Search, identification and collection of marine litter with autonomous robots

SeaClear

https://seaclear-project.eu

D6.1

Tourism-oriented demonstrator with assessment.

WP6 –Demonstrations

Grant Agreement no. 871295

Lead beneficiary: University of Dubrovnik

Date: 20/12/2023
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	D6.1: Tourism-oriented demonstrator with assessment
Work package	WP6: [Demonstrations]
Deliverable leader	UNIDU
Delivery date	Contractual: 31.12.2023 Actual: 20/12/2023
Status	Draft ☐ Final ☒
Type[1]	R ☐ DEM x DEC ☐ OTHER ☐ ETHICS ☐
Dissemination level[2]	PU x CO ☐ CI ☐
Authors (Partner)	[I. Palunko] [UNIDU]
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Deliverable description	The overall system developed in WP3, WP4 and WP5 is tested in two Dubrovnik demo sites.

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
[I. Palunko]	20/12/2023	V[0.1]	First draft of demo 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
- **UAV:** Unmanned aerial vehicle
- **ROV:** Remotely operated vehicle
- **LARS:** Launch and Recovery System

Executive summary

From 04. – 13. October 2023 the whole SeaClear consortium gathered in Dubrovnik, Croatia for the final system demonstration focusing on the tourism-oriented use case in a nature protected and mariculture environments.

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 cleaning missions.

1. Introduction

During project duration a large number of trials were conducted to test the SeaClear system as a 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 Dubrovnik in October 2023.

Due to the projects requirement and regulations for the deployment of unmanned systems in public and nature protected environments in Dubrovnik-Neretva County, 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.

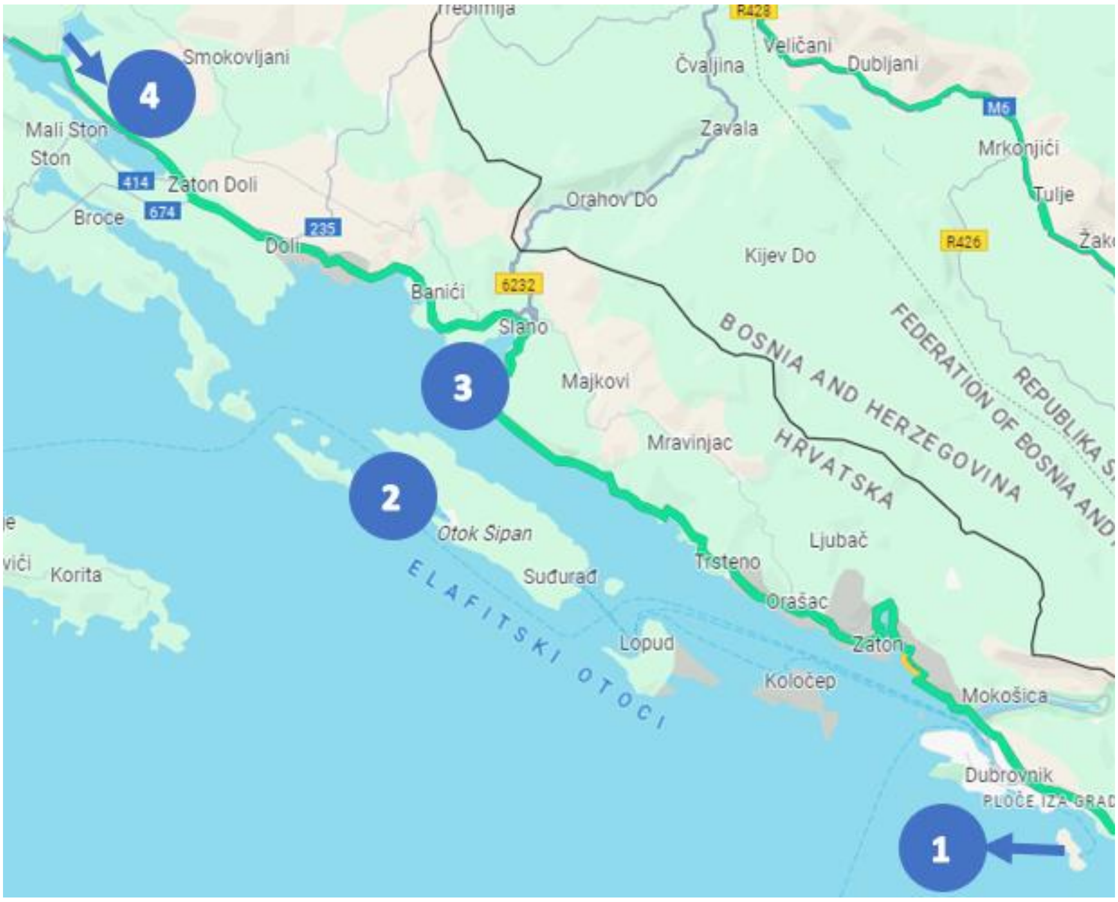


Figure 1: Potential test locations in Dubrovnik area

In the first phase the team conducted trials all four locations from Figure 1. During these trials locations number 1 (Lokrum island) and number 4 (Bistrina Bay) were chosen for as demonstration sites. Figure 2 highlights these locations in more details. After test campaigns in 2021 the locations on Lokrum,

