Search, identification and collection of marine litter with autonomous robots

SeaClear

https://seaclear-project.eu

D3.3

Collection basket design report

WP3 — Robotic hardware developments

Grant Agreement no. 871295

Lead beneficiary: 3 - CML
Date: 05/07/2022
Type: R
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	D3.3: Collection basket design report
Work package	WP3: Robotic hardware developments
Deliverable leader	3 - CML
Delivery date	Contractual: 30/06/2022 Actual: 30/06/2022
Status	Draft ☐ Final ✓
Type[1]	R ✓ DEM ☐ DEC ☐ OTHER ☐ ETHICS ☐
Dissemination level[2]	PU ✓ CO ☐ CI ☐
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Deliverable description	The current work describes the development of the basket and includes a description of the interface designed for the ROV to enter and deposit the collected litter. The initial mechanical requirements will be listed as well as any additions made over the course of the project. Based on those requirements, the hardware design will be described with a full summary of the final basket setup. In addition, included electronics will be described and how they function together to deliver a sufficient position estimation for feeding it to the Tortuga ROV, which is programmed to autonomously navigate to the basket and drop the collected waste into its custom designed interface, even under bad visibility conditions. Furthermore, the interface concepts designed and tested during the initial phase of this work package and the benefits of the selected interface, will be summarized.

[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
E. Banken	15/06/2022	V0.1	rough draft
C. Delea, M. Ghorab	20/06/2022	V0.2	additional technical aspects
Lucian Busoniu	29/06/2022	V0.3	first review
Elisabeth Banken	30/06/2022	V0.4	feedback implementation
Cosmin Delea	30/06/2022	V0.5	final version

Disclaimer of warranties

SeaClear has received funding from the European Union's Horizon 2020 research and innovation programme, under Grant Agreement no. 871295. The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed in the deliverable lies entirely with the author(s).

Table of Contents

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 and Services.
- **HPA:** Hamburg Port Authority.
- **Subsea Tech:** Subsea Tech SAS.
- **UTC:** Technical University of Cluj-Napoca.
- **TUM:** Technical University of Munich.
- **UNIDU:** University of Dubrovnik.

Executive summary

The current document describes the SeaClear system development and design of the collection basket. With the help of system prerequisites of the other
glssclr systems as well as considering environmental preconditions, the process of manufacturing the basket and testing different ROV-basket interfaces will be explained.
The deliverable summarizes the basket specifications and highlights the conducted experiments, which ultimately led to the final conceptualization of the basket design. This design was not only manufactured into an aluminum frame hexahedron with minimal electronic components as desired. Some sensors were added to enable and improve the localization of the basket by the Collection-ROV, which were first tested in simulation and later validated during the Hamburg Trials in 2022. While the trials showed good results, some minor issues were determined that were since altered and demand validation during the project demonstrations in Marseille in September 2022.

1 Introduction

Within the scope of the SeaClear project, a team of unmanned underwater, surface and aerial vehicles are being built to find and collect litter from the seafloor. The surface vehicle is a medium-size autonomous ship, responsible of gathering and managing acquired information from the rest of the robots and presents the transport system for all other processes included. While one underwater vehicle is tasked with the search, identification and mapping of litter, a second one, in charge of picking up the litter and depositing it into a collection basket, will be fitted with a special gripper and suction device for both small- and medium-sized waste. The project also plans to use an aerial vehicle to study if underwater litter can be detected from the air. The developed system will be demonstrated in two case studies: one in port cleaning (with end-user Hamburg Port Authority), and the other in a touristic area (Dubrovnik with end-user DUNEA). Figure 1 presents the overall concept of the project. The goal is to develop a robotic system with general applicability, regardless of the environmental particularities of the subject area or of the customer's profile.

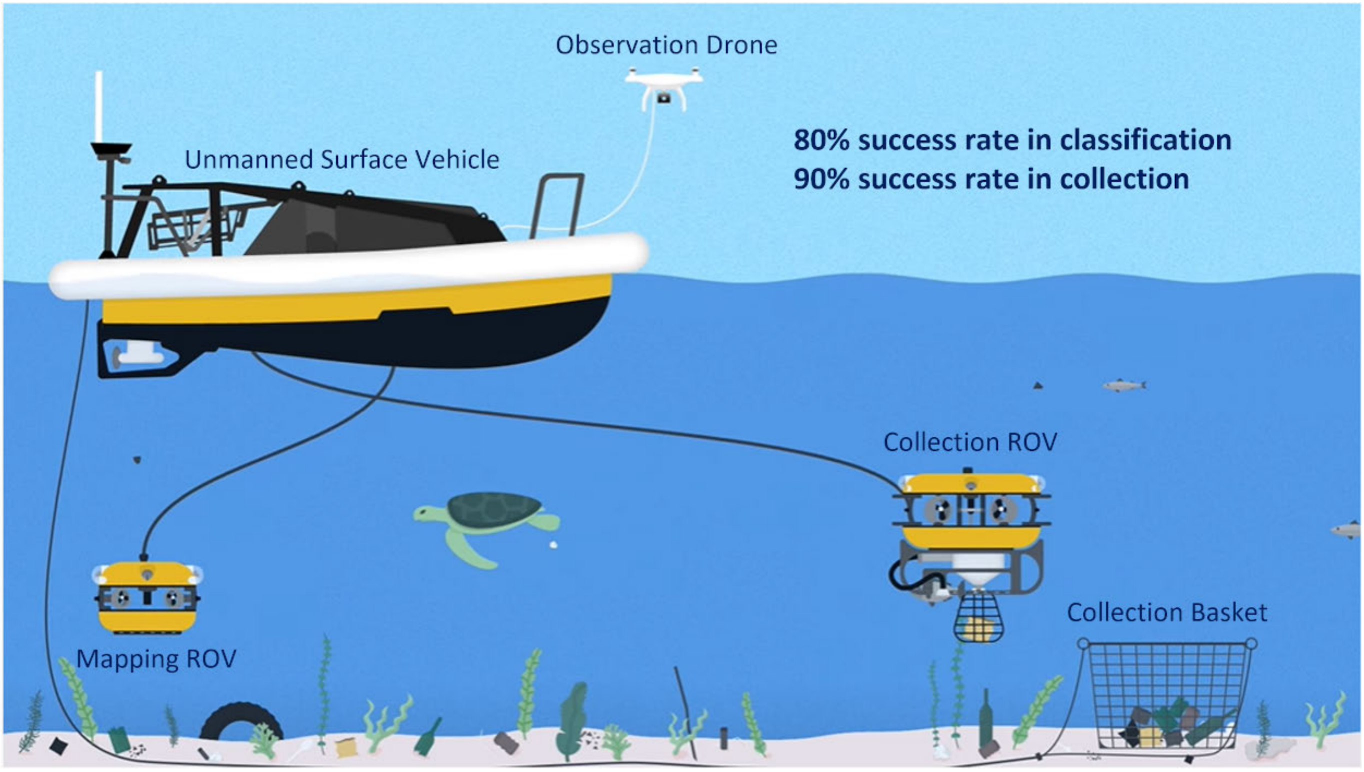

Figure 1: SeaClear concept. An unmanned surface vehicle acts as the hub of the system, an observation underwater vehicle maps the litter, and a collection underwater vehicle collects identified pieces of litter with a gripper and possibly also a suction device to collect smaller litter and fragments. A Unmanned Surface Vehicle (USV) assists with detection and other tasks.

Among others, Fraunhofer CML has been tasked with the development of the collection basket that allows the gathering of litter picked up by the ROV's gripper or suction hose. The basket is attached to the back of the USV and is lowered to the seafloor when the ship has reached its target area. The other devices involved in the search, identification, and collection process scan and roam the designated clean-up area and gather the litter. To avoid their constant return to the USV on the ocean surface after collecting one piece of litter, a collection basket was included in the mission processes. This way, the ROVs can remain at their depth and simply deposit litter into a basket. Once sufficient litter has accumulated in the basket, it is lifted out of the water again and transported to the nearest harbour for the litter deposition and thus, emptying the basket for its next mission.

The initial goal for the basket design was to develop a simplistic collection container that would function completely mechanically without including parts, components or devices requiring electrification provided from the surface vehicle. Based on the results of the experiments and an ongoing discussion among all parties involved, the design was constantly adjusted and refined over time to overcome observed challenges and problems.
This deliverable is based on the design, development and manufacturing of the collection basket and details system and end-user requirements as well as iterations included in the final design of the basket. The goal of this deliverable is to give an overview of the work conducted within the hardware developments Work Package (WP) and explain the functions and features included in the SeaClear collection basket. Therefore, it makes use of the case studies presented in the Deliverable 2.1 - *Use-case definition document* and Deliverable 2.2 - *Specification and design document* and incorporates previous findings and requirements as basic design guidelines into the development of the basket. As determined by Deliverable 2.2 the environmental conditions of the five selected test sites vary greatly and therefore present a diverse range of requirements. Consequently, the basket was designed to fit all of the site's requirements, allowing it to be used in all of the test sites. Furthermore, the gripper and suction tube connected to the ROV were developed simultaneously, hence provided constraints and specifications during the developmental stage and demanding for adjustments in the baskets design.

In this Deliverable 3.3, the system and design requirements, as well as constraints and specifications for included components will be explained and summarized first. Afterwards, the design approach will be presented including the manufacture of a small-scale prototype basket and several interface designs tested in order to find the most suitable interface solution. Then, the final basket design will be described together with the ROV-basket interface, the electrical components and the development of the Launch and Recovery System (LARS).

2 Overall System Requirements

The intended use of the basket developed within the scope of the overall SeaClear system is to demonstrate and provide a simple system capable of letting the Collection-ROV (ColROV) deposit collected litter and retain it effectively to prevent its further distribution. Once litter is collected using either a gripper or a tube, it should be safely deposited into the basket. Originally, the basket was conceptualized to have two separate volumes for the tube and gripper collection mechanisms on the ColROV, with a connection between suction tube to the surface vehicle via a discharge tube. However, due to the positioning of the tube as well as its estimated capabilities for litter collection, a separate compartment was considered unnecessary. Hence, the single compartment entrance needed to be big enough to let the gripper with a size of ca. 24x20x24cm (WxLxH) of into the basket.
The basket should further be mountable on the USV together with the necessary infrastructure to lower the basket to the seafloor and recover it after a success mission. During the mission, the basket should maintain its position and enable the deposition of litter without greatly impacting the surrounding ecosystem. Since the SeaClear project aims to deploy an autonomous robotic solution, the basket should be easily detectable and locatable by the ROVs. It should further be usable over the duration of a complete SeaClear mission, collecting up to 150kg of litter from the seafloor. Afterwards, the basket should be recoverable and placed on the surface vehicle for the transport to shore.

2.1 Problem Description

From the start, the basket was intended to function with little active components to reduce the amount of energy consumed by the overall system. However, as mentioned above, the environmental conditions at the five selected test sites vary greatly and demand a collection basket tailored to associated specifications to enable a proper collection regardless of the location. This influenced the development of the localization scheme in particular, since the visibility conditions at the Hamburg test sites would not allow an exclusively optical based system for the basket approach from afar. Hence, the balance between using sufficient types and number of sensors to locate the basket and remaining a low-tech solution was key.
Another important fact was to prevent litter from escaping the basket due to current flow, local water movements and the approaching ROV depositing additional litter. While most of the litter is anticipated to be located on the seafloor and can therefore be assumed to sink to the bottom of the basket upon deposition as well, some of the litter on the seafloor or within the water column may demonstrate neutral buoyancy. This would cause litter to float around the basket or remain in the position it was deposited in. Hence, the basket should present a mechanism to deal with such litter and prevent already collected litter to escape again.
Lastly, the basket design entailed a solution for the LARS to safely deposit the basket on the seafloor in the beginning of a SeaClear mission and pull it back up after the mission is concluded. Hence, basket components needed to be compatible with the LARS infrastructure. In addition, the LARS as well as possible electronics would require ropes and/or cables running from the USV to the basket. Yet, additional ropes in the water create a more difficult navigation environment for the tethered ROV and poses the risk of entanglement during the basket approach. Thus, the basket design and development needed to account for the added risk and possibly include features to reduce it.

2.2 Basket Design Requirements

Based on the problems and challenges identified, basic design requirements for the basket were set before commencing the basket conceptualization and design phase, which are listed in Table 1. Due to the mass constraints of the USV, the maximum weight was set to 350 kg, including the weight of the basket itself and its maximum payload after a day's work of collecting litter as well as the LARS infrastructure mounted on the SeaCat USV.
During the conceptualization phase of the basket as well as the design, manufacture and testing process, several further

constraints were identified. To that effect, the basic design requirements were extended by design parameters as listed below (Table 1). Due to the spatial arrangement and space available on the USV, the decision to mount the basket at the back of USV was taken quickly and the maximum basket dimensions subsequently derived from the available space. The spatial setup is depicted in Figure 2. In order to maximize the payload of litter to be collected during a single SeaClear mission, the goal mass for the basket structure itself was set to approximately 50 kg. While larger fish were assumed to be too fast to be swept up by any gripping activity of the collection ROV, the targeted litter may contain some smaller fish and marine life. While they may be deposited together with the litter during the collection process, the basket should allow them to quickly escape afterwards. Thus, the mesh size of the basket netting was adjusted accordingly.
Furthermore, the accuracy of the localization data and subsequent navigation of the ROV was assumed to be sub-optimal upon finalization of the project based on limitations of available technologies, thus requiring some kind of provisions on the basket to account for such inaccuracies and still achieve a successful entry of the gripper into the basket.
Lastly, since the USV will continuously be subjected to the pull of currents and waves on the surface, it would have to actively act against that motion to maintain its position above the basket. Hence, it was decided that the basket should act as an anchor for the USV, thereby keeping it in the approximate launch spot of the robotic system.

