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Contents

Glossary

AUV	Autonomous Underwater Vehicle
FLS	Forward-looking sonar
GD	GroundingDINO (a state-of-the-art vision-language)
HAUV	Hovering Autonomous Underwater Vehicle
MBES	Multibeam Echosounder
NID	Nature Inclusive Design
OTS	Offshore Test Site
OWF	Offshore windfarm
RHIB	Rigid Hull Inflatable Boat
ROV	Remotely Operated Vehicle
SS	Sea State
SSS	Side scan sonar
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle (ROVs and AUVs)
VD	Voordelta

Summary

This report is part of the Nature Regeneration North Sea Programme (NN)[1] (2023–2030) and contributes to its objectives by testing various innovative monitoring techniques using Unmanned Underwater Vehicles (UUVs). These UUVs are equipped with various sensors, including acoustic sensors, video and photo cameras, stereo cameras, and instruments for measuring abiotic variables. Such monitoring approaches will be required in future NN projects, for example in upcoming reef restoration initiatives. The results of this study are not only described in this report, but also made available in an interactive format as web pages or 'interactive mission dashboards' within the Rich North Sea Toolbox[2]. For researchers intending to use UUVs, practical guidelines are provided based on the experiences obtained during this project (see Chapter 4). Finally, a project video[3] compilation of the various field testing activities is available for a visual impression.

Ecological monitoring in the Dutch North Sea is important for understanding habitat conditions, biodiversity trends, and the effects of offshore wind farms and Nature-Inclusive Design (NID) measures. Traditional methods, including diver surveys and vessel based sampling, face limitations due to safety risks, weather dependence, and restricted coverage. Modern underwater robots, such as Unmanned Underwater Vehicles (UUVs), could offer a scalable and efficient alternative. This project evaluates seven Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV) in real-life conditions to assess their operational performance, data quality, navigation reliability, and suitability for ecological monitoring at two representative case studies, a biogenic reef in the shallow (~5 m) Voordelta (VD) and artificial reefs in the deeper (~20 m) Offshore Test Site (OTS), a few kms offshore The Hague (The Netherlands).

Across both locations, most platforms were successfully launched and recovered from small vessels (RHIBs), demonstrating practical feasibility. Operational performance was influenced by currents, visibility, vessel drift, and platform-specific navigation capabilities. Tethered ROVs provided precise manoeuvrability for close-range inspections but required stable vessel handling and skilled operators. AUVs offered greater spatial coverage and produced more consistent georeferenced datasets, though limited obstacle-avoidance constrained their ability to operate near complex vertical structures. Navigation performance of AUVS varied widely, systems with underwater positioning ability achieved repeatability within a few metres accuracy when revisiting predefined transects.

Optical sensors provided the highest ecological detail, but their effectiveness strongly depended on environmental conditions and vehicle stability. UUVs can be used to obtain species presence and density information for macrobenthic fauna (larger >~3 cm). However, organisms hidden by structures, other organisms, or burrows were not visible in the optical data output. Species level identification was possible for part of the fauna when image quality was sufficiently high. Achieving this required stable, slow, low-altitude navigation (approximately 0.5 m above the seabed), low turbidity conditions, and sufficient ambient light availability.
In the Voordelta, several platforms produced imagery of sufficient quality for species-level assessment and fine-scale georeferenced habitat mapping. At the OTS, higher turbidity reduced optical performance, although useful imagery of artificial reef structures could still be obtained to determine general biodiversity patterns.

Acoustic sensing provided robust and consistent spatial information across the range of environmental conditions encountered during the field tests. Forward-looking sonar (FLS), side-scan sonar (SSS), and multibeam echosounder (MBES) data each contributed to identifying reef structures, substrate types, and seabed morphology. In the Voordelta, FLS performed better than SSS, as the shallow water increased multipath effects (where sonar signals reflect multiple times between the seabed and water surface before reaching the sensor) resulting in reduced signal-to-noise ratio in the SSS data. Despite these limitations, MBES and FLS datasets yielded reliable georeferenced products.

[1] https://www.natuurversterkingnoordzee.nl/en/
[2] https://toolbox.therichnorthsea.com/inspirational-projects/innovative-monitoring-of-underwater-life/
[3] https://www.natuurversterkingnoordzee.nl/en/project/innovative-monitoring/.

Overall, the results show that UUVs can strengthen ecological monitoring programmes by providing safer, more scalable, and spatially extensive data acquisition than many traditional approaches. However, as of yet, UUVs are unlikely to fully replace conventional monitoring, especially where physical sampling is required for detailed species identification or assessment of infaunal communities. Instead, currently UUVs are best used as a complementary tool within existing monitoring frameworks. For example, acoustic and optical sensors can first be used for broad-scale habitat mapping and identification of ecological patterns, after which targeted conventional sampling can be conducted for detailed biological assessment and validation. Future work should therefore focus not only on technological improvements, but also on standardised workflows and integration of UUVs into existing monitoring programmes.

1 Introduction

1.1 The Nature Regeneration North Sea (NN) programme

The Nature Regeneration North Sea Programme (NN) (2023–2030) is a Dutch national initiative aimed at achieving a healthy, resilient, and ecologically rich North Sea, where natural processes are strengthened alongside sustainable human use. The programme seeks to ensure that recent and future developments in the North Sea can go hand in hand with nature development.

Marine ecosystems and protected species are already under pressure from long-standing human activities, including bottom fisheries and sand extraction. In addition, the expansion of offshore wind energy and the effects of climate change are expected to further impact ecosystem structure and functioning. To address this, NN initiates and funds pilot projects and larger-scale activities focused on the restoration of habitats and species, including fish, marine mammals, seabirds, and benthic communities forming the base of the food web. These efforts are complementary to existing policies and legislation, such as the Marine Strategy Framework Directive (MSFD), Natura 2000, the Common Fisheries Policy (CFP), OSPAR, and the Nature Restoration Regulation (NRR).

Effective monitoring is needed to evaluate these restoration efforts. This report contributes to NN by testing innovative monitoring techniques using Unmanned Underwater Vehicles (UUVs), which may be applied in future projects to address fundamental biological and ecological research questions, such as assessing biodiversity, reef structures, and oyster beds. The results of this study are presented in this report and made available through "interactive mission dashboards" within the Rich North Sea Toolbox[4]. In addition, a project video[5] provides a visual impression of the fieldwork and testing activities.

1.2 Background and context

Marine ecological monitoring plays an important role in understanding the condition of underwater ecosystems, tracking changes in biodiversity, informing conservation and management strategies, and assessing the ecological impacts of human activities such as offshore energy development, fisheries, and aquaculture. Traditionally, such monitoring has mostly relied on ship-based sampling, diver surveys, and sonar-based mapping techniques. While effective in specific contexts, these approaches are time- and resource-intensive and typically provide limited spatial and temporal coverage. Diver-based surveys can also involve significant safety risks at certain locations and/or conditions. Together, these constraints hinder the detection of fine-scale/large-scale habitat patterns, seasonal dynamics, and cumulative impacts.

These challenges are particularly pronounced in the Dutch North Sea, where rough sea states, limited visibility, and strong currents restrict both the frequency of surveys and the safe deployment of divers. As a result, achieving consistent, repeatable, and spatially extensive datasets is difficult, which limits the ability to monitor (both short and long-term) ecological change and evaluate the effectiveness of mitigation or restoration measures.

In response to these limitations, underwater drones, commonly referred to as Unmanned Underwater Vehicles (UUVs), have gained increasing attention as potential tools for marine ecological monitoring (see Kingma et al. (2025)). This category includes Remotely Operated Vehicles (ROVs), which are tethered and controlled in real time, and Autonomous Underwater Vehicles (AUVs), which execute pre-programmed missions without direct human control (Figure 1.1). UUVs have already long been used in industrial, military, and geophysical applications. Recent advances in sensor technology, computer vision, and automated image analysis have

[4] https://toolbox.therichnorthsea.com/
[5] https://www.natuurversterkingnoordzee.nl/en/project/innovative-monitoring/.

expanded their capabilities to include the collection of biologically relevant information, thereby increasing their value for ecological research and monitoring. At the same time, the availability of smaller, more affordable, and operationally accessible platforms led to their adoption within scientific and ecological monitoring tasks.

UUVs offer several key advantages over traditional approaches, including high-resolution optical imaging, acoustic mapping in turbid or low-visibility conditions, integration of environmental sensors, and the ability to collect georeferenced and repeatable data. By reducing the need for direct human presence underwater and enabling flexible and minimally invasive access to reefs, substrates, and structures, these systems can support monitoring continuity and improve safety compared to the before mentioned traditional methods.

These characteristics make UUVs well suited for monitoring the ecological effects of for instance offshore developments such as offshore wind farms, artificial reefs, and aquaculture installations, where repeated and standardised access to structures is often required. At the same time, expanding offshore wind development and Nature-Inclusive Design (NID) elements increase the demand for efficient and repeatable underwater monitoring tools.

This project builds upon the study by Kingma et al. (2025), which provided an overview of relatively small ROV and AUV platforms (Figure 1.1) suitable for ecological monitoring. One of the main conclusions of that study was that direct comparison between individual manufacturers are of limited value, as many platforms often offer similar functionalities. Instead, a more general report was made showing different types of platforms, as well as an overview of sensors and add-ons that can be mounted on such platforms, such as side-scan sonar, (stereo)cameras, video, lasers, light, salinity, depth, turbidity, chlorophyll-a (Table 1.1). In addition, several workflows for different case studies were proposed for analysing the resulting photo and video data, including the use of computer vision (AI) tools for automated processing.

As a next step, Kingma et al. (2025) proposed to test and validate a selection of platforms, equipped with different sensor configurations, under real operational conditions. This recommendation was adopted within the current NN project. Seven ROV and AUV manufacturers were invited to participate in representative field trials in the Dutch North Sea.

Figure 1.1: Overview of compact UUVs (smaller sized portable ROVs and AUVs) (Kingma et al. 2025).

Table 1.1: Overview of sensors and add-ons that can be mounted on UUVs (see Kingma et al. 2025 for more details).

Type of sensor	**Purpose**
1. Acoustic sensors	
Multibeam Echosounder (MBES)	Mapping seafloor topography, identification of sediment types.
Side scan sonar (SSS)	Mapping of the seafloor and objects on the seafloor, identification of biogenic reefs and abiotic reefs such as boulders
Forward Looking Sonar (FLS)	Supporting navigation, object detection, and qualitative assessment of reef presence
2. Optical sensors	
Laser scanner	Creating 3D point clouds of objects
2D video	Recording video tracks of the seafloor and its biodiversity.
2D and 3D photo mosaicking	Recording 2D georeferenced photo mosaics of the seafloor or a 3D image of an object. Can be used to assess biodiversity.
3. Other sensors and add-ons	
Robotic arms, grabs, water samplers	Grabbing sediment samples (grain size, eDNA) or taking water samples (eDNA)
Environmental sensors	Measuring environmental parameters to explain observed biodiversity patterns (Temp, Chl-A, pH, O2 etc.)

1.3 Objective

The objective of this NN project is to increase the knowledge base on the applicability of small ROVs and AUVs (UUVs) for ecological monitoring in the Dutch North Sea. The project aims to provide insight into how different UUV platforms perform under real operational conditions, with respect to data quality, robustness, and their suitability for (long-term and scalable) ecological monitoring programmes. By documenting operational experiences and assessing data quality and repeatability, this report supports researchers, environmental managers, and policy-makers in making informed decisions on the adoption of UUVs for ecological monitoring programmes

This report specifically evaluates the field performance of in total seven ROV and AUV platforms during deployments at two representative case study locations. The two case study sites consisted of a biogenic reef in the Voordelta (VD) and an artificial reef at the Offshore Test Site (OTS), representing contrasting habitat types and monitoring challenges. The Voordelta is a dynamic, shallow, sediment-rich environment with an extensive reef area, whereas the Offshore Test Site is characterised by deeper water and three-dimensional structures (point locations) that require precise navigation and stable data collection.

1.4 Scope and limitations of study

This study evaluates the potential of UUVs for ecological monitoring in dynamic marine environments in the Dutch North Sea. The assessment focuses on four main aspects: (1) operational performance under field conditions, including deployment, recovery, and robustness (defined as the ability of a UUV system to continue operating and collecting usable data under varying environmental and operational conditions) in varying environmental conditions; (2) data acquisition capabilities of optical, acoustic, sampling, and environmental sensor systems; (3) suitability of the collected data for ecological monitoring applications such as species and habitat assessments; and (4) repeatability and georeferencing of surveys to support temporal comparisons and long-term monitoring.

The study primarily aims to assess the functional capabilities and ecological value of UUV systems. Operational limitations and constraints are considered subsequently, where relevant, as part of evaluating their applicability within ecological monitoring programmes. In addition to technical performance, practical considerations such as vessel support, personnel requirements, operational procedures, and maintenance are discussed to provide broader insight into the feasibility of implementing UUV based monitoring approaches.

Several factors fall outside the primary scope of this project. Environmental and operational constraints such as extreme weather, sea state, strong currents, turbidity, and depth limitations are not systematically tested, although they may influence UUV performance and data quality. Platform endurance, battery life, and mission range are also not explicitly evaluated. Furthermore, aspects related to data management, post-processing workflows, sensor calibration, and integration with existing monitoring datasets are not quantitatively assessed. Financial considerations, including acquisition costs, maintenance, data processing, and vessel-related operational expenses, are outside the scope of this study, although these aspects are briefly considered where relevant to practical deployment.

1.5 Research aim and questions

The overarching aim of this project is to assess the potential of UUVs for ecological monitoring in the Dutch North Sea. The project investigates the extent to which UUV platforms can support ecological surveys through reliable data acquisition, repeatable monitoring, and practical deployment under (nearshore and offshore) field conditions. Building on the objective and scope defined above, the study addresses the following research questions (RQs):

Operational performance
RQ1: How do the UUV platforms perform under real life field conditions with respect to launch and recovery, operational robustness, and handling of variable currents, and visibility?

Perception ability & suitability of data for ecological monitoring
RQ2: What is the quality, coverage, and resolution of the optical, acoustic, sampling, and environmental sensor data collected by the UUVs during the field tests? (where quality refers to the usability and interpretability of the data, and resolution to the level of spatial detail captured).
RQ3: To what extent is the collected data suitable for ecological monitoring tasks such as species and habitat assessment, environmental characterisation, and detecting habitat changes?

Motion ability
RQ4: How reliably can the UUVs revisit locations and produce consistent, georeferenced datasets that support repeatable surveys and temporal comparisons?
RQ5**:** Is the manoeuvrability of the UUV platforms sufficient to inspect benthic life on and around complex three-dimensional structures?

Operational and logistical considerations:
RQ6: What are the practical requirements for deploying UUVs in offshore monitoring campaigns, including vessel support, crew needs, and operational procedures?

Contribution to long-term monitoring
RQ7**:** How can UUV derived data contribute to long term ecological monitoring, including continuity, standardisation, and integration into existing monitoring programmes?

By addressing these questions, the project aims to provide actionable insights for marine researchers, environmental managers, and policy-makers considering the integration of UUVs into ecological monitoring programmes.

1.6 Report structure

This report is structured as follows:

Chapter 2 describes the methodology, including the case study sites, parameters of interest, tested UUV systems, and the data handling workflow. It explains how the field trials were conducted and which metrics were used to assess the performance of the ROV and AUV platforms.

Chapter 3 presents the results of the field trials, summarising the main findings and lessons learned. It provides an analysis of operational performance, data acquisition quality, and the suitability of the platforms for different ecological monitoring applications.

Chapter 4 translates these findings into a practical UUV selection guideline. It discusses important UUV selection criteria, operational considerations, and future developments relevant for the integration of UUVs into ecological monitoring programmes.

Chapter 5 contains the conclusions of this study, including the main insights, recommendations, and implications for the future use of UUVs in long-term ecological monitoring.

Annex A provides summaries per field test per UUV, with links to online (interactive) dashboards.
Annex B contains detailed technical information for optical data analysis and the use of AI.
Annex C describes analysis of acoustic data (rugosity calculations).
Annex D describes reef object localisation.

2 Methodology

2.1 Case study areas

Two distinct case study areas were selected to evaluate the performance of the tested UUVs (ROV and AUV platforms) (Chapter 2.3) under representative North Sea conditions. The first site, located in the Voordelta, features a biogenic reef dominated by Pacific oysters, European flat oysters and blue mussels. This area is characterized by dynamic, sediment-rich environments and has been the subject of ongoing flat oyster restoration and monitoring efforts (Figure 2.1). The second site, located in “plot six” of the Offshore Test Site[6] (OTS), contains artificial reef structures installed to enhance biodiversity within an offshore wind farm context (Figure 2.2). These contrasting environments were chosen to capture a broad range of ecological monitoring challenges and to assess the versatility of the tested UUV platforms. More information on the two case study areas can be found in the following sections.

Figure 2.1: Voordelta flat oyster reef (photo by Floor Driessen)

Figure 2.2: “Reefcube egg” (for cephalopods), *artificial reef deployed at the Offshore Test Site (photo by Klaudie Bartelink – Dutch Maritime Productions)*

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[6] https://www.northseafarmers.org/offshore-test-site

2.1.1 Voordelta: biogenic reef system

Biogenic reefs are reefs formed primarily by living organisms (so called 'reef-builders'). In the Netherlands most relevant (native) species include *Mytilus edulis* (blue mussel), *Ostrea edulis* (European flat oysters), *Sabellaria spinulosa* (Ross worm) and *Lanice conchilega* (sand mason worm) (Sas et al., 2023). The three-dimensional structures provided by these organisms can offer refuge, feeding grounds, and breeding sites for various other organisms and thereby form biodiversity hotspots.