(Figure 2, left, number 5) and in Bistrina Bay (Figure 2, right, research concession 16a) were chosen as demonstrations sites. All the following campaigns as well as the final demonstrations were conducted in these two areas.

Figure 2: Potential test sites in Dubrovnik: Lokrum locations(left) and Bistrina Bay(right)

1.1. Final demonstration sites

In Dubrovnik area the final demonstrations have been conducted in two separate locations, with slightly different environmental conditions.

In ***Bistrina Bay***, the demonstration took place in front of the Laboratory for Mariculture, University of Dubrovnik (UNIDU) (42°52'16.2"N, 17°42'04.3"E), a research facility situated near a number of mariculture farms, Figure 3. The conditions here involved relatively low currents, with a visibility of around 10m, but slightly turbid water which negatively influences the visibility.

Figure 3. Bistrina Bay (left) (source: http://old.dubrovniknet.hr/novost.php?id=64065#.Xv3DAW37SUk) and the designated demo area (right) (source: Google maps)

At Bistrina demo the operation center was setup in front of the main building so the operators can clearly see all the robots while in operation and at the same time providing efficient seating arrangements for easier communication between the operators. Also, a separate area was designated for the end users, members of community of practice and members of SeaClear 2.0 consortium so they can follow the demo without interrupting the operators, see Figure 4.

Figure 4: The “Operation center” (left and center) and the area for non-operators to follow the demo (right) at Bistrina demo site

Since the premises for the Bistrina demo are the UNIDU facility this was the most suitable area where the preparations and final system integration for the final demo took place.

The demo site Portoč Bay at the **Lokrum island** (42°37'32.7"N, 18°07'23.4"E) has a significantly better visibility than any other test site used in the project, with objects being visible up to around 20m and very low turbidity, see Figure 5.

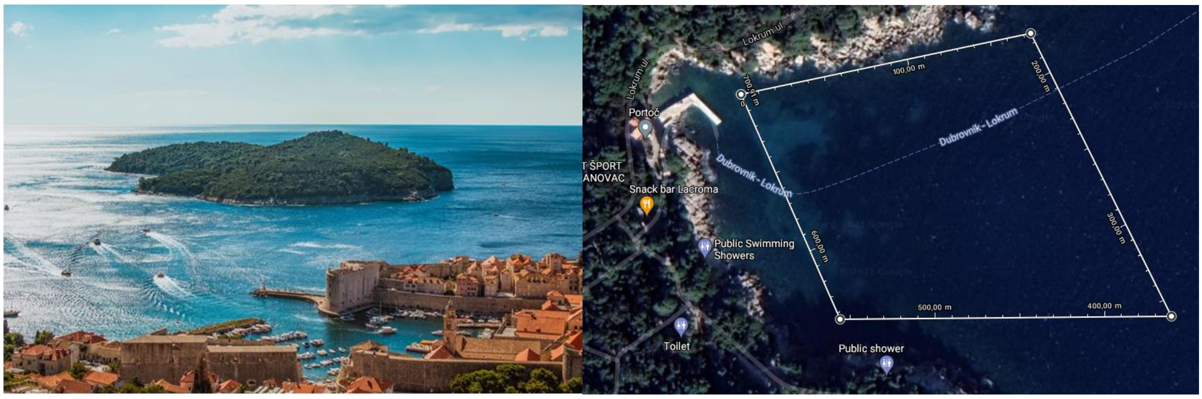


Figure 5. Lokrum Island (left) (source: http://www.lokrum.hr/blog/galerija/galerija-lokrum/) and designated demo area at Portoč Bay (right) (source: Google Maps)

Since Lokrum is an island situated in front of Old town of Dubrovnik, is a protected natural reserve and a tourist attraction without suitable facilities, the operation center was set up on board of the UNIDU research ship “Naše more”. Onboard the ship the team was able to setup separate operator and non-operator areas, see Figure 6. The reviewers from the European commission were present onboard this ship during this final demo.

Figure 6: The "Operation center" onboard the ship and the viewing area during the Lokrum demo

Due to the large interest from the press and the public for the Lokrum demo, the team organized a second accompanying ship. On this ship the attendees were able follow the live stream of the demo through onboard screens. Also, at the same time they were able to get acquainted with AI-based litter detection algorithms, demonstrated using a tablet and samples of litter, see Figure 7.