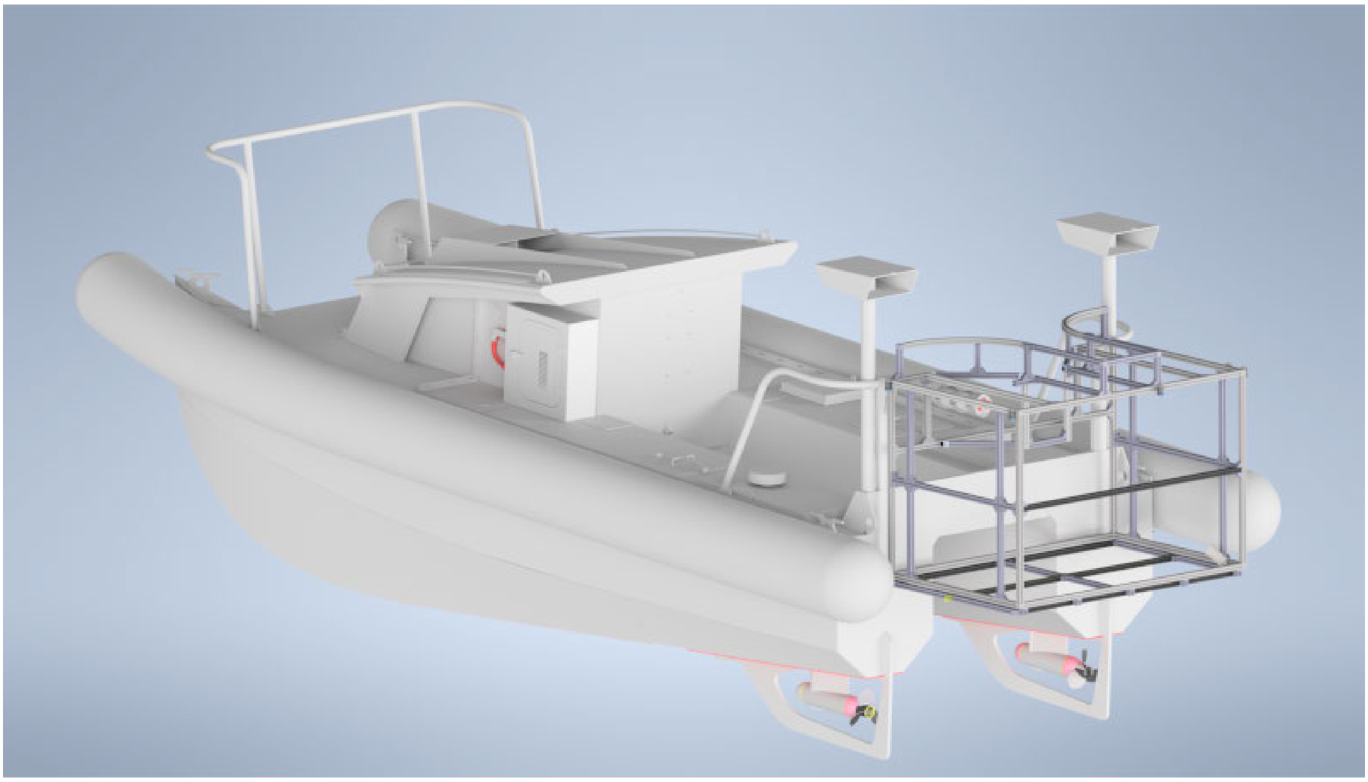

Figure 2: CAD model of the USV with the basket positioned at the back.

2.3 Launch and Recovery System Design Requirements

The LARS responsible for launching the basket from board the USV and recovering it from the seafloor was designed and built in collaboration by Fraunhofer CML and SST. The maximum weight of the system was set to about 100 kg. Several options were considered during the design process, including double winch systems, davit arms and A-frames. The challenge of this system lay in the mass to be pulled up out of the water once the basket was full with collected

Table 1: Basket Design Requirements and Additional Parameters.

Initial Design Requirements	Additional Design Parameters
• Maximum mass (with payload) of 350kg • Basket attachment and mounting on the USV • Include a system for basket launch and recovery • Consider risk of rope entanglement and possibly find precautions • Provide localization information to the USV and collection ROV • Allow applicability within all five selected test sites • Enable gripper entrance without litter escaping the basket • Reach 90% litter retention success rate • Little impact on local flora and fauna (leave room for escape for accidental catches of small fish)	• Maximum basket size: 2.2m (length) • Maximum basket frame mass (empty): 50 kg • Mesh size: 2 - 3 cm • Interface localization: allow for resolution errors of +/- 50cm • Act as anchor for the USV

litter after successful completion of a SeaClear mission. Discussions furthermore encompassed debates about two versus a single tether, ropes or chains.

3 Design Ideas and Considerations

To commence the basket design and development, a morphological box approach was created, where each basket feature to be considered was added into a table and filled with all possible ideas and approaches. A simplified version is presented in Table 2 together with advantages and disadvantages of each idea.
In terms of material choice, aluminum profiles were quickly decided as material for the basket frame thanks to their mechanical properties and great manufacturability as well as resistance to corrosion when in contact with sea water. The basket's wall structure was chosen to consist of a meshed netting, similar to the materials conventionally used within the maritime industry. The net was attached to the aluminum profile frame. However, one idea related to the meshing that was discussed was to possibly have one side extend beyond the frame of the basket and therefore create a larger volume capacity. This idea, while interesting, was rejected due to difficulties assumed with the recovery process of a lob-sided basket and its weight distribution.
For the shape of the basket, three options were identified: square/rectangular, round and streamlined. The round option was eliminated rapidly due to the difficulties associated with manufacturing a round basket. A streamlined basket was considered an interesting option as it would allow the litter to be automatically pushed further into the basket upon deposition thanks to local currents. However, while a streamlined basket shape could also improve its hydrodynamic characteristics underwater, it was assumed that it would not be possible to know underwater current directions in advance and therefore orient the basket accordingly. Hence, the streamlined effect would be lost in most instances. Therefore, the shape of the basket was selected to be square/rectangular, which is most simple for the manufacturing process and also perfectly aligns with the back of the USV in its desired position.
Furthermore, due to the considerable weight of the basket at the end of a SeaClear mission, the position of the basket during the transport to shore was decided to be fully pulled out of the water to prevent high resistive forces at the back of the USV and reduce the required motor power. This also meant, however, that the entire mass of the full basket must be carried by the USV.
Another feature considered during the collection of design ideas was the maintenance of the basket's as well as the USV's position. Three different options were identified: 1. using a conventional anchor additionally to the robotic systems to be lowered to the seafloor once the USV is in position, 2. using the basket as an anchor for the USV, and 3. having no anchor at all. Due to the complexity of rope management and risk of entanglement as well as the added weight of the anchor and associated infrastructure on the USV, the idea of an additional anchor was dismissed. Likewise, using no anchor for the system at all was considered non-functional. Thus, it was decided that the basket would to be used as an anchor to maintain the position of the entire system.
Since the SeaClear system aims to keep the harm to local flora and fauna to a minimum, ideas were discussed to reduce the effect of placing the basket on the seafloor. In addition, the five test sites show very different sea bed compositions, and therefore present uneven terrains. One idea was to add a compartment underneath the basket fillable with some liquid or gas that could adjust the seabed even in rocky or angled terrain, thus providing an even positioning of the basket. However, fluid management would have presented considerable effort and substances would have needed to be stored on board the USV. Similarly, while a gel-filled membrane or memory foam bottom would have been able to circumvent most of these problems, but the adjustment would always be dependent and limited by the thickness of the bottom layer. As an alternative, the possibility to dangle the basket on the tether cable was briefly discussed , therefore, not disturbing the seafloor at all and being independent from the ground structure. Yet, this would present great difficulties for the ROV approach under strong current conditions and would lead to an unfavorable weight distribution of the surface system. Hence, it was decided that no adjustment would be included in the basket design and the ROV would still be able to successfully enter the interface. In addition, the expected impact to fauna caused by basket positioning was deemed acceptable in exchange for cleaning up litter from the ground.
For the interface between the ROV's gripper and the basket, five different options were considered: 1. a simple opening with no cover for the gripper to enter and exit trough, 2. elastomer lips covering the opening area but flexible enough to enable gripper movement, 3. a spring hatch that opens with the pressure of the entering gripper, 4. a bio-inspired opening mimicking the baleen of baleen wales, and 5. an electrical opening what opens upon approach

of the gripper. The simple opening with no cover was dismissed since it would allow litter to independently float out of the basket or being driven out by current or the ROV motor's turbulances after being collected. Furthermore, the electrical opening was rejected on the basis of the additional power requirements this interface would entail. In addition, creating a waterproof opening system that will continue to perform despite high amounts of suspended particles in the water as observed at the Hamburg test site seemed rather complex. Since it was not possible to choose the most appropriate interface out of the remaining three based on considerations and assumptions alone, experiments were conducted to determine the best performing one. Hence, the interfaces and their function are described in more detail below (Section 4.1).

The same interface options were also considered for the suction tube. However, since the development and therefore specifications on the location and size of the tube and thus, the design requirements of the corresponding interface were initiated only towards the end of the WP, no testing could be conducted. It was later on decided that the tube would use the same interface as the gripper and would not collect smaller sized debris that would justify the necessity of a separate compartment with a smaller mesh size.

Table 2: Basket Parameters and all identified ideas for each gathered in a Zwicky box to assess advantages and limitations of each idea and chose the most appropriate ones.

Feature	Ideas	PROS	CONS
Basket Shape	square / rectangular	• fits to the back of the USV	• recovery orientation matters
	round	• uniform, recovery orientation irrelevant	• difficult to manufacture
	streamlined	• less resistance to currents • automatic litter movement into the basket along current	• effects are highly directional
Basket Transport Position	pulled behind USV in water	• allows for higher payload and size of basket as no restrictions apply	• weight of pulling the basket through water is large
	on board USV	• better control over USV center of gravity and behavior	• limited basket payload • system for launch and recovery required
Location Maintenance	basket anchoring	• basket acts as anchor to maintain USV position • no additional anchor needed • maintaining the position during entire mission	• increased basket complexity and function • impact on local fauna and terrain • possible sinking of bottom structure into seabed
	use a conventional anchor	• proven concept for location maintenance • no impact on local flora	• added weight to the USV structure • added rope management complexity

Table 2: Basket Parameters and all identified ideas extended.

Feature	Ideas	PROS	CONS
	No anchor	• no impact of local flora	• no position maintenance during mission • continuous re-adjustment of USV position required
Terrain Adjustment	fluid volume adjustment bottom	• highly compliant adjustment to angled or rough terrain	• pressure and substance storage problems
	memory foam bottom	• good terrain adjustment depending on seabed structure	• adjustment range constrained by foam width
	suspended from tether	• straight position of basket • no impact on local flora	• susceptible to current flow • constant pressure on tether cable
	no adjustment	• lower basket complexity	• possibly angled position
Gripper-Interface	simple opening	• low complexity and low-tech	• risk of deposited litter escaping the basket • access for marine life to swim into the basket accidentally
	elastomer lips	• compliant opening preventing the escape of litter	• size limitations due to material integrity
	spring hatch	• low complexity and low-tech • established solution for many applications	• size limitations due to spring attachments • danger of gripper getting stuck if springs are too strong • springs susceptible to entanglement with algae / local flora
	baleen-inspired interface	• innovative and compliant opening	• orientation of individual baleen structures not controllable • difficult to get through
	electrical opening upon approach	• reliable option to create a large opening for approaching gripper	• higher complexity and controls • higher power consumption
Connection Suction Tube	simple opening	• low complexity and low-tech	• risk of deposited litter escaping the basket

Table 2: Basket Parameters and all identified ideas extended.

Feature	Ideas	PROS	CONS
	spring hatch	• simple and low-tech • established solution for many applications	• danger of tube getting stuck if springs are too strong • springs susceptible to entanglement with algae / local flora
	baleen-inspired interface	• innovate and compliant opening	• spaces between individual baleen structures potentially too large to contain small-scale debris
	electrical opening upon approach	• reliable option to create an opening for approaching tube	• higher complexity and controls • higher power consumption

4 Small-Scale Basket Prototype and Preliminary Experiments

As a first step of the basket development, a smaller sized prototype basket cube with 0.5 m side length was built as shown in Figure 3A) that would allow easier handling and provided the possibility of trying various basket configurations. This way, different interfaces and their position could efficiently be altered upon demand, allowing for simple experimentation of design iterations under consideration of different design requirements.
The basic cube structure of the basket was made from aluminum profiles providing stability and great manufacturability during the development process. Furthermore, a mesh grid with a mesh size of 13mm was attached to the frame using customized grid holders as presented in Figure 3C). While these were sufficient during the experiments, they were later exchanged for a more permanent and reliable solution (see Section 5).
Each interface concept was designed and manufactured using 3D-printing, allowing for a rapid and simple prototyping approach. Afterwards, they were tested above and below water, using a manually operated gripper depicted in Figure 3B), down-scaled to match the size of the basket prototype. The basket was placed on a lowering platform as shown in Figure 4 and submerged under water with cameras attached in various places to show the side of the basket, the interfaces from below and the deposition process from the gripper's perspective to deliver information on any problems or constraints. To test the interface's functionality, the gripper was filled with different litter objects of varying density and size and then pushed through each interface multiple times, simulating the proposed litter deposition process of the ROV. Factors that were evaluated included successful penetration with the interface with the gripper, successful deposition of the litter contained within the basket, and successful retention of litter already inside the basket.

4.1 Interface Design Challenges

The challenge for the interface between the ROVs gripper and the basket was to ensure a safe transfer of the litter without it escaping or even creating new, and possibly smaller litter pieces in the process. Hence, the gripper needed to be fully enclosed by the basket before opening.
Different types of litter were tested to investigate the interface's capability of coping with various hydrodynamic behaviours of the litter, which included glass and plastic bottles, cans, plastic cups, plastic bags, aluminum parts, and masks. During the experiments, it became clear that high-density objects such as glass bottles were the easiest to deposit, since they would immediately sink to the bottom after being released by the gripper. Floating litter and buoyancy-neutral litter (mostly plastic pieces) presented more of a challenge for a reliable retention within the basket. Thus, mechanisms were required that account for most possibilities to ensure a successful transfer into the basket without accidentally pulling litter out of the basket again together with the gripper. As mentioned above, three different interface concepts shown in Figure 5 were tested during the experiments: a spring hatch interface, a baleen-inspired interface, and a compliant elastomer interface.

Spring Hatch Interface
The first iteration of the hatch interface had one flap with an area slightly bigger than the gripper base area and was fitted with two springs on one side to be pushed open by the approaching gripper, as shown in Figure 6A) and B). During the first experiments, it was observed that the gripper could easily enter the basket and deposit the collected litter. However, when inserting the gripper fully into the basket, the hatch closed around its thinner part, thus preventing the gripper from being removed as the hatch only opened one way. To cope with this design flaw, the gripper was only inserted halfway through the interface and opened in this position, depositing most of the litter successfully without opening all the way. Larger pieces of litter, however, remained inside the gripper and were not deposited. Moreover, buoyant or buoyancy neutral litter often remained at their position of release. Thus, when the gripper was closed after the deposition process, the litter would be collected again and removed from the basket through the gripper.

