembling the basket, preparing the drone, setting up the mesh network, test site and workstations on the pontoon.

2.2 Stakeholder involvement

Since there has been a large press conference with TV, Radio, and Print Media during the trials in May 2022, this time around the consortium exclusively invited one TV team for a two-day shoot and otherwise used the demo mainly to involve stakeholders with an industry perspective. Therefore, experts with professional interests from different HPA departments joined.

- **Harbor Master Division**: They are responsible for safe and secure ship traffic in the Port of Hamburg, also granting permission to operate autonomous underwater and surface vehicles. Their aim was to see the robots and SeaCat in operation in the real time environment, which gave them confidence of the functionality of the SeaClear system, but also with the use of autonomous vessels in the Port in general, as they are not regular participants in the ship traffic of the port yet.
- **Environmental department**: They were interested in the SeaClear system from a technical point of view and how it may be adjusted to suit the use cases they are facing in their daily work like taking water and sediment samples. Also, they wanted to find out about the performance of litter detection and collection and the operability in higher current areas, which tend to occur during high and low tide phases.
- **Port strategy**: The department had a general interest in the system, but specifically asked about the fueling, as Hamburg Port aims to become a zero-emission port. Questions regarded the potential use of hydrogen to power the SeaCat and the robots attached and wanted to know, whether solar panels are an alternative energy source to make the system compliant to environmental standards. They also were interested in the systems interaction with marine life like fish.
- **Hydrographic Department**: This department is responsible for bathymetry surveys to determine sufficient water depths for ship traffic in the port. Sometimes the surveys identify obstacles on the seafloor which need further investigation. ROVs may be a valuable supplement to the ships, hence the images and quality from the ROVs as well as the operation were of interest.
- **Human Resources**: This department looked at the SeaClear system from a "Future of Work" point of view. Raising operational safety issues, shortage of skilled workers and the combination of human-machine cooperations were main aspects for their visit.
- **Technical Division – Department Building inspection and Maintenance**: They monitor all the bridges, quay walls and locks within the port area, covering underwater and surface inspections. Their key interest in innovative technology and new approaches lies in facilitating their everyday work. The SeaClear system is a recognized solution, especially as the power supply is secured through the USV will allow for prolonged operations with UAVs. Operating the ROVs for data collection and their ability to potentially reaching narrow, and shallow water areas is equally appealing.
- **Port Authority**: They assume the responsibilities under public law e.g., soin protection, emission control, nature conservation and have a subdivision looking into unexploded ordnance (UXO) and ammunition clearance. SeaClear could offer a huge cost saving solution regarding metal detection and classification as well as removal of harmless objects compared to involving divers to do a proper survey to obtain UXO clearance.
- **Reply Robovers**: Reply is an external industry partner and strategy consulting firm specialized in integration scenarios in the area of robotics, reality capture and mixed reality, where cloud or on-premises infrastructures require enterprise-ready solutions.

Figure 5: Images of the stakeholder involvement. Upper row - explaining the litter app, bottom row introducing the SeaClear system.

In summary, the four-day demonstration of the SeaClear project on developing robots for cleaning marine litter showcased significant progress and achievements. Throughout the demonstration, the assembly and deployment of the full SeaClear robotic system was finalized, various tests were conducted, and key objectives accomplished.

2.3 Lawnmower Approach

SeaCat USV underwent tests involving the lawnmower approach, which refers to a specific control procedure that ensures systematic coverage of an area for effective litter detection. The tests aimed to refine and validate the autonomous control procedure. The scan has been performed using manual control, due to the slow rate of turn of the USV and for the high inertia noted at 90 degrees corners, as depicted in figure 6.