Figure 7: The accompanying ship for the press and the public. On the bottom right, a demonstrator of litter detection is visible.

During the preparation week and the demo week the team was supported by a team of professional divers, see Figure . The divers placed several controlled litter objects on the seabed for underwater detection, mapping, and collection.

Figure 8. Professional divers providing support on both Bistrina(left) and Lokrum(right) demo sites

Different litter elements were scattered around the two demo areas at Bistrina and Lokrum. The litter elements consisted of common marine waste elements, that were collected during diver clean-up actions that took place few weeks before the final demo. A few of the items are being shown in

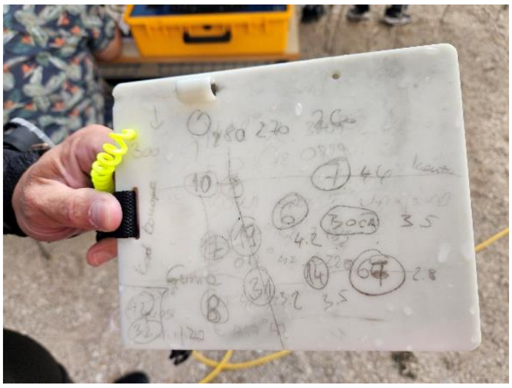


Figure . To emulate the realistic conditions the litter elements were placed freely on the seafloor by the divers without any contraptions which could interfere with the system. The divers provided the raster of the litter elements with respect to the tires which provided the team with a ground truth reference, see Figure 9. All the litter elements placed on the seafloor were retrieved after the demonstrations.

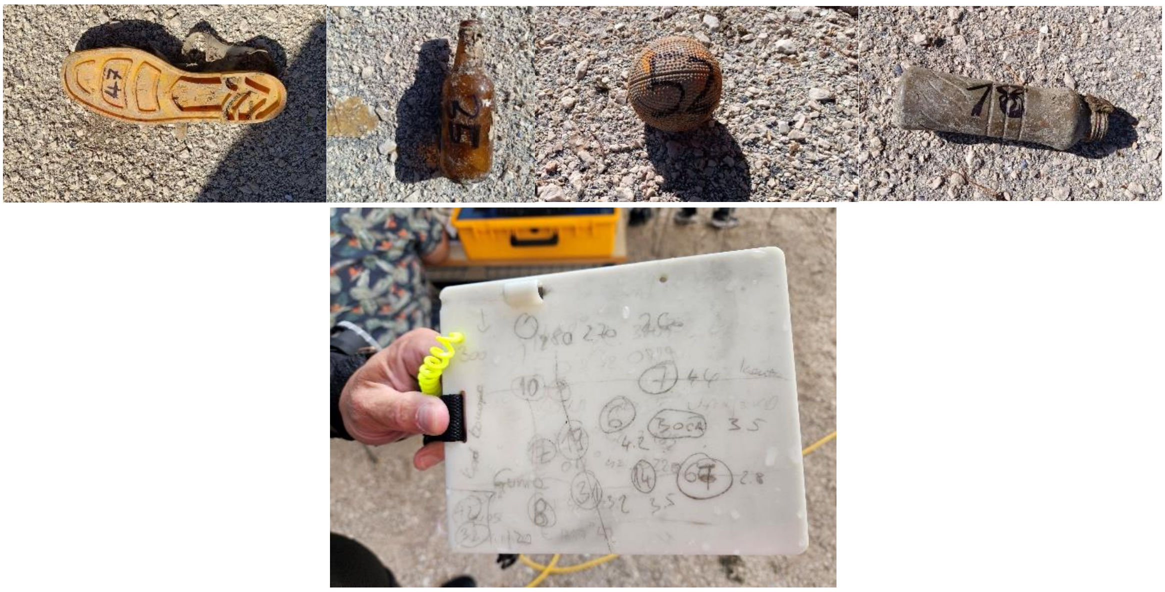


Figure 9. Sample of litter elements collected and scattered around the test areas for showcasing the SeaClear system (top row) and the litter raster mapped by the divers

1.2. Schedule

The schedule comprised a total of 4 days dedicated to preliminary tests and final integration and two days devoted to a full system demonstration, one for each demo site, Figure 10.