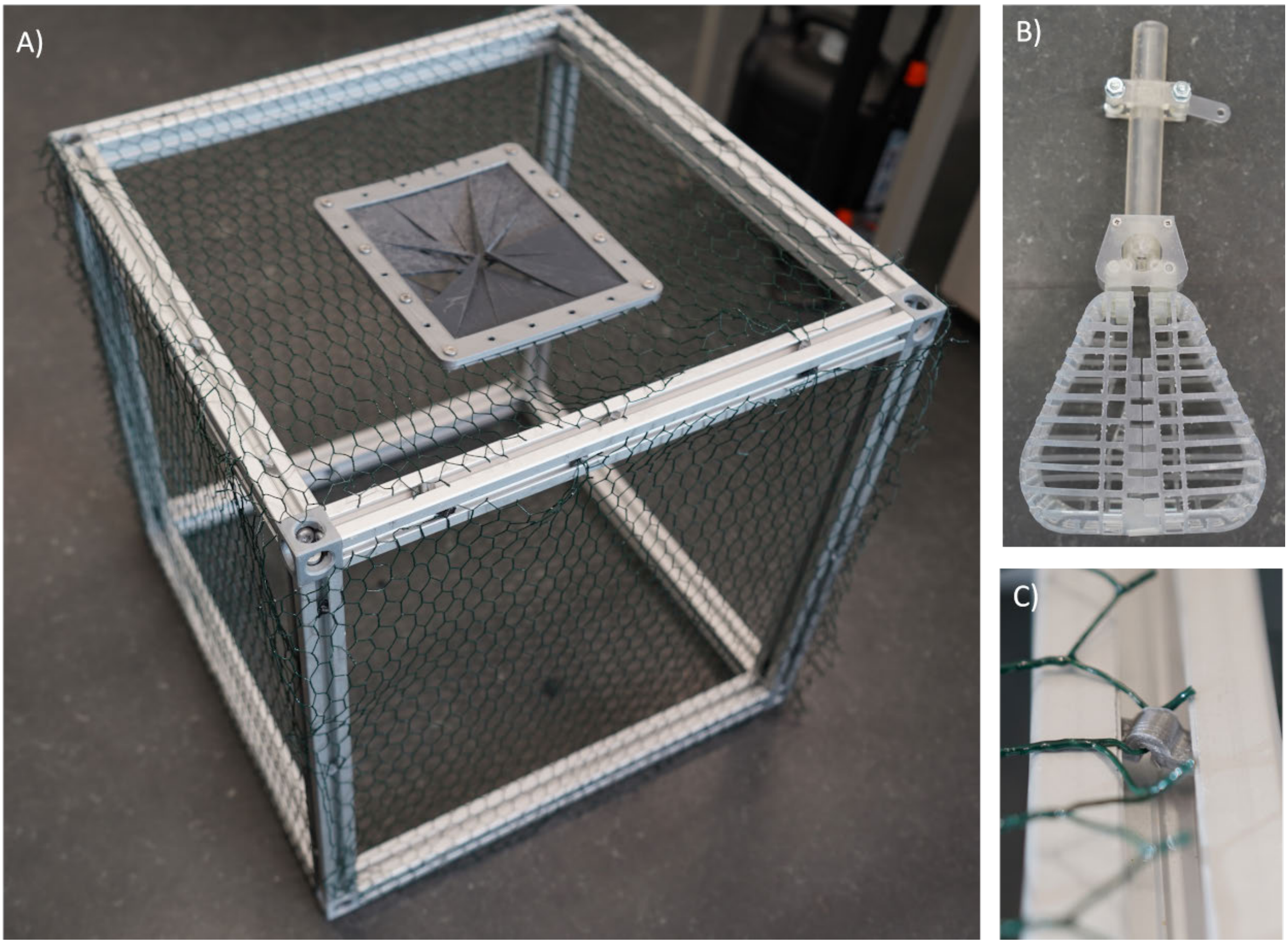

Figure 3: A) Photograph of the small prototype basket used for the conceptualization and testing of different interface variations, B) down-scaled manually operated gripper prototype, C) 3D-printed insert attachment of the set to the basket frames (enlarged).

First Re-Iteration of the Hatch Interface After the first tests, the interface was adapted by using springs of less strength and splitting it into two flaps that could open upon the grippers touch instead of only one presented in Figure 6C). The flaps opened parallel to the gripper's halves like the first spring hatch design, which distributed the forces from the two hatch flaps evenly over both sides of the gripper. Hence, it was assumed that the gripper would have an easier time entering and exiting the interface. Nevertheless, the same difficulties were observed as with the first design iteration.

Baleen-Inspired Interface

The biomimetic baleen whale inspired interface design consisted of elastic straps mounted on a 3D-printed structure at their ends. The elastic straps (70% PES, 30% Nylon) were 60mm wide, 2.5mm thick and cut into strips of 200mm length. To hold these strips into place, 3D-printed mounting structures were designed to be arranged in parallel with a 10mm distance between them, as depicted in Figure 7. Hence, the strips were connected on both ends to restrain their rotational motion.

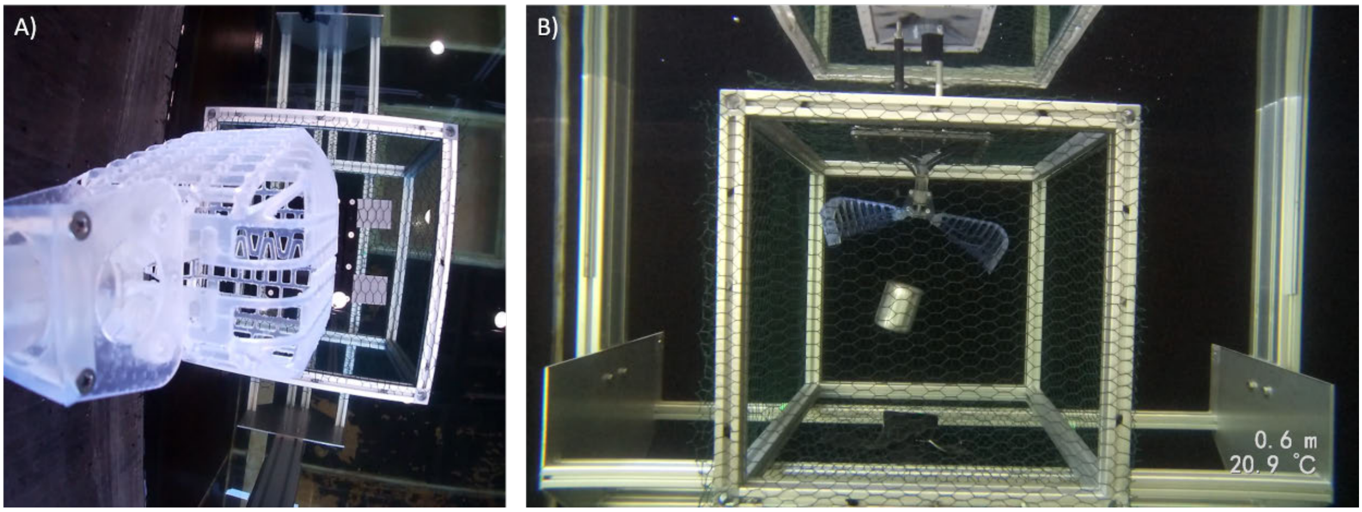

Figure 4: Photographs of the test setup taken during the experiments conducted with the small prototype basket. A) Down-scaled gripper fitted with a camera to observe the interface approach and detect problems during the deposition process, B) side view of the deposition process with the gripper inside the basket.

During the first tests performed with this configuration of the biomimetic baleen interface, several problems were observed. When trying to push the gripper through, the straps closest to the center did not converge to the sides. Instead they rotated by about 90, creating a wider surface covering the opening, thus preventing the gripper to push past and get into the basket. The deposit attempt was repeated after straightening the individual strips by hand, however, the gripper was still not able to enter. When manually pushing the strips in the center aside, the gripper entered the basket, but the same problems occurred when trying to remove it and it got stuck again. Nevertheless, it was possible to push certain types of litter through the interface without the gripper entering the basket itself. This was easiest with litter that would naturally sink to the bottom of the basket (aluminum cans, glass bottles). The deposit of buoyant or buoyancy-neutral items presented more difficulties since small litter pieces floated past the baleen interface and out of the basket.

First Re-Interation of the Baleen Interface In order to avoid the rotation of the straps and keep them from turning onto their flat side, the width of the mounting structures fixing the individual straps in parallel position was increased to connect and attach them over the entire length of both endings. Unfortunately, this alteration did not improve the ability to push litter through into the basket. The strips still had enough elasticity to rotate. Hence, alterations like decreasing the spaces between each strip to reduce the possibility for litter to float out, and using less-elastic material to reduce their rotation were considered. Yet, since both would make the entry of the gripper even more difficult, the idea was not further pursued.

Compliant Elastomer Interface
The elastomer interface was made by printing a 3.5mm thick plate with a flexible resin using an SLA 3D-printer. This plate was then sliced into lips and attached to the same frame as the other interfaces. This interface was the easiest for the gripper to enter due to the compliance of the lips without the application of a lot of overhead force. Hence, high-density litter was easily deposited in the basket and the gripper was removed without difficulties. It was noticed, however, that the gripper must enter the basket fully to prevent any litter to escape. Otherwise, the elastomer lips would be facing downwards unable to bend the other way, thus allowing an easier exit when the gripper was retracted. Furthermore, it was not possible to deposit buoyant materials as they stayed within the gripper area and pulled out of the basket once the gripper closed around them again.

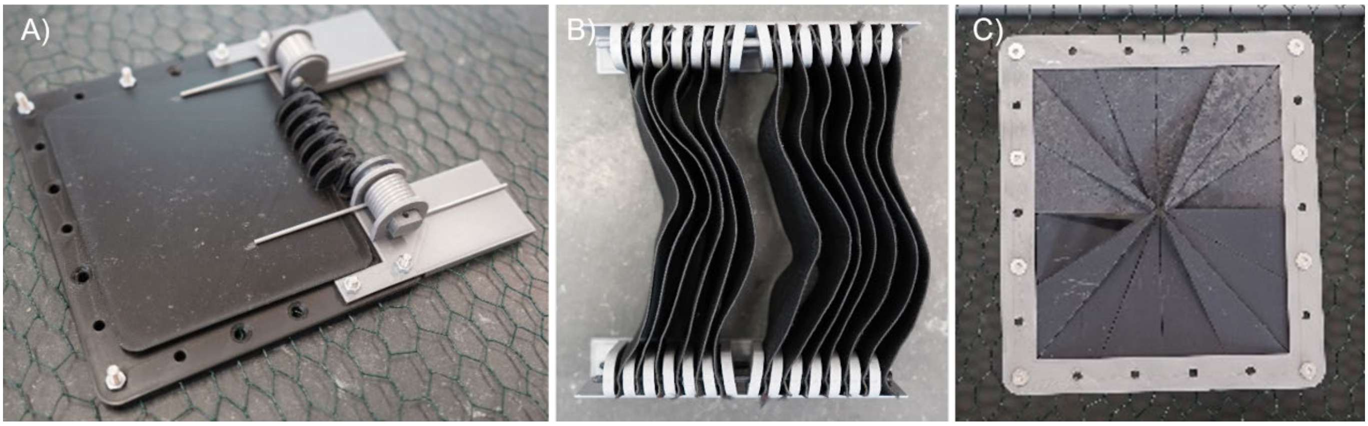

Figure 5: Photograph of the three different interface iterations tested during the prototyping phase of the basket design. A) Photograph of the spring-hatch interface, B) Baleen-inspired interface made from wide rubber strips, C) Photograph of the flexible elastomer lip interface.

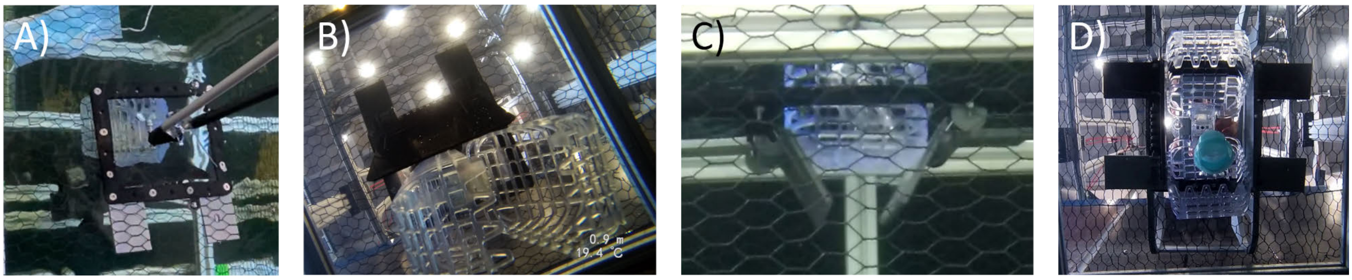

Figure 6: Photographs of the 'hatch' interface during testing. A) Top view of the manually operated gripper inside the interface with the hatch pushing on the two halves and preventing an easy retraction of the gripper, B) Bottom view of the gripper being stuck due to the hatch flap, C) Side view of the second hatch design iteration with two flaps opening while the gripper enters the interface, D) Bottom view of the third iteration of the hatch interface with the two hatch flaps opening perpendicular to the gripper halves.

Several limitations regarding the ROV system and gripper were identified that influenced the interface design significantly. Due to the growing concern that the ROVs localization and navigation accuracy would prohibit a precise maneuvering into the interface with the exact dimensions as the gripper, the interface would have to allow for some offset in arrival of ROV and gripper. This would allow the gripper to enter the basket even if the positioning was not perfect.
In addition, small buoyant objects presented an issue since they continued to float to the highest point of the opened gripper halves instead of staying suspended in the water column. Therefore, there was no way to successfully remove them. In an attempt to deal with the floating litter and reduce this problem, two main concepts were discussed, which are described in section 4.2.

To tackle the offset arrival issue of the ROV, both interfaces were revised in a second re-iteration. The hatch interface was made bigger and adjusted by rotating the flaps so that they open perpendicular to the gripper halves as depicted in Figure 6D). Furthermore, the springs were exchanged by ones capable of achieving an angle up to 180. This fixed the problem of the gripper getting stuck in between the flaps. Still, in this configuration, the hatch pushed directly against the opening direction of the gripper, causing it to struggle to open even when operated manually.

Figure 7: Photographs of the 'baleen' interface during testing. A) Top view of a can positioned right over the interface, B) Side view of the gripper trying to push through the interface but being restrained by one of the elastic strips, C) Bottom view of a can being successfully pushed through the interface without gripper.

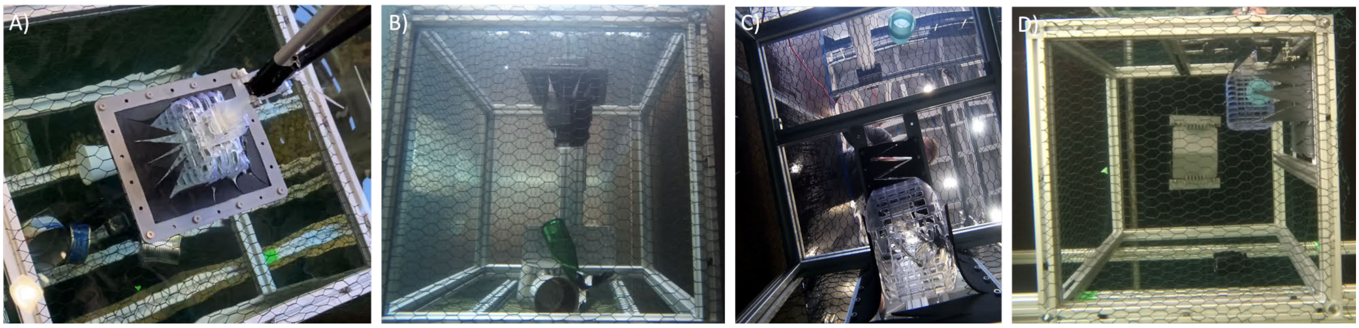

Figure 8: Photographs of the 'elastomer lips' interface during testing. A) Top view of the manually operated gripper exiting the interface, B) Side view of gripper depositing a bottle through the interface, C) Bottom view of the side-top approach with rubber lips on the sides and top while the gripper is entering, D) Side view of the side-top approach while the gripper is entering to deposit a plastic cup.