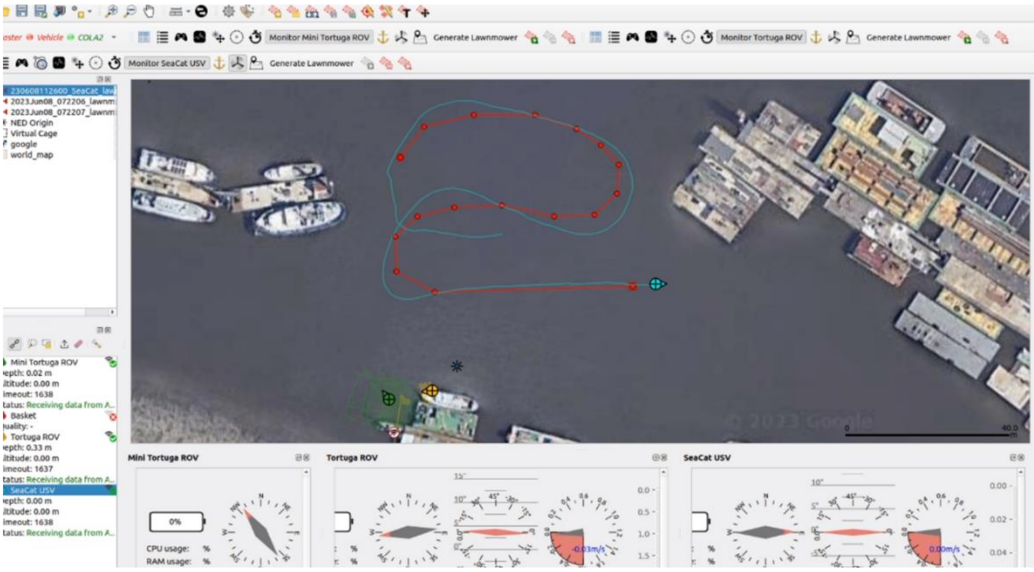

Figure 6: USV lawnmower path (red) and actual (blue) shown in the operator application.

2.4 Mini-Tortuga (obsROV) pose estimation, control, and mapping

The primary objective of the obsROV tests was to evaluate its capabilities in autonomous navigation and underwater mapping tasks. The tests aimed to assess the obsROV's performance in various underwater scenarios and its effectiveness in identifying and collecting marine litter. The osbROV has been deployed from the USV and manoeuvred (first manually, and afterwards in an automatically controlled lawnmower pattern) around the test area. The raw data has been saved and post-processed to obtain the pose estimation. The estimated pose has been compared to the position indicated by the DJI UAV while the ROV was close enough to the surface. In that sense, the position accuracy could be indicated only for the points where the ROV was close to the surface.
For underwater mapping several objects have been placed on the riverbed. The scanning was performed with the BluePrint Oculus M750D imaging sonar, fixed on the skid of the obsROV. Finally, the mapping procedure was conducted by automatically generating a sequence of waypoints in shape of lawnmower.
The procedure allowed the ROV to create a map of the underwater litter while simultaneously determining its own position.

Underwater pose estimation: The osbROV successfully validated its pose estimation capabilities, providing accurate localisation within 1.86m RMSE compared to the drone-based reference position, see Figure 7.

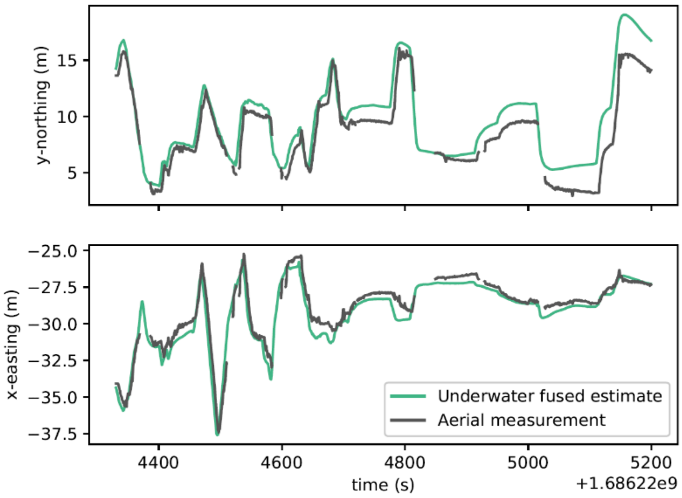

Figure 7: Pose estimation result in Hamburg: evolution over time of the planar positions X and Y. The horizontal axis depicts Unix epoch time in seconds.

Underwater litter mapping

The underwater litter mapping was composed of the bathymetry map, onto which the identified litter was overlaid. The bathymetry map used the global reference system the RTK-enabled GNSS system onboard the SeaCat USV, while the mapped litter made use of the pose estimator described in the previous section together with projections to find the location of the litter in the same coordinates as the bathymetry map. A visual representation of these layers is given in Figure 8.

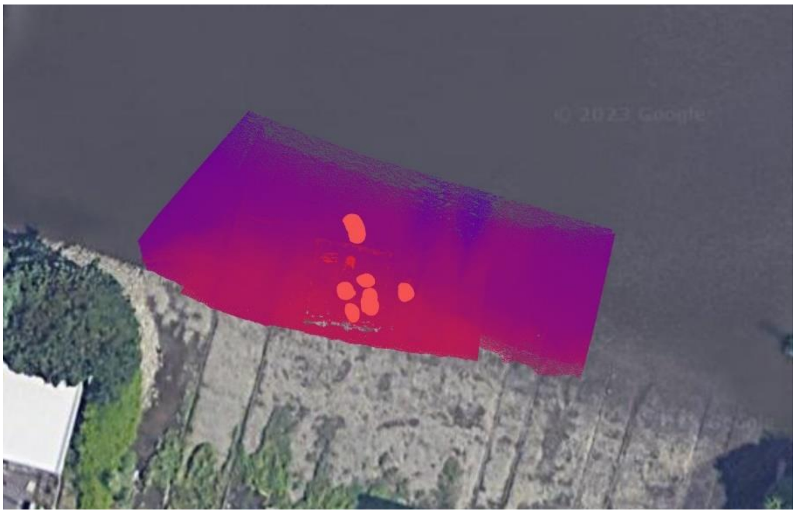

Figure 8: Satellite map (source: Google) overlaid with the bathymetry map and with identified litter elements.