Preparation week

	Bistrina Wed 4th October 2023	Bistrina Thur 5th October 2023	Bistrina Fri 6th October 2023	Sat 7th October 2023	Sun 8th October 2023
07:00 - 08:00	Transfer to Bistrina (m.p. Student Dorm)	Transfer to Bistrina (m.p. Student Dorm)	Transfer to Bistrina (m.p. Student Dorm)		
08:00 - 09:00	- Divers placing the litter - Mapping the litter for the ground truth - SeaCat craned in water with MBES and SBL - initial meeting and disscusion on the schedule etc	- Divers placing the litter - re-Mapping the litter for the ground truth	- Divers placing the litter - re-Mapping the litter for the ground truth		
09:00 - 10:00		Demo prep	Demo prep		
10:00 - 12:00	Demo prep			Back-up demo prep	Back-up demo prep
12:00 - 13:00	Lunch	Lunch	Lunch		
13:00 - 18:00	Demo prep	Demo prep	Demo prep		
19:00 - 20:00	Transfer to Dubrovnik (m.p. Bistrina parking)	Transfer to Dubrovnik (m.p. Bistrina parking)	Transfer to Dubrovnik (m.p. Bistrina parking)		

Demo and meetings week

	SC1 Bistrina demo Bistrina Mon 9th October 2023	SC2 GA meeting UNIDU main building Tue 10th October 2023	Lokrum demo prep Lokrum island Wed 11th October 2023	SC1 Lokrum demo Lokrum island Thr 12th October 2023	SC1 final conference and GA UNIDU main building Fri 13th October 2023
09:00 - 10:00		WP1 (15') WP2 (30') WP3 (30')			
10:00 - 11:00	Demo for EC	Coffee break (15') WP4(30') WP5(30')	Demo prep	Demo for EC	Welcome (10') Intro presentation (20') Panel (90') Q&A(20')
11:00 - 12:00					
12:00 - 13:00	Lunch	Lunch	Transfer from Lokrum & lunch	Transfer from Lokrum & lunch	Lunch
13:00 - 14:00		WP6 (30') WP7 (30') WP8 (30')		Equipment packing etc.	
14:00 - 15:00	Demo for EC	Coffee break (15') WP9 (30') WP10 (30')			Discussion on KPIs, coffee break (15') Review, conclusion
15:00 - 16:00					
16:00 - 17:00		Wrap-up, etc.			
17:00 - 18:00	Transfer to Dubrovnik (m.p. Bistrina parking)				
18:30 - 20:00				Guided tour of Old town (Brsalje)	
20:00 - 22:00				Official dinner	

Figure 10. Agenda of the Dubrovnik Demo

The last day, Friday was devoted to a public presentation of the project given by the project coordinator and a panel discussion with a representative of each partner. In the afternoon, the consortium meeting took place where the partners discussed on the overall results and lessons learned.

1.3 Stakeholder involvement

The SeaClear project received a large interest of public and potential stakeholders from the start. During first Dubrovnik trials in September of 2021 there has been a short press-release about the project since the main focus was on conducting the trials. Thus, during the final demonstrations in Dubrovnik in 2023 the team decided to include the press, public and stakeholders in the demonstrations. This was done by organizing the supporting ship during Lokrum trials and by organizing a separate open-door event on the last day of the demonstrations where the project was presented by the coordinator and later in more details in the panel where each partner had a representative. The presentation and the panel were open to the public and were hosted at University of Dubrovnik main campus building, Figure 11.

Figure 11. Project presentation and a panel discussion at UNIDU

The representatives of the stakeholder community and community of practice were presented on both events.

2. Methodology

The sea trials focused on demonstrating our prototype of the robotic system designed for the detection, classification, and collection of underwater litter. The operation was divided into two stages.

In *Stage 1*, the SeaCat USV was utilized, following a path generated to cover the search area. A Multibeam Echo Sounder (MBES) was employed for mapping the underwater environment, with subsequent litter mapping conducted with underwater cameras and using MBES data as base for planning. Path planning for the obsROV was derived from the MBES map, which used RTK-enabled GPS readings for the spatial mapping. The UAV was utilized for mapping larger submerged objects and for providing the ground truth when the visibility was favorable.

In *Stage 2*, the litter mapping transitioned to camera data onboard colROV, refining the obsROV map for increased precision. Additionally, path planning for the colROV was based on the obsROV map, with successful path following and station-keeping control. The system executed the grasping stage for efficient litter collection, followed by the drop-off stage for depositing the collected litter.

These stages were designed to address specific objectives, including the development and demonstration of collaborative heterogeneous robots, integration of AI-based algorithms, and testing control algorithms for optimal collaboration and autonomy within the robotic team. The successful execution of these stages marks significant progress toward achieving the project's objectives.

2.3 Sea Trial Procedures

This chapter provides a detailed account of the testing procedures conducted during demonstrations, outlining each stage's specific steps, adjustments made based on initial results, and resolutions to unexpected challenges encountered.