Similar problems were anticipated to occur with the real-sized ROV and gripper.
The elastomer interface was also made bigger and the lips were replaced by pieces cut from a 3mm thick rubber mat due to restriction of the printer's building platform and volume.
The deposition worked as well as in the first round of experiments and the larger interface allowed for some offset in ROV position upon arrival. Yet, the buoyant litter still presented an issue for both interfaces. In addition, the final ColROV setup and the position of the gripper inside the skid was finalized during the testing of the interfaces. Hence, according to the new setup, the gripper is perfectly aligned with the bottom of the skid after opening the it completely to about 180. Therefore, it sits completely inside the skid as depicted in Figure 15, creating a problem for both interfaces, since this prevented the gripper from opening all the way. A possible solution for this problem could have been building an even bigger interface to fit the entire skid rather than only the gripper. However, it was thought that this result in a high risk of deposited buoyancy-neutral litter to escape the basket.
Instead, the position of the interface on the basket was revised and changed to a sideways approach in order to cope with the position of the gripper inside the skid as well as depositing buoyancy-neutral litter. Since the elastomer interface presented the most promising results, it was the chosen concept to test the new position of the interface. Hence, the lips were not only attached at the top of the basket but extended to one of the top's edges and covered half of a side on the basket as depicted in Figure 9. Hence, the ROV would move the gripper into the basket from the side, all the way to the end of the interface, open and release the litter, then move towards the the exist a little before closing

to avoid re-collecting deposited litter, before finally existing the basket. This approach worked quite well and it was possible to deposit most types of litter. Furthermore, custom 3D-printed curved profiles were made to attach to the remaining frame of the basket and hold the rubber lips using 3D-printed profile inserts. The curvature in the profiles enabled a wider field of entrance for the gripper on the side and automatically guided it towards the center of the interface. Therefore, positioning errors could be mechanically adjusted.

One problem observed with this interface iteration was the slight bending of the rubber lips through the pull of gravity. The rubber material's characteristics and their structural integrity did not hold up the own weight of the longer lips. Furthermore, based on the anticipated position and orientation control of the ROV (pitch, yaw, roll), the interface should pose little resistance to the approaching ROV to prevent influencing its orientation. Therefore, simply choosing thicker rubber or exchanging it with more rigid material was not an option. Instead, the rubber lips were exchanged by lightweight and flexible plastic bristles, sturdy enough to remain straight when attached horizontally but compliant enough to permit the gripper to enter.

Since the bristle approach proved most successful during the basket prototype tests, it was adapted and implemented in the final basket design. During the first tests of the basket, ColROV, and the approach process during the Hamburg trials in May 2022, plastic bristles were used to simulate the interface. It was determined that, while the interface concept was valid, the stiffness of the bristles was too large to allow the gripper to enter successfully, propelled by the motors of the ROV. Instead, due to missing pitch control, the ROV continuously tipped over, making an entry very difficult. Based on these results, the interface was adapted to include less stiff natural fibers, which do not only present a better ROV-entrance but are also better for the environment. Delailed description of the interface is presented in Section 5.

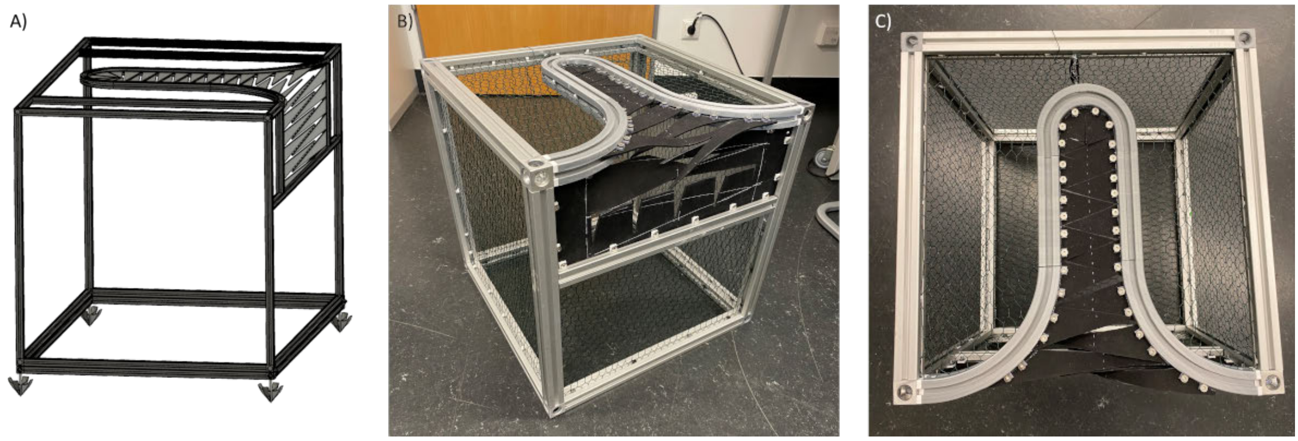

Figure 9: Presentation of the side-top approach. A) 3D-model of the interface design, B) front view and C) top view of the interface made by 3D-printing curved profiles to hold the rubber lips in place.

4.2 Removing Buoyant Litter from Inside the Gripper

One challenge identified during the first prototype tests was that buoyant or buoyancy-neutral litter would remain within the halves of the gripper and therefore would be removed from the basket when the gripper exited. Hence, two main options were investigated to ensure that floating or buoyant litter were removed from the grasping area of the gripper. Since the basket was supposed to have few electronics and thus low power consumption, only passive mechanical options were considered which could be operated through gripper movements alone.

The first option consisted of curved spikes of descending height attached along the rim of the interface and bent towards the opening as depicted in Figure 10A). These spikes were envisioned to move through the mesh of the gripper halves and push collected litter downwards, away from the grasping area. Hence, they were printed in PLA with 8 different sizes dependent on the distance to the center of the Gripper and attached to a tarp to hold them in place,

yet enabling them to movement enough to find their way through the gripper mesh and avoid fractures. The tarp was connected with small ropes to four the corners of the prototype basket as well as along the opening in the middle.
During the experiments conducted with the scaled-down version of the gripper, it was determined that fitting the spikes through the mesh opening present difficult. Furthermore, the spikes did not sufficiently move the litter out of the grasping area even if they made contact with the collected item. Instead, it was simply moved around. In addition, small floating items such as bottle caps (diameter: 5cm, height 1.5cm) were especially hard to remove since they tended to travel towards the highest point of the opened gripper, yet the spikes were only reaching the lower part of the gripper mesh, as no spikes could be attached in the middle of the interface at the top of the gripper halves.
Thus, a second removal option was tested. This time, instead of spikes, the force of multiple small water streams were conceptualized to push the litter out from under the grasping area of the gripper. The idea was to attach two compartments on either side of the interface with multiple nozzles that would squirt water upon pressure applied through the opening gripper halves. Thus, due to the motion created in the water, buoyant litter was theorized to be pushed out. To conduct preliminary tests, the small-scale gripper was placed into the test chamber and holes were drilled into the curved sides to hold five syringes on each side, mimicking the squirting water from above the opened gripper halves as shown in Figure 10B).
This setup was tested with different kinds of litter as well as varying water stream angles and flow rates. The best results were achieved by emptying all syringes simultaneously and facing as far up into the gripper as possible. The litter moved towards the opening of the gripper, but the water streams did not last long enough for the litter to reach it and escape the grasping area. Instead, after the syringes were emptied the buoyant litter rose up into one of the gripper halves once again. In addition, the litter positioned at the very top of the gripper was only slightly effected and did not move to the opening.

Since both options presented unsatisfactory results, they were dismissed. Instead, it was concluded that most of the litter collected by the ColROV would be heavy enough to sink to the bottom as they had settled on the bottom before. Hence, the deposition process could achieve a sufficient success rates to still generate a positive outcome of the mission. In addition, according to the new side-top interface approach, the gripper would open to deposit the litter in the basket, and is kept in this position during the ROVs sideways or upward retreat out of the basket. In case buoyancy-neutral litter was originally weighed down by seabed silt and sludge and thus appears to be floating after deposition, the gripper would be removed in open position to avoid the risk of accidentally pulling this kind of litter back out of the basket. It was further assumed that the local water turbulence created by the motion of the ROV's motors would suffice to move the litter away from the interface opening.

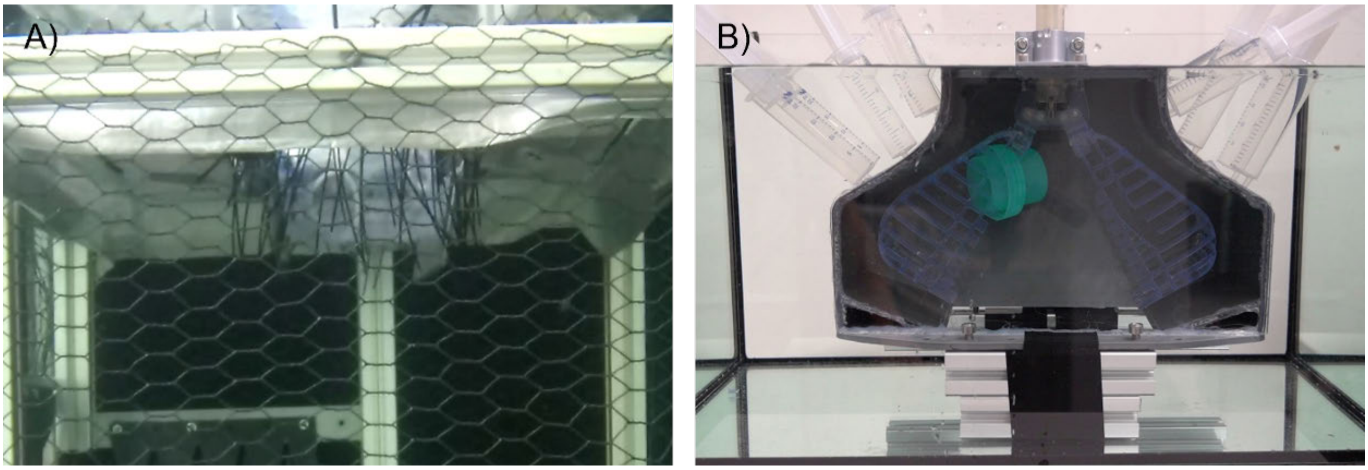

Figure 10: Photograph of the two options investigated to remove buoyant debris away from the gripping area of the gripper once litter is deposited in the basket. A) Passive spikes attached along the rim of the interface that are flexible enough to push through the opening on the gripper and push collected litter downwards away from the grasping area, B) passively actuated water streams that blow the litter out of the way by squirting water through the openings of the gripper halves.

5 Final Basket Design

The hardware, electronic and software components unified in the collection basket were designed and selected based on the aforementioned design requirements and parameters. However, while the final state of the design is described below, several design iteration have taken place, continuously adapting components to newly acquired challenges and constraints. Similarly, the design presented below may not present the most ideal concept for all applications but fits very well into the scope of the SeaClear project and associated demands. Nevertheless, the SeaClear system still needs to be deployed in the five demonstration sites and its effectiveness has to be verified.

5.1 Hardware and ROV-Basket Interface Design

The general shape for the final SeaClear basket design was chosen to be a rectangular hexahedron with the dimensions of 1.5 x 1 x 1.2 m to efficiently occupy the designated space on the USV shown in Figure 2, while allowing for the largest basket volume possible (under consideration of mass and payload restrictions). In addition, this shape also presents a high stability on the sea floor and provides large surfaces for the ROV-Basket interfaces. The frame was made from aluminium profiles that can easily be built into a sturdy construction but are simultaneously modular to dismantle and possibly adjust the design. Inbetween the individual profiles, a net with a mesh size of 2 - 3 cm was attached to retain the collected litter while allowing smaller fauna to escape. During the Hamburg trials, the net was fastened to the profiles using 3D-printed inserts tailored to the cavities in the profile as depicted in Figure 11. The net was pushed through the insert narrowing and additionally secured in place using a screw and a nut. Afterwards, the inserts were replaced with screws and hammer nuts as depicted in Figure 12 to provide a quicker and more sturdy alternative to the 3D-printed inserts.

holder inserts.png

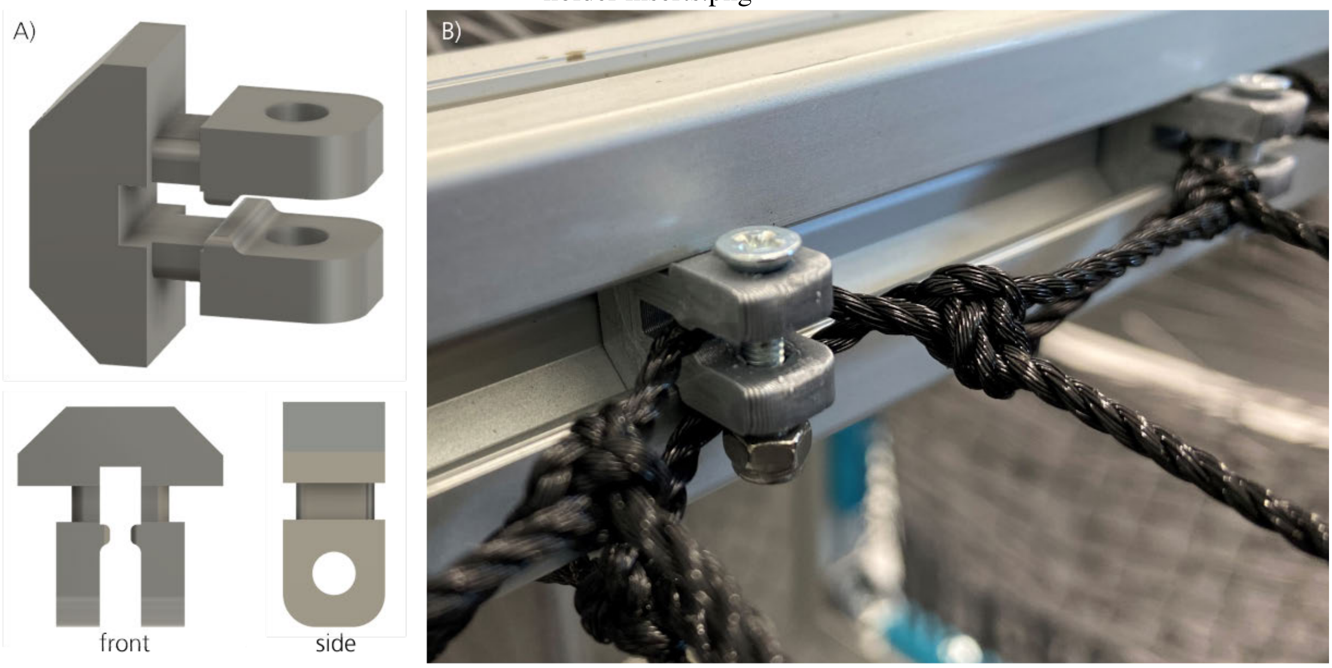

Figure 11: Net holder inserts. A) CAD drawing of the inserts, B) 3D-printed inserts holding the net inside the profile cavity.

(49).png 

Figure 12: Photograph of the final net holders attaching the net to the profiles.

