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

SeaClear2.0

https://www.seaclear2.eu

D4.1

Sensory system upgrade report

WP4 – Perception overhaul

Grant Agreement no. 101093822

Lead beneficiary: Subsea Tech

Date: 23/10/2023
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Deliverable description	This report describes the results of trials with the sensors to be mounted on the observation ROV, the USV, the UAV and the grapple for litter detection and classification. The trials were carried out by Subsea Tech in Marseilles harbour. The report also explains the final selection made, based on data quality, ease of use of the format, immunity to environment parameters, ease of integration and cost.

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

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

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DEFINITIONS

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

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

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

ABBREVIATIONS

- **EC**: European Commission
- **WP**: Work Package
- **UAV:** Unmanned Aerial Vehicle
- **ROV:** Remotely Operated underwater Vehicle
- **UUV:** Unmanned Underwater Vehicle
- **USV:** Unmanned Surface Vehicle
- **OEM:** Original Equipment Manufacturer

EXECUTIVE SUMMARY

In order to optimize marine litter detection and classification, a set of various underwater sensors have been tested in real conditions (Marseilles harbour) to determine the most suitable ones for integration on the observation ROV and other robotic system components. Different types of sensors have already been tested during the SeaClear Project, both visual and acoustic, including conventional video with standard and UV lights, a time of flight camera (Utofia), and a multibeam imaging sonar (Blueprint Oculus 750d). A set of new sensors has been selected to be tested in SeaClear2.0, in order to upgrade the existing sensory system. This new set consists of a high resolution imaging sonar (Blueprint Oculus M3000d or M1200d), a side scan sonar (Blueprint Starfish 990F XD), a magnetic sensor (JW Fishers RMD-1), a photogrammetry sensor (IVM Hydro 300), as well as a multispectral camera (QCell).

This report gives the results of the different trials followed by a comparative analysis recommending the sensors giving the best performance for the purpose. The analysis is based on data quality, ease of use of the format, immunity to environment parameters such as water turbidity, ease of integration including weight and dimensions, and cost. While the former parameters define the detection and classification capabilities, cost is a major factor for the scalability of the system and the envisioned business case.

The recommended sensors are:

For the observation ROV: Full HD video + image enhancement software, high resolution imaging sonar, magnetometer and side scan sonar.

For the UAV: 4K camera.

For the USV: Multibeam sonar.

For the motorised grapple: Full HD video cameras.

1. Introduction

1.1 SeaClear 2.0 at a glance

SeaClear 2.0 is the next step to the ongoing H2020-funded SeaClear (https://seaclear-project.eu), where several of the SeaClear2.0 partners have been developing the first autonomous robotic system for seafloor litter collection. An unmanned surface vehicle (USV) called SeaCat acts as a hub for a flying vehicle (UAV) that searches for litter from the air, an observation unmanned underwater vehicle (ROV) called Mini-Tortuga that searches for litter underwater, and a collection ROV called Tortuga that picks up the litter with a custom gripper-plus-suction device and deposits it in a basket lowered from the USV. The very nature of SeaClear (labelled 1.0 in the document) as the first project to design such a solution means it must focus almost exclusively on technological developments in robotics hardware and algorithms, with a single system.

Moreover, the system is limited to only seafloor litter of up to tens of cm in size and at depths of up to tens of meters; it cannot pick up surface litter or larger objects like fishing equipment, bikes, e-scooters, tires, shipping equipment, etc. The aim of SeaClear 2.0 is to upscale and upgrade the system initially made for SeaClear 1.0. This means collecting bigger and heavier litters with a modified SeaCat and a smart grapple, storing them and shipping them to shore with a dedicated USV Tender, as well as collecting surface litter with a USV and a team of surface robots. In the end, SeaClear 1.0 and SeaClear 2.0 will be working together, exploiting their shared and complementary litter detection and collection capabilities.

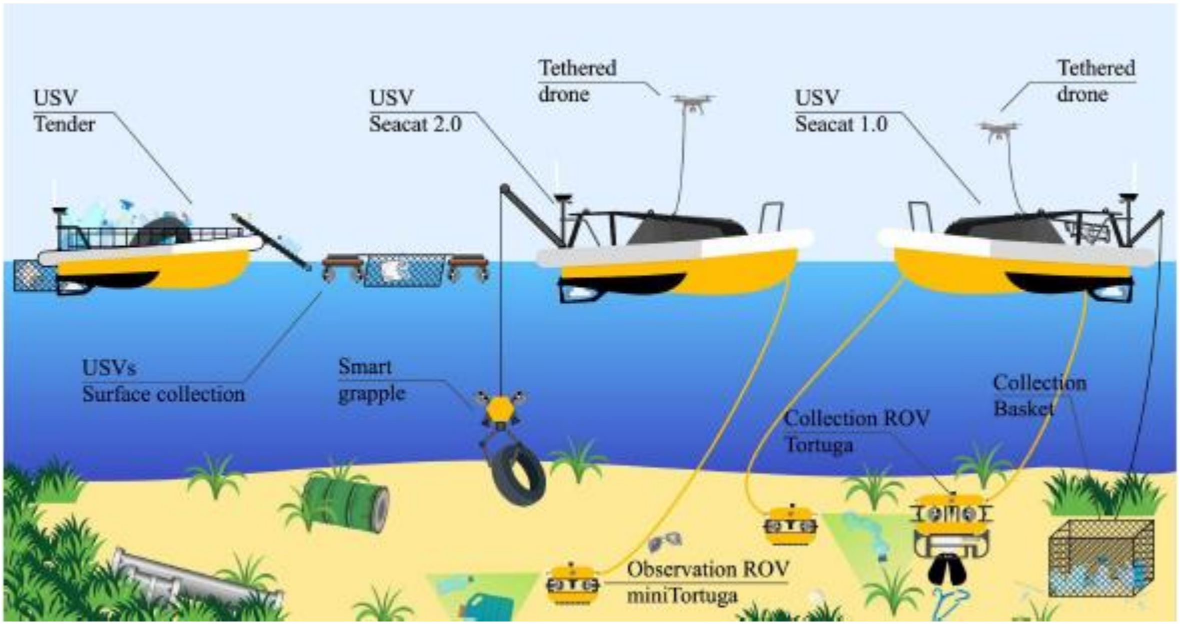
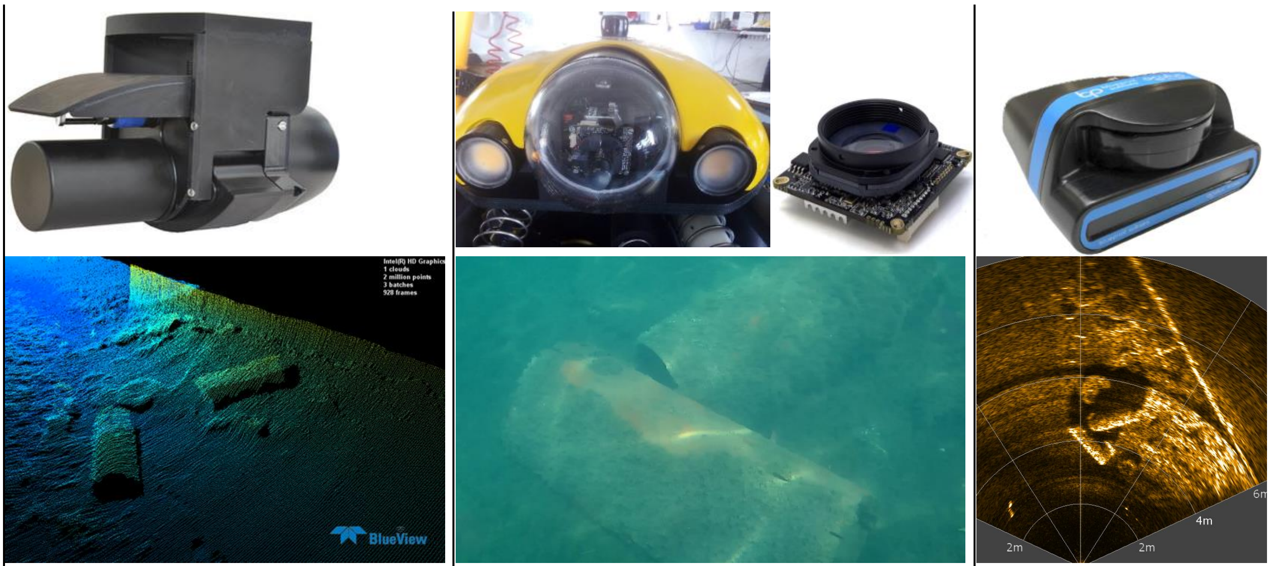