When the global positions were compared with the drone-based positioning system, onboard the UAV, the mapping errors were 0.7m on average, as to be seen in Figure 9 below. The drone-based positioning system refers to the (visually) estimated position of the litter elements in the UAV camera image, which by combining with the current GNSS position of the UAV itself gives a litter position in the same frame as the bathymetry map. This direct visual observation was possible at low tide when the litter elements were in plain sight.

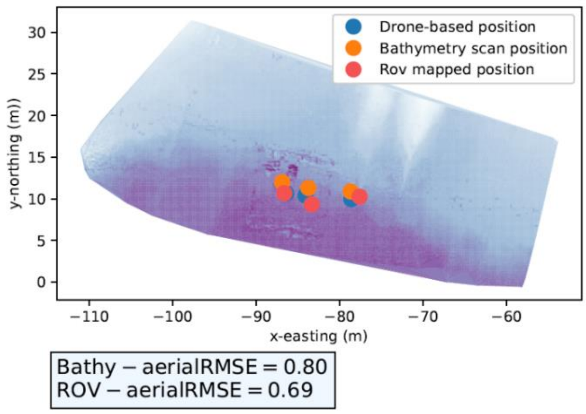

Figure 9: UUV mapped litter positions versus DJI-based ground truth and manually identified litter position in bathymetry scan.

For pose estimation, control, and mapping the following conclusions were drawn:

- **Validation of pose estimator:** The Mini-Tortuga underwent intensive testing to validate its position and orientation estimation capabilities. The procedure allowed the ROV to create a map of the underwater litter while simultaneously determining its own position. These tests involved comparing the obsROV pose estimator performance against a DJI drone and utilising sonar references for accurate localisation. To obtain a reference position to compare against, the obsROV was kept for stretches of time at 0.5 meters below the surface to enable position estimation from a DJI drone.
- **Underwater Mapping:** Additional tests were conducted to assess the accuracy of the pose estimator and the quality of underwater mapping achieved by the obsROV. The ground truth for the litter map was established using the DJI drone.
- **Lawnmower navigation:** The Operator application has been successfully used for generating and sending lawnmower paths to the obsROV and commanding it to each waypoint.
- **Key Findings and Conclusion:**
    - The osbROV successfully validated its pose estimation capabilities, providing accurate localisation within 1.86m RMSE compared to the drone-based reference position.
    - Mapping errors were 0.7m on average.

2.5 Tortuga (colROV) control, grasping and basket approach

The litter grasping and delivery to the collection basket consisted in multiple sub-tasks. Within the basket approach procedure, the USV has been sent to a reference position, where the litter concentration hotspots have been previously determined. The basket has been lowered to the bottom of the riverbed, while the colROV was sequentially launched from the stern launch and recovery system (LARS).

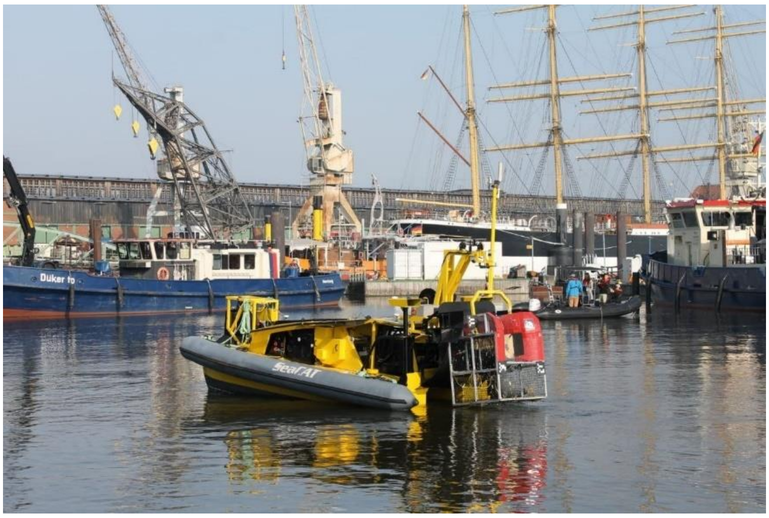

Figure 10: SeaCat approaching the litter hot spots for basket deployment and collection.