The interface was designed in a way that would allow the ROV to approach from above and the front. While an omni-directional approach would have been preferable to reduce the complexity of the steering requirements, this would have meant a greater risk of entanglement between the ColROV tether and the basket rope. Therefore, the approach direction was restricted to the front and top, and openings inside the mesh structure were created. The width of the openings was tailored to the dimensions of the gripper of ca. 24x20x24cm (WxLxH) and ranged over the entire depth of the basket surface. On the front of the basket, the length of the opening was also constrained to the gripper dimensions to leave little room for collected litter to escape. While the openings were restricted to the size of the gripper, the frame was adjusted in the front to form a funnel-shape, connecting the front opening situated about 50cm inside the basket to the two corners. Hence, when the gripper makes contact with this part, it is automatically led into the middle of the basket and therefore to the opening. The same structure was duplicated above the basket top as a guiding rail with a slightly larger width to match the dimensions of the skid. Hence, in case of very bad visibility conditions that do not provide a usable camera feed, the skid can be used to 'feel around' for the interface, being automatically guided towards the opening through the shape of the guiding rail. Since the closed gripper is located below the skid and ROV and partially inside the skid (about 2cm of the top), it was difficult to find a solution that would permit the gripper to open all the way, while the litter stayed within the basket. The bristled opening cover provided the opportunity to retain the litter inside the basket even when the gripper halves open 180, thereby leaving the interface at the top. This eliminated the risk of the gripper accidentally pulling litter out of the basket again during its way to the exist of the interface. Instead, the gripper remains open during the ROV exit and ready for the collection of the next litter object.
The bristle design for the final basket were specifically manufactured to fit the cavities in the aluminum profiles that

make up the frame of the basket as depicted in Figure 13. Using an epoxy resin and a molding process, different amounts of fibres were attached to the inserts to test different stiffness. In addition, the fibres of choice were natural bio-based fibres to present an environmentally friendly alternative that would not produce further litter in case single fibers broke off during the deposition process.

interface.png

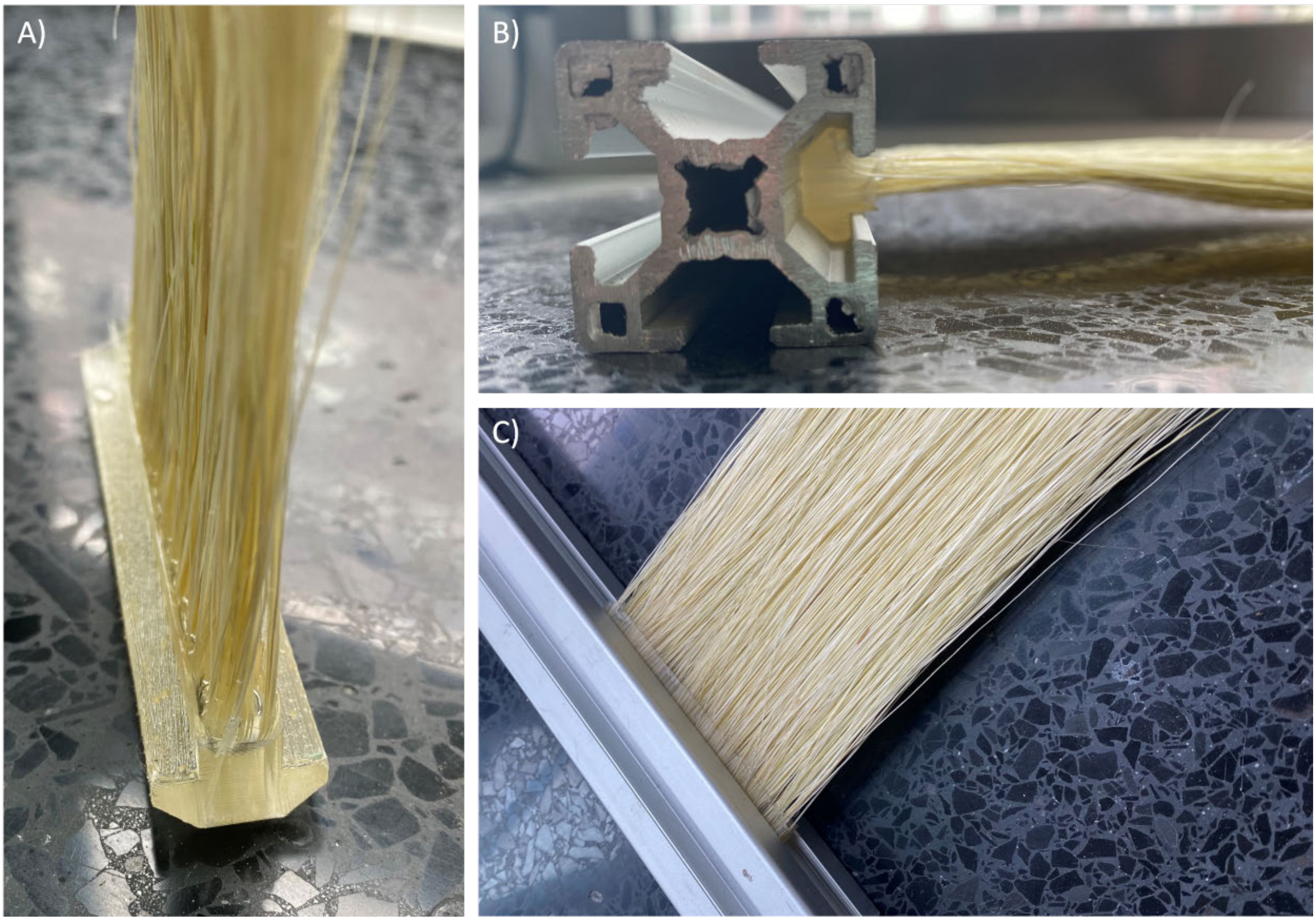

Figure 13: New interface manufactured with epoxy resin and natural fibers. A) Fibers incorporated into the epoxy resin, B) fibers fitting perfectly into the profiles, C) fibers in horizontal position.

5.2 Basket Launch and Recovery System

Due to the high complexity of the cable or tether management of the deployed robotic systems of the holistic SeaClear solution, it was decided that the basket would only be attached to the USV via a single tether. The tether is rolled up on a winch system that is located on top of the roof of the ColROV housing as indicated in Figure 17B). From there, the tether is fed over a pulley system on an arm extending beyond the back of the USV and connects to an arm on the basket. As an intersection between the tether and the basket, an arm was added by attaching it to both sides of the basket in order to provide the opportunity to move the tether away from the interface while the basket sits on the seafloor. To do so, the motion of the arm was restricted in all but one direction as shown in Figure 17C), and, with the help of a weight, pulled to the back of the basket once the tension is released from the tether. Therefore, the risk of entanglement between the basket's and the ColROV tether is reduced as well as preventing the cable from floating within the area of the interface, which is presented in Figure 17D).

+ descriptions.png

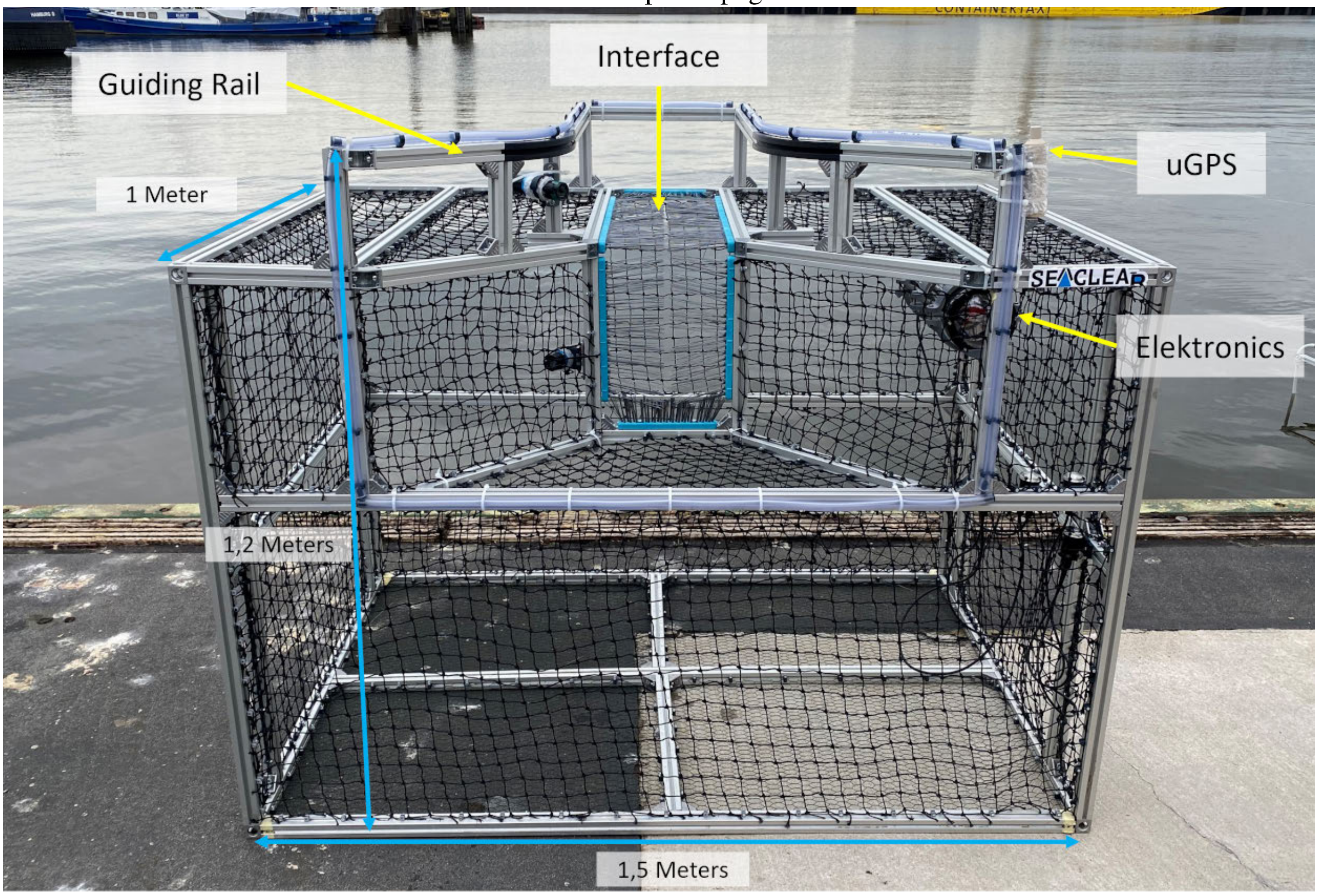

Figure 14: Photograph of the basket during the tests of the Hamburg Trials in May 2022. The interface shows the guiding rail as well as the plastic bristles that were later exchanged with the natural fibres.

5.3 Basket Electronics and Software Design

The objective of the electronics included in the basket design was to compute the basket's position (latitude, longitude, depth) and orientation angles (X, Y, Z). This information is crucial for the ColROV during its approach towards the basket in order to find the interface opening and properly position itself inside the basket. Underwater localization is tricky due to low bandwidth, high delay in propagation, and high error rate of the acoustic channel[3]. Therefore, the first step was to find suitable sensors that could be combined to achieve the objective. In order to allow for a precise localization of the basket without relying on the ROV's own sonar, several other sensor systems were included and their outputs merged to reduce approach inaccuracies.

A barometer was used to determine the depth of the interface (z position) underwater relative to the water surface. This data was combined with the that generated by an underwater-Global Positioning System (GPS) system. The underwater-GPS uses acoustic signals that are transmitted to four receivers located just below the water surface attached to the USV as depicted in Figure 26. These receivers send the signal to a positioning computer, which uses triangulation to determine the basket's position with a resolution of about 7 meters. This information in particular can be used to measure the position of the basket relative to the USV. An Inertial Measurement Unit (IMU) can directly de-

[3] Su et al. (2020) A Review of Underwater Localization Techniques, Algorithms, and Challenges, Journal of Sensors, (https://downloads.hindawi.com/journals/js/2020/6403161.pdf)

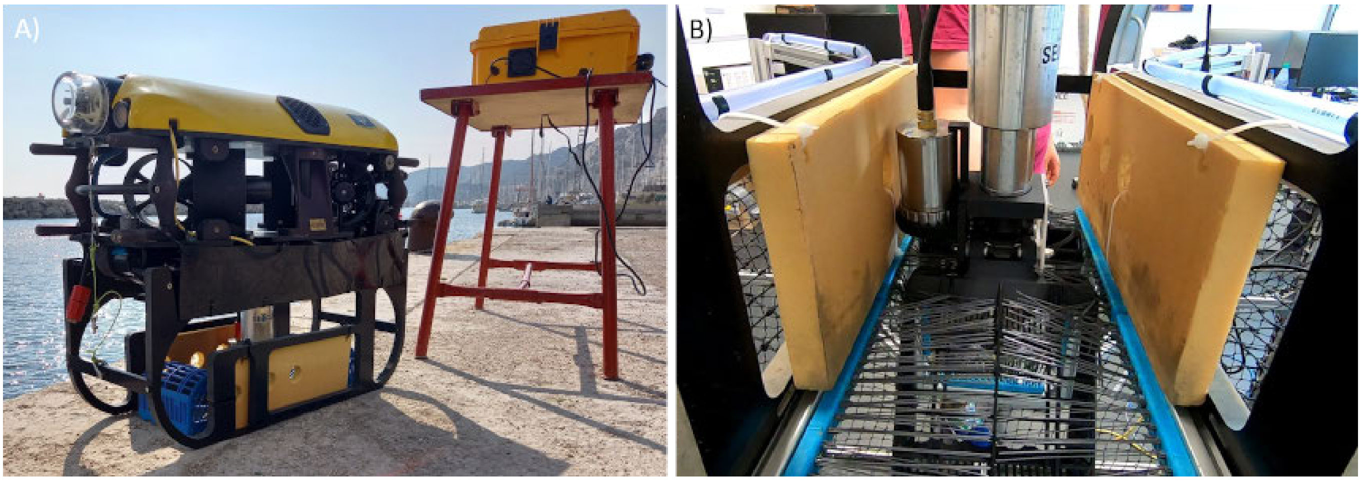

Figure 15: Photograph of the ROV with the skid and gripper in the basket. A) Full ROV setup with skid and open gripper, B) ROV setup positioned in its designated spot on the basket with the gripper submerged within the interface.

Table 3: Basket Parameters.