Figure 1: Concept of SeaClear 2.0 robotic system (left/middle) and SeaClear 1.0 (right)

1.2 Reminders of SeaClear 1.0 sensor trials

A sensor test campaign has been organized by Subsea Tech in 2020 in order to define the sensory system of SeaClear 1.0. During these trials, the following sensors were tested: a conventional Full HD video with standard lights and with UV lights, a time of flight camera and a multibeam imaging sonar (Blueprint Oculus 750d).

At the end of this first campaign, Subsea Tech has recommended to use the conventional full HD video camera with high power LED lights and the dual frequency multibeam imaging sonar Oculus 750d on the observation ROV. The first one has been used mainly in clear water to low turbidity waters (e.g. Dubrovnik sites) and the sonar has been essential in low visibility environments (Hamburg harbour). Also, it has been recommended to use a bathymetry sonar (Norbit WBMS) for a pre-survey campaign from the USV.



a. BlueView Norbit WBMS b. Full HD camera c. Blueprint Oculus 750d

Figure 2: Seabed in front of Subsea Tech: pipelines and tires, observed with SeaClear 1.0 sensors

In the context of SeaClear 2.0, we aim to enhance this sensing with new types of sensors or upgraded versions. The major objective is to improve the detection of partially buried litter that could be pulled out of the silt by the SeaClear 2.0's grapple.

1.3 Deliverable objectives

The main objective of this deliverable is to report on the design of the upgraded sensory system that has been chosen for SeaClear 2.0, in order to improve the litter detection and classification. Two methods have been taken into account. The first one is to use an upgraded version of an equipment chosen for SeaClear 1.0. The second way is to explore new kind of sensors that could be complementary to the SeaClear 1.0 system.

The report presents the different tests and their results, together with a comparative analysis on performance, to make recommendation on the best suited sensors for our application.

2. Set-up and location of the trials

Most of the trials have been performed in Marseilles harbour, in front of the Subsea Tech facilities, using the inspection class ROV Mini-Tortuga, which is the designated observation ROV (see Figure 3). Some preliminary tests have been carried out in the Subsea Tech test tank. The side scan sonar has been deployed on the small Subsea Tech USV Catarob (see Figure 12: BluePrint Starfish 990F XD on Catarob USV).

The location of Subsea Tech facilities immediately next to the seaside, within the harbour, allows deploying the ROV directly from our offices. Besides, the presence of numerous litter in this area, due to the public access to the water front, makes it a natural test site for litter detection.

The place used for the trials is in very shallow water (<5m depth), quite low turbidity in general but high exposure to the solar light. The seabed is mostly composed of algae and silt, with a presence of litters of various sizes and types due to the proximity of human activity.

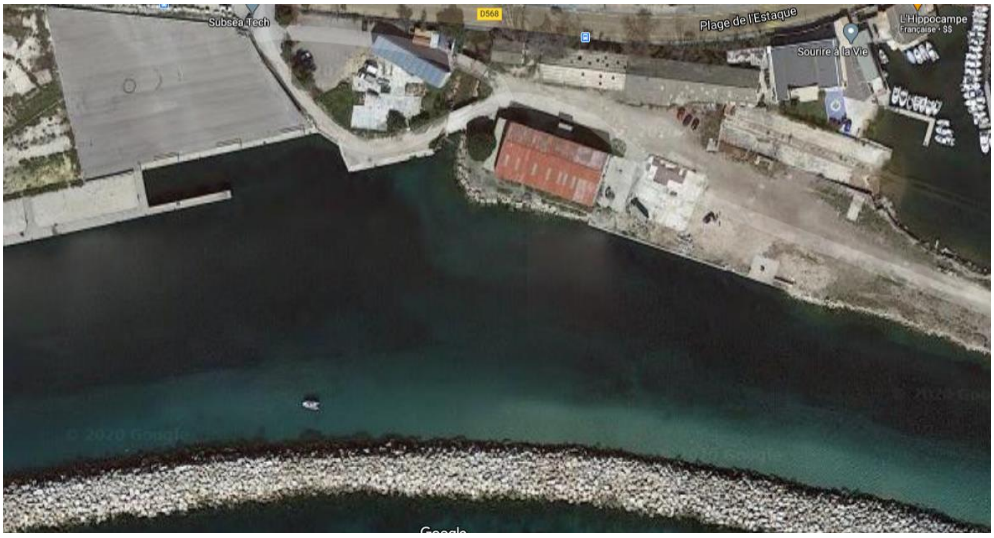


Figure 3: Subsea Tech facilities on the seaside within Marseilles harbour

Figure 4: Subsea Tech inspection class ROV Mini-Tortuga

The inspection class ROV Mini-Tortuga is one of the standard underwater vehicles designed and manufactured by Subsea Tech. Based on the Tortuga ROV design, it is cost-effective, compact, lightweight and easily deployable by SeaCat. It is the best suited for observation purposes.