Flat oyster reefs once covered around 20% of the Dutch North Sea floor but have since become rare due to overfishing, diseases, and climate change. In 2015, a mixed reef of Pacific oysters (*Magallana gigas*) and European flat oysters with blue mussels was discovered in the Voordelta (Christianen et al., 2018). The oyster reef is located near the Brouwersdam (Zeeland, The Netherlands), where a storm surge barrier separates the former sea inlet (Lake Grevelingen) from the North Sea. Since 2008, the Voordelta area has been designated as a Natura 2000 site.

As part of a monitoring programme for flat oyster reef restoration in the North Sea, the area has been surveyed annually for several years using 50 m Scuba diver transects (Figure 2.3), sonar imaging, oyster spat collectors, and larval sampling (Kamermans et al., 2025). The transects are located at depths ranging from 2.0 to 3.2 meters LAT, specific coordinates are provided in Table 2.1.

The environmental conditions of the site include mixed flat and Pacific oyster/mussel reefs situated on a mostly sandy seabed, with a depth ranging from 0.5 to 6 m. The current in this area is limited as it is a near coastal area and did not exceed 1 knot during the field visits of this project. The sea state varies between SS0 and SS2, and visibility ranges typically from 0.5 to 4 m.

Table 2.1: Coordinates (WGS84) of 50 meter line transects.

ID	Transect	X begin	Y begin	X end	Y end
1	Mussel bed	3.859358234	51.78021516	3.858633892	51.78020572
2	Sand	3.859041775	51.78174472	3.858317409	51.78173528
3	South	3.86016639	51.77999464	3.860844393	51.77991464
4	Middle	3.861636396	51.78402064	3.8623654	51.78410164
5	North	3.857876376	51.79181564	3.858514379	51.79198264

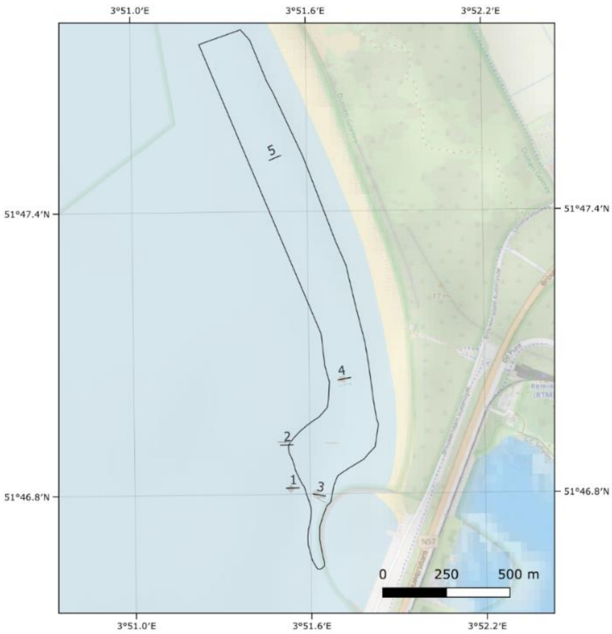


Figure 2.3: Location of the Voordelta mixed flat and Pacific oyster/mussel reef, including the positions of the monitoring transects.

2.1.2 Offshore Test Site: artificial reefs

Artificial reefs are man-made, stand-alone structures designed to enhance marine biodiversity by providing shelter, feeding grounds, and settlement surfaces for a wide range of marine species (Kingma et al., 2025). While offshore wind turbines and related structures (such as scour protection) can create "reef effects," they are not specifically intended to stimulate reef formation. By incorporating artificial reefs as NID elements within offshore wind farms (OWFs), these effects can be enhanced, supporting populations of benthic species and fish. Artificial reefs are now placed throughout OWFs in the Dutch North Sea.

Within the Offshore Test Site (OTS), a dedicated area for ecological innovation, four different concrete artificial reefs were installed in 2021 as part of The Rich North Sea initiative. These installations aim to study and promote biodiversity enhancement in and around offshore wind energy infrastructure. Three of the four reefs placed at the OTS are included in this case study (Table 2.2 and Figure 2.4 & Figure 2.5): the "Reef cube egg" (highest priority and first inspected), the "Reef cube mussel", and the "WERC-dock", the latter only being surveyed if time and conditions permitted.

The OTS is characterized by a sandy seabed (Figure 2.5, A), with depths ranging from 20.4 to 21.9 meters (relative to Lowest Astronomical Tide as of April 1, 2024). Currents in this area vary between 0.2 and 1.5 knots, as recorded by the RWS waterlog. Sea state fluctuates between SS0 and SS4–5, and underwater visibility ranges from 0.5 to 2 meters.

This case study provides an opportunity to evaluate the performance of UUVs in monitoring complex artificial reef structures under challenging offshore conditions.

Table 2.2: Priority table monitoring artificial reefs in the Offshore Test Site (WGS84).

ID	Reef name	Priority	Lat N	Lon E
1	Reef cube egg	High	52.161460	4.100510
2	Reef cube mussel	Medium	52.161854	4.100980
3	WERC-dock	Low	52.160722	4.099676

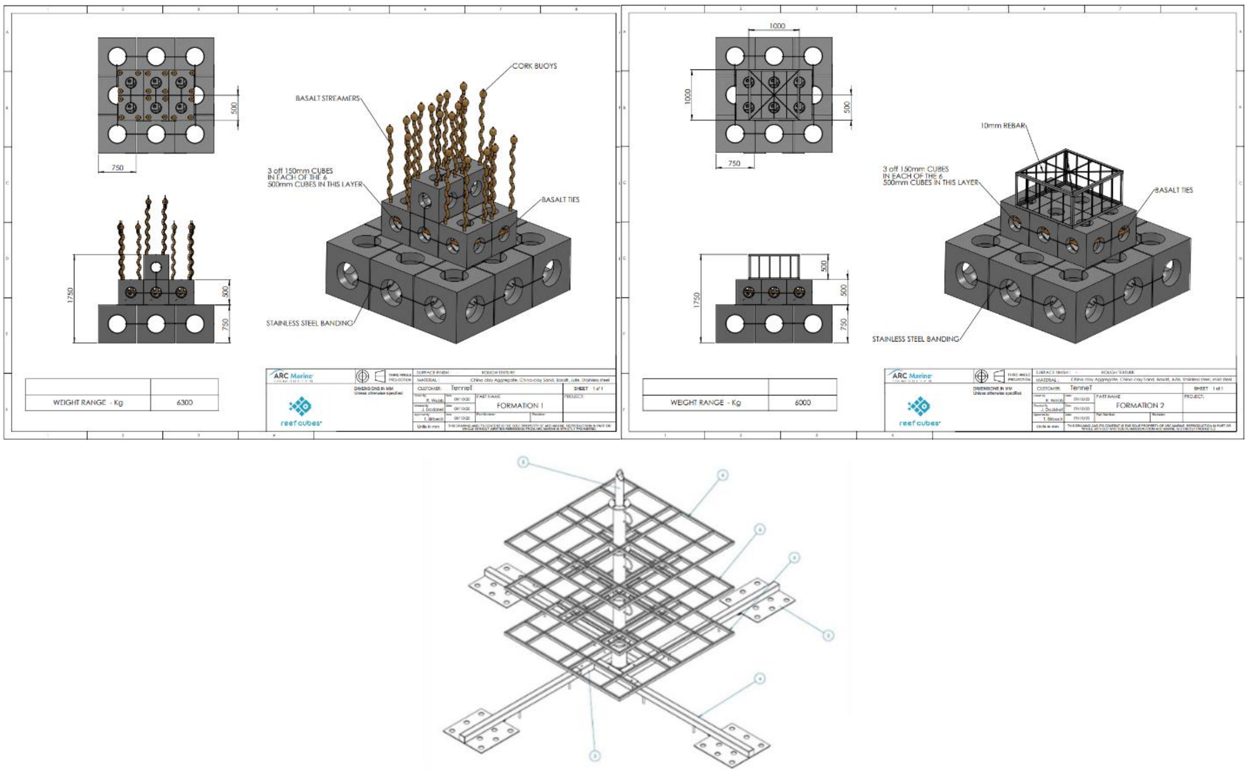


Figure 2.4: Schematic designs of the Reef cube egg (left), the Reef cube mussel (right), and the WERC-dock (below). Reference of images: Arc Marine and Waardenburg Ecology via The Rich North Sea.

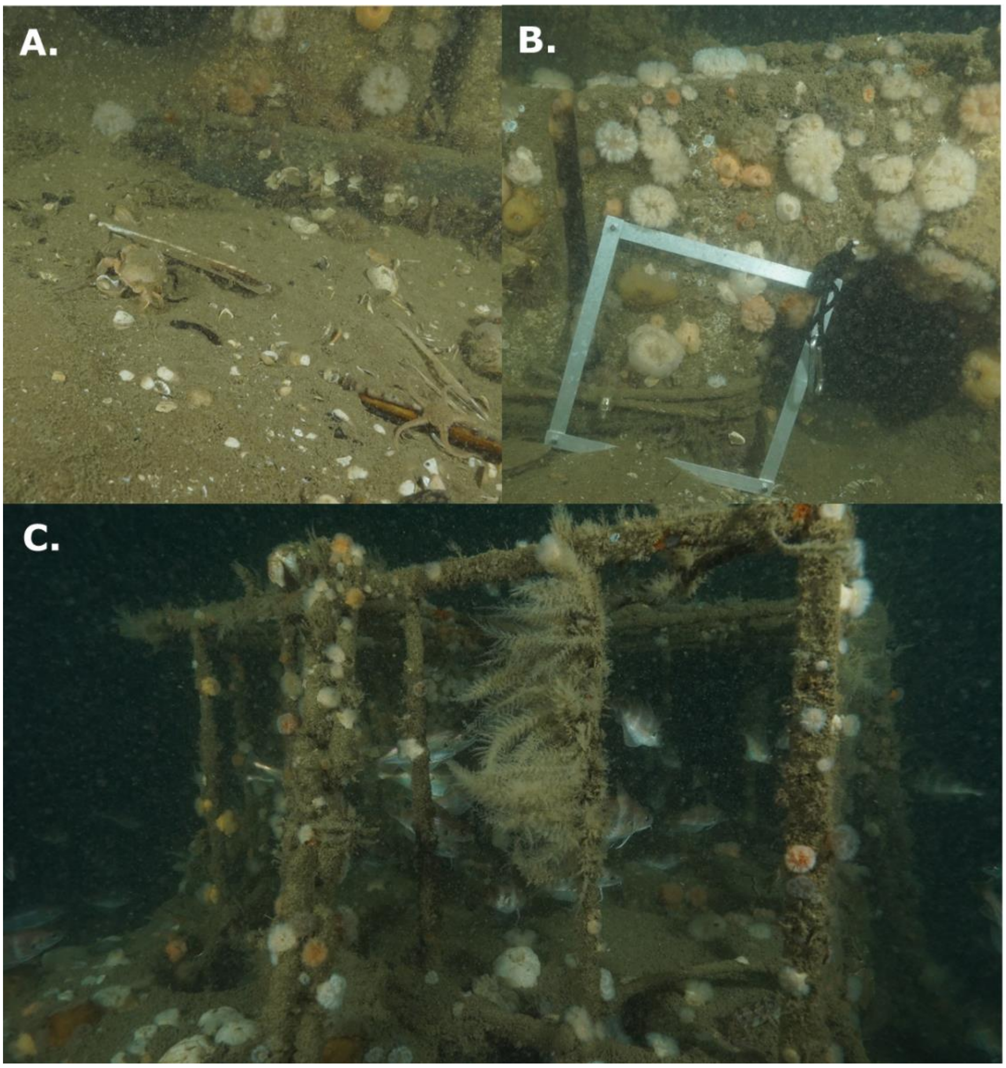


Figure 2.5: A: Sandy seabed around artificial reef, B: Reef cube bottom element, C: Reef cube mussel cage. (photos by Klaudie Bartelink – Dutch Maritime Productions)

2.2 Parameters of interest

In this study, a set of common ecological and environmental parameters was selected to characterise habitat structure and biological conditions at both the Voordelta and the Offshore Test Site. These parameters were chosen based on their relevance in marine ecological monitoring and their usefulness for assessing biodiversity, habitat composition, and environmental context.

The parameters include surface biodiversity, reef presence and type, shell and substrate characteristics, seabed morphology, and background variables such as temperature, salinity, and chlorophyll-a levels. Measurements were obtained using a combination of optical imaging systems, acoustic technologies (FLS, SSS, MBES), in-situ environmental loggers, and water and sediment sampling tools.

Table 2.3 provides an overview of the parameters, the corresponding measurement techniques, and the locations at which each was assessed. This approach ensured consistent and reproducible data collection suitable for comparing the two study sites.

Table 2.3: Overview of parameters monitored during the study, including the corresponding measurement methods and the locations where each parameter was assessed (Voordelta (VD) and Offshore Test Site (OTS)).

Metric	Used sensor	VD	OTS
Surface biodiversity (species/m^2)	Camera	Yes	Yes
Surface biodiversity (#unique species)	Camera	Yes	Yes
Reef presence	Camera Imaging Sonar (FLS/SSS/MBES BS) Profiling Sonar (MBES Bathy)	Yes	Yes
Reef type	Camera Imaging Sonar (FLS/SSS/MBES BS)	Yes	Yes
Shell presence	Camera Imaging Sonar (FLS/SSS/MBES BS)	Yes	No
Soil type	Camera Imaging Sonar (FLS/SSS/MBES BS)	Yes	Yes
Seabed morphology	Camera Imaging Sonar (FLS/SSS/MBES BS) Profiling Sonar (MBES Bathy)	Yes	Yes
Reef rugosity as measure for reefiness (the ratio of 3D surface area to its projected 2D planar area)	Camera Imaging Sonar (FLS/SSS/MBES BS)	Yes	No
Background environmental parameters (incl. temperature, conductivity, chlorophyll-a, pH)	Loggers	Yes	Yes
Sediment and water samples	Samplers	No	Yes

2.3 Selection process and overview of tested UUVs

The UUVs evaluated in this project were selected through a structured process aimed at capturing the diversity of underwater platforms currently relevant for ecological monitoring. Organisations identified in Kingma et al. (2025) were invited to participate in this project and demonstrate the capabilities of their systems within the selected case study areas (Chapter 2.1). To align expectations and address the challenges faced by ecological researchers during underwater monitoring, a dedicated work session was held for interested parties to discuss project details and technical requirements.

The final selection includes both ROVs and AUVs of varying size, sensor configurations, and operational concepts. This mix allowed the project team to explore a wide range of capabilities, ranging from close-range visual inspections to larger-scale acoustic mapping and environmental sensing. All systems were deployed at one or both case study sites (Voordelta and the Offshore Test Site), enabling cross-comparison across contrasting habitats and environmental conditions. Table 2.4 provides an overview of the participating organisations and the UUV configurations deployed during the field tests. Figure 2.7 shows a picture of each of the UUVs. More detailed information can be found in Table 2.5. A short summary per ROV/AUV per case study test site is given in Annex A.

Table 2.4: Overview of UUVs that where tested during the field tests.*

Manufacturer	Operator	Model	Country	Location	Business model**
BeeX[7]	BeeX	A.Ikanbilis Hovering AUV (HAUV)	Singapore	VD+OTS	Subcontract
Lobster Robotics[8]	Lobster Robotics	Scout II AUV	Netherlands	VD+OTS	Subcontract
Videoray[9]	DCN Diving[10]	Defender ROV	USA	OTS	Purchase/ Subcontract
Subsea Tech[11]	Subsea Tech	Mini Tortuga Hydro ROV	France	VD+OTS	Subcontract
Seaber[12]	Seaber	Marvel-SCAN AUV	France	VD+OTS	Purchase/ Subcontract
Seaber	Seaber	Yuco-PHYSICO AUV	France	VD+OTS	Purchase/ Subcontract
Deep Trekker[13]	H2O Drones[14]	Revolution ROV	Canada	VD+OTS	Purchase/ Subcontract
IQUA Robotics[15]	IQUA Robotics	Sparus II AUV	Spain	VD+OTS	Purchase

* It should be noted that these systems were tested during the summer of 2025, and further developments and improvements may have occurred since then. For most up to date information regarding the tested systems we recommend checking their websites.
** Subcontract: a UUV and UUV pilot team are provided by the manufacturer. Purchase: the UUV can be purchased and operated by the client.

Figure 2.6: IQUA Robotics and WMR team on their way to the Voordelta oyster reef test site, waiting in the sluice of Stellendam (July 2025, photo Oscar Bos, WMR).

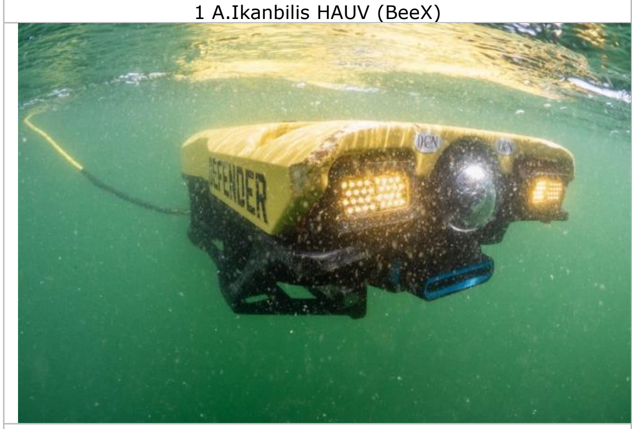
[7] https://beex.sg/
[8] https://www.lobster-robotics.com/
[9] https://videoray.com/
[10] https://dcndiving.com/
[11] https://www.subsea-tech.com/
[12] https://seaber.fr/
[13] https://www.deeptrekker.com/
[14] https://www.h2o-drones.com/
[15] https://iquarobotics.com/

Table 2.5: Technical specifications of the tested UUVs.