Parameter	Quantity & Unit	Additional Info
Mass (dry)	50 Kg	maximum weight to guarantee sufficient payload capacities
Dimensions	1.5 x 1 x 1.2 m (L x W x H)	perfectly filling up the space at the back of the USV
Interface	1	manufactured from natural fibres and epoxy resin to fit the cavities in the aluminum profiles, enabling the entrance of the ColROV with closed gripper while retaining already collected litter
Tether cables	1	connected to a special arm attached on the top of the basket to launch and recover the basket during a mission

termine the angular velocity as well as the linear acceleration of a system (about the x, y and z axis) and can therefore create estimations of missing states based on the raw noisy and discontinuous sensor measurements using appropriate filtration and sensor fusion techniques. Furthermore, it indirectly computes its own orientation when Madgwick or complementary filters are applied to the direct readings of the IMU. Lastly, an extended Kalman Filter can be used to fuse the acceleration data from the IMU to smooth down the position reading coming from the underwater-GPS, so that the robot-localization Robot Operating System (ROS) package can be adapted to tackle sensor fusion and state estimation problems. Hence, when combining an underwater-GPS with an IMU as well as an extended Kalman-Filter, the localization resolution can be improved to approximately one meter and can be used for the far- to medium-range approach of the basket. In addition, during the Hamburg Trials, it became apparent that the ROV's sonar can be used in even bad visibility conditions (high amounts of particles and suspended solids) to determine not only the basket's location from about 30 meters away but also clearly identify the orientation of the interface based on the imagery.
For the close-range approach (ca. 1 meter), the localization resolution needed to be further improved to achieve a successful arrival of the ROV every time, especially during a fully autonomous operation of all contained subsystems and robots. Therefore, lights were attached asymmetrically on the basket so that they are visible to the ROV camera during a top and side approach. Using image processing, these lights can be used to further deduce the orientation of the basket and therefore identify the opening on the basket. Moreover, Aruko-markers were attached on the front of

Figure 16: Photograph of the new interface with natural fibres for a more environmentally friendly alternative to the plastic bristles, A) top view, B) front view.

the basket at the height of the guiding rail for the front-facing camera on the ROV and determine in which direction the interface is situated. One additional Aruko marker was added on the back of the basket at the height of the ROV's front-facing camera when it has reached its designated position, giving the ROV an indication that it can safely open the gripper to deposit the litter. Together with the mechanical guiding rail implemented on top of the basket, the data are sufficient to navigate the ROV into the basket interface.

All of the information collected from the electronics and sensors contained in the basket were sent to the USV via tether cable, which processed and transmitted the position to the ColROV. The electrical circuit for the electronic integration is depicted in 18A). All of the water-sensitive parts are contained within a water-tight tube as shown in Figure 18B) to D).

Table 4: List of components incorporated in the basket electronics and their specifications.

Component	Quantity	Description	Type and Brand
Mass (Dry)	50 Kg	maximum weight to guarantee sufficient payload capacities	-
Pressure sensor	1	to determine the distance between the surface and the basket underwater for localization purposes	BlueROV Solution Bar30 High-Resolution 300m Depth
underwater-GPS	1	to determine the underwater-GPS data sent to 4 receivers attached to the USV just below the water surface	WaterLinked G2 Kit, Locator U1
IMU	1	to measure the baskets acceleration, angular velocity and orientation using the combination of the sensor's accelerometer, gyroscope and magnetometer	TDK MPU9250 and ST LSM92S1
Lights	6	to increase the visibility of the basket for long-range approach and to confirm orientation through asymmetrical placement	BlueROV Solution Lumen Subsea Light for ROV/AUV
Camera	1	to enable the operator / user to observe the deposit process, determine the available basket capacity during a mission and identify potential problems	SubSea Tech UVS100RL Underwater Camera
Aruko markers	5	to improve the close-range approach accuracy by the ColROV through image processing	3D-printed

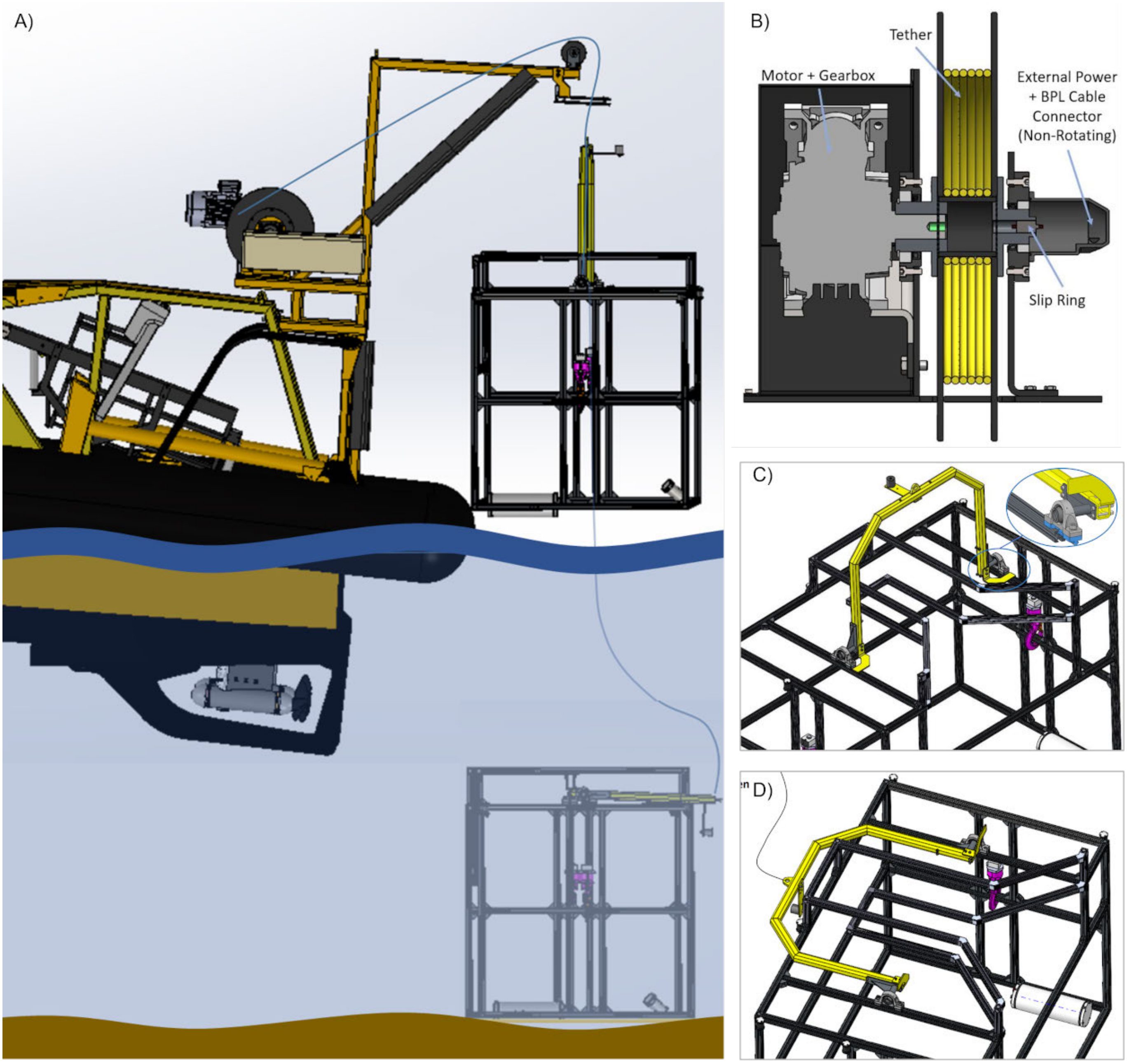

Figure 17: Sketch of the designed LARS system behind the USV. A) Sketch of the LARS system used to launch and recovery the basket to and from the seafloor, B) drawing of the winch responsible for winding the tether cable, C) Basket arm and connection between LARS and Basket, D) position of the basket arm while the collection process in ongoing and no tension is applied to the tether.

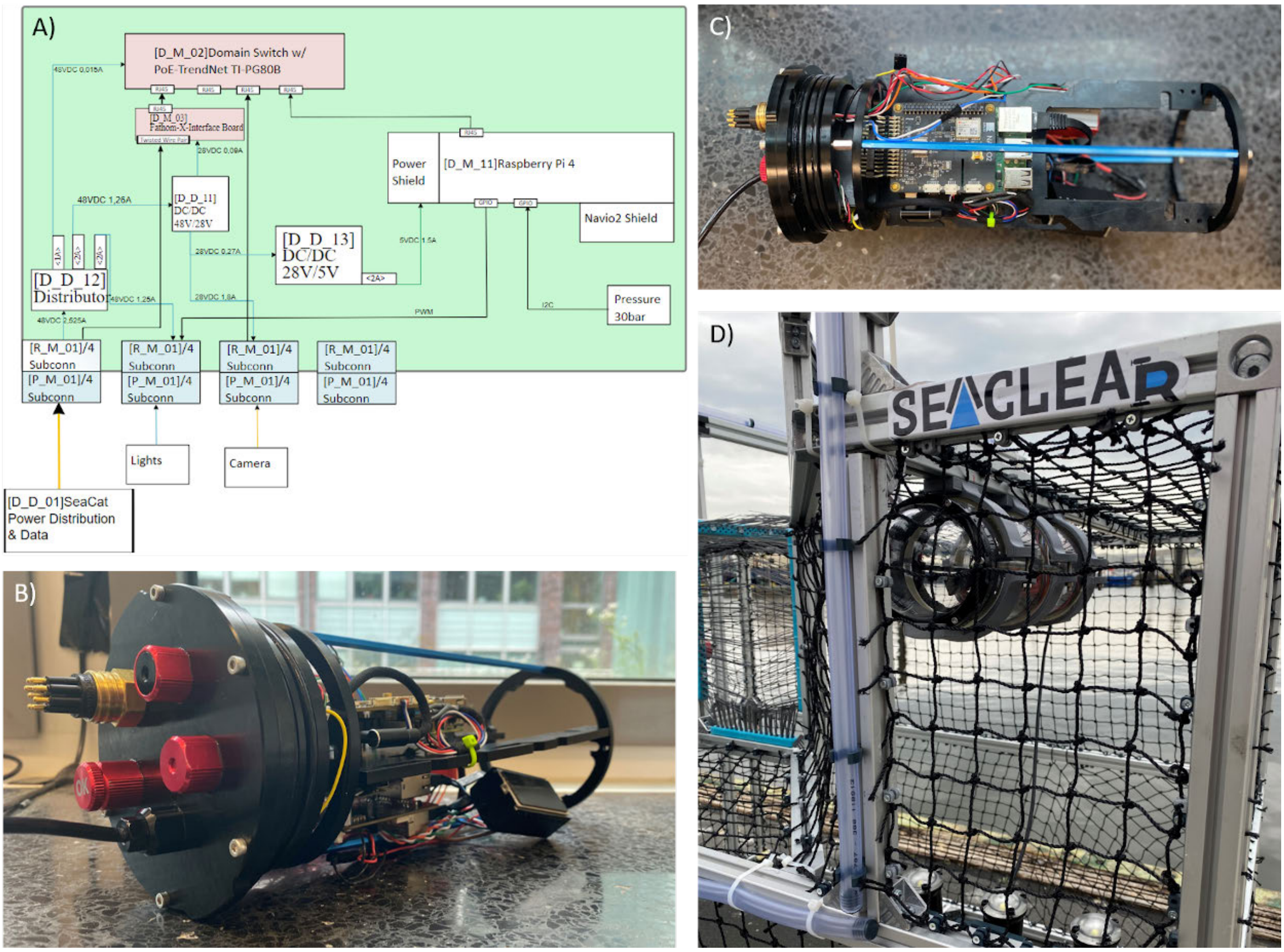

Figure 18: Electronics of the basket. A) Sketch of the electronic circuit of contained sensors and electronic components, B) photograph of the electronics tray (side view), C) photograph of the electronics tray (top view), D) photograph of the electronics tube attached to the basket.

6 Simulation and Deployment

Before deployment in water, the collection basket was modelled into a virtual environment with the help of Gazebo Simulator[4]. This has been used to test the dynamics and pose estimation algorithms for localising the basket.

6.1 Basket Simulation

For the modelling in the Gazebo Simulator, the mechanical design of the basket as well as required sensor emulators (as plug-ins) were imported into the system. As depicted in Figure 19, some detailed elements, such as the meshes or the interface have been left out from the mechanical design and, implicitly, from the simulation, due to their limited effects and associated high modelling efforts. The main goals of the simulation was the testing of the localization algorithm (pose estimation) in a cost-effective and reliable environment and, secondly, of the integration with the complete SeaClear digital twin.

For fulfilling the first purpose, the localization algorithms have been tuned on emulated data, with an example of output information depicted in Figure 20. The raw and filtered data have been published on corresponding ROS topics, with the goal of informing the ColROV about the position and orientation of the basket, so that the trajectory for litter deposition could be automatically generated by the guidance module of the robot.

6.2 Basket Localization

The final basket has been equipped with a sensory system, which has been described in Section 5. As depicted in Figure 22, the data from the IMU, pressure sensor and underwater-GPS are filtered and fused together for obtaining the pose of the collection basket. The readings of the IMU were conducted at 50 Hz, the pressure sensor at 10 Hz, while the underwater-GPS readings were made at 40 Hz. The pose estimation task has been carried out using the *robot localization*[5] ROS package. For the Attitude Heading Reference System (AHRS) node, responsible for filtering and fusing IMU data, both self-written filters and the *imu tools*[6] ROS package has been used. The workflow for filtering and fusing GPS and IMU data is shown in Figure 21.

The position of the collection basket expressed using absolute coordinates and Euler's angles for orientation are published on corresponding ROS topics, and intermediate results can be viewed the same way, as depicted in Figure 22.

Prior to the sea trials, the accuracy of the underwater-GPS has been evaluated by comparing the fused sensor readings with the output of another GPS device, which was receiving correction from a Real-Time Kinematics (RTK) station via internet. In order to perform the test, the underwater-GPS transponder was mounted on a small-sized ROV for convenience and submerged 1 m in water. From the small-sized ROV a long metallic rod enabled mounting the GPS device with RTK corrections on the same axis with the SBL transponder, with minimal offset. The setup is depicted in Figure 23.

By examining the collected data shown in Figure 24, the underwater-GPS presented a continuous track, without any sudden jumps. However, the root-mean square value was situated around 7 m on average of the tests performed. The errors are believed to be generated by the poor performance of the magnetometer onboard the Waterlinked topside computer. The addition of an external GPS and magnetometer for fusing the acoustic data are being investigated for the final setup of the SeaClear system.