In order to make preliminary tests before deploying the ROV and the sensors in a natural environment, Subsea Tech also uses a test tank, located in its facilities and which can be filled up with fresh or sea water as desired. Besides, the tank allows adjusting accurately the water turbidity by adding a given amount of silt, which can then be removed by the filtering system.

The tank has been first used for the metal detector and the multibeam imaging sonar.

Figure 5: Subsea Tech test tank with Mini-Tortuga and Tortuga

3. Results of the trials

3.1 High-frequency multibeam imaging sonar

Multibeam imaging sonars, also called “acoustic cameras” are high resolution sonars capable of creating instant images, unlike scanning or side scan sonars, thanks to their multibeam arrangement generating a full scene image instantaneously. Blueprint imaging sonar Oculus is a double-frequency sensor. Thus, it allows to switch between two frequencies according to the situation.

Figure 6: Blueprint Oculus M3000d mounted on Mini-Tortuga ROV

	M750d MT750d MD750d	M1200d MT1200d MD1200d	M3000d MT3000d MD3000d
Operating Frequency	750kHz / 1.2MHz	1.2MHz / 2.1MHz	1.2MHz / 3.0MHz
Range (Max)	120m / 40m	40m / 10m	30m / 5m
Range (Min)	0.1m	0.1m	0.1m
Range Resolution*	4mm / 2.5mm	2.5mm / 2.5mm	2.5mm / 2mm
Update Rate (Max)*	40Hz	40Hz	40Hz
Horizontal Aperture	130°/ 130°	130°/ 60°	130°/ 40°
Vertical Aperture	20°/ 20°	20°/ 12°	20°/ 20°
Number of Beams (Max)	512	512	512
Angular Resolution	1°/ 0.6°	0.6°/ 0.4°	0.6°/ 0.4°
Beam Separation	0.25°/ 0.25°	0.25°/ 0.16°	0.25°/ 0.1°

Figure 7: Specification table of Blueprint Oculus sonars

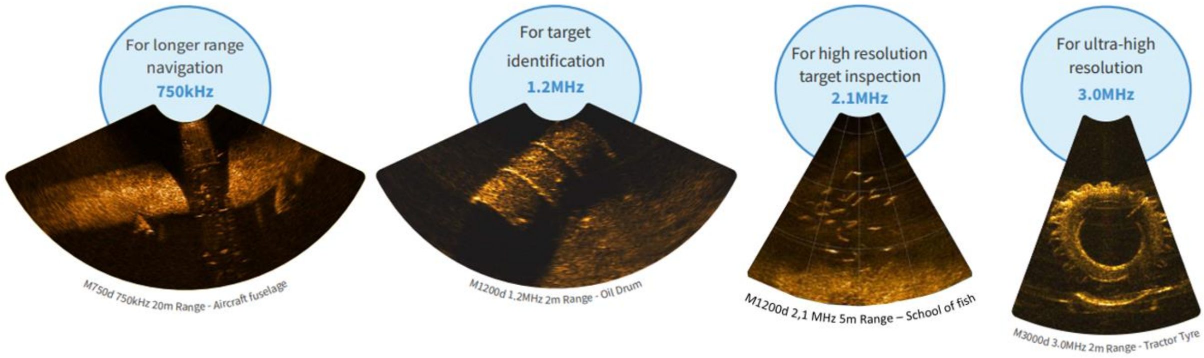


Figure 8: Impact on range, aperture and resolution according to the frequency (images from datasheet)

The chosen frequency significantly impacts the image size (range and aperture) as well as the resolution. The Oculus 750d model is well-suited for navigation and identification of large targets. In practice, the 1.2MHz frequency is most frequently used due to its large aperture and good resolution. Increasing the frequency enhances resolution, a crucial criterion for effective litter classification. Higher frequencies (2.1MHz / 3.0 MHz) could improve waste classification efficiency but come at the cost of reducing the viewing angle, thereby significantly increasing scanning time. The dual frequency of 1.2 MHz/2.1 MHz, while offering higher resolution, strikes a good balance between range, angle, and resolution. An automated switch from 1.2 to 2.1 MHz could enhance classification capacity.

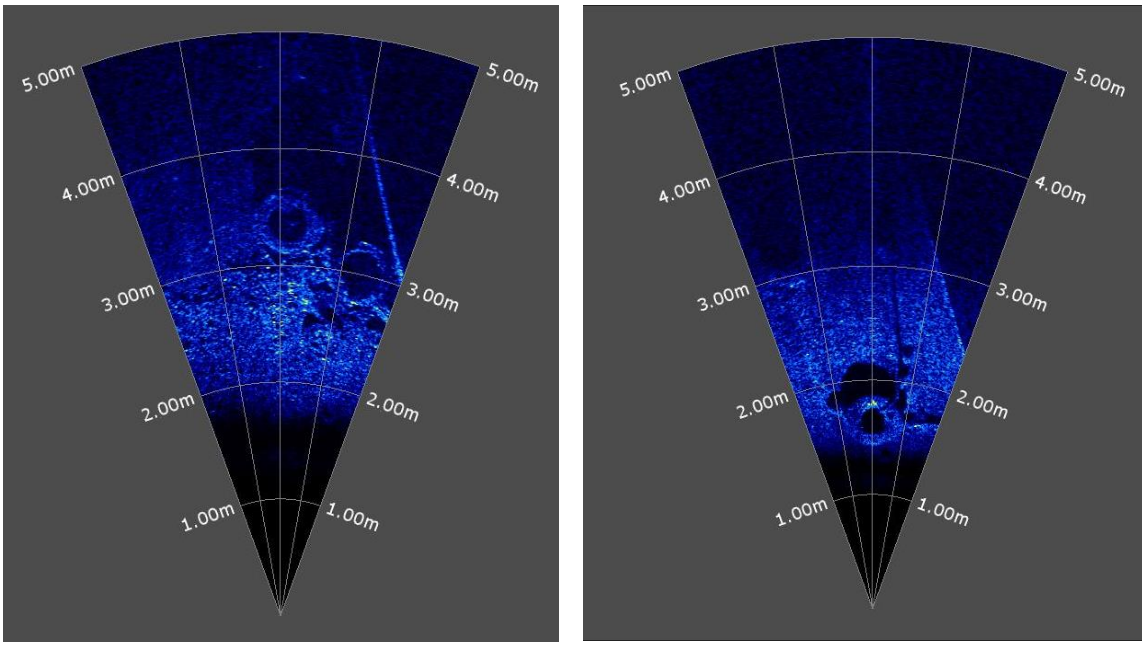


Figure 9: Tires in front of the quayside at 3MHz (M3000d)