2.3.1 Stage 1: In-Situ Mapping and Classification

The UAV scans the area for detection of large pieces of underwater litter, thus providing the initial potential hotspots of the litter. The USV began the procedures in Stage 1, performing a bathymetry scan of the test site, as seen in Figure 12.

Figure 12. UAV performing aerial visual scan in the free-flight mode and USV performing bathymetry scan, with the inbound data being processed at the Shore Operation Centre (on the carrier ship).

The USV's movements were focused on a lawnmower path, important for covering the whole area and facilitating Multibeam Echo Sounder (MBES) map generation of the underwater environment. The MBES data was used to generate a three-dimensional map, serving as base for underwater navigation and further litter mapping. The SeaCat USV could be depicted on the Operator App.

The primary objective for the UAV is to map larger pieces of underwater litter and provide the ground truth for the ROVs. Figure 13 demonstrates visibility conditions and ground truth labels of submerged tires during Lokrum demo.

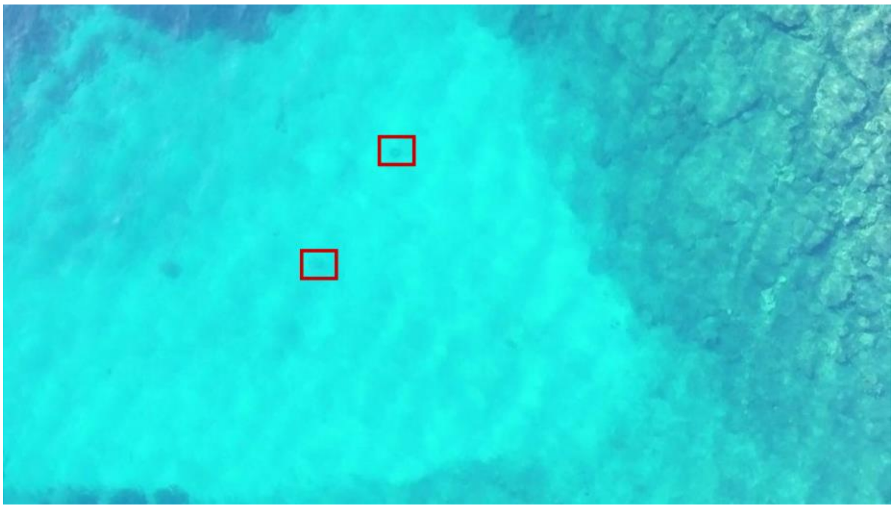


Figure 13. Visibility conditions and ground-truth labels for underwater objects

Path planning for obsROV was successfully derived from the MBES map in the form of a three-dimensional, inclined lawnmower path, as seen (in a 2D projection) in Figure 14, and the obsROV followed the path, maintaining a constant heading.

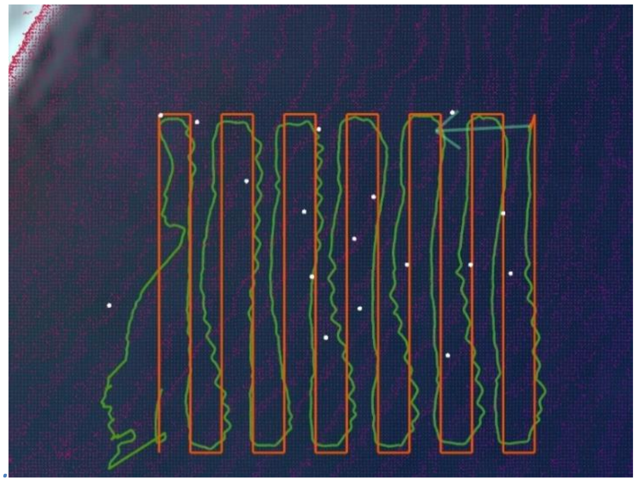


Figure 13. Lawnmower to be executed by the obsROV (red line) and actual obsROV trajectory (green); mapped litter objects (white dots). The deviation on the left is not real behavior, but a transient issue with the ROV positioning sensor.

The map generated during the bathymetry scan was refined with a camera-based litter detector and classifier onboard the obsROV. Figure 14 shows an example detection of trash from the camera image. Sealife detection is also illustrated.