[4] https://gazebosim.org
[5] http://wiki.ros.org/robot_localization
[6] http://wiki.ros.org/imu_tools

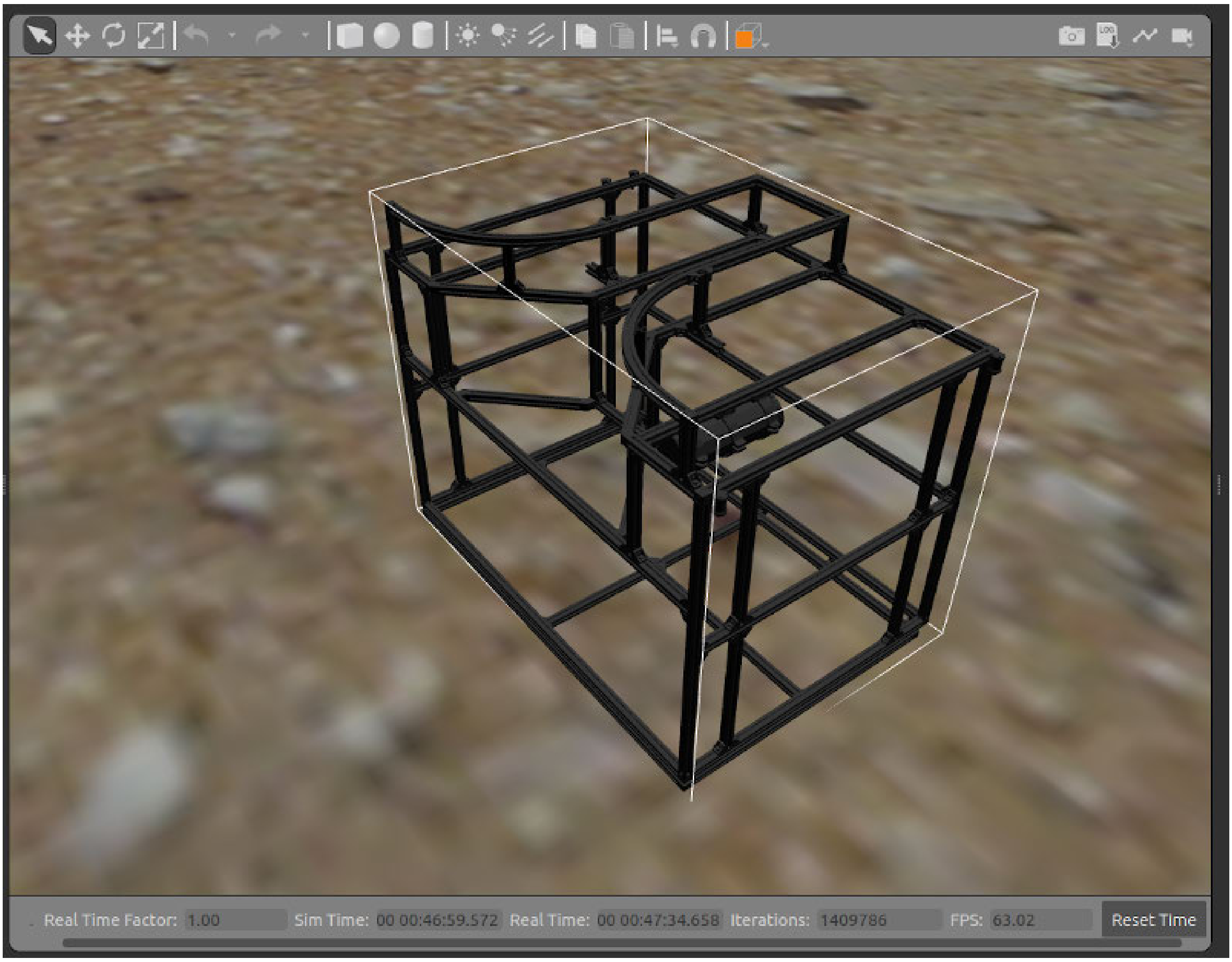

Figure 19: Collection basket has been exported from the mechanical design software and imported into Gazebo Simulator, while preserving its physical properties and its dynamics. Inside the electronics compartment, the plug-ins for the emulated sensors have been fitted

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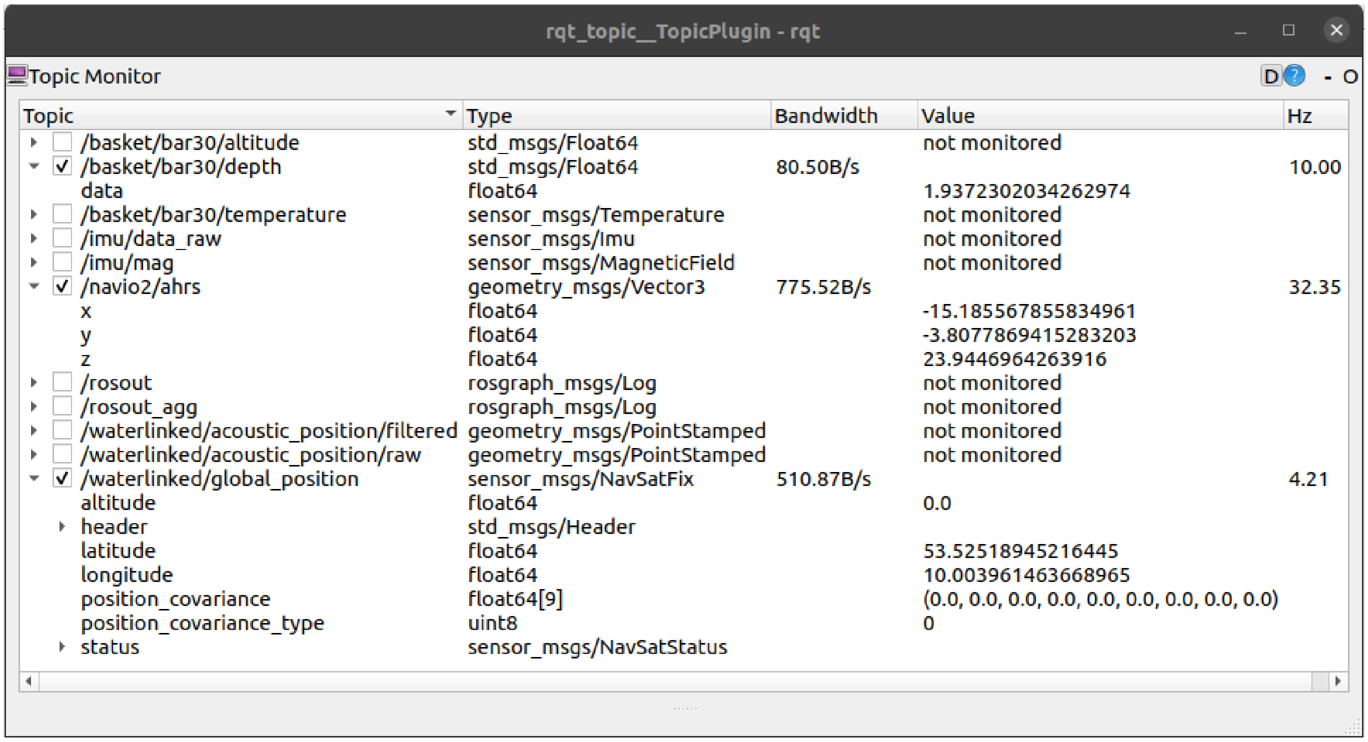


Figure 20: The output of the basket sensors are being published on ROS topics, each having their corresponding namespace. The AHRS node fuses IMU data, the depth is obtained through the pressure sensor, while the global positioning is done through the Short Baseline (SBL)-based underwater-GPS device, which fused both GPS and acoustic data. In the simulation, the readings are done by the emulated sensors and the ground truth is obtained directly from the Gazebo Simulator for comparison

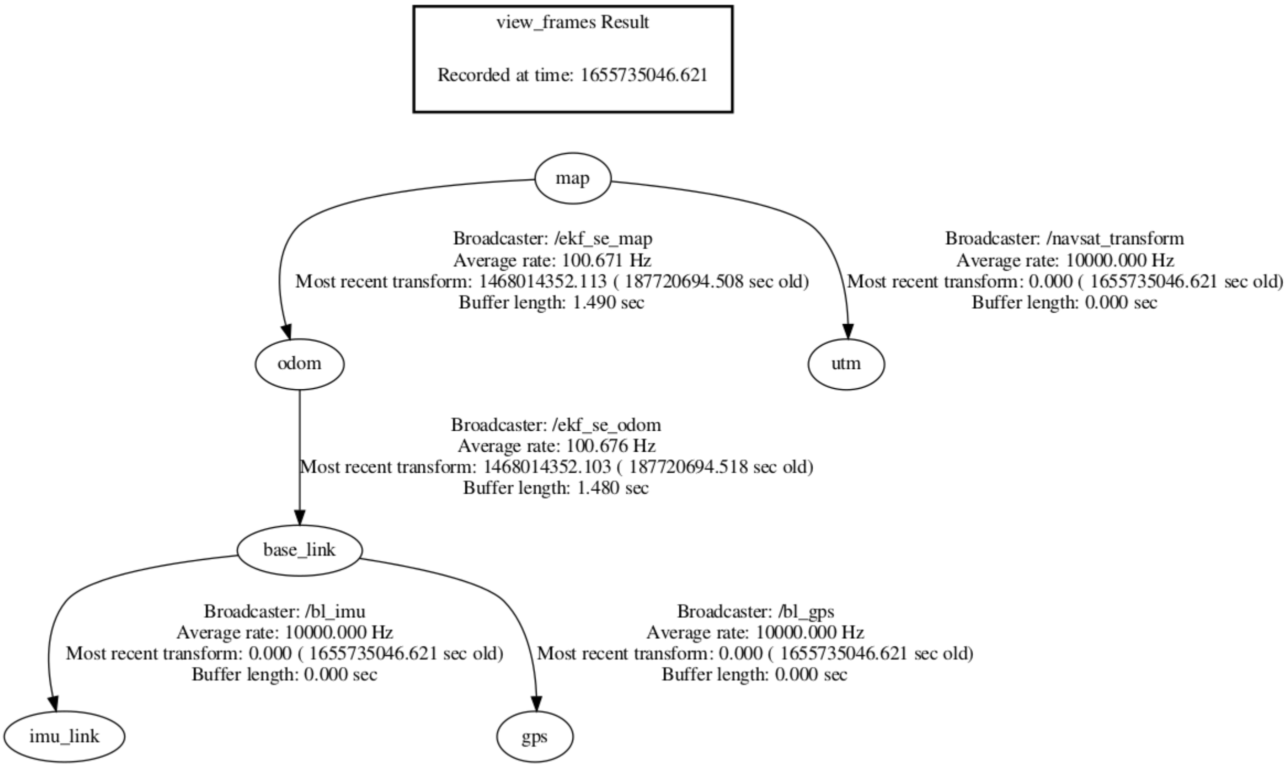


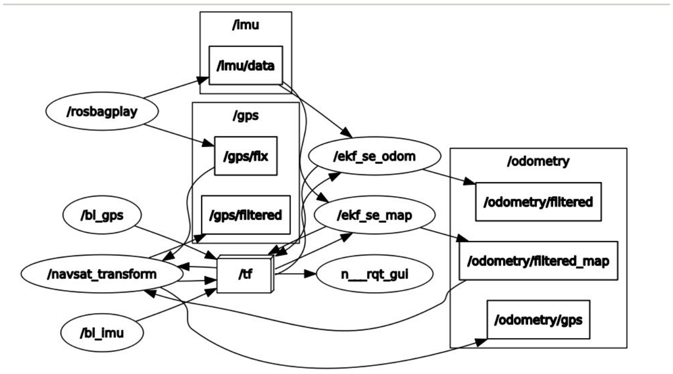
Figure 21: The workflow for fusing GPS and IMU data consists in fusing the filtered IMU data with the averaged GPS readings and integrating the resulted position to the last known one. Underwater GPS data is inherited by the GPS link and latter used for forming the Extended Kalman Filter (EKF) odometry map. The *navsat transform* is the node containing all the fused data and its output can be compared to the ground truth

The errors observed in the results were rooted in the data filtering, as noisy environments, such as ports, can cause higher peaks in sensor readings, which cannot be entirely filtered out during the process of estimation. As seen in Figure 25, the raw sensor readings of the GPS sensor in the Port of Hamburg needs to be averaged at higher rates in order to avoid jumps in order of meters between subsequent readings.

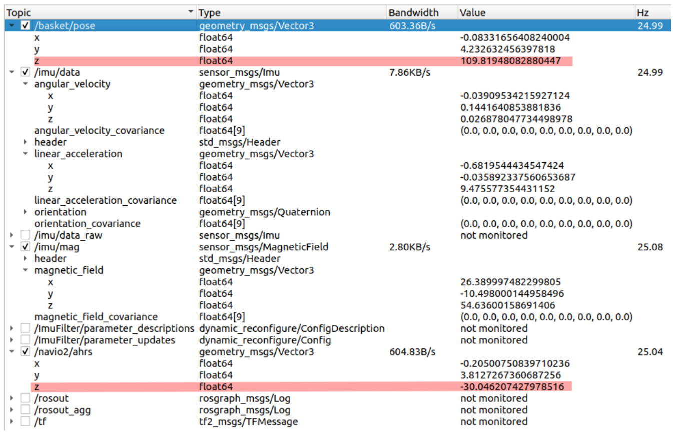
Before deployment in water, the collection basket was tested within the premises of Fraunhofer CML. The IMU and pressure sensor were placed into the main electronics compartment (in form of a cylinder), which was mounted inside the basket for protection. The SBL transponder, on the other hand, was mounted close to the topside edge, in order to avoid attenuation of transmission of acoustic signals to the baseline receivers. That generated an offset between the reference systems of the aforementioned sensors, that needed to be taken into consideration during fusion. Nevertheless, the underwater-GPS's acoustic communication could not be tested on the premises, due to the lack of a sufficiently deep water tank. The lights have been programmed to be commanded remotely through ROS services in order to save energy when the basket is not submerged.

6.3 Sea Trials in the Port of Hamburg

During the Hamburg trials conducted from 9th to 13th of May 2022, the basket and ColROV with attached skid and gripper were tested for the first time. In absence of a dedicated LARS onboard the SeaCat USV, the basket was placed



(a) ROS node list



(b) ROS topic list

Figure 22: The localization software for the collection basket is decomposed in multiple ROS nodes (A), which publish and consume relevant ROS topics (B). Raw and filtered data can be read at each time step, while the final odometry readings are read by the ColROV guidance module

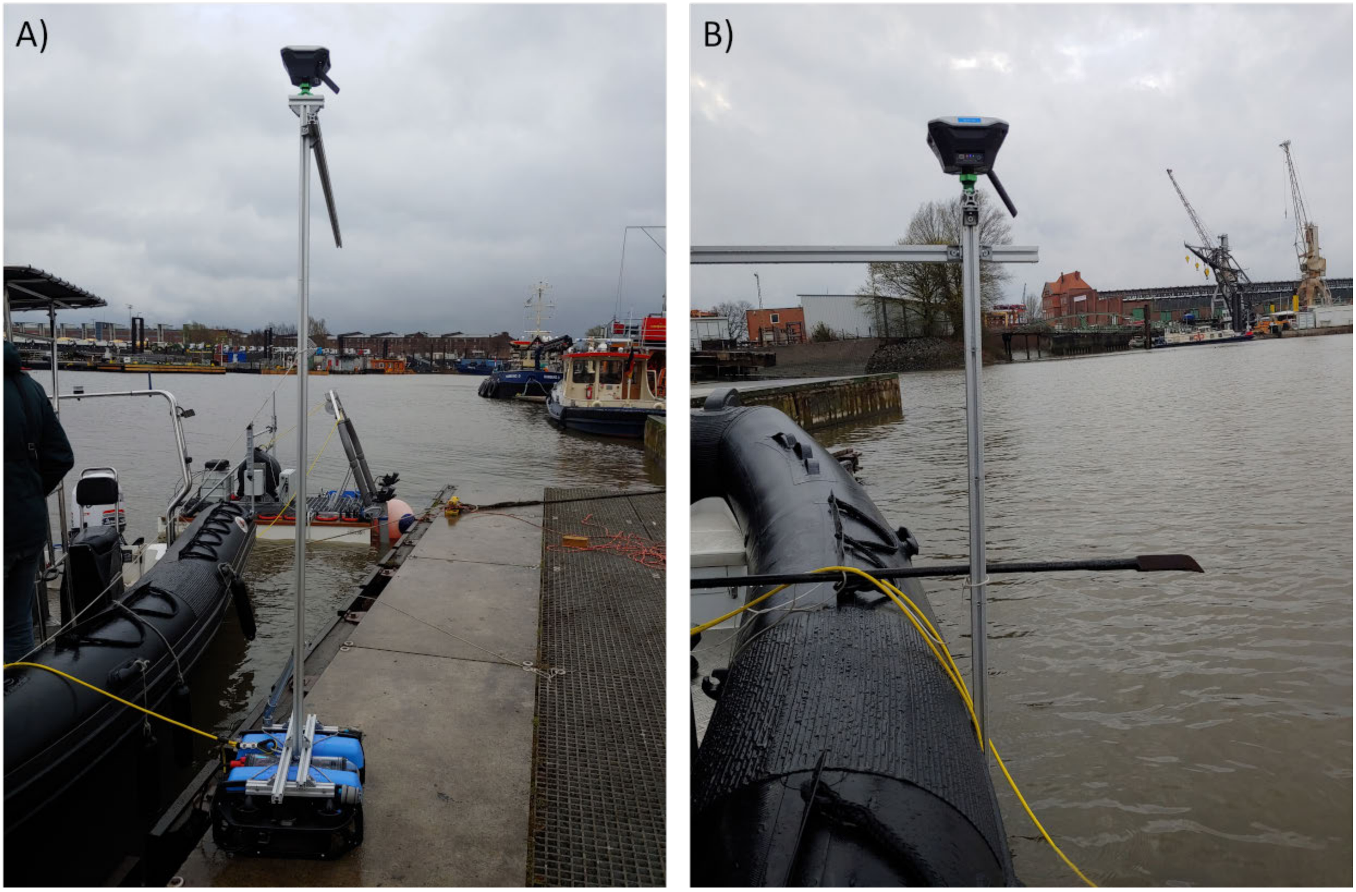


Figure 23: Photographs of the SBL system on the small-sized ROV during preliminary tests. A) The RTK-enabled Emlid RS+ GPS device has been mounted on a $2.5\,\mathrm{m}$ long metal rod, which in turn has been mounted on the central axis of a commercial ROV onto which the SBL transponder was also mounted on the ROV. The aim of the test was to find out the accuracy of the SBL solution for underwater-GPS, B) same system setup with the small-sized ROV submerged in the water from a separate carrier motor boat.