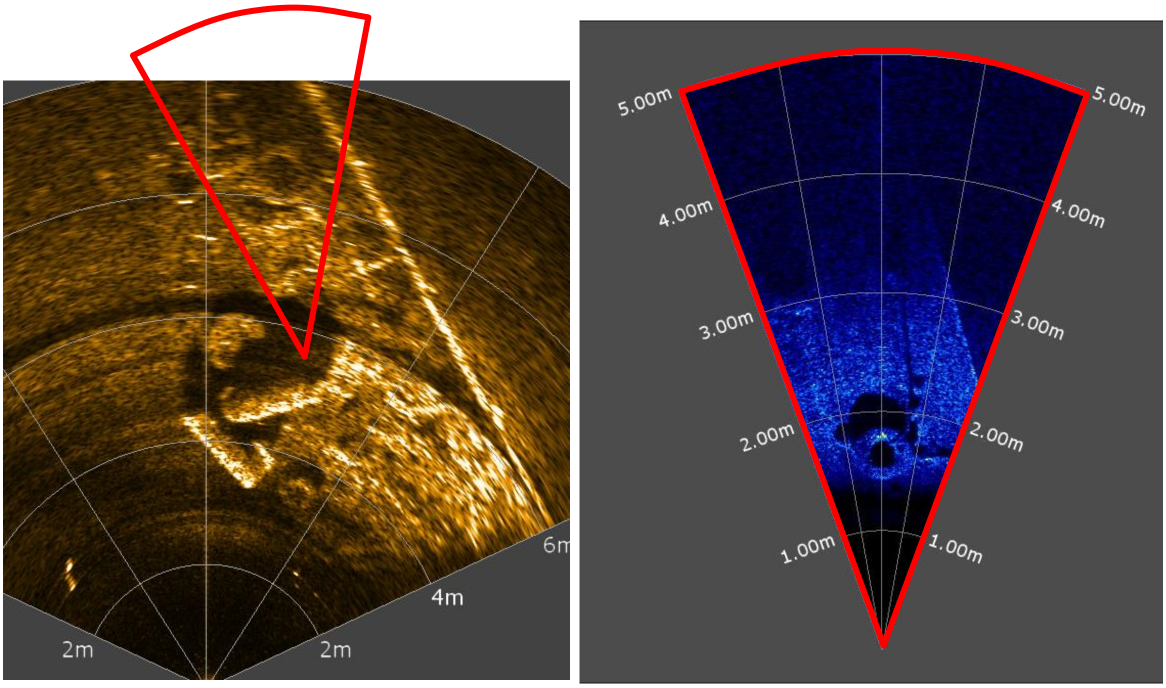


Figure 10: Comparison (not at scale) M750d (left) and M3000d (right). Target: tire

3.2 Side-scan sonar

The Starfish side scan sonar is a towed fish that can be deployed from a USV and produces photographic quality images of the seabed due to its high operating frequency. It allows a fast and easy localisation and identification of objects like wrecks, tires, etc.

It exists in hull-mounted version for USV integration, or in OEM version that can be integrated into a ROV. For this project, we plan to mount the side scan sonar on the ROV to avoid towing it from the surface.

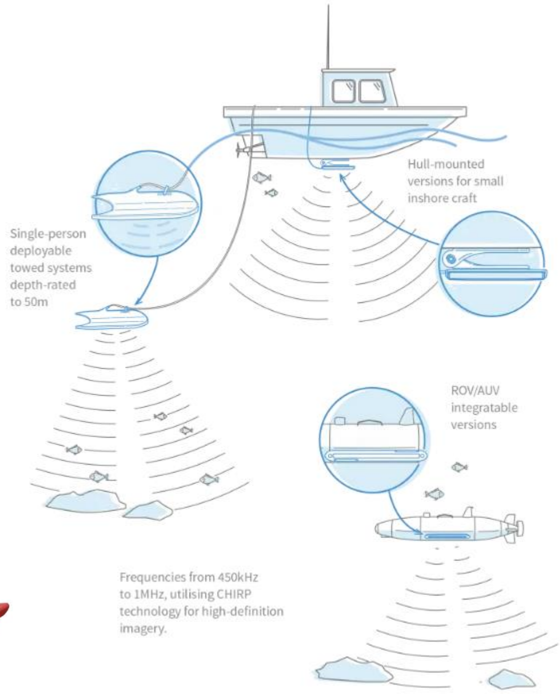


Figure 11: Starfish sonars can be integrated on USV or ROV

Sonar	StarFish 452F PRO	StarFish 990F XD	StarFish 992H	StarFish 454OEM	StarFish 992OEM
Frequency	450kHz CHIRP	1MHz CHIRP	1 MHz	450kHz CHIRP	1MHz CHIRP
Operating Range	Up to 100m (328ft) per channel	Up to 35m (115ft) per channel	Up to 100m (328ft) per channel	Up to 100m (328ft) per channel	Up to 35m (115ft) per channel
Horizontal Beam Width	0.8°	0.3°	0.3°	0.5°	0.3°
Vertical Beam Width	60°	60°	60°	60°	60°
Transducer Angle	Tilted Down 30° from Horizontal	Tilted Down 30° from Horizontal	Tilted Down 30° from Horizontal	Variable (OEM Specified)	Variable (OEM Specified)
Length x Width x Height	378mm x 97mm x 110mm	378mm x 97mm x 110mm	240mm x 95mm x 25mm	390mm x 22.5mm x 40mm	282mm x 22.5mm x 30mm
Weight (in air)	2.0kg	2.0kg	0.7kg	0.8kg	0.7kg
Construction	Polyurethane Rubber	Polyurethane Rubber	Polyurethane Rubber (Acetal Housing)	Polyurethane Rubber (PA6 Housing)	Polyurethane Rubber (PA6 Housing)
Colour	High-Vis Yellow	High-Vis Red	Black	Black	Black
Depth Rating	50m	50m	50m	2000m	2000m

Figure 11: Specification table of Blueprint Starfish sonars

The Starfish sonar is available under several versions with different operating depths, ranges, and frequencies (and thus, resolution). For this project, the 990F XD version has been selected and tested on a USV in shallow waters (< 5 m). It has the highest proposed frequency (resolution) and a horizontal range of 35 m each side.