The bathymetry map augmented with the litter map has been used as a base for planning the trajectory of the colROV. Given the static obstacles and the desired litter target position, the colROV has been given an automatically generated trajectory and sailed using a path following controller. With the litter target objects being defined in the previous step, the colROV sailed to each of them. For enabling the autonomous navigation, a 3D-trajectory has been generated using the bathymetry data and the recent map refinements augmented by the obsROV. Using the trajectory controller, the colROV sailed to the given local position. The grasping procedure required camera assistance, which given the visibility conditions in the Port of Hamburg and the absence of a sonar pipeline, a manual operation has been favoured. When reaching the desired position, the operator took over and manually adjusted the position of the colROV and commanded the gripper for picking up the litter elements in the metallic trays.

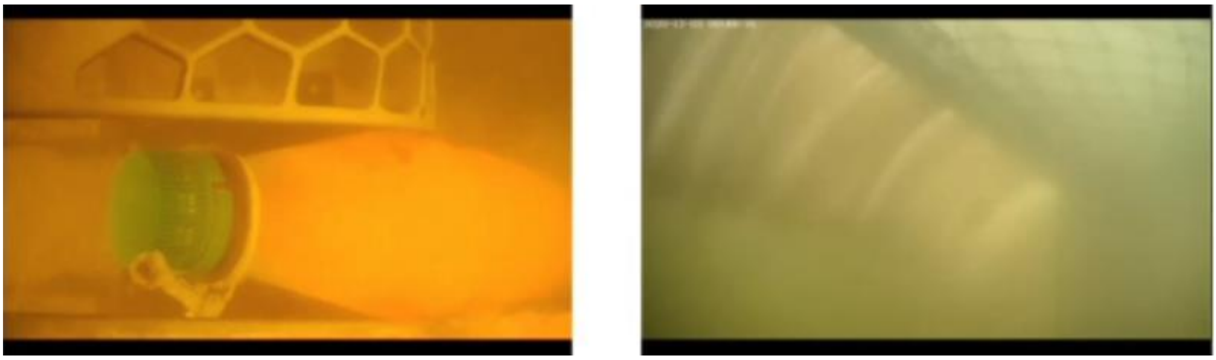

Figure 11: Gripper camera (left) showing the successful grasping of a bottle in Hamburg and entering the basket for drop off (right).

Before launching the colROV, the basket had been lowered to the riverbed and its pose estimator has started broadcasting its position in local and global frames. After grasping the litter element, the colROV has been sent in the proximity of the basket and then manually inserted in the basket's funnel. The colROV has been manually sailed into the basket interface, with the gripper permanently open.
No litter drop test of any litter element has been tested, therefore, the resistance and possible interference of the bristles with the gripper and/or litter element has not been tested. Moreover, due to the low visibility the visual servoing could not be used for the approach. Hence, the manual control was preferred to the last meters. The following conclusions are made:

- **Autonomous Navigation and Grasping:** The colROV was tested for autonomous navigation and grasping tasks. Using the maps previously generated by the obsROV, colROV autonomously navigated to designated targets, selecting optimal paths while avoiding obstacles. The colROV successfully grasped three pieces of litter using a combination of sonar and camera sensors.
- **Basket pose estimator:** the pose estimator of the basket has shown inconsistent estimation in the local frames, when comparing its output with the obsROV's estimation.
- **Basket approach:** the basket has been manually approached by the colROV and successfully entered.

2.6 Summary

Test	Outcome	Problems (needed to be solved)
USV Bathymetry and Control		
USV Bathymetry	Designated test area in Hansa Port and the underwater litter trays have been correctly mapped.	
USV Control	Waypoint control has been successfully tested with the Operator App.	Better pre-planning needed for copping with the high inertia and low rate of turn of the USV.
obsROV pose estimation, control and mapping		
ROV Pose Estimation	Underwater pose estimator validated	
Underwater mapping	Underwater litter trays have been correctly mapped	
obsROV lawnmower control	Pipeline validated using Operator App	Lawn mower tracking performance low due to poor controller response
UAV underwater litter mapping and ground truth support		
ROV-basket approach&collection		
colROV control	Successfully generated trajectory based on the obsROV's octoMap and autonomously sailed to reference point	
colROV grasping	Manually grasped at least 3 types of litter	Autonomous grasping
Basket pose estimation	Position estimation approx. 30m difference from the position indicated by the obsROV's renewed litter map	
Basket approach	Manual approach successfully	Autonomous approach and docking