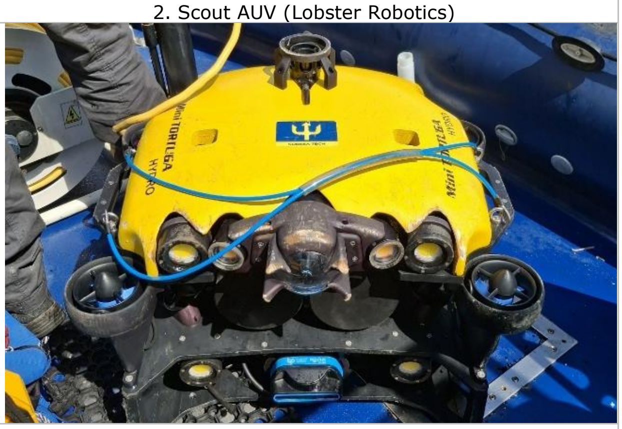
Model	Size	Mass	Power	Motion ability	Perception ability
A.Ikanbilis HAUV	L = 90 cm W = 80 cm H = 40 cm	60 kg	Battery	Teleoperation & waypoint following	MBES (837BXi DeltaT, 260 kHz), FLS (Oculus M750d, 750/1200 kHz), Camera (HD, pitch controlled) GoPro camera (4K) + laser scaler
Scout II AUV	L = 200 cm D = 60 cm	50 kg	Battery	Waypoint following	Camera (fixed downward)
Defender ROV	L = 71 cm W = 39 cm H = 24 cm	17 kg	External	Teleoperation	FLS (Oculus M1200d, 1.2/2.1 MHz) Camera (Full HD, fixed forward)
Mini Tortuga Hydro ROV	L = 67 cm W = 68 cm H = 50 cm	46 kg	External	Teleoperation	FLS (Oculus M750d,750/1200 kHz) Front camera (1920 x 1080 p, pan and tilt) HYDRO300 calibrated stereo photogrammetry kit
Marvel-SCAN AUV	L = 103 cm D = 12 cm	11 kg	Battery	Waypoint following	SSS (680 kHz)
Yuco-PHYSICO AUV	L = 123 cm D = 12 cm	9.5 kg	Battery	Waypoint following	Water conductivity, pH (AML Oceanographic Instruments)
Revolution ROV	L = 72 cm W = 44 cm H = 24 cm	26 kg	Battery	Teleoperation & waypoint following	FLS (Oculus M1200d, 1.2/2.1 MHz) Camera (HD) + Laser scaler Seabed & water sampler Above sensors on 260 deg. Rotating head
Sparus II AUV	L = 160 cm W = 46 cm H = 49 cm D = 23 cm	55 kg	Battery	Waypoint following, obstacle avoidance	MBES (Norbit WBMS, 400 kHz) FLS (Oculus M1200d, 1.2/2.1 MHz) Camera (FLIR blackfly, Fixed downward)

1 A.Ikanbilis HAUV (BeeX)

2. Scout AUV (Lobster Robotics)



3. Defender ROV (Videoray)



4. Mini Tortuga Hydro ROV (Subsea Tech)

5(a) Marvel-SCAN, (b) Yuca Physico AUV (Seaber)

6.Revolution ROV (Deep Trekker)

7. Sparus II AUV (IQUA Robotics)

Figure 2.7: Photos of the UUVs that where tested within the project

2.4 Approach

The field tests in this project were conducted as technology demonstrations rather than controlled experiments. The aim was not to select the best platform, or to compare and rank platforms. Instead, the primary aim was to evaluate how different UUV platforms equipped with a variety of sensors operate under real North Sea monitoring conditions. This approach provides practical insight into operational behaviour and data acquisition under realistic constraints, rather than producing directly comparable quantitative performance metrics.

First, all navigation and sensor datasets were subjected to a quality-control check to determine which portions were suitable for analysis. Given the diversity of platforms, sensor configurations, data formats, and mission styles, post-processing steps were applied to harmonise datasets where possible. These steps included organising raw files, generating optical or acoustic mosaics when applicable, extracting navigation tracks, and converting acoustic outputs into comparable visual representations. The level of post-processing depended on the type and completeness of the data delivered by each manufacturer.

For each mission, an interactive mission dashboard was created. These reports document the deployment context, summarise the executed activities, and present representative examples of the acquired data. When georeferenced datasets were available, spatial products such as mosaics, imagery, and sonar outputs were overlaid with vehicle navigation tracks to support visual interpretation. The interactive mission dashboards are available within The Rich North Sea Toolbox[16].

Insights from the mission-level analyses were subsequently used to address the research questions. Because the demonstrations were not designed as standardised benchmark trials, the emphasis of the analysis is qualitative. The focus is on identifying operational patterns, evaluating the suitability of different sensing modalities for ecological monitoring tasks, and highlighting lessons learned across contrasting environmental settings.

Finally, the findings of these evaluations informed the development of guidelines and recommendations for selecting UUV platforms that match specific monitoring objectives and environmental conditions.

[16] https://toolbox.therichnorthsea.com/inspirational-projects/innovative-monitoring-of-underwater-life/

3 Results and discussion

This chapter presents and discusses the findings from the field tests carried out at the Voordelta and the Offshore Test Site. It summarises the missions executed with the different ROV and AUV platforms, the types of data collected, and the conditions under which they operated. The results outline the overall performance the UUVs in terms of operational robustness, data acquisition, navigation, and ecological monitoring suitability. These insights form the basis for the analyses and guidelines discussed in the following sections of this report. More detailed methods and results can be found in Annex A (summary per field trip), Annex B and C (optical data) and Annex C (acoustic data). The results are not only described in this report, but also displayed more interactively as web pages or 'interactive mission dashboards' in the Rich North Sea Toolbox[17].

3.1 Summary of tests and acquired data

Table 3.1 shows the various tests that were conducted at the Voordelta and the Offshore Test Site. For each experiment, an interactive mission dashboard is generated that contains a summary of the completed activities and shows a representation of the acquired data. In case the data is georeferenced, it is also shown on a mission map overlaying the AUV position data with the collected mosaics.

Table 3.2 and Table 3.3 provide an overview of the collected data (type, format, size and georeferencing) for the VD and OTS respectively.

Table 3.1: Overview of tests conducted at the Voordelta and Offshore Test Site.

Model	***Location***	***Date***	***Start time (local)***	***End time (local)***	***Duration (hh:mm)***
A.Ikanbilis ROV	Voordelta	9 Jul 2025	12:01	14:48	02:47
	OTS	10 Jul 2025	12:57	15:06	02:09
Scout II AUV	Voordelta	15 Aug 2025	9:00	11:45	02:45
	OTS	14 Aug 2025	10:00	12:08	02:08
Defender ROV	OTS	18 Jul 2025	12:08	13:44	01:36
Mini Tortuga Hydro ROV	Voordelta	14 Aug 2025	10:30	12:47	02:17
	OTS	15 Aug 2025	10:30	14:00	03:30
Marvel-SCAN AUV	Voordelta	13 Aug 2025	12:31	14:37	02:06
Yuco-PHYSICO AUV	Voordelta	13 Aug 2025	12:54	14:13	01:20
Marvel-SCAN AUV	OTS	12 Aug 2025	10:43	11:11	00:28
Yuco-PHYSICO AUV	OTS	12 Aug 2025	9:56	10:37	00:41
Revolution ROV	Voordelta	12 Aug 2025	12:17	15:37	02:20
	OTS	13 Aug 2025	10:33	13:49	03:16
Sparus II AUV	Voordelta	10 Jul 2025	11:06	14:48	03:42
	OTS	11 Jul 2025	12:22	14:49	02:27

[17] https://toolbox.therichnorthsea.com/inspirational-projects/innovative-monitoring-of-underwater-life/

Table 3.2: Overview of the acquired data for the Voordelta test site.

Model	Sensor/ data type	Format	Size	Georeferenced
A.Ikanbilis ROV	Camera/ Video	.mp4	706 MB	No
	MBES/ Point cloud	.xyz	13 MB	Yes
	FLS/ Acoustic mosaic	.png, .pgw	6 MB	Yes
	GPS/ Navigation log	.csv	10 MB	Yes
Scout II AUV	Camera/ Mosaic	.tif	3.4 GB	Yes
	Camera/ 3D model	.obj, .jpg, .mtl	2.0 GB	No
	GPS/ Navigation log	.csv	23 MB	Yes
Mini Tortuga Hydro ROV	Camera/ Mosaic	.jpg, .ply	2.0 GB	No
	FLS/ Sonar images	.oculus	833 MB	No
	SSS/ Waterfall plot	Starfish .logdoc	54 MB	No
Marvel-SCAN AUV	SSS/ Waterfall plot	.sbrdump	475 MB	Yes
	GPS/ Navigation log	In .sbrdump		Yes
Yuco-PHYSICO AUV	Water properties	.sbrdump	228 MB	Yes
	GPS/ Navigation log	In .sbrdump		Yes
Revolution ROV	Camera/ Video	.mp4	7.6 GB	No
	FLS/ Sonar images	.oculus	15.2 GB	No
Sparus II AUV	Camera/ Mosaic	.png, .tif	330 MB	Yes
	Camera/ Images & 3D model	.obj, .jpg	11.7 GB	No
	MBES/ Bathymetry	.png, .tif	343 MB	Yes
	FLS/ Acoustic mosaic	.tif	330 MB	Yes
	GPS/ Navigation log	.csv	20 MB	Yes

Table 3.3: overview of the acquired data for the Offshore Test Site.

Model	Sensor/ data type	Format	Size	georeferenced
A.Ikanbilis ROV	Camera/ Video	.mp4	1.08 GB	No
	FLS/ Acoustic mosaic	.png, .pgw	2 MB	Yes
	GPS/ Navigation log	.csv	12 MB	Yes
Scout II AUV	Camera/ Mosaic	.tif	4.1 GB	Yes
	GPS/ Navigation log	.csv	17 MB	Yes
Defender ROV	FLS/ Sonar images	.oculus	8.4 GB	No
	Camera/ Video	.mp4	10.7 GB	No
Mini Tortuga Hydro ROV	Camera/ Mosaic	.jpg, .ply	2.3 GB	No
	FLS/ Sonar images	.oculus	237 MB	No
Marvel-SCAN AUV	SSS/ Waterfall plot	.sbrdump	144 MB	Yes
	GPS/ Navigation log	In .sbrdump		Yes
Yuco-PHYSICO AUV	Water properties	.sbrdump	165 MB	Yes
	GPS/ Navigation log	In .sbrdump		Yes
Revolution ROV	Camera/ Video	.mp4	8.1 GB	No
Sparus II AUV	Camera/ Mosaic	.png, .tif	473 MB	Yes
	Camera/ Images & 3D model	.obj, .jpg	5.3 GB	No
	MBES/ Bathymetry	.png, .tif	525 MB	Yes
	FLS/ Acoustic mosaic	.tif	725 MB	Yes
	GPS/ Navigation log	.csv	15 MB	Yes

3.2 Detailed analysis

3.2.1 Operational performance

RQ1: *How do the UUV platforms perform under real life field conditions with respect to launch and recovery, operational robustness, and handling of variable currents and visibility?*

The tested UUV platforms were successfully deployed and recovered during the field trials and generally performed as expected during the conducted missions, without major platform failures. Launch and recovery operations were feasible from RHIBs across all platforms (for both ROVs and AUVs), indicating a high level of practical field operability under typical North Sea conditions. The launch and recovery method varies per platform, depending on its weights and size; from throwing overboard by one person to using a crane or sledge. Figure 3.1 provides impressions of the diverse launch and recovery techniques encountered during the field tests.

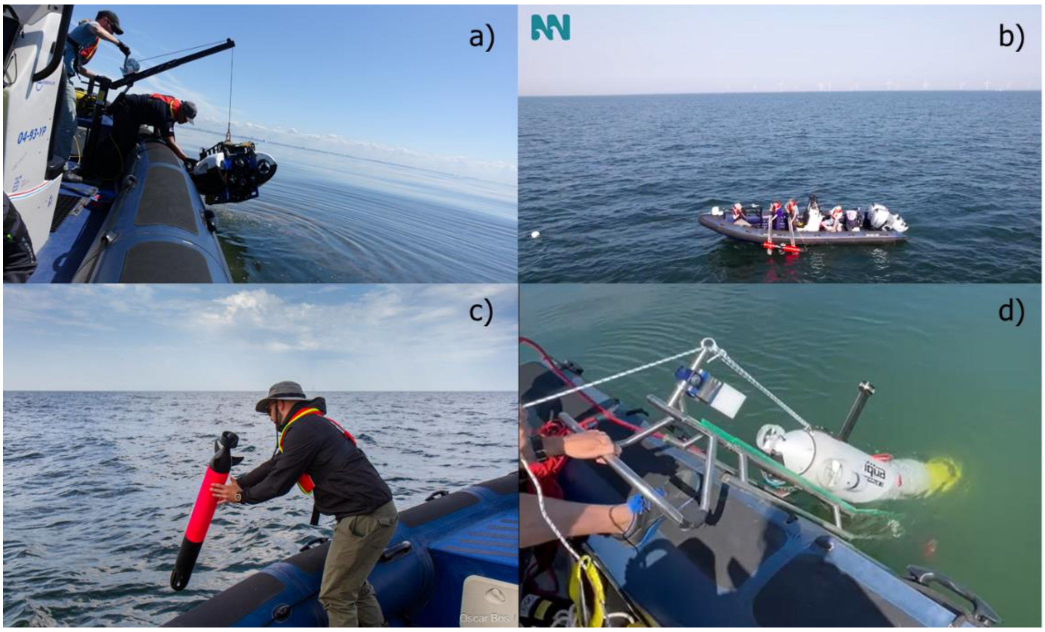


Figure 3.1: Various UUV planform launch and recovery techniques. a) BeeX ROV recovery by a crane; b) Lobster AUV launch by a sledge; c) Seaber AUV launch by throwing overboard; d) IQUA Robotics AUV launch by a sledge.

The main operational constraints encountered were related to vessel drift and the limited ability to maintain precise positioning in the absence of surface GPS (and no anchor possibilities), which occasionally slowed target reacquisition and survey continuity. Operator-interface performance was also affected during operations from small RHIBs, where strong sunlight reduced screen readability and control comfort, potentially increasing operator workload. Environmental forcing, such as cross-current conditions from waves, tides, and wind, influenced platform stability during along-current transects, which shows the sensitivity of certain platforms to current direction and strength. For instance, the GPS track of the IQUA Robotics AUV in Figure 3.2 shows a curved track influenced by a cross current during the transects to survey the VD site.

Figure 3.2: GPS track of the IQUA Robotics AUV at the VD site showing straight transects and curved transects due to the cross current.

In low-visibility conditions, ROV pilots frequently depended on forward-looking sonar (FLS) to navigate toward areas of interest. Visual navigation alone was often insufficient to locate reef structures at the OTS or maintain spatial awareness, making FLS essential for target reacquisition and safe approach in turbid or dynamic environments.

Platform-specific limitations were observed, including the lack of obstacle-avoidance functionality on one AUV, restricting safe operations in close proximity to complex structures, and a navigation module malfunction on one ROV that prevented autonomous waypoint following. Despite these constraints, several missions were completed without any material operational issues, demonstrating that routine UUV deployments are well achievable when platform capabilities, environmental conditions, and mission objectives are aligned.

3.2.2 Perception ability & suitability of data for ecological monitoring

RQ2: *What is the quality, coverage, and resolution of the optical, acoustic, sampling, and environmental sensor data collected by the UUVs during the field tests?*

3.2.2.1 2D optical data

Optical data quality varied strongly between sites and platforms, and was mostly influenced by environmental conditions (visibility, turbidity, ambient light), camera configuration, and vehicle stability (altitude control, speed, and motion). When water clarity was sufficient and platforms maintained a slow, steady, low-altitude trajectory, optical systems produced imagery suitable for species-level identification of macro organisms (>~3 cm) on the surface, habitat characterisation, and, in some cases, detailed mosaics and 3D reconstruction. These conditions were often met in the Voordelta, where several platforms delivered sharp imagery and high-quality mosaics.

At the Offshore Test Site, higher turbidity levels frequently limited observing ecological detail. In these situations, the platforms were still able to capture the overall reef-cube structure and broad biofouling patterns, although fine-scale species identification remained more difficult and was only feasible for a subset of the data and for larger organisms. Overall, optical performance was constrained more by environmental limits and platform handling than by the technical specifications of the cameras themselves.

Camera mounting and configuration further influenced the type and quality of data collected. AUVs used downward-facing cameras optimised for seabed mapping, however this limited their ability to inspect vertical faces of artificial structures. ROVs, by contrast, carried forward-looking or adjustable cameras, enabling targeted inspection of 3D elements when pilots could maintain position despite currents and vessel drift.

Camera focus, lighting, and altitude also affected sharpness. For example, systems with fixed-focus cameras performed best when their altitude matched the preset optimal range. The camera of the IQUA Robotics system, for instance, was set to manual focus at 1 m. Consequently, the sharpest frames were obtained when the vehicle was positioned at an altitude of 1 m (Figure 3.3). This shows the importance of adjusting the focus distance to the height that provides maximum visibility, especially for the cameras with shallow depth of field.

Figure 3.3: Frames (1936x1464 px) (no artificial light) collected at different altitudes (meters) in VD test location using the Sparus II AUV of IQUA Robotics. a) 0.5 m; b) 1 m; c) 1.5 m. speed for all 0.5 m/s.