Figure 12: BluePrint Starfish 990F XD on Catarob USV

The side scan sonar complements the 2D imaging sonar Oculus 750d by giving lateral images each side of the ROV. While the Norbit bathymetry sonar generates a 3D model of the seabed, the Starfish produces a 2D acoustic image reconstruction. It is however easier to operate, not requiring high precision positioning, sophisticated software or skilled operators like the bathymetry sonar.

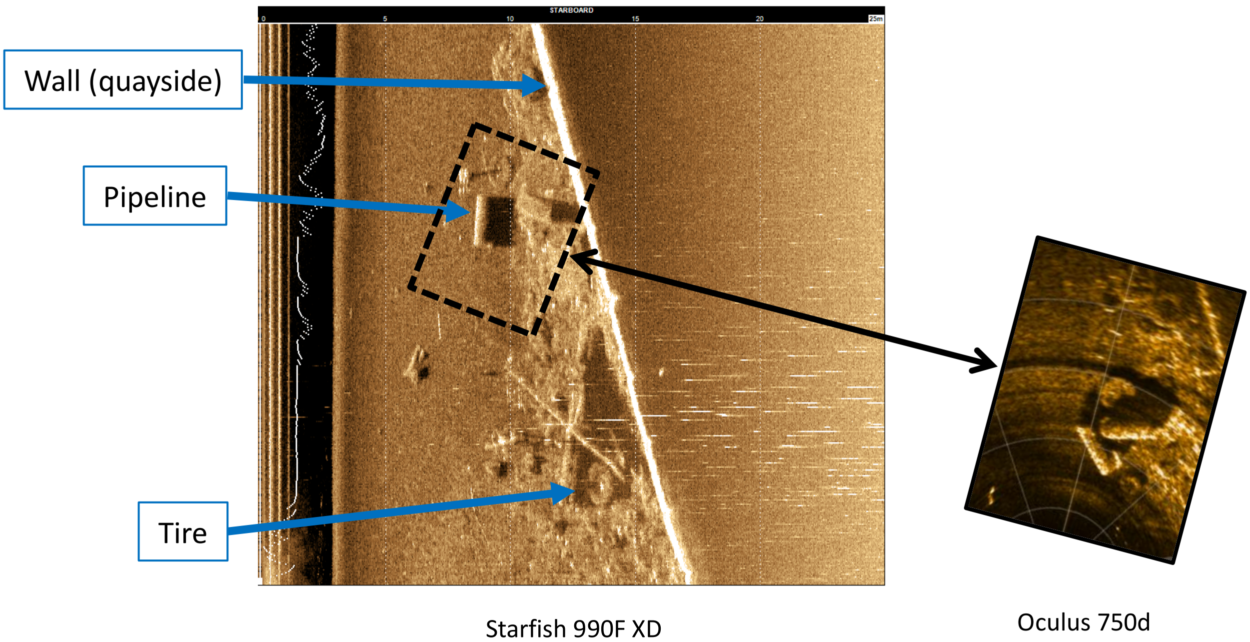


Figure 13: Pipes and tires in front of Subsea tech offices in Marseille

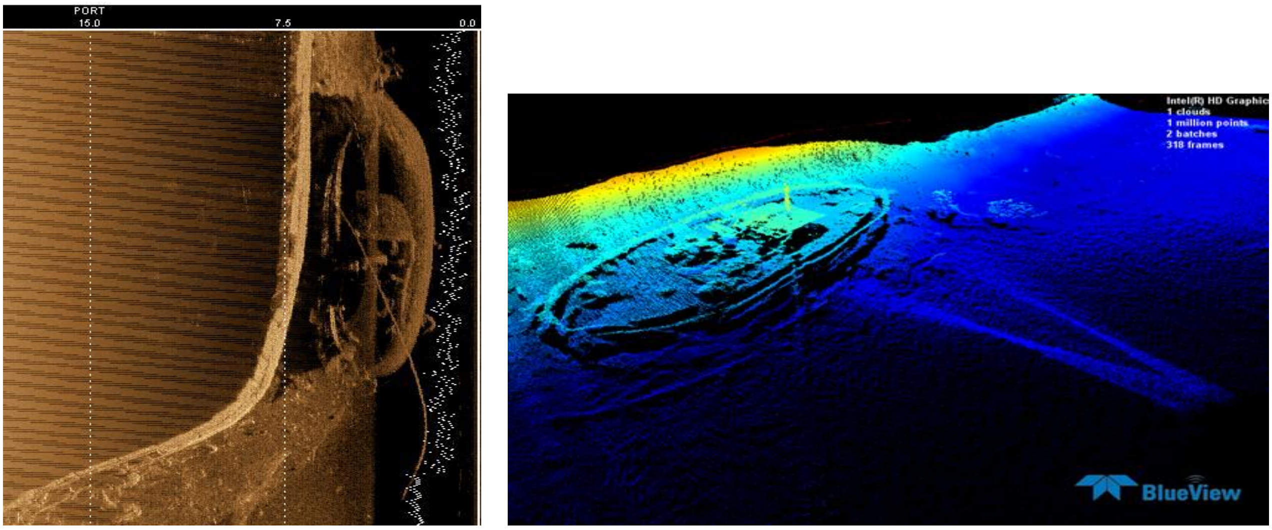


Figure 14: Small ship wreck. Left: Starfish side scan sonar / right: same wreck with Norbit WBMS

3.3 Bathymetry sonar

The Norbit WBMS sonar already used on Seaclear 1 project provides quickly a 3D model of the seabed which is then used for mapping purposes.
Therefore, and although its resolution does not allow to detect small targets, it will be kept for Seaclear 2.0.