Figure 24: Localization data collected during the preliminary tests. A) Data indication on a map of the test site, B) close-up of the recorded data points.

in water from a manned ship and not connected to the SeaCat USV. This, however, enabled good maneuvrability between testing systems, as the risk of entanglement between the tether cable of the ROV and the tether and the ropes used for submerging the basket was quite high.

The SBL-based solution from Waterlinked[7] was used for obtaining underwater position in global reference system. The baseline for the SBL solution was deployed on a metallic structure next to the pier, facing the test area. The receivers were set approximately 2 m apart from each other and at 0.5 m depth, with the transponder being capable to communicate with the baseline receiver's up to 100 m range. In the final setup, the baseline will be retrofitted into the SeaCat USV so that the range of will not be limiting factor of the testing. The aforementioned depth was needed in order to ensure that the receivers were not blocked in any direction by the pontoons onto which the piers were floating. To ensure the fixed position, the receivers were run through rigid, non-metallic tubes, that also kept them in upright elicitation, which can be seen in Figure 26.

As a first step, the basket was driven about 10 m to 20 m away from shore and lowered from an external carrier ship (not included in the regular SeaClear system) as depicted in Figure 27. This safe distance was kept in order to allow the tether cable to be connected to the shore infrastructure. In the final setup, the communication will be done through the SeaCat USV companion computers, as explained in Section 5. Afterwards, the ROV together with the skid and gripper were submerged deployed into water directly from the SeaCat USV, while the latter keep its position.

Due to the instability of the current navigation controllers onboard the ROV, the navigation and approach to the collection basked was done by remotely controlling the ROV and guiding it based on acoustic images generated by the sonar and, in the close-range of 0 m to 1 m, using the visual camera alone. It was possible to observe the frame of the basket on the sonar of the ROV, which was then used to approach the basket. Even the interface as indicated in Figure 28 was visible, therefore the orientation of the basket could be deduced. For the close-range approach, the front-facing camera of the ROV was used to manoeuvre the ROV to fit its skid and gripper into the right position. After several attempts to maneuver into the interface using the guiding funnel of the basket structure, it was possible to position the ROV correctly over the interface. Due to a lacking pitch control, it was not possible to attempt the approach with a closed gripper, since the contact between ROV's gripper and the basket's interface generated sufficient resistance on the navigational axis that caused unreasonably high pitch angles, which didn't allow the ROV to enter the funnel.
Due to the common safety restrictions imposed by the local port authority (Hamburg Port Authority (HPA)) to reduce the risk of producing litter on the seafloor within the harbor area, the rope forming an emergency connection to land got entangled with a rotor of the ROV. While the systems could be untangled successfully, this incidence highlighted the challenge imposed by loose ropes and thus, may require future simulation and modelling to investigate risks and

[7] https://www.waterlinked.com/underwater-gps

possibilities further. To that extend, the consortium plans detailed assessments and simulations, which will be published in future research articles.
Since some problems between the interface and the gripper were only identified during the trials in May, the interface was adjusted accordingly afterwards as described in Section 5. While initial tests show promising results, the final test with the actual hardware will only be performed during the next project meeting in Marseille in July or September 2022.

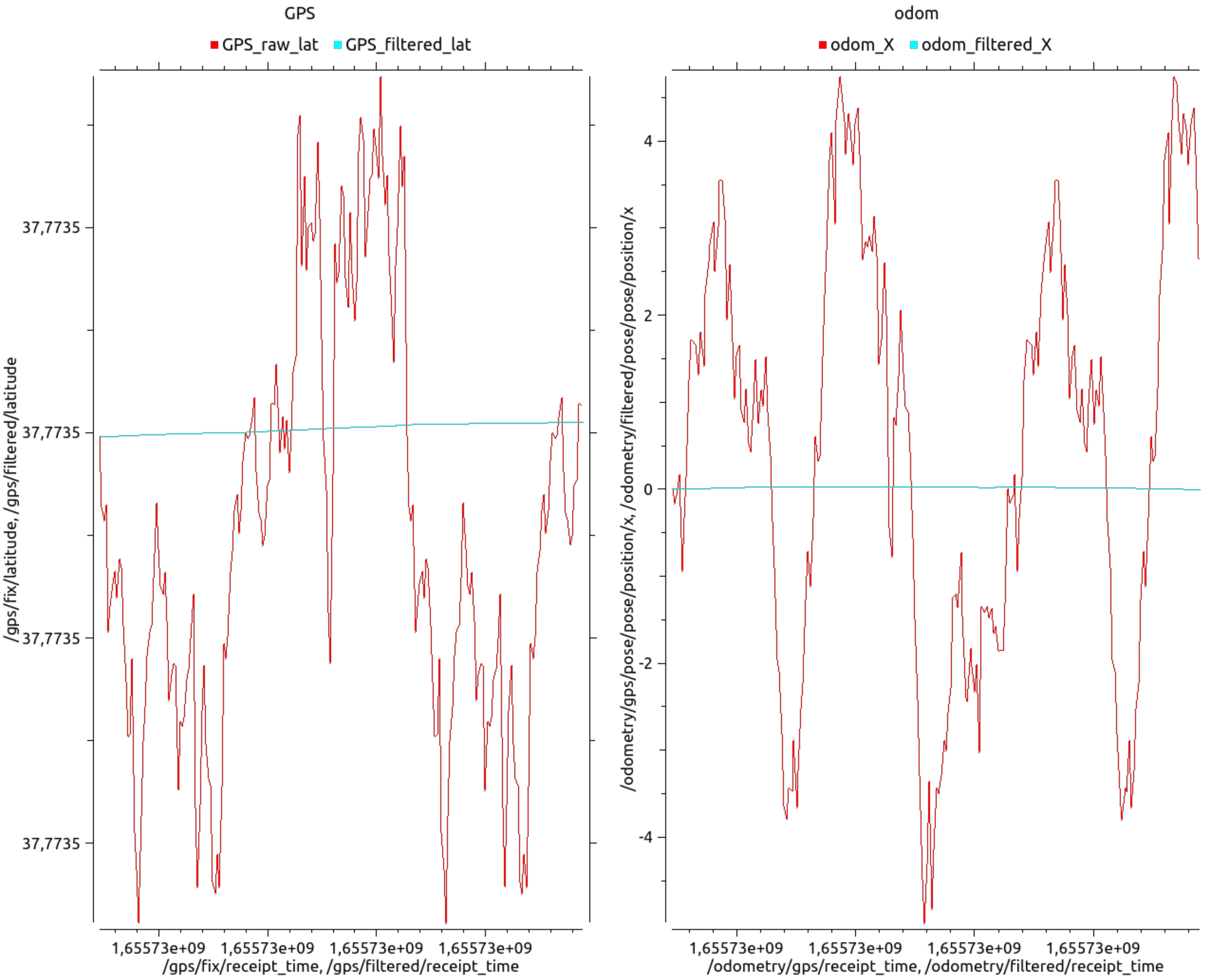


Figure 25: The raw GPS data (red) is plotted against the filtered GPS data (cyan). The filtered data is used for obtaining the odometry of the collection basket, while fusing it with the other sensors on-board. Due to the noisy environment, but also to the quality of the received signal, the raw data tends to have bit jumps between subsequent readings which result in errors in magnitude of meters

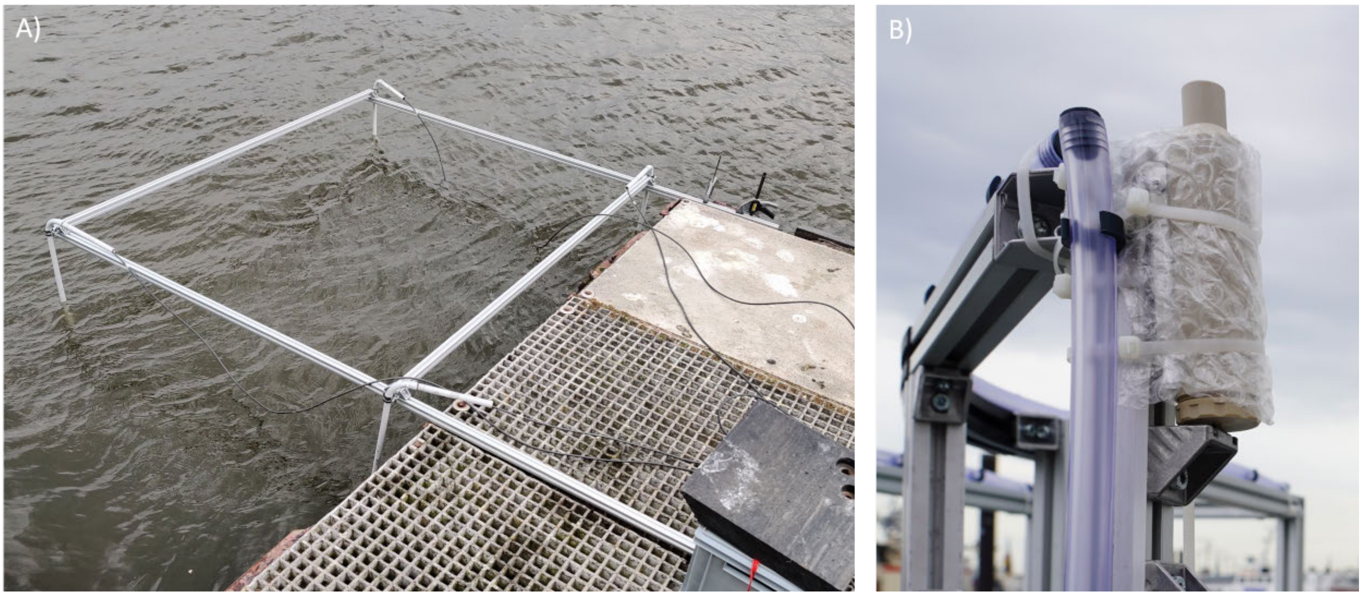


Figure 26: Underwater-GPS setup. A) SBL setup, B) Transponder attached to the basket.

lowering.png

Figure 27: Photograph of the process of lowering the basket onto the seafloor from the external motor boat during the Hamburg trials in May 2022.

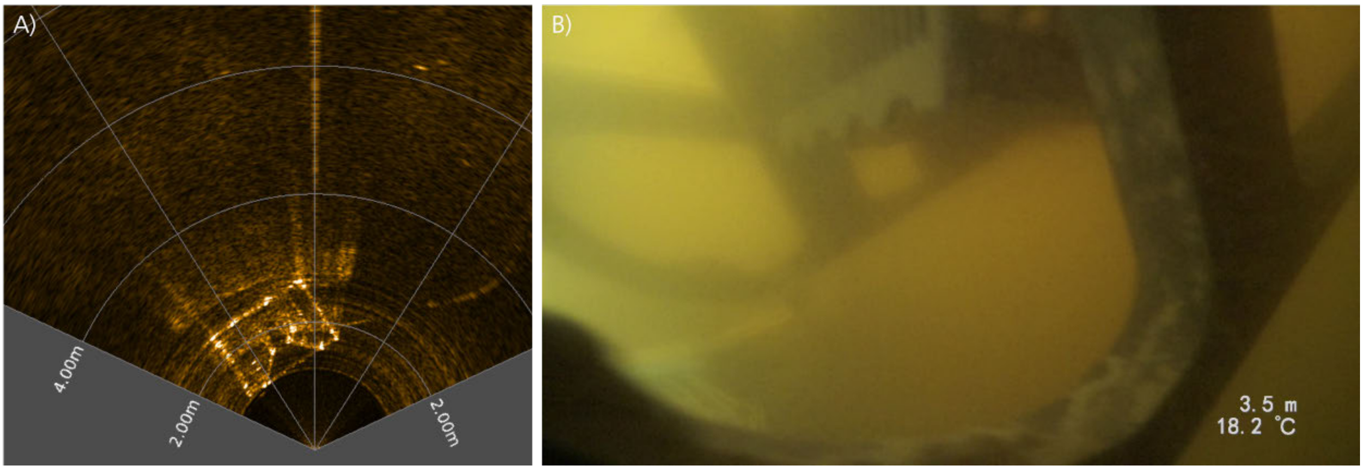


Figure 28: Photographs taken during the trials, A) Sonar picture taken during the tests of the Hamburg Trials in May 2022, clearly showing the frame of the basket as well as the interface opening, B) Snapshot of the video recorded of the skid and gripper attached to the ROV approaching the basket and attempting to be manually navigated into the interface underwater. The photograph displays the bad visibility conditions that had to be overcome during the trials and highlights the necessity of sensor integration of the mentioned components above.

7 Summary and outlook

The current work gives a comprehensive overview of the collection basket developed within the SeaClear project. The deliverable highlights all of the work conducted under this task (T3.5) and details each developmental step leading to the manufacture of the final basket. It explains the design requirements established within the initial phase of the development and subsequent design choices. Furthermore, the tests conducted during the Hamburg Trials in May and the corresponding results are summarized.
The developed collection basket enables the ROV to enter through the custom-made interface and safely deposit collected litter. Different litter types were tested, most of which did not present any challenges. Buoyant litter remains problematic, but nevertheless, it is not considered a key target litter for the SeaClear system.
While the full functionality of the basket system remains to be validated during the additional trials conducted in July 2022 in Marseille or the demonstrations scheduled towards the end of the project, preliminary tests show excellent performances.