Differences in image quality were also influenced by camera type and frame resolution (pixel count). Figure 3.4 presents example frames collected at the OTS by BeeX (a; 720p) and DeepTrekker (b; 1080p), although it should be noted that these images were captured at different distances from the target object. While higher-resolution footage can provide greater detail, this advantage diminishes at larger observation ranges or under conditions of high water turbidity, where even high-resolution imagery may not contain sufficient detail for reliable species identification. In addition, motion-related effects such as blur during sharp manoeuvres and sediment resuspension caused by thrusters occasionally reduced image clarity (Annex B). Together, these observations indicate that vehicle control and environmental conditions are the most important factors determining the suitability of optical imagery, and that higher camera resolution alone cannot compensate for turbidity or unstable vehicle movement.

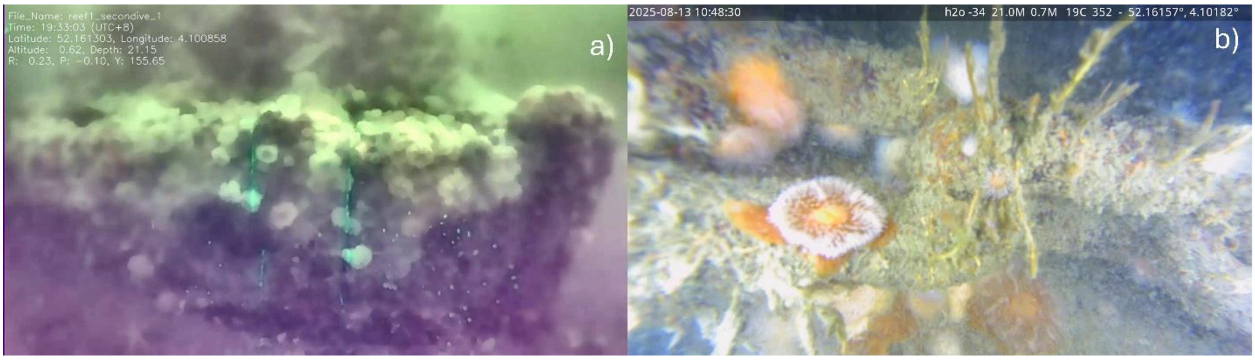


Figure 3.4: a) Beex in-built camera with laser scales (1280x720); b) DeepTrekker >0.5 m range to a chain at the OTS (1920x1080).

3.2.2.2 2D photo mosaicking

Georeferenced raw frames can be used to generate a photomosaic, this for instance allows for inspecting species distribution and density in the scanned area. Mosaic generation is based on identification of matching features between frames for further alignment and stitching in a mosaic. Mosaic is typically used for seabed mapping; its application for 3D structures is less straightforward, however it allows estimating biofouling on the horizontal surfaces of 3D structures.

Georeferenced image frames can be used to generate a photomosaic, which provides a spatially continuous overview of the surveyed area. Such mosaics allow inspection of species distribution and density across the scanned surface. Mosaic generation is based on the identification of matching visual features between overlapping frames, which are then aligned and stitched together into a single composite image (Figure 3.5a). This approach is widely applied in seabed mapping. The quality of a mosaic strongly depends on the presence of identifiable features and sufficient overlap between frames. When matching features cannot be detected, alignment becomes unreliable and the resulting mosaic quality decreases (Figure 3.5b), or the alignment cannot be generated.

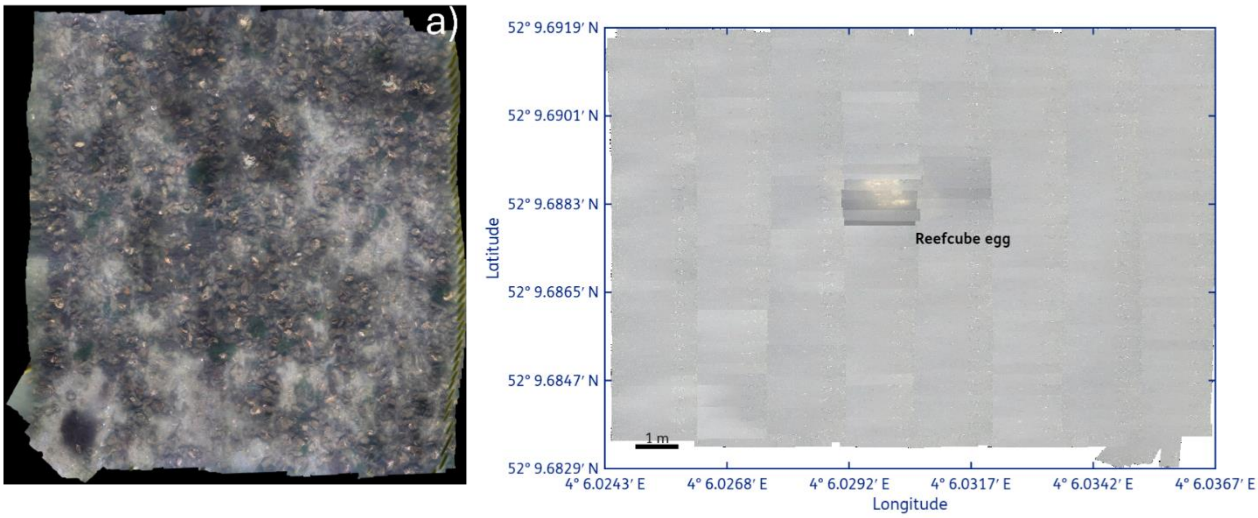


Figure 3.5: Photomosaic samples generated by Lobster Robotics. a) 5 x 5 m in the Voordelta. b) georeferenced mosaic generated around the Reefcube egg in the OTS.

Photomosaics can support ecological assessments through investigating spatial distribution and relative abundance of species within the survey area. However, when large areas are mapped, analysing the entire mosaic becomes challenging due to the scale of the resulting dataset. To maintain the usefulness of mosaics for ecological analysis, high image resolution must be maintained so that species can still be identified when zooming into smaller sections of the mosaic (Figure 3.6). Post-processing and stitching can also introduce mild distortions in the imagery (Figure 3.7), which may complicate species identification and limit the accuracy of measurements.

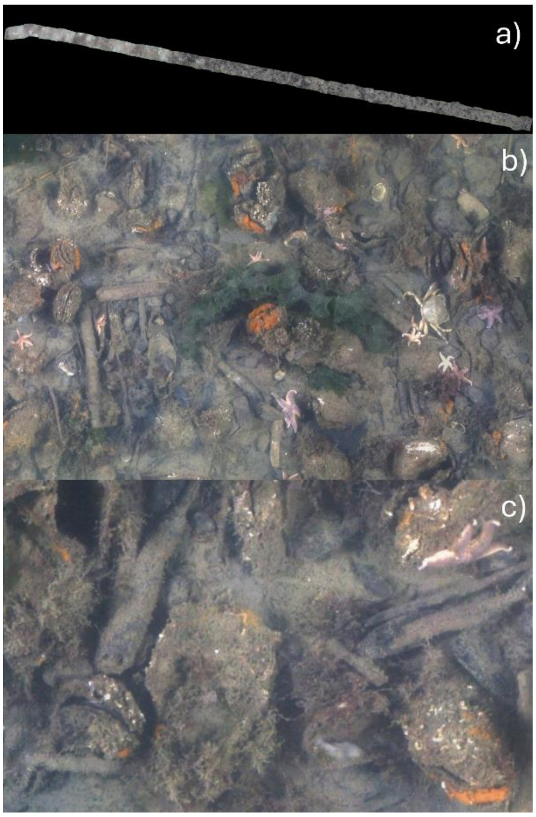


Figure 3.6: Visual post-processed data sample collected by Lobster Robotics in Voordelta a) a resulting mosaic of a transect; b) 50% zoom to the part of mosaic; c) 150% zoom to the part of mosaic.

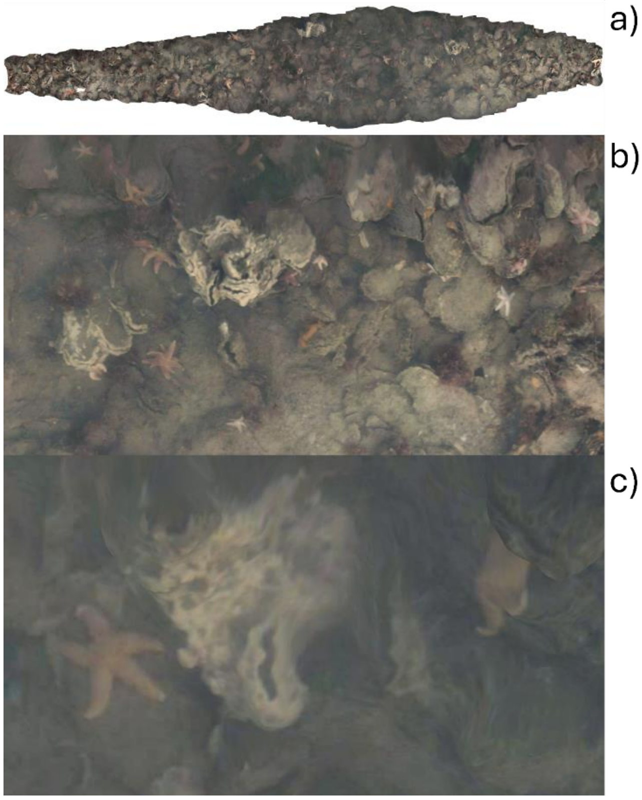


Figure 3.7: Visual post-processed data sample collected by IQUA Robotics in Voordelta a) a resulting mosaic of a part of a transect; b) 50% zoom to the part of mosaic; c) 150% zoom to the part of mosaic

Its use for three-dimensional structures is more challenging but can still be valuable and provide insights on the horizontal surfaces of the object (Figure 3.8). For AUV based seabed mapping, cameras are typically mounted on the underside of the vehicle at a 90° angle to the seabed. Surveying complex 3D structures requires a stepwise approach. At the OTS artificial reef, the top compartment was surveyed at approximately 1 m above the reef surface (Figure 3.8a), followed by the lower compartment at roughly 1.5 m above the seabed and 1 m above the bottom surface of the reef (Figure 3.8b). While the resulting mosaics allows for estimation of species coverage on the horizontal surfaces (particularly the upper compartment) the vertical sides of the reef remained largely uncaptured.

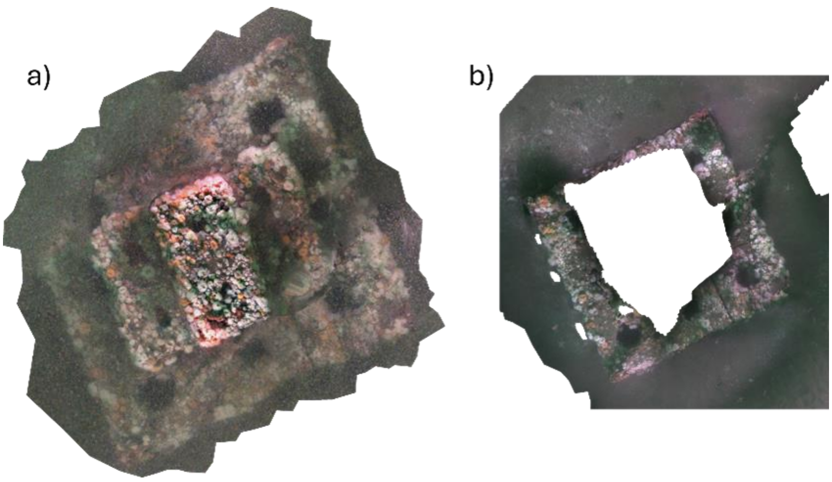


Figure 3.8: 2D mosaic of the mussel reef in OTS generated by IQUA Robotics: a) top compartment of the reef is in focus; b) bottom compartment of the reef is in focus

3.2.2.3 3D optical data

In this study, 3D data were acquired using either a monocamera system, which reconstructs multiple viewpoints through vehicle motion (Lobster Robotics and IQUA Robotics), or a stereocamera system, which simultaneously captures left and right perspectives in combination with platform movement (Subsea Tech). These approaches allow for the generation of three-dimensional representations that can be used for habitat classification and the estimation of organism size, among other purposes. For instance, using the Subsea Tech HYDRO300 stereocamera it was possible to measure the oyster opening width in the Voordelta and the dimensions of an anemone attached to the artificial reefs in the OTS (Figure 3.9).

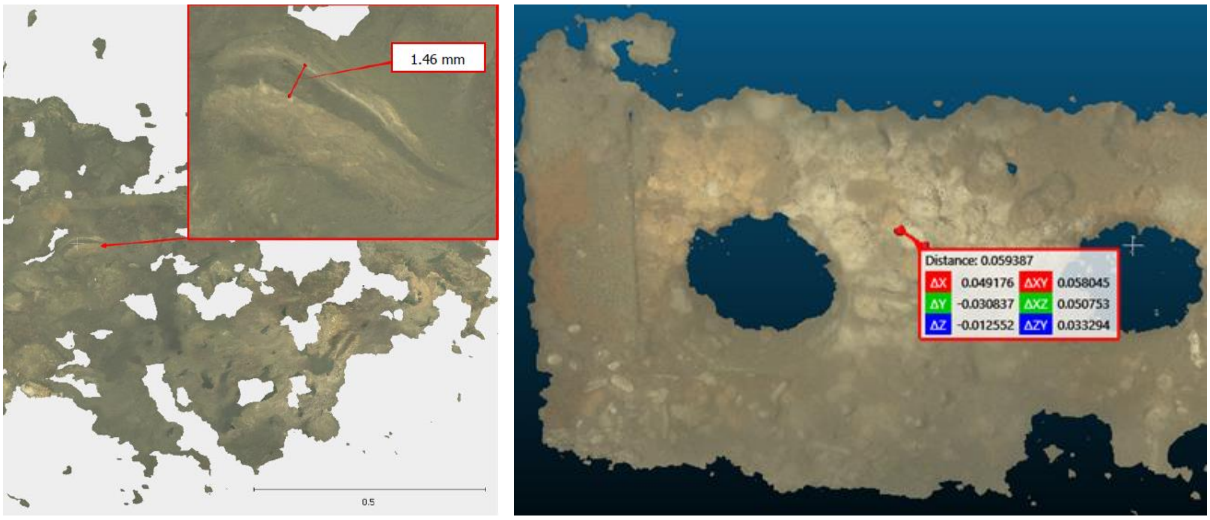


Figure 3.9: a) Example of oyster opening measuring using a point cloud provided by SubSea Tech. b) 3D scan of the reef side generated by SubSeaTech stereocamera and an example measurement of an anemone.

Figure 3.10 presents examples of 3D seabed maps, or Digital Elevation Models (DEMs), collected in the Voordelta and visualized using CloudCompare (v2.14 beta) for Subsea Tech and Lobster Robotics. Lobster Robotics generated DEMs for a 5 × 5 m survey area by conducting multiple transects. As the associated material file was unavailable, surface colour and texture were displayed using default settings.

The DEMs enabled calculation of rugosity (defined as the ratio of 3D surface area to its projected 2D planar area, see Annex C), which is used as a measurement for the reefiness. For the 5 × 5 m survey area (Figure 3.10a), rugosity was 1.45, based on a measured 3D surface area of 58 m^2 and a projected 2D area of 40 m^2. The slightly larger-than-expected 2D area is attributed to the fitted 2D plane extending beyond the actual scanned reef surface. For comparison, Roncolato et al. (2024) report that naturally developed reef structures typically exhibit rugosity values between 1.45 and 1.82, where 1.45 reflects moderate surface complexity relative to a flat planar surface. In contrast, the DEM provided by Subsea Tech yielded a rugosity of 0.65, likely due to gaps in the model caused by missing data (Figure 3.10b). These gaps were likely caused by sediment resuspension generated by the ROV thrusters while operating close to the seabed under turbid conditions. In contrast, the artificial reef structure was located more than 1 m above the seabed, and the resulting point cloud contained fewer missing values (Figure 3.9b). This difference supports the hypothesis that the data gaps observed in the seabed scan were primarily caused by sediment disturbance from the ROV thrusters. Although water turbidity was higher at the OTS compared to the VD site, the resulting point cloud was more complete, providing further evidence that turbidity alone was not the main driver of missing values and that near seabed thruster induced sediment resuspension likely played a role in this.

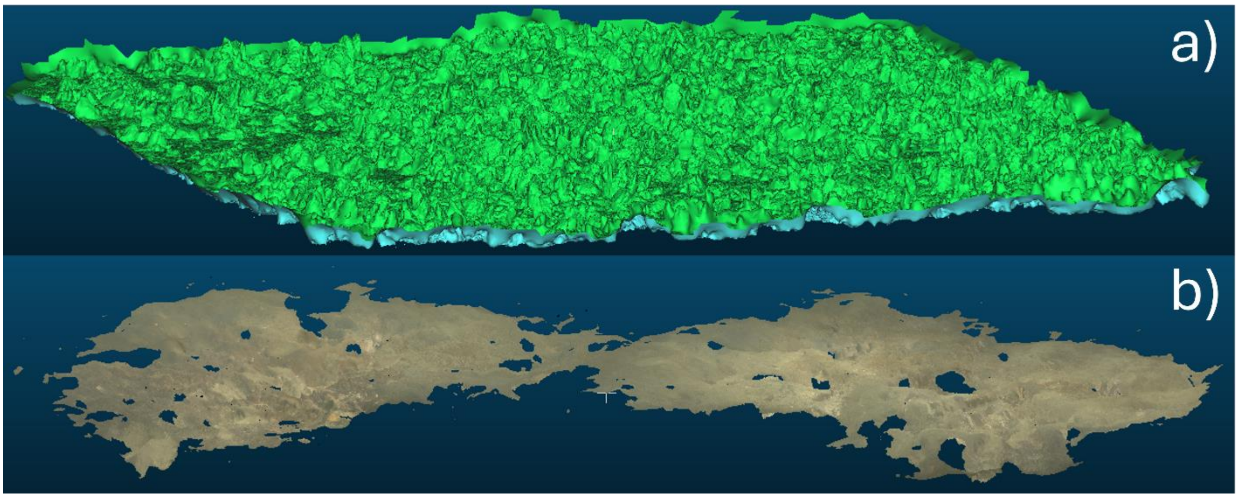


Figure 3.10: Digital elevation seabed maps collected in Voordelta by a) Lobster Robotics (5x5 survey area); b) Subsea Tech.