3.4 Magnetic sensor

Most of the commercially available magnetic sensors for underwater applications are designed either for divers or for work-class ROVs. We are proposing the RMD-1 from JW Fishers, which is a unique system specifically designed to be integrated on observation-class ROVs.

This sensor provides the capability to detect objects that are buried or covered by algae and which therefore may not be visible by the video camera or sonar. It can detect both ferrous and non-ferrous metals objects beneath the ocean floor while ignoring mineralization in the salt water and seabed. The system employs two coils moulded into rugged ABS shells and firmly attached to the underwater vehicle with a corrosion-proof tubular PVC frame. The frame provides a sturdy mount and keeps the coils far enough away from the ROV so as not to be affected by the metal parts. The oval coils produce a detection envelope which extends more than 5 feet into the bottom.

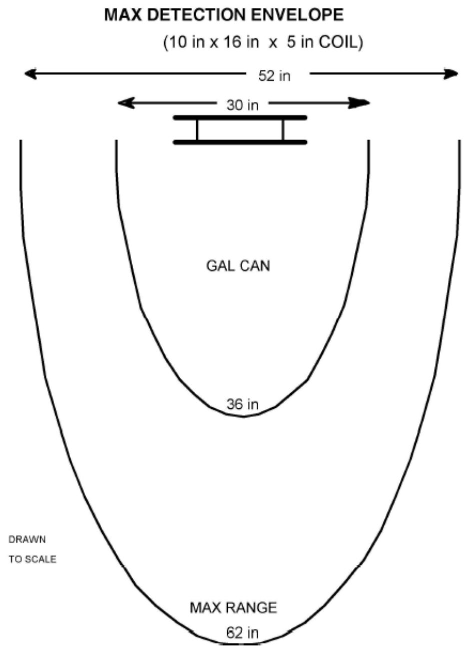


Figure 15: Operating range of JW Fisher's metal detector

The sensor has the capability to send an analog signal ranging from 0 to 5 volts, which corresponds to the distance from the detected object. In our case, the output signal is transmitted by serial communication from the electronic box of the sensor to the ROV. Through our observations, we have noted that the output signal often presents as binary, indicating either the presence or absence of metal. However, it is important to highlight that we have the flexibility to adjust the sensor's sensitivity. This means that we can configure the sensor to consider metal as detected with a lower or higher output signal, depending on our specific requirements.

While fully buried litter presents a considerable extraction challenge, we should emphasize the sensor's capabilities. Even at its lowest sensitivity setting, it can effectively detect objects at depths of nearly 1 meter beneath the sensor, which aligns well with our application's needs. However, it is important to acknowledge that the sensors do not provide specific information regarding the size, weight, or type of detected litter. Consequently, classifying the detected objects remains a complex task with this sensor configuration. Further data analysis will be necessary to decide if classification is feasible.

Figure 16: JW Fisher metal detector on Mini-Tortuga ROV, during preliminary tests

Magnetic sensors also exist for aerial surveys, and can be implemented on a UAV. Theoretically, the detection could work from above the water, since water does not have any effect on the magnetic fields. However, it is mostly used for a large-scale measurement (variation of earth magnetic field) rather than for locating relatively small objects. Manufacturers did not recommend the use of such a sensor for the detection of litter from above the water, especially at our working depth (up to 100m). They indeed recommend an altitude of 4-5m maximum for the typical objects that we want to detect in SeaClear 2.0. Thus, this option has been ruled out.

Figure 17: Example of magnetic sensor for UAV (SENSYS)

3.5 Photogrammetry

Photogrammetry is the science of making measurements based on photographs. The photogrammetry system Hydro 300, proposed by IVM Technologies, involves creating a scaled 3D model based on pairs of photographs. It comprises four main steps:

1. **Survey:** This step involves acquiring photographs.
2. **Image processing:** During this phase, elements are extracted and matched across different photographs.
3. **Photogrammetry:** Cameras' positions in space are reconstructed to create a sparse point cloud of the matched elements.
4. **Modeling:** This phase involves densifying the point cloud, generating surfaces, and applying texturing based on the colour information from the pictures.

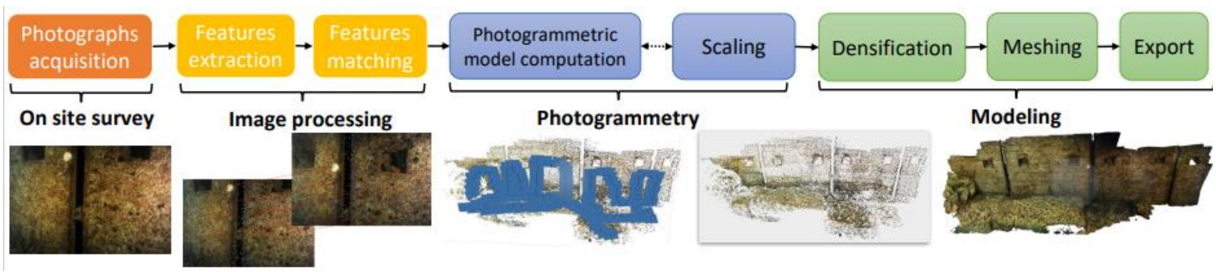


Figure 18: Full photogrammetry process (extract from IVM Technologies training presentation)

Even though the HYDRO 300 is light and compact compared to competition, it remains too big and heavy for the standard Mini-Tortuga ROV. It would cause serious navigation problems due to drag and weight balance. A version of Mini-Tortuga specifically designed for photogrammetry purposes has been created but it is too bulky to be deployed form the USV bow.

L x W x h mm	226 x 338 x 288
Weight air kg	11.2
Weight water kg	2.2
Material	Aluminium

Figure 19: IVM Hydro 300 (extract from datasheet)

Figure 20: Mini-Tortuga Hydro ROV

Photogrammetry can produce 3D models with a sub-millimetric accuracy but the post-processing takes extensive time (several hours) and it can hardly be used for the litter classification will requires a real time result.

Below is an example of photogrammetry of the quayside in front of Subsea Tech. The final model can be shown in various ways such as a textured model, a shape model or a wireframe model.