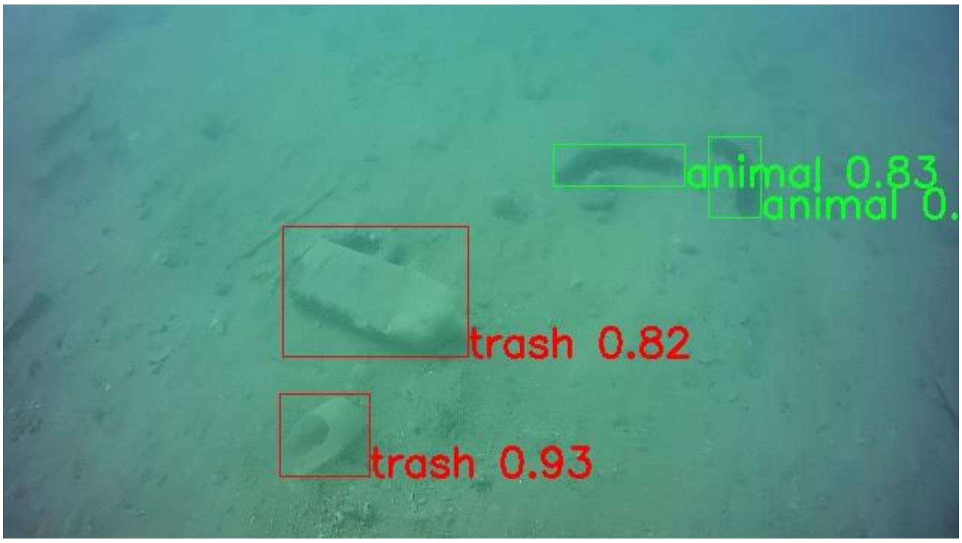


Figure 14. Example detection of trash and sealife by the deep-learning detector

Figure 15 shows the litter positions as mapped with the obsROV compared to those mapped with the drone, which are treated as ground truth. Two caveats apply. First, because the coordinate system of the drone is offset from that of the obsROV by an unknown amount, we shifted the detection by an amount given by the difference in the tire detections from the UAV and from the ROV (i.e. we moved the red diamond to be on top of the black diamond). Due to this the tire is excluded from the computation of the RMSE given below. Secondly, because it was not known exactly which ground-truth position corresponds to which object seen in the ROV video, we took the shortest distance between each mapped object and any ground truth. Thus, the RMSE of 1.0025m that we obtain is an optimistic, lower bound on the error. Despite these uncertainties, overall, compared to the errors of about 0.7m in sonar detections in the Hamburg demonstration, which did *not* suffer from these two sources of uncertainty, the conclusion is clear: sonar detection is preferable.

Key Findings and Conclusion: The mapping procedure performed with the obsROV marked the completion of Stage 1 and, in addition, yielded several key findings:

1. Mapping lawnmowers were successfully executed
2. Litter was successfully detected in ROV camera images. During the tests 87 % of the litter was correctly detected and classified by the camera-based computer vision algorithm, as it was validated by counting the detected and correctly classified objects in the respective recorded videos.

3. Mapping errors from camera were estimated (see above for caveats) at around 1m (compared to 0.7m from sonar). Thus, we conclude that using sonar detections is preferred, which allows the use of a single sensor in all water visibility conditions.
4. Larger pieces of litter were detected from a UAV camera when the visibility was favorable.