3.2.2.4 2D AI-based image recognition

The value of automated analysis of visual data is receiving increasing attention, especially in ecological monitoring programmes that generate large volumes of imagery. This is relevant when using UUVs equipped with optical sensors, i.e. cameras, such as those tested in this study, which can collect extensive high-resolution datasets within a short time frame. Manual annotation and analysis of these datasets would be time-consuming and resource-intensive which shows the need for automated approaches.

Computer vision refers to a field of artificial intelligence that allows computers to interpret, analyse, and extract meaningful information from images and video data. By applying machine learning algorithms to visual inputs, computer vision systems can perform tasks such as object detection, classification, segmentation, and tracking. One of the most common computer vision tasks in real-world applications is object detection, which involves identifying and localising objects of interest within an image, typically by drawing bounding boxes around them. Object detection offers a practical trade-off between model accuracy and inference speed and can reduce the annotation effort required for dataset preparation. Within this project, the potential for automating analysis of the collected optical data was explored, with automated species detection identified as a first step.

In the field of automating ecological monitoring typically a substantial human expertise is required to prepare the annotated dataset where target species need to be localised and identified, i.e. labelled. The approach of using manually labelled data for training and evaluation of the AI models is referred to as supervised learning. Object detection task can be split into two sub-tasks: i) object localisation (with the bounding box), ii) localised object classification (adding a class label to the localised object). These two sub-tasks typically vary in complexity as object localisation is commonly easier compared to identifying species relying only on the image representation. Both of these sub-tasks substantially rely on image quality; for object localisation it is often enough for the object to have a number of outstanding features, e.g. geometrical or color compared to the background, whereas for object classification often more features are required including multiple views on the object to allow for fine-grained identification.
To reduce the annotation efforts, large pretrained AI models can be used to create initial annotations – bounding boxes with a generic label around the target object of interest. In this study we used one of the large, pre-trained AI models as tool to evaluate collected data suitability for automated analysis.

To assess the quality of the collected data and the expected effort required to achieve reliable automated species detection, we evaluated the performance of a foundation model for object detection on a subset of the collected data (see more details in Annex B). GroundingDINO (GD), a state-of-the-art vision-language, was selected as object detection model which is available in open source (Liu et al., 2024). Figure 3. shows results using the text prompt "oyster" on image samples collected in the Voordelta. In the first example (Figure 3.a), a sponge covering an oyster was detected, while in the second example (Figure 3.b), a starfish was detected

instead of the target species. This shows that the model likely has not been trained sufficiently to detect oysters.
At the Offshore Test Site, different species assemblages were observed, and therefore alternative text prompts were applied. Figure 3.12 shows the results obtained using the prompts "anemone" (a) and "crab" (b). In the first case, several anemones were correctly detected. In the second case, crabs were detected despite turbidity and a relatively large distance from the structure. However, localisation accuracy could be improved, as bounding boxes did not always fully cover the detected individuals.

Overall, animals with distinct shapes and contrasting colours (e.g. sponges, sea stars, crabs) were recognised more easily by general-purpose foundation models. At the same time, the domain shift between the training data used for GD and the underwater imagery collected in this study appears to not be fully overlapping, which is likely affecting the detection accuracy. This challenge can be addressed with fine-tuning GD or another use-case specific model with the collected data (target domain). For the supervised and semi-supervised learning approached a representative sample of the data needs to be annotated by human expert.
The complexity of the object detection task also depends strongly on the definition of the target class. Detecting a generic class (for instance a "bivalve") typically requires a lower level of visual detail than detecting a specific species of bivalve, where fine-scale morphological features become important. Moreover, if the target task requires other types of annotation than simple bounding boxes, such as segmentation or keypoint detection, higher image quality, improved visibility, and greater structural detail may be necessary. Additionally, if the target object is not visible in the image or video frame due to e.g. occlusion (obstruction of the target object by another object), then it will be skipped by human expert and consequently by the AI model. On the other hand, automated analysis allows for processing large amount of data and hence cover larger areas of monitoring.

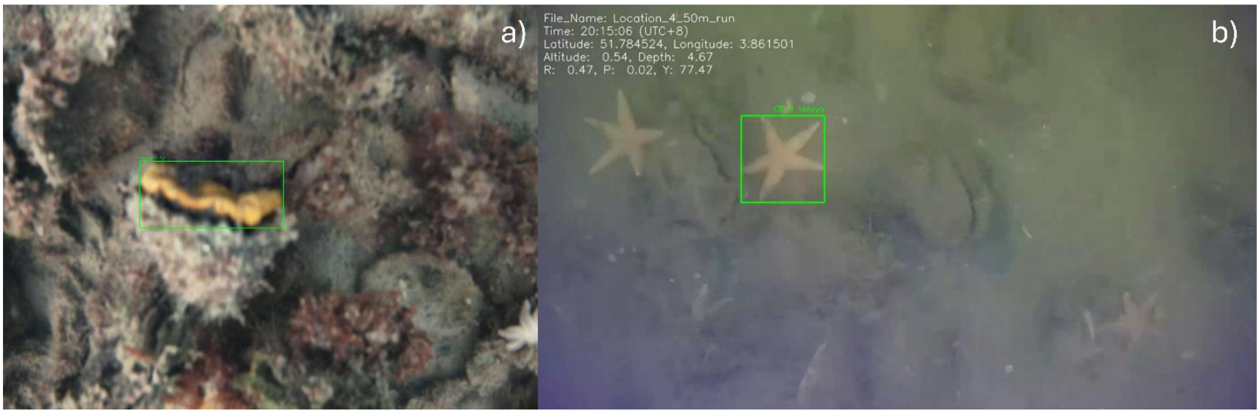


Figure 3.11: GD inference results with a text prompt 'oyster' on sample frames collected at 0.5 m altitude in VD: a) IQUA; b) Beex.

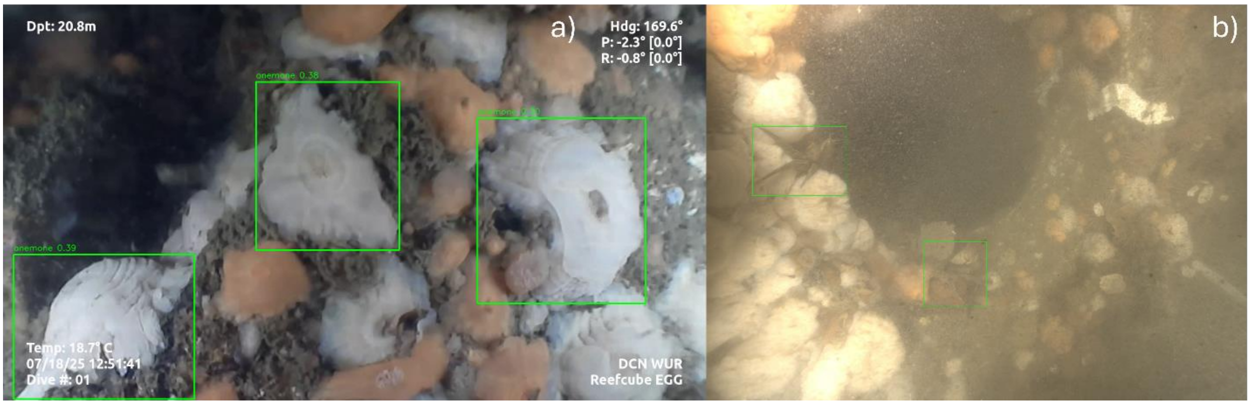


Figure 3.12: GD inference results on sample frames collected in OTS: a) VideoRay (DCN), ~0.5 m distance from the reef, text prompt 'anemone'; b) SubseaTech, >1 m from the reef, text prompt 'crab'.

3.2.2.5 Acoustics

The field tests showed that data quality and coverage varied across platforms and sensor types. Acoustic systems, including forward looking sonar (FLS), side scan sonar (SSS), and multibeam echosounders (MBES), produced interpretable spatial information on seafloor structure, reef presence and absence, and general habitat patterns.

At the shallow Voordelta site, FLS produced more interpretable acoustic imagery than SSS under the test conditions encountered. The SSS data was affected by multipath reverberation, where sonar signals reflect multiple times between the seabed, water surface, or other objects before returning to the receiver. These additional echoes increase noise and reduce the signal-to-noise ratio, making it more difficult to distinguish seabed features and reef structures. This effect is amplified in shallow water because the short distance between the sonar, seabed, and surface allows repeated reflections within a short time window. FLS was less affected in this setting because it typically uses a narrower more focused beam and images forward rather than sideways. This does not mean that FLS is generally superior to SSS. SSS remains valuable for efficient wider-area seabed mapping and for detecting larger objects. For example, at the deeper OTS, SSS was suitable for presence-absence detection of reef cubes, which can be seen in the SSS plots from the Seaber AUV in Figure 3.13. An example georeferenced FLS image of the Voordelta site obtained by the BeeX ROV is shown in Figure 3.14, where the boundary between the sandy seafloor and the mixed oyster/mussel reef can be identified.

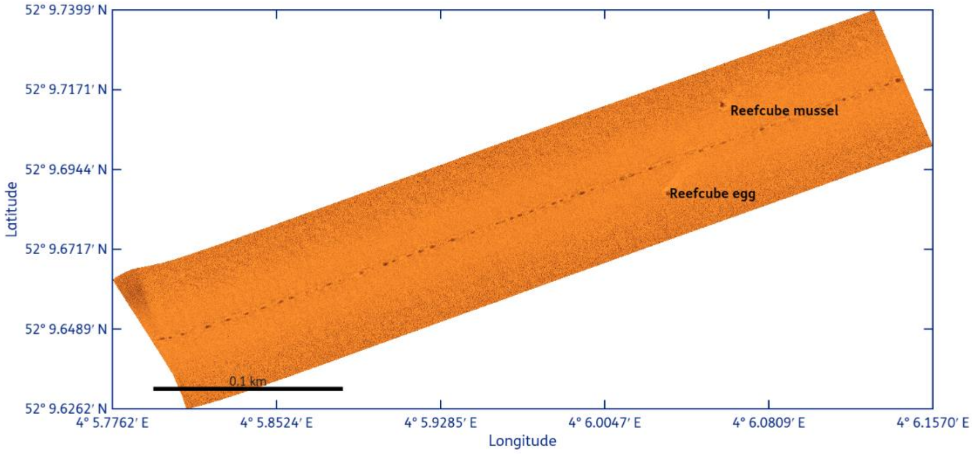


Figure 3.13: Georeferenced SSS image of a transect survey at OTS by Seaber AUV, showing the reef objects.

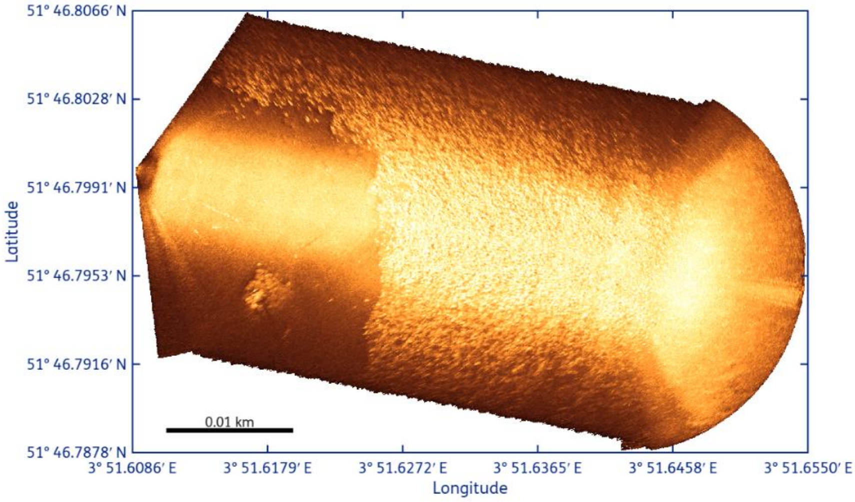


Figure 3.14: Georeferenced FLS image of the VD site surveyed by BeeX ROV, showing a clear boundary between the sandy seabed and the mussel reef.

The MBES provides bathymetry data as a point cloud, which is essentially a collection of depth points representing the seafloor. These data can be processed to calculate rugosity (measure of how complex or rough the seafloor is) similar to the approach used for 3D optical data (Annex C).
An example comes from an MBES transect surveyed by the IQUA Robotics AUV at the Voordelta site (Figure 3.15). The left subfigure shows the bathymetry of this transect, with an overall rugosity of 1.16. This is lower than the value of 1.45 obtained from optical sensors. However, it is important to note that the MBES and optical sensor surveys were conducted at different times/locations and therefore do not overlap.
Rugosity values from MBES data also depend on the point-cloud resolution. For this transect, using a finer point spacing of 5 cm produced a rugosity of 1.16, while a coarser 10 cm spacing gave 1.06. In contrast, the optical sensor mesh had a much denser spacing of less than 1 cm, which naturally captures more surface detail and could also explain the higher measured rugosity. If one wants MBES-based rugosity to match optical data more closely, a higher-frequency MBES system (around 1.2 MHz) would be needed.

Calculating a single rugosity value for the entire survey area can also mask local variations. To capture these finer-scale differences, we applied a sliding-window approach, calculating rugosity within 1 × 1 m squares. Figure 3.15b shows that this localized method can reveal rugosity values up to 1.6, comparable to the optical sensor results. This demonstrates that local calculations could be more informative for assessing habitat complexity.

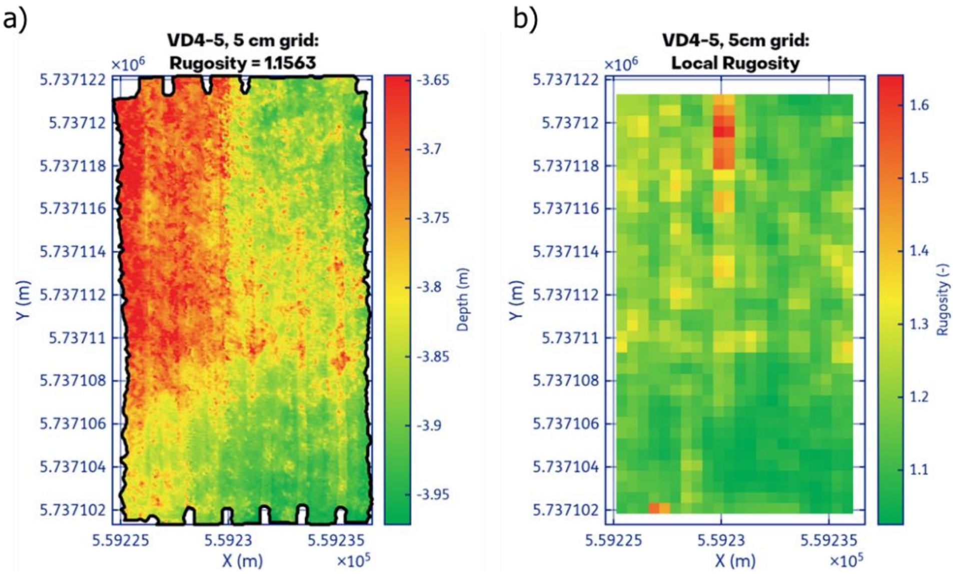


Figure 3.15: a) Bathymetry plot of the VD survey by an MBES on board the IQUA Robotics AUV with the overall rugosity of 1.1563; b) Local rugosity calculation of the same site calculated by a sliding-window technique.

Acoustic mosaics and MBES bathymetry were generally consistent georeferenced products across systems. Differences in manufacturer-provided post-processing, raw data formats, and sensor configurations contributed to variability in output resolution and interpretability. An example of the inherent sensor difference is shown in Figure 3.16. In this figure, the FLS image of a reef object at the OTS is shown. The top subfigure was provided by an Oculus M750d FLS mounted on the Subsea Tech ROV while the bottom subfigure was provided by an Oculus M1200d FLS mounted on the Videoray ROV. The latter has a higher operating frequency (1200 kHz instead of 750 kHz). The data collected by the Oculus M1200d FLS therefore provides more visual details due to the higher resolution. The data however covers a shorter range due to the higher absorption loss. These results indicate that the selection of an FLS model for ecological monitoring involves a trade-off between detection range and image resolution, depending on the objectives of the specific research question.