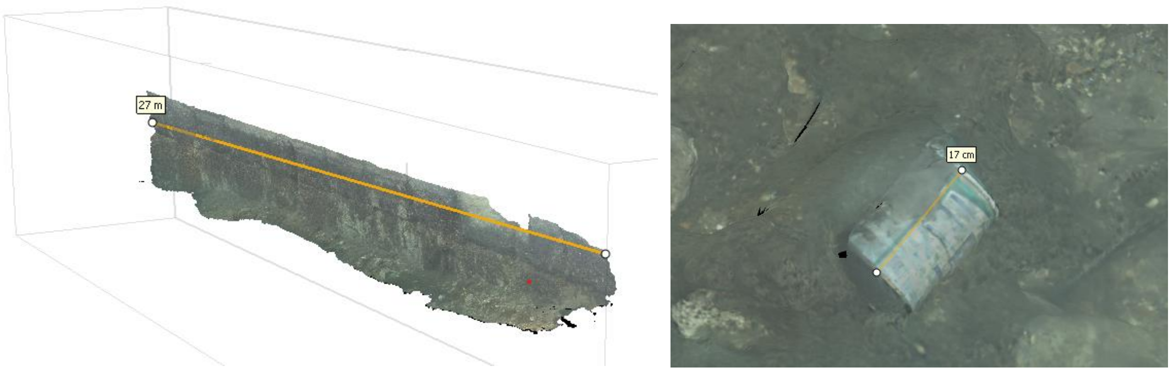


Figure 21: Textured 3D model of the quayside and zoom on a paint can

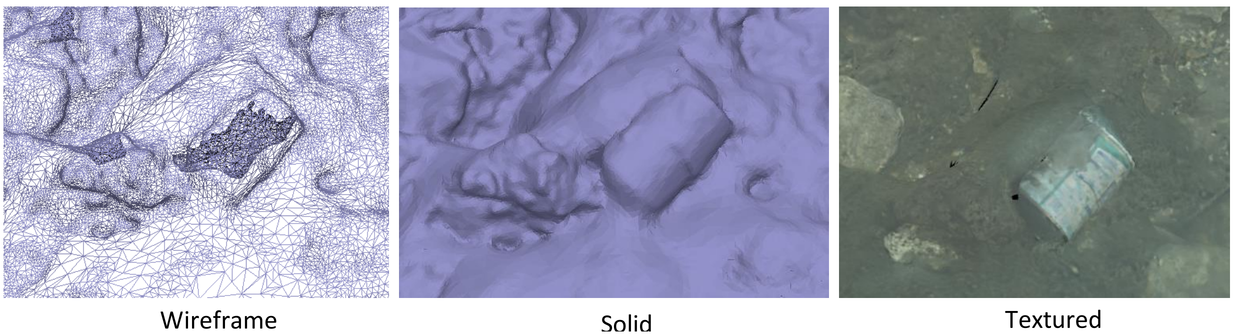


Figure 22: Paint can on the seabed on different model types

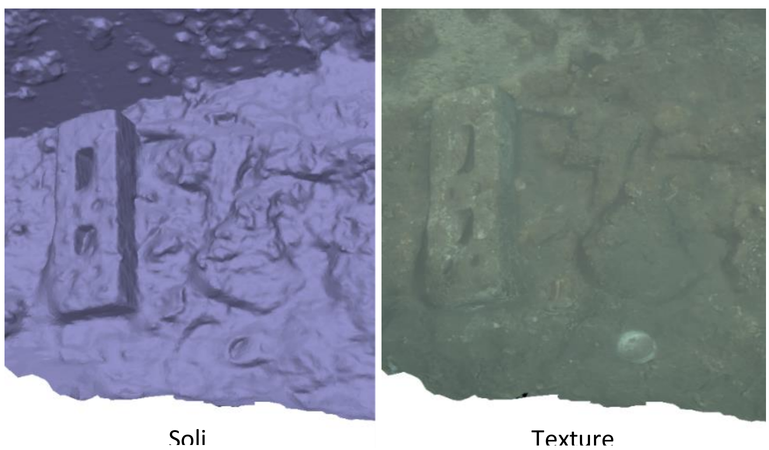


Figure 23: Cinder block and buried can

It took almost two days to generate the final textured model. The final data are more suited for an analysis made "by-hand" rather than for an automatic survey in real-time. Moreover, such an accuracy is not necessary to identify litter. Photogrammetry sensors are expensive and inconvenient to integrate on a small ROV as Mini-Tortuga.

3.6 Multispectral camera

Multispectral and hyperspectral cameras are largely deployed in many out of water applications and industries. Quality inspection of food [1] and beverage products, pharmaceutical products inspection and sorting, colours inspection, process monitoring, agriculture imaging [2], and more recently plankton satellite imaging [3] and coral reef aerial imaging are just few of examples of how non-visible imaging components are used into machine vision systems.

On the other hand, their use underwater is still very limited as applications cases are very few, underwater systems are not available off the shelf, and performance is not as good as above water one due to environmental constraints (light attenuation and turbidity particularly).

Figure 24: QCell multispectral camera on Mini-Tortuga ROV

We performed trials in Marseille with the system from QCell, a Greece based company. A metal plate has been installed in the water for a few weeks in order to let it be covered by biofouling. One of the corners has been cleaned so we could see the difference between a recently submerged metal litter and litter that is covered by algae.

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[1] : Saha D, Manickavasagan A. Machine learning techniques for analysis of hyperspectral images to determine quality of food products: A review. Curr Res Food Sci. 2021 Feb 3;4:28-44. doi: 10.1016/j.crfs.2021.01.002. PMID: 33659896; PMCID: PMC7890297.

[2]:Nik Susič, Uroš Žibrat, Saša Širca, Polona Strajnar, Jaka Razinger, Matej Knapič, Andrej Vončina, Gregor Urek, Barbara Gerič Stare, Discrimination between abiotic and biotic drought stress in tomatoes using hyperspectral imaging, Sensors and Actuators B: Chemical, Volume 273, 2018, Pages 842-852, ISSN 0925-4005, https://doi.org/10.1016/j.snb.2018.06.121.

[3] : Olivetti D, Cicerelli R, Martinez J-M, Almeida T, Casari R, Borges H, Roig H. Comparing Unmanned Aerial Multispectral and Hyperspectral Imagery for Harmful Algal Bloom Monitoring in Artificial Ponds Used for Fish Farming. Drones. 2023; 7(7):410. https://doi.org/10.3390/drones7070410

As expected, the multispectral camera has good performance to detect biofouling but it is not efficient to identify litters. We can isolate an area where biofouling is not present (i.e. sand, plastics and recently immerged metals) but it does not help the classification and the detection is not more exploitable than with a standard video camera. It also excludes metal litter that are covered by biofouling. Moreover, the results we had were highly dependent on the lighting conditions and distance from the object.