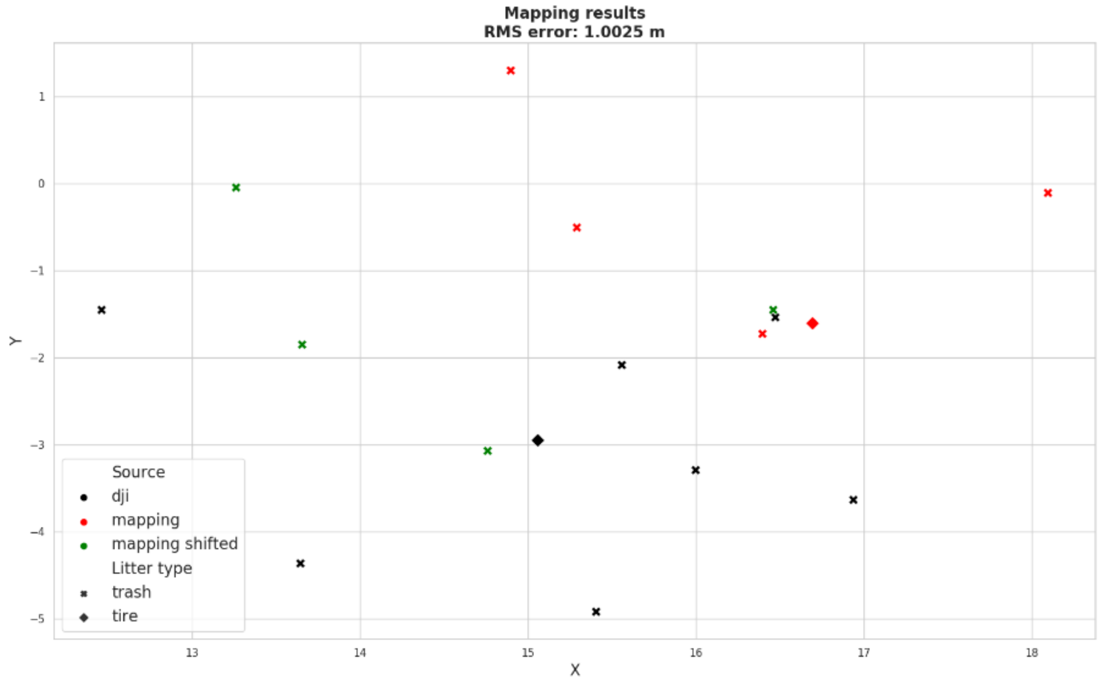


Figure 15. Estimation of mapping accuracy. Black coordinates are UAV "ground truth", red coordinates are mapped from the obsROV, and green coordinates are shifted to compensate for the offset in the system of coordinates, see the text. The tire is denoted by diamonds and other trash items by X symbols.

2.3.2 1Stage 2: Collection

Building upon the completion of Stage 1, Stage 2 delved into advanced detection and collection mechanisms. The return of the obsROV back to the SeaCat USV and the lowering of the collection basket at the collection spot marked a transition into the next phase. The colROV followed a path, based on the obsROV-augmented marine litter map.

Before launching the colROV, the collection basket had been lowered to the seabed and its pose estimator 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.

The final stage of the sea trials was marked with marine waste collection. The colROV showcased sufficiently accurate path following (within the magnitude of the localization errors) to require targets in the field of view of the downward-facing camera and station-keeping control, leading to successful grasping and drop-off stages, depicted in Figure 16 and Figure 17. A caveat applies to the automatic grasping procedure: while successfully shown in Bistrina, in the Lokrum trials, the detection of litter objects was not consistent enough to enable stable tracking and, thus, an autonomous approach. Litter identification in Lokrum was supported by the operator in a shared control approach, in which guidance was provided by the operator and stabilization was performed by the system.

Figure 16. View from the colROV downwards cameras with view inside the litter gripper (left) and collection basket camera (right) _during the marine litter disposal phase with the colROV gripper inside the bristled interface of the collection basket.

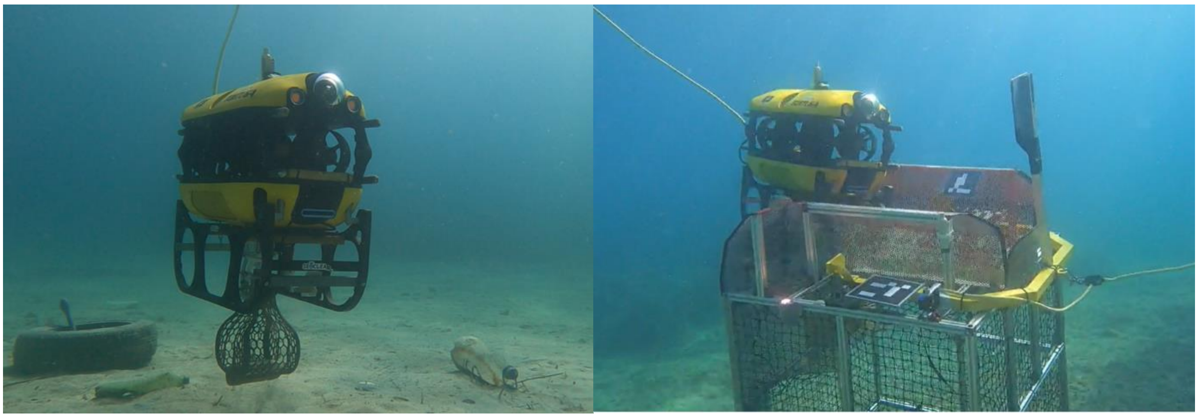


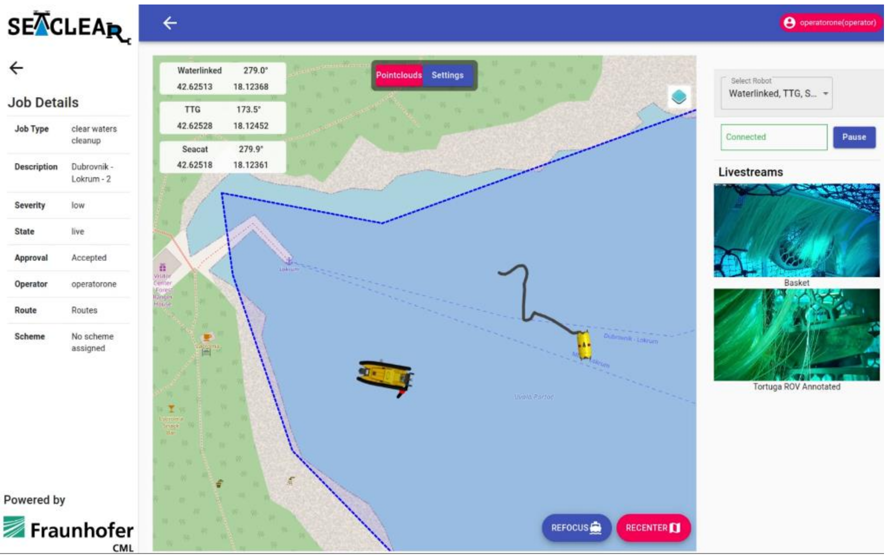
Figure 17. View of the colROV collecting the litter (left) and entering the basket for its disposal (right)