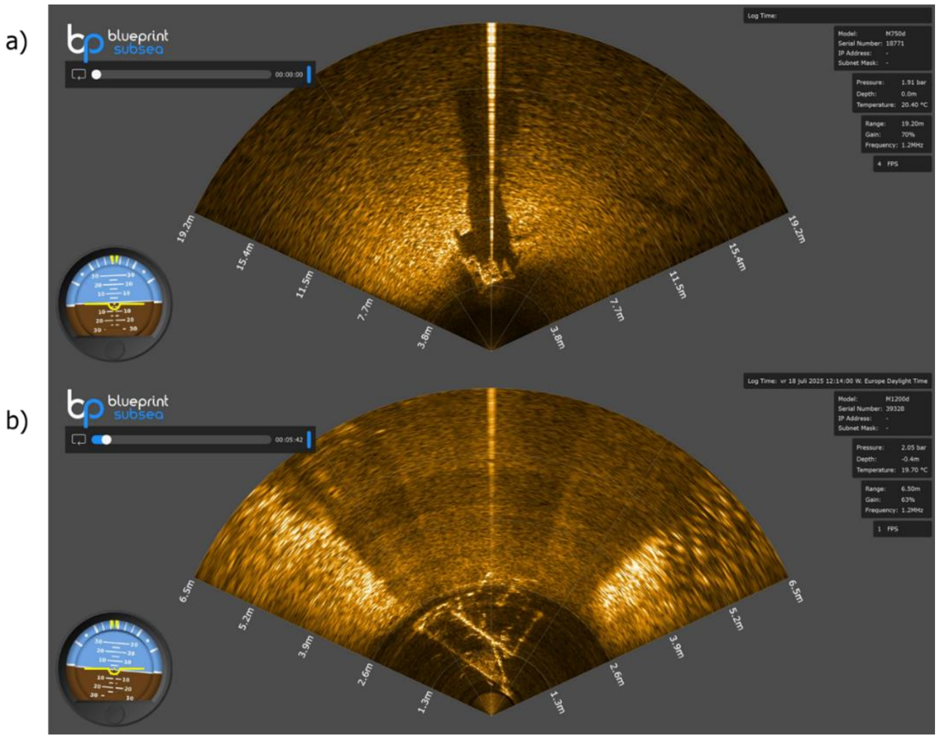


Figure 3.16: FLS image of a reef object at the OTS. a) Collected by an Oculus M750d FLS mounted on the Subsea Tech ROV; b) Collected by an Oculus M1200d FLS mounted on the Videoray ROV.

3.2.2.6 Sampling and environmental sensors

DeepTrekker demonstrated two types of end-effectors for sediment and water sampling (Figure 3.18). Because stabilizing the ROV at the OTS was challenging, sediment and water samples were collected at the harbour upon return. Sediment sampling required locking the vehicle altitude close to the seabed and coordinate the motion with sediment gripping. Water sampling required stabilising the vehicle at the selected altitude and activating water sampling. In the tested configuration a sample of 100 ml could be collected by spreading the arm of the ROV.

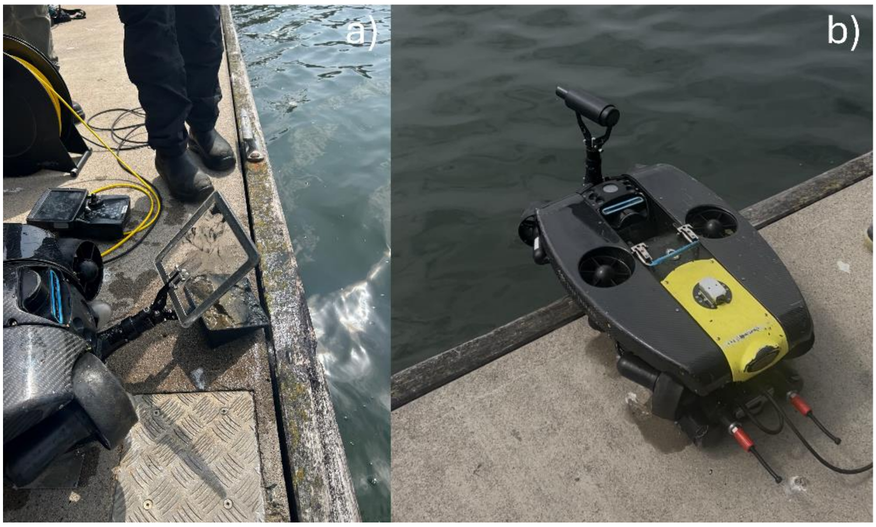


Figure 3.18: DeepTrekker Revolution sediment sampler (left) and water sampler (right).

Continuous monitoring of water properties was demonstrated by the Yuco-PHYSICO AUV of Seaber at both the OTS and the VD locations. The data collection was done through an AML Oceanographic sensor probe onboard the AUV during the mission. In this way, water properties were georeferenced and linked to the operational metadata such as the AUV depth. A visualisation of the water properties (conductivity, conductivity temperature, pH, chlorophyll-a concentration) can be seen in Figure 3.19. The water properties from the same dataset can also be visualised with respect to the depth as shown in Figure 3.20. This figure shows an interesting variation of the water properties with depth, such as the decreasing conductivity temperature and pH with increasing depth.

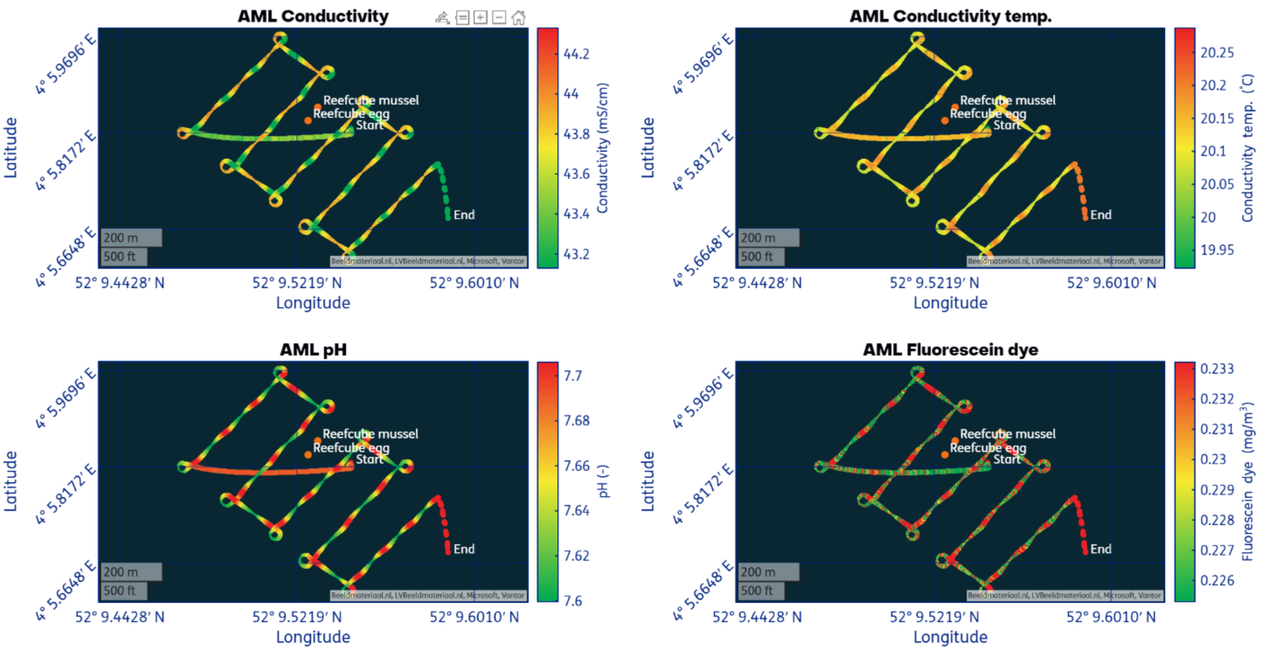


Figure 3.19: Water properties with respect to location at the OTS collected by Seaber Yuco-PHYSICO AUV.

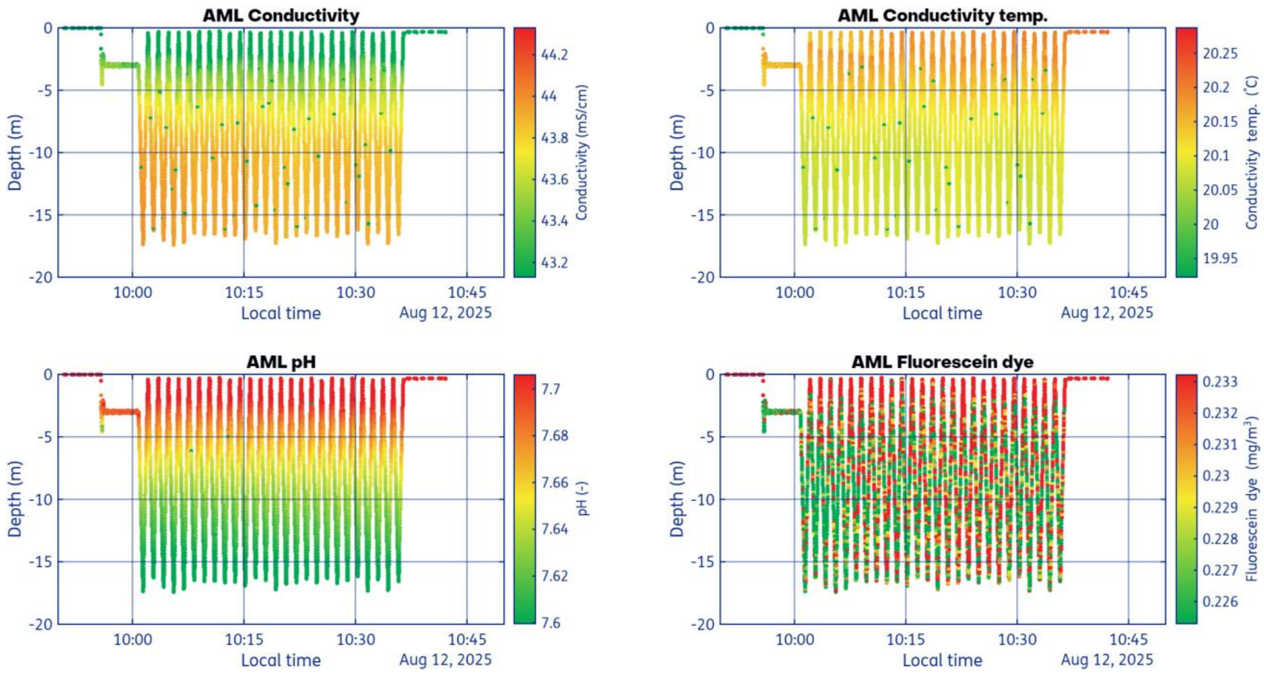


Figure 3.20: Water properties with respect to depth at the OTS collected by Seaber Yuco-PHYSICO AUV.

3.2.2.7 Synthesis

Overall, the field tests demonstrated that UUVs can acquire optical, acoustic, sampling, and environmental datasets of sufficient quality for ecological monitoring, although performance strongly depended on environmental conditions, sensor configuration, and vehicle operation.

Optical sensors generally provided the highest detailed information which enabled species-level identification of macrobenthic under favourable visibility conditions. Coverage was limited by camera field of view and survey altitude, and image quality decreased under high turbidity, sediment resuspension, and unstable vehicle motion. Photomosaics and 3D reconstructions extended the spatial coverage of optical surveys but required sufficient image overlap and identifiable features.

Acoustic sensors offered larger spatial coverage and were less affected by water turbidity than optical systems. They successfully detected reef structures, habitat boundaries, and seafloor morphology. Higher-frequency acoustic systems improved resolution but reduced effective survey range.

Sampling systems demonstrated targeted sediment and water collection, while onboard environmental sensors continuously recorded georeferenced water quality parameters throughout the missions. These datasets complemented the optical and acoustic observations by providing environmental context that can support ecological interpretation.

Overall, the results indicate that optical sensors are most suitable for detailed biological observations, whereas acoustic sensors provide tools for large scale habitat mapping under a wider range of environmental conditions. Environmental sensors and sampling systems could add complementary ecological information that cannot be derived from imagery alone.

RQ3: *To what extent is the collected data suitable for ecological monitoring tasks such as species and habitat assessment, environmental characterisation, and detecting habitat changes?*

Optical data discussed in Section 3.2.2.1 provided the highest ecological detail and were suitable for species identification, documentation of epifauna, and fine-scale habitat assessment when visibility allowed and when platforms maintained at low-altitude from the seabed with stable navigation. In the Voordelta, these conditions were frequently met, enabling species-level observations and detailed photomosaics. At the OTS, lower visibility/turbidity limited ecological resolution for some missions, but several systems still produced imagery adequate for documenting reef cube surfaces, associated organisms, and structural complexity.

The suitability of the collected data for ecological monitoring differed with sensor type, environmental conditions, and platform stability. Examples shown in Section 3.2.2.5 demonstrated that acoustic datasets (FLS, MBES, SSS) were suitable for broad-scale ecological tasks such as detecting reef presence, mapping seafloor morphology, and distinguishing substrate types. The applicability of certain sonar techniques onboard UUVs depend on the environmental setting. For instance, SSS has less value in shallower environments such as the Voordelta. However, overall the sonar modalities allowed for identification of features such as oyster and mussel beds, sandy areas, reef cube structures, and small-scale seabed texture, which provides a basis for habitat classification and environmental characterisation across both case study sites.

Environmental sensor data from the Yuco-PHYSICO AUV shown in Section 3.2.2.6 contributed additional context by capturing parameters such as chlorophyll-a, pH and conductivity temperature, which could support interpretation of observed ecological patterns.

3.2.3 Motion ability

RQ4: *How reliably can the UUVs revisit locations and produce consistent, georeferenced datasets that support repeatable surveys and temporal comparisons?*

The UUV platforms demonstrated varying levels of reliability in revisiting locations and generating consistent georeferenced datasets. Systems equipped with stable navigation sensors and georeferencing workflows achieved repeatable transects and accurate spatial products. An extensive examination of the offset between the provided georeferenced reef object locations and their actual GPS location is described in Annex C. Results showed deviations of 1–3 metres between georeferenced detections of reef cubes and their known positions, indicating good spatial consistency under favourable conditions, whereas other platforms and sensor types exhibited larger offsets of up to 10–20 metres, demonstrating that navigation accuracy varied considerably across systems and environmental settings

Navigation reliability was observed to be strongly affected by currents, which caused track curvature and drift for some missions as illustrated in Figure 3.2. Safety constraints also limit the vehicle's motion ability when they lack advanced navigation aids or have to operate close to complex structures (such as the dam present in the Voordelta and the artificial reef structures at the OTS). Platforms without functional autonomous navigation modules, were less able to maintain consistent positioning underwater. This is because the operator had to manually control the platform and rely on onboard sensors such as the FLS for navigation and obstacle avoidance.

Overall, georeferenced AUV datasets were the most reliable for repeatable surveys, while ROVs could revisit targets effectively only when vessel position and current conditions allowed stable control which for the OTS heavily relied on neap tide conditions.

RQ5: *Is the manoeuvrability of the UUV platforms sufficient to inspect biodiversity on and around complex three-dimensional structures?*

The manoeuvrability of the UUV platforms differed across systems and was influenced by current conditions and navigation capabilities. Platforms with precise low-speed control and real-time operator input, such as tethered ROVs, were generally able to approach and inspect complex three-dimensional reef structures effectively when vessel drift was manageable. Autonomous platforms could collect useful imagery around reef cubes when environmental conditions were favourable, particularly when operating at low altitude and with stable heading control. However, AUVs without obstacle-avoidance systems were limited in their ability to safely approach vertical or intricate structures, restricting the level of detail that could be collected. Current-induced drift also reduced fine-scale manoeuvrability for several missions. Overall, detailed inspection of complex 3D habitats such as the artificial reefs was most reliably achieved by platforms with active operator control or robust navigation and stability, while fully autonomous systems were effective primarily when conditions allowed controlled, low-altitude passes.
Complete scan of artificial reef structure would require consistent scanning of all sides of the structure from bottom to the top. In this case, relying on GPS position is not enough and would require relying on real-time input from the sensors during path-planning to minimize repetitive data and maximize the structure coverage. Additionally, smaller animals especially during higher turbidity conditions may require smaller range to capture sufficient amount of details, while larger animals (e.g. anemones) may require larger range as they are elevated from the substrate.

3.2.4 Operational and logistical considerations

RQ6: *What are the practical requirements for deploying UUVs in offshore monitoring campaigns, including vessel support, crew needs, and operational procedures?*

The field tests showed that practical deployment requirements influenced the usability and efficiency of UUV platforms. Most systems could be launched and recovered from small RHIBs, but vessel drift, inability to anchor, and limited deck space affected the ease of operation and the ability to hold position during ROV deployments. UUV operator expertise played an important role, particularly for tethered ROVs that required real-time piloting, interpretation of sonar imagery, and tight coordination with vessel movements. Environmental factors such as sunlight glare on control screens, sea state, and currents directly affected operability and operator workload. Several platforms also required pre-deployment configuration time, calibration steps, and careful handling of cables or auxiliary equipment. Overall, effective UUV deployment depended on matching platform requirements with vessel capabilities, ensuring sufficient crew skills for piloting and troubleshooting, and managing environmental and logistical constraints during (offshore) operations.

Further considerations when carrying out monitoring campaigns in/around offshore windfarms include the use of certified equipment, vessels and crew, and standardized procedures and risk assessments. For the OTS location, a standard risk assessment was carried out for all carried out scopes. We found that especially for small AUVs at offshore locations a RHIB can be a feasible platform for launch and recovery.

In general, when an external power supply is required (Subsea Tech and DCN Diving/Videoray) the space onboard the RHIB is quickly becoming insufficient. RHIBs are generally not allowed in OWFs due to the lack of emergency equipment, exposure to the harsh elements and low workability. Therefore, when considering OWF monitoring works, one should keep in mind that launch and recovery from a larger vessel (e.g. a CTV) might be needed. Considerations then are a larger freeboard (1-2m) resulting in deployment with a small crane or davit and compatibility of the UUVs with a crane for launch and recovery.