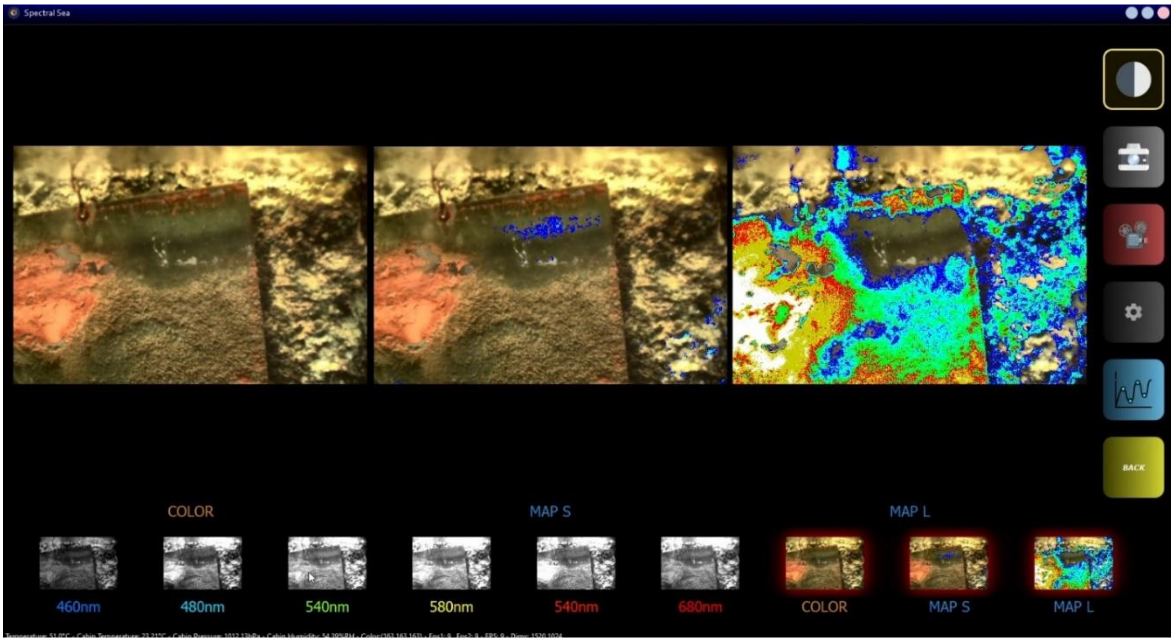

Figure 25: Test on a metal plate partially cleaned (top-right corner).
Left: standard coloured image / middle: detection of late-stage biofouling / right: detection of light biofouling

The software provided by the manufacturer proposes to change the wavelength taken into account to produce the image. Thus, it is possible to ignore the wavelength that produces the blueish / greenish blur underwater and achieve a better long-range vision with a monochrome image or deal with turbid waters.

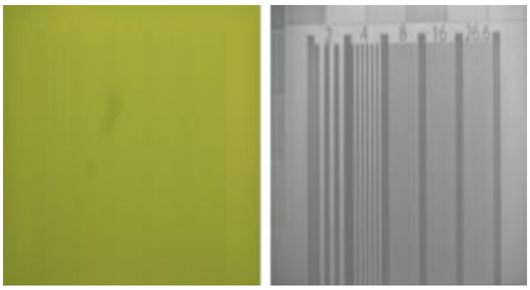

Figure 26: colour image (left) / spectral image (right)

Since underwater multispectral cameras are not frequently used yet, their development is on an early stage. They are fixed-position cameras integrated in big enclosures, which are not easily integrable on our observation ROV.

4. Conclusions

In order to compare the various sensors with respect to their potential use in the SeaClear2.0 project, we have defined several criteria which are graded from 1 to 5 (1: poor, 2: fair, 3: good, 4: very good, 5: excellent).
These criteria are:

1. Image quality (in the sense that the sensor can help to identify and classify marine litter via good resolution)
2. Immunity to water turbidity
3. Immunity to solar light
4. Ease of integration on small vehicle (maximum power, weight and dimensions)
5. Cost

Sensor	Image quality	Immunity to turbidity	Immunity to solar light	Ease of integration	Cost	Overall note
High-frequency 2D imaging sonar	4	5	5	5	2	44
Sidescan sonar	4	5	5	5	4	46
Magnetic sensor	1	5	5	5	4	37
Photogrammetry	5	2	4	1	1	31
Multispectral camera	3	3	1	4	4	28

Comparison with sensors chosen for SeaClear 1.0:

Sensor	Image quality	Immunity to turbidity	Immunity to solar light	Ease of integration	Cost	Overall note
Conventional video	5	1	5	5	5	38
2D imaging sonar	3	5	5	5	3	42
Bathymetry sonar	2	5	5	2	1	34

The last column is an overall note considering all the criteria but with different weighing as some of them are more important than the others. The first 2, i.e. image quality and immunity to turbidity are weighed with a coefficient 3, immunity to solar light is weighed with a coefficient 2, while the last two, ease of integration and cost, have a coefficient 1.

For our project, we have carefully selected three distinct sensors to address our underwater detection needs. Firstly, the side-scan sonar serves as our initial detection tool, providing a broad and comprehensive overview of the seabed and its contents. Secondly, the high-frequency imaging sonar has been chosen for its ability to provide detailed and clear imagery, allowing us to closely identify objects in the underwater environment and also filling the middle gap left by the side scan sonar.

Finally, the metal detector plays a vital role in our detection strategy, enabling us to identify submerged objects that may be concealed beneath sediment or covered by algae. Together, these sensors form a comprehensive and effective detection system tailored to our specific requirements and also compatible with turbid environments. The full HD camera remains as a primary detection sensor when visibility allows it.

The Oculus M1200d imaging sonar, along with the metal detector, is intended for integration with the ROV. The side-scan sonar will be also deployed from the ROV top optimize scanning angles and avoid towing from surface. The Norbit multibeam sonar will stay on the USV as the bathymetry sonar but also as a global detection sensor for large targets.

The primary sensor for the UAV, a high-resolution camera, will be utilized for detecting floating debris and assisting in pinpointing the locations of USVs and ROVs from an aerial perspective.

Finally the grapple will use high-definition cameras (number to be assessed during grapple design) to relocalise targets and allow video based auto navigation control.