Key Findings and Conclusion: The tests conducted in Stage 2 yielded several key findings:

1. The colROV's grasping mechanism proved capable of successfully collecting pieces of litter, highlighting its potential for marine litter cleaning operations.
2. The basket's pose estimator exhibited inconsistencies with the position estimation generated by the obsROV during the underwater litter remapping.

2.4 Operation Monitoring

For coping with the demand of future end-users of the SeaClear system, the team has developed a web-application where the marine operation can be monitored remotely through a standard web-browser, as seen in the snapshot in Figure 8. On the SeaClear web-application, the user interface plotted in real-time the same trace that could have been seen also in the operator application.



2.

Figure 18. Unmanned system traces and video streams displayed over SeaClear web-application.

In addition to the mission-relevant data and the video streams, the users could also view the images acquired in any of the positions represented on the map, as illustrated in Figure 9.

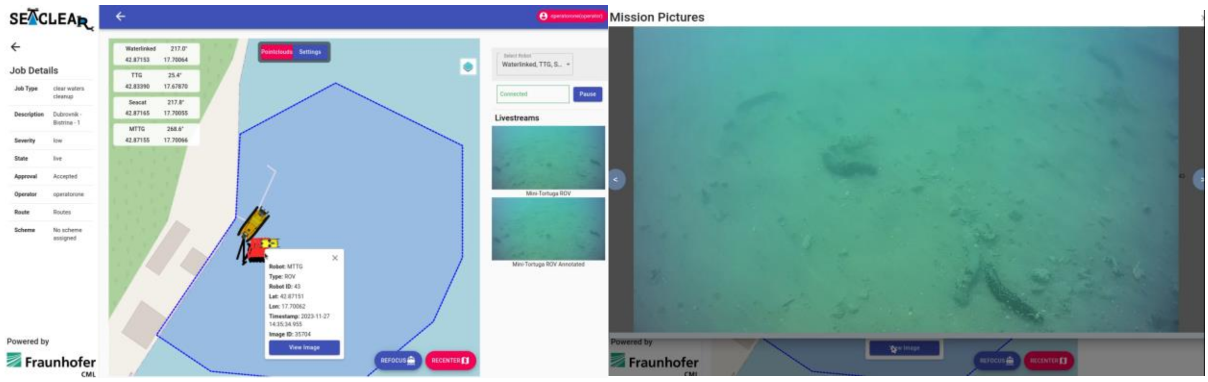


Figure 19. Example of interaction with the SeaClear web-app: by clicking over any point in the traces left by the robots, the images collected at the location were also displayed in form of a pop-up

The activities conducted by the SeaClear team were broadcasted over large screens in Bistrina and Lokrum for external viewers, as seen in Figure 4 and Figure 6.**Error! Reference source not found.**

Key Findings and Conclusion: In the operation monitoring, the following key conclusions were drawn:

1. The video streams required significant bandwidth, as they were consumed also in the SOC by the operators and by the object detector. Future implementations should leverage the usage of a dedicated video server
2. Operation data was successfully saved in an SQL database, which enabled further usage with third party applications. However, little concern was given to data security and streaming the information outside the LAN.

3. More information about the ongoing operation would have been desirable on the web-application

2.5 Free flight and tethered drone

For the UAV to serve as a possible ground truth feedback, when possible, and to help with situational awareness of the system, the team designed and developed the winch for control of the tether providing the power to the drone from the SeaCat, see Figure 20. The developed algorithm combined cooperative control of the tether length and autonomous landing of the UAV on the winch platform.

Figure 20. UAV in free flight and a tethered drone on a landing platform onboard of the SeaCat

Key Findings and Conclusion:

1. In the case when the visibility is good a UAV can detect large pieces of litter from air, but it is not trivial and, in some cases, not possible to perform the classifications as well.
2. In maritime operations UAV can be used to provide a reliable ground truth for the underwater objects and vehicles in cases when the visibility is good
3. The UAV performed free-flight and tethered operations as well as landing on the platform in autonomous mode.

3. Summary

In summary, the six-day final 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.