3.2.5 Contribution to long-term monitoring

***RQ7:** How can UUV derived data contribute to long term ecological monitoring, including continuity, standardisation, and integration into existing monitoring programmes?*

The field tests showed that UUV derived data can support long-term ecological monitoring by providing repeatable, georeferenced observations of seafloor habitats and artificial structures under both nearshore and offshore environmental conditions. Acoustic datasets, such as MBES bathymetry and FLS mosaics, offer spatial output that can be repeated over time, which allows for detection of habitat changes and long-term trends. Optical datasets provide finer ecological detail for species-level assessments when visibility and platform stability allow, making them valuable for documenting biota within reefs and artificial structures.

The ability of several platforms to follow predefined transects and produce spatially consistent outputs supports the development of standardised monitoring protocols. When combined with environmental sensor data, UUV datasets can also help contextualise ecological variation and possibly link biological observations to changing environmental conditions. Although the demonstrations in this current study were not designed as formal benchmark trials, the results indicate that UUVs can complement or (partially) replace diver-based and vessel-based surveys, improving safety and continuity (and possibly reduce costs). Integration of UUV outputs into existing monitoring programmes is feasible when consistent navigation, data handling, and processing workflows are established.

4 UUV selection guideline

4.1 Purpose and scope of this guideline

This guideline provides practical support for selecting suitable UUVs for ecological monitoring. It translates the operational insights gained from the field trials in the Voordelta and the OTS into recommendations for researchers, environmental managers, policy makers, and operators.

Building on the research questions, case-study requirements, sensor configurations, and field-test results presented in the preceding chapters, the guideline summarizes the main operational, sensing, navigation, and logistical considerations that influence UUV selection. An overview of the guideline is provided in Figure 4.1.

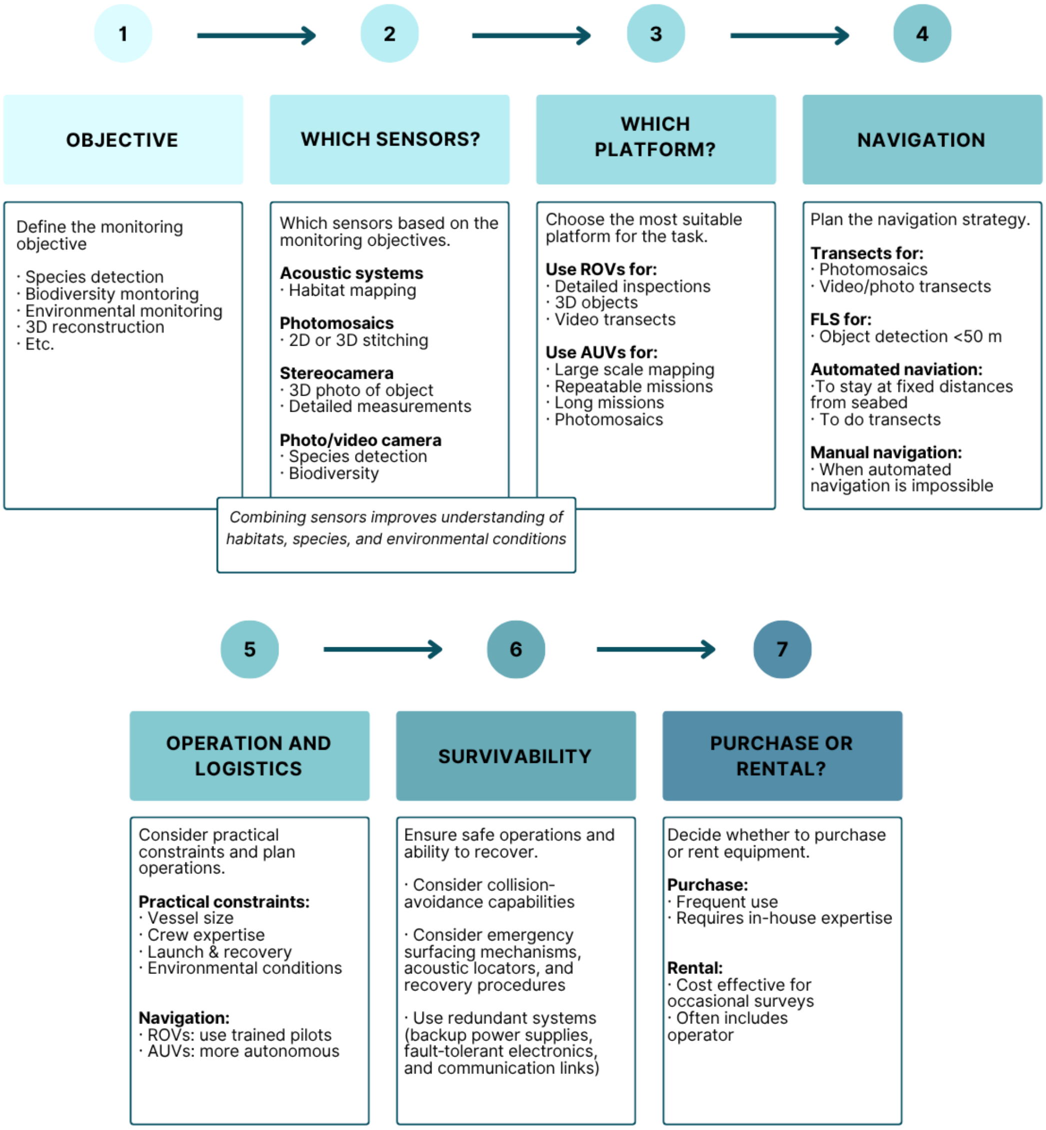


Figure 4.1: Summary of the UUV selection guideline

4.2 Factors influencing UUV selection

Selecting an appropriate UUV for ecological monitoring requires matching technical capabilities with the specific demands of a monitoring task. This section outlines the most important factors that determine whether a particular UUV is suited for the ecological monitoring task at hand.

4.2.1 Mission type and monitoring objective

The first and most decisive step in selecting an appropriate UUV is addressing the requirements to meet the research questions and the primary monitoring objective. Different ecological monitoring tasks place distinct demands on a platform, influencing the required level of mobility, sensing capability, and autonomy. Large-area mapping tasks, such as surveying broad seafloor habitats (for instance the Voordelta mixed oyster reef) or producing acoustic or optical mosaics typically favour AUVs, which can cover extensive areas efficiently and generate georeferenced products suitable for spatial analysis. In contrast, close-range inspections of complex structures, such as artificial reefs (at the Offshore Test Site) or biodiversity enhancement elements, benefit from ROVs equipped with precise station-keeping and manoeuvrability around three-dimensional objects.

Species and habitat assessments require high-quality visual data, often collected at low altitude from the seabed and/or from stable hovering positions, whereas environmental characterisation and water-quality monitoring depend on dedicated sensors. Finally, targeted sampling missions, such as sediment or water collection, can only be performed by platforms capable of carrying and operating specialised hardware (sampling tools).

Clarifying the monitoring objective therefore helps narrow the range of suitable UUV types and ensures that platform capabilities align with the ecological questions to be addressed.

4.2.2 Environmental complexity

Environmental conditions strongly influence which UUV is suitable for a given monitoring task. The field tests in the Voordelta and the Offshore Test Site showed that factors such as visibility, currents, depth, and structural complexity directly affect the ability of a platform to collect high-quality data, the precision of a mission, and to operate safely.

Visibility proved to be one of the most important constraints with regards to marine ecological monitoring: optical systems required clear water and low turbidity to produce usable imagery and mosaics, while acoustic systems were less sensitive but still limited by shallow water multipath effects. Currents affected the manoeuvrability and station-keeping ability of both ROVs and AUVs, with stronger flows reducing the ability to maintain consistent altitude or follow pre-defined paths. Depth and seabed conditions also played a role in determining which sensors could be effectively deployed, and whether close-range inspections were feasible.

Finally, the geometry and complexity of the monitored structures, such as artificial reef elements, determined the need for precise navigation, hovering, and obstacle avoidance capabilities. Platforms operating around three-dimensional objects required stable control and sufficient sensor awareness to prevent collisions while still collecting detailed data.

4.2.3 Sensor suite/configuration

The choice of sensor suite is central to determining whether a UUV is suitable for a particular ecological monitoring task. Different monitoring objectives require different use of optical, acoustic, and environmental sensors, and the field tests in this study demonstrated that the effectiveness of any platform depends as much on its sensors as on its mobility or autonomy. Optical cameras remain essential for species-level identification, habitat characterisation, and detailed inspections of natural and artificial reef structures. High-definition video and still imagery are particularly valuable when visibility is sufficient, and stable low-speed control enables the acquisition of data suitable for photogrammetry and mosaicking. However, the usefulness of optical systems rapidly declines with turbidity, shallow-water backscatter, or low ambient light, conditions frequently encountered in both test sites.

Acoustic sensors complement optical imaging by providing broader spatial coverage and the ability to operate effectively in low-visibility conditions. Forward-looking sonar (FLS) supports navigation, object detection, and qualitative assessment of reef presence, while side-scan sonar (SSS) and multibeam echosounders (MBES) deliver larger-scale seafloor mapping products that can reveal habitat structures and substrate transitions. These acoustic systems differ in resolution and operational range, making the choice of sensor dependent on the scale and detail required. For fine-scale morphology or object detection, high-frequency systems offer sharper imagery but reduced range; for area mapping, lower-frequency systems provide broader coverage but coarser detail.

Environmental sensors further expand monitoring capability by enabling the measurement of background parameters such as temperature, salinity, turbidity, dissolved oxygen, and nutrients. These measurements can be of importance for interpreting ecological patterns and for linking biological observations to environmental context. In addition, some platforms can carry dedicated water or sediment sampling tools, allowing the collection of physical samples for laboratory analysis (such as eDNA and sediment characteristics), an important requirement for integrated ecological assessments. For instance another model of the Seaber Yuco AUV is capable of collecting eDNA samples[18].

Ultimately, selecting an appropriate sensor suite requires matching the sensing modalities to the ecological questions being addressed. Combining optical, acoustic, and environmental sensing capabilities can provide a more complete understanding of habitat structure, species distribution, and environmental conditions. The field tests confirmed that no single sensor type is universally sufficient; instead, platform suitability depends on the extent to which its sensor configuration aligns with the spatial scale, level of detail, and environmental conditions relevant to the monitoring task.

4.2.4 Platform mobility & autonomy

The mobility and autonomy of a UUV determine how effectively it can execute ecological monitoring tasks, particularly in dynamic offshore environments. The field tests showed that platform control, navigation capability, and the degree of autonomy strongly affect both data quality and operational efficiency.

ROVs, which are tethered to a surface vessel, offer precise manoeuvrability and the ability to hover or maintain station near complex three-dimensional structures. This makes them well suited for detailed inspections, close-range biodiversity assessments, and sampling activities. Their dependence on vessel position, however, limits their operational range and makes them more sensitive to drift, currents, and vessel motion.

AUVs, by contrast, operate untethered and are capable of following predefined mission tracks. This makes them well suited for large-area mapping, georeferenced transects, and broad-scale habitat surveys. Their ability to maintain steady altitude and speed supports the acquisition of optical mosaics and acoustic datasets. However, the absence of real-time operator control means that close-range work around obstacles or vertical structures is more challenging, especially in low-visibility or high-current conditions. Safe proximity operations depend strongly on the availability of reliable obstacle-avoidance capabilities and accurate navigation sensors.

Navigation performance determines to a great extent the mobility of a system. Platforms that rely only on surface GPS are generally limited to shallow or calm environments where frequent surfacing is feasible. UUVs with advanced navigation sensors, such as Doppler Velocity Logs and inertial navigation units, can estimate their underwater position more accurately. This supports repeatable surveys and more stable altitude control above the seabed. These capabilities were important for producing georeferenced products in the field tests and play an important role in detecting temporal changes in ecological conditions.

Motion characteristics such as turning radius, stability, and responsiveness to currents further influence the suitability of a UUV. Stable, low-speed control is required for optical imaging and photogrammetry, whereas higher speeds may be acceptable or even advantageous for acoustic mapping. The ability to resist or compensate for current-induced drift proved particularly important in the North Sea, where environmental conditions vary across sites and seasons.

[18] https://seaber.fr/yuco-auv-edna

Finally, the level of autonomy affects mission reliability. Basic waypoint following allows standardised survey design, while more advanced autonomous behaviours, such as adaptive altitude control or path adjustment in response to seabed features, improve data consistency and reduce operator workload.

4.2.5 Operational and logistical considerations

Operational and logistical constraints play a role in determining whether a UUV can be effectively deployed for ecological monitoring. The field tests demonstrated that vessel size, crew expertise, launch and recovery conditions, and data-handling workflows all influence the practicality and reliability of a mission.

Vessel size: Some platforms operate efficiently from small RHIBs, while others require a more stable working deck to ensure safe deployment, secure equipment handling, or effective tether management. These vessel-related requirements also determine the ability to maintain position in currents or waves, which is particularly relevant for tethered ROVs that depend on a steady platform for precise manoeuvring.

Crew experience further shapes operational success. ROVs typically require trained pilots capable of maintaining situational awareness, interpreting both sonar and optical imagery in real time, and compensating for vessel drift. AUVs reduce piloting demands but introduce other responsibilities, such as mission planning, waypoint configuration, and post-mission data verification. In both cases, familiarity with sensor configuration, navigation systems, and troubleshooting procedures is important to ensure that deployments deliver usable data.

Launch and recovery procedures can also impose limitations. Waves and strong currents restrict the safe handling of UUVs and may limit the depth or area that can be surveyed during a given mission window. For some platforms, environmental conditions at the moment of launch and recovery are more restrictive than conditions encountered while the vehicle is submerged. Ensuring a feasible and safe deployment cycle is therefore an important consideration when selecting a platform for routine monitoring. Additionally, depending on the weight of the platform a crane is required for launch and recovery of heavier systems, which is important to take into account when planning an operation with a UUV.

Data management: Finally, data management requirements influence operational planning. High-resolution optical mosaics, multibeam sonar datasets, and long camera transects can generate large volumes of data that require structured workflows for storage, processing, and interpretation. The availability of user-friendly software, open data formats, and automated reporting tools significantly impacts the speed and consistency with which ecological information can be extracted.

4.2.6 Survivability[19] & dependability[20]

The survivability and dependability of a UUV are considerations for ecological monitoring, particularly when operating in the dynamic and sometimes unpredictable conditions of the North Sea. A platform must be capable of completing its mission safely, avoiding collisions, and returning usable data even when conditions deviate from expectations. The field tests demonstrated that reliability depends not only on the robustness of the mechanical design, but also on the availability of fail-safe features, navigation redundancy, and situational awareness systems.

Collision-avoidance capabilities are important when operating near natural reef structures or artificial installations. Platforms equipped with forward-looking sonar or obstacle-detection sensors are better able to navigate complex environments and reduce the risk of impact. Emergency surfacing mechanisms, acoustic

[19] Survivability refers to a robot's ability to continue operating, at least in a degraded mode, when exposed to adverse conditions. It emphasizes resilience, fault tolerance, and recovery under hostile or unpredictable conditions.

[20] Dependability is the degree to which a robotic system can be relied upon to perform its intended function correctly and consistently over time. It encompasses attributes such as reliability, availability, safety, integrity, and maintainability.

locators, and clear recovery procedures further contribute to safe mission completion, ensuring that a vehicle can be retrieved even if communication or navigation issues arise.

Systems, such as backup power supplies, fault-tolerant electronics, and resilient communication links, help maintain operational continuity in case of hardware or environmental disturbances. Proper energy-management systems also play a role in this, particularly for AUVs, through providing sufficient endurance to complete planned transects and return to the launch point without mission abort.

4.2.7 Purchase, rental or subcontracting

In addition to technical and operational considerations, the choice between purchasing a UUV, renting a platform, or subcontracting a complete service influences the feasibility and continuity of ecological monitoring activities. Each option supports different levels of organisational capacity, flexibility, and long-term commitment.

Purchasing a system is most suitable for organisations that require frequent deployments, wish to build in-house operational expertise, or need full control over sensor configuration and mission planning. Ownership enables long-term capability development but also requires investment in training, maintenance, data-processing workflows, and storage infrastructure.

Rental models offer access to specialised UUVs for short-term projects or pilot studies without the financial and logistical burden of ownership and maintenance. This approach is particularly useful when specific sensors or capabilities are only needed occasionally, or when multiple platform types must be tested before deciding on a long-term strategy.

Subcontracting a complete service, where an external operator provides both the system and an experienced crew, can be effective when operational complexity is high or when reliable data delivery is more important than developing internal capacity. This option reduces risks related to environmental conditions, equipment handling, or data quality, as responsibility for mission execution lies with the service provider.
Selecting the most appropriate business model therefore depends on the frequency of monitoring activities, the desired level of internal expertise, available vessel and crew resources, and the degree of flexibility needed to respond to varying ecological or regulatory requirements.

4.3 Matching Monitoring Tasks to UUV Types

Selecting an appropriate UUV depends on how well its capabilities align with the ecological monitoring task. Building upon the field test results, this section provides practical guidance for matching common monitoring tasks to suitable UUV types. The aim is not to recommend specific models, but to outline which platform characteristics are most effective for different operational needs.

4.3.1 Natural reef & seabed habitat monitoring

Monitoring natural reef systems and broader seabed habitats typically requires consistent spatial coverage, stable altitude control, and the ability to produce georeferenced products such as optical mosaics or acoustic maps. UUV configurations suited for these tasks generally include autonomous platforms capable of following predefined transects while maintaining a steady height above the seabed. These systems benefit from downward-facing cameras for optical documentation, or acoustic sensors when visibility is poor. Their autonomy enables efficient coverage of large areas, while accurate navigation systems support repeatable surveys that are essential for detecting habitat changes over time.

4.3.2 Artificial reef & structure inspection

Close-range inspection of artificial reef elements, biodiversity structures, and other complex offshore installations requires precise manoeuvrability and safe operation near three-dimensional objects. Tethered configurations with real-time operator control are often the most effective, particularly when equipped with forward-looking sonar for collision awareness and high-resolution cameras for documenting fine structural features. Hovering stability, station keeping support, small turning radius, and responsive thrusters can be characteristics that enable the operator to navigate confined spaces and capture detailed imagery of vertical faces, cavities, or overhangs. These configurations are especially relevant when the monitoring task involves inspecting biofouling, inspecting structural integrity, or recording species associated with artificial reef units.

4.3.3 Species and biodiversity assessments

Species-level identification, behavioural observations, and biodiversity assessments rely on optical image quality. For such tasks, UUV configurations that can operate at low speeds, maintain a stable viewing position, and carry high-definition cameras (preferably full HD, 4K or better) are needed. In clear-water conditions, autonomous configurations can be used to perform broader-scale biodiversity transects, but when visibility is variable, or when specific species, substrates, or microhabitats must be examined in detail, tethered configurations provide greater control and allow the operator to adjust viewing angles in real time. The choice of configuration therefore depends largely on environmental conditions and the required level of taxonomic resolution.

4.3.4 Environmental parameter monitoring & sampling

Environmental characterisation tasks, such as measuring temperature, salinity, turbidity, dissolved oxygen, or nutrients, require UUV configurations equipped with specialised environmental sensors or water-sampling tools. Autonomous platforms with stable trajectories and consistent depth control are effective for collecting spatially coherent environmental data, especially when repeated transects or vertical profiles are needed. Tethered platforms become relevant when the task requires targeted sampling, such as collecting sediment or water from precise locations or navigating carefully around structures to sample boundary layers or near-bed conditions.

4.3.5 Impact and disturbance assessments

Assessing physical disturbance, seabed alteration, or broad habitat impacts, such as changes associated with construction, maintenance activities, or environmental stressors, typically requires broad spatial coverage and standardised mapping techniques. Autonomous configurations with acoustic mapping capabilities, such as side-scan sonar or multibeam echosounders, can be suited to these tasks due to their efficiency and consistent navigational accuracy. They allow large areas to be surveyed quickly and provide spatially referenced datasets suitable for change detection. In cases where anomalies or areas of interest are identified, tethered configurations equipped with optical or sonar sensors can be deployed for follow-up inspections at finer scales.

4.4 Concluding remark

These task-specific guidelines demonstrate that no single UUV platform is universally optimal. Instead, effective ecological monitoring requires aligning platform characteristics with the spatial scale, environmental conditions, and data needs of the task. It is possible that, in order to obtain a complete ecological picture, a combination of UUV platforms is required, and that some degree of physical sampling may still be necessary.

5 Conclusion

5.1 Key results and conclusions

The field tests demonstrated that a diverse range of UUV platforms can be successfully deployed under realistic North Sea conditions and can provide data relevant for ecological monitoring. At both study sites, most platforms could be launched and recovered from small vessels (RHIBs), and several completed their missions without major operational issues. Operational performance was primarily influenced by environmental forcing, vessel drift, and platform-specific navigation or interface limitations, showcasing the importance of matching platform capabilities to local site conditions. From a logistical perspective, successful deployment required an appropriate vessel platform, experienced operators, and operational procedures adapted to environmental conditions. Practical challenges included sunlight glare on screens, limited deck space, equipment handling requirements, and vessel drift during launch and recovery.

Sensor performance differed between optical and acoustic approaches. Optical sensors provided the highest level of ecological information when visibility was sufficient, vehicle motion was stable, and navigation could be maintained at very low altitude. In the Voordelta, multiple platforms produced high-quality imagery and mosaics suitable for species identification and fine-scale habitat assessment. At the Offshore Test Site, higher turbidity reduced optical data quality during some missions, although several platforms still generated usable imagery of reef cubes and associated fouling communities (especially larger organisms). Overall, successful optical surveys required slow and stable vehicle control at an altitude of approximately 0.5 m above the seabed or target structure.

Acoustic sensors proved to be robust data sources across environmental conditions. FLS, MBES, and SSS allowed for reliable detection of reef structures, substrate characteristics, and seafloor morphology. In the shallow Voordelta environment, FLS performed better than SSS, mainly due to reduced sensitivity to multipath interference and improved close-range imaging capability. At both sites, acoustic mosaics and MBES derived maps resulted in georeferenced spatial products suitable for assessing reef distribution, such as the flat oyster reef in the Voordelta, and for detecting artificial reef units at the Offshore Test Site.

Navigation performance varied substantially between platforms. AUVs equipped with advanced navigation and georeferencing systems were able to execute repeatable transects with positional deviations of only a few meters, showing strong potential for long-term repeatable and scalable monitoring applications. Platforms relying on surface GPS or less robust submerged navigation showed larger positional offsets (approximately 10–20 m), making them more sensitive to currents and reducing spatial accuracy and survey repeatability. For UUV-based methods to contribute to long-term ecological monitoring, repeated access to the same area is necessary but not sufficient. The collected data must also be comparable between survey moments. This requires sufficient consistency, or at least clear documentation, in survey design, positioning accuracy, sensor settings, image and acoustic data quality, environmental context, and post-processing workflows. For optical monitoring, comparable detection power for species identification and counts is also important, including consistent image quality and stable performance of any automated image-recognition tools. Repeatability and georeferencing should therefore be seen as one part of a broader set of requirements for long-term monitoring.

Effectiveness of AUVs vs ROVs: The effectiveness of inspecting complex three-dimensional structures depended strongly on manoeuvrability, environmental conditions, and site characteristics. In the dynamic shallow-water conditions of the Voordelta, AUVs were more effective than tethered ROVs for documenting the biogenic reef. They were less affected by vessel drift, could maintain consistent low-altitude transects, and produced stable optical and acoustic datasets. At the Offshore Test Site, tethered ROVs proved more suitable for close-range inspection of artificial reef cubes, as real-time operator control allowed precise positioning around complex structures. AUVs could only approach these objects safely under low-current conditions and when obstacle-avoidance constraints did not limit proximity. Consequently, detailed biodiversity observations on complex offshore structures were most reliably obtained using ROVs, whereas AUVs delivered more consistent habitat-scale coverage in the Voordelta.

Overall, the results show that UUVs can support a wide range of ecological monitoring tasks and can complement (or in some cases partially replace) diver and other traditional ship based surveys. Acoustic sensors provide reliable habitat-level information across varying conditions, while optical sensors can give high-resolution ecological information. However, consistent georeferencing, stable navigation, and clear operational procedures are essential prerequisites for integrating UUV data into long-term monitoring programmes. Furthermore, if highly detailed ecological data are required, physical sampling may still be necessary to accurately assess the organisms present. This is especially relevant for infaunal and sediment-dwelling species, as well as smaller organisms that may remain undetected by optical imaging systems.

5.2 Future developments

Several future developments can further enhance the use of UUVs in ecological monitoring and strengthen their integration into long-term (offshore) monitoring programmes.

Collaborative autonomy: A key direction is the advancement of collaborative autonomy, where multiple UUVs, or combinations of UUVs and Unmanned Service Vehicles (USVs), operate together during monitoring campaigns. Coordinated missions can increase efficiency, expand spatial coverage, and enable adaptive strategies, for example by allowing a USV to act as a communication relay, support long-endurance AUV missions, or provide real-time mission updates. Such concepts are particularly relevant for wind farms that are located far offshore, where vessel time is limited and operational windows are short.

Data standardisation is another important required development. The field tests of this current study highlighted large differences in sensor configurations, file formats, metadata structure, and post-processing pipelines across manufacturers. These differences currently limit data interoperability and complicate comparisons between platforms and operators. Establishing standardised data products, quality-control steps, and reporting formats would reduce post-processing effort and enable easier integration of UUV outputs into existing monitoring programmes. As datasets grow in size and complexity, centralised storage solutions and efficient data-management workflows will also become increasingly important.

Operational standardisation: Although this report already identifies which monitoring tasks are better suited to autonomous or tethered systems, further development is needed to translate these insights into a consistent operational framework. This includes formalising when and how each platform type should be deployed, defining standard procedures for mission planning and data acquisition, and consolidating these elements into a practical doctrine that supports reliable long-term use.

Increasing vehicle intelligence will also be important. Capabilities such as adaptive vehicle altitude depending on *in situ* observed visibility, onboard assessment of data quality, improved obstacle detection and avoidance. Enhanced navigation, including SLAM-based approaches[21], will also support more reliable and repeatable operation around complex structures and in low-visibility environments.

Finally, improved data fusion and change-detection methods will help translate UUV outputs into meaningful ecological insights. Combining acoustic, optical, and environmental datasets with AI-based feature detection and automated labelling can accelerate processing, reduce manual interpretation, and support early identification of habitat changes over time.

Together, these developments can significantly increase the reliability, efficiency, and ecological value of UUV-based monitoring in offshore environments.

[21] SLAM (Simultaneous Localization and Mapping) is a navigation technique that enables a vehicle to build a map of an unknown environment while continuously estimating its own position within that map, improving operational reliability in complex and low-visibility subsea conditions.

5.3 Way ahead

Building on the technological and methodological developments outlined in Section 5.2, the next step is to translate these insights into practical implementation within ecological monitoring programmes. The field tests demonstrated that multiple UUV platforms are already capable of delivering useful optical, acoustic and environmental datasets under realistic North Sea conditions. To make effective use of these capabilities, monitoring organisations should begin incorporating UUVs in a structured and gradual manner.

A **first step** is to establish clear operational guidance based on the best-performing procedures observed in this study. This includes identifying suitable survey altitudes, speeds, and deployment windows for different habitat types, and clarifying which data products (e.g., optical mosaics, MBES bathymetry, FLS mosaics) are most appropriate for specific monitoring questions.

A **second step** is to integrate UUV workflows into existing monitoring frameworks. This involves determining where UUV derived metrics can complement or partially replace diver/ship-based surveys, how UUV-based mapping can support long-term trend analysis, and how datasets from different platforms should be archived and processed to maintain consistency across years and operators.

A **third step** is to build organisational readiness. This includes developing internal capacity for mission planning, data management, and interpretation of UUV-derived datasets, as well as preparing vessels and operational teams for deployment. However, organisations do not necessarily need to acquire UUV systems themselves. For specific monitoring tasks, it may be more efficient to contract specialised service providers that offer UUV platforms, pilots, and data processing as a service. Such flexible deployment models can lower initial investment thresholds and allow organisations to gain experience with UUV-based monitoring before deciding on long-term in-house implementation. As the technology continues to mature, a combination of in-house expertise and external service provision is likely to provide the most robust and adaptable monitoring capacity. Given the rapid pace of technological development and the need for continuous methodological adaptation, relying solely on internal research capacity may not always be sufficient. Collaborating with specialised external partners can therefore help ensure access to up-to-date tools, expertise, and workflows, while allowing researchers to focus on interpretation and ecological insight.

Finally, gradual adoption through pilot-scale implementation, for example by adding UUV surveys alongside existing monitoring campaigns, allows organisations to build experience and trust, refine workflows and evaluate data quality in a controlled manner. This phased approach ensures that UUV-based monitoring is integrated responsibly and sustainably, without disrupting ongoing ecological assessments.

Together, these steps provide a path forward for incorporating UUVs into routine monitoring practice, complementing the broader technological and methodological developments described in Section 5.2.

5.4 Application of the results for the NN programme

For the NN programme it is important to monitor the success of NN funded nature regeneration projects, such as the biodiversity of biogenic reefs that will be created in the first large 2026 NN funded project ReefCreate-XL. The test results and practical insights obtained from testing the different sensors and UUV platforms in this report will be helpful for determining future NN monitoring strategies. Also the NN network around innovative monitoring was expanded, connecting ecologists and NGOs with industry partners who usually focus on technical inspections or military use of UUVs. The scheme in Chapter 4 will assist in choosing the optimal combination of platforms and sensors needed.

6 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

Annex A: Summary per field work test

BeeX

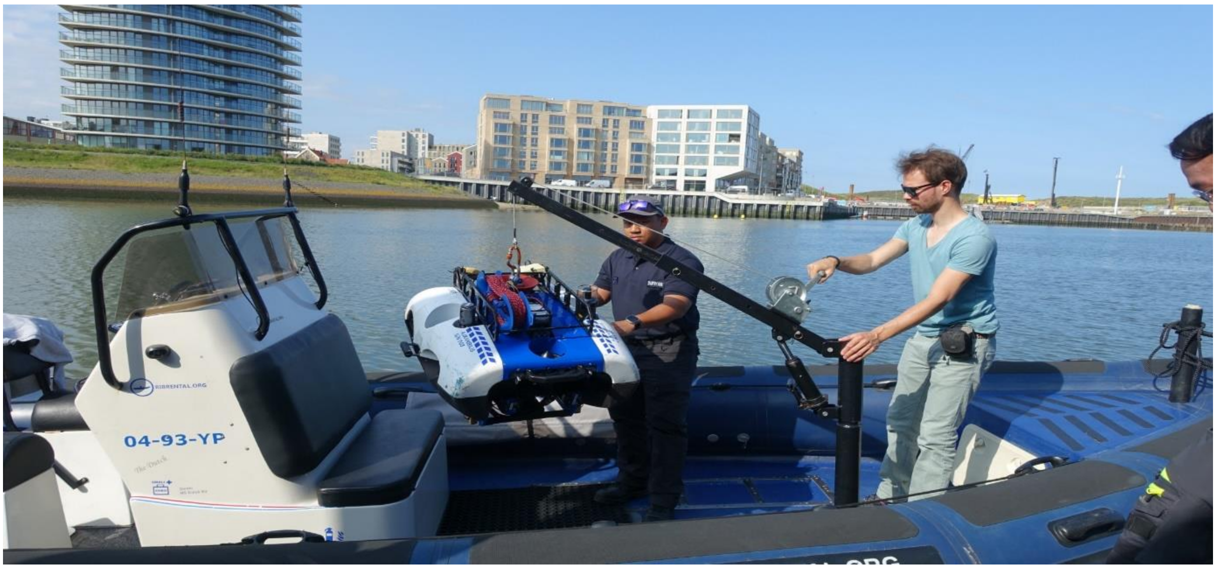


Figure A1: BeeX A.Ikanbilis in the harbour of Scheveningen.

Voordelta

BeeX demonstrated the capabilities of the A.Ikanbilis ROV in the Voordelta, successfully achieving autonomous waypoint following and collecting georeferenced MBES, FLS mosaic, and video data using the default camera. The FLS imagery revealed a clear distinction between two seafloor types (sand and mussel bed) and three of the five designated areas were visited during the mission. The camera data could be used to identify species on the seabed. Launch and recovery were successfully conducted from the RHIB. The MBES data supports seabed-morphology mapping and complements the FLS and video observations.

No specific operational issues were encountered.

Filename mission dashboard: BeeX-ROV-VD-report.html

BeeX – Offshore Test Site

BeeX demonstrated the capabilities of the A.Ikanbilis ROV at the Offshore Test Site, successfully achieving accurate underwater tracking of the teleoperated ROV and collecting FLS mosaic and video data, collecting data for the targeted Reef cubes. The FLS imagery showed the size of the targeted reef cubes and provided insights into seabed morphology, including small sand ripples. The camera data could be used to identify species on the reef cubes. Launch and recovery were successfully conducted from the RHIB.

No specific operational issues were encountered.

Filename mission dashboard: BeeX-ROV-OTS-report.html

Lobster Robotics

Figure A2: Lobster Robotics in the Voordelta.

Voordelta

Lobster Robotics demonstrated the capabilities of the Scout II AUV in the Voordelta, successfully acquiring high-resolution camera data and generating mosaic for three of the five predefined transects as well as an additional 5×5 m grid for which also a 3D model was created. Launch and recovery were conducted from the shore ramp rather than from the RHIB.

While the mission was executed successfully, several operational issues were observed. The northernmost transect could not be surveyed due to time limitations. Initial survey attempts produced insufficient-quality imagery, preventing mosaic generation for the middle transect. This issue was identified during the mission, enabling the flying altitude to be reduced to 0.5 m so that high-quality data could be obtained for the three southern transects.

Filename mission dashboard: Lobster-AUV-VD-report.html

Offshore Test Site

Lobster Robotics demonstrated the capabilities of the Scout II AUV at the Offshore Test Site, successfully capturing camera data near the Reefcube egg and the WERC-dock reef cube, as well as conducting a seabed survey. Launch and recovery were successfully demonstrated from the RHIB.

While the transects were executed, visibility was insufficient to acquire camera data of adequate quality for generating mosaics, with visibility being less than one meter. Although the AUV can operate at 0.5 m above the seabed, it lacks obstacle-avoidance capability, preventing safe close-range data acquisition near the targeted reef cubes.

Filename mission dashboard: Lobster-AUV-OTS-report.html

DCN Diving

Figure A3: DCN Diving with the VideoRay Defender in the harbour of Scheveningen.

Offshore Test Site

DCN Diving demonstrated the capabilities of the Defender ROV by VideoRay at the Offshore Test Site, acquiring both camera and FLS data for the targeted. The FLS imagery showed the size of the targeted reef cubes and provided insights into seabed morphology, including small sand ripples. The camera data could be used to identify species on the reef cubes. Launch and recovery were successfully conducted from the RHIB.

While data was collected, multiple operational challenges reduced mission efficiency. The ROV has no georeferencing ability, and without this navigation support, it proved difficult to quickly locate the targeted reef cubes on the seabed. Both the RHIB and the ROV were drifting, and the RHIB could not anchor in the survey area. In addition, the absence of GPS on the RHIB further complicated accurate positioning.

Filename mission dashboard: DCN-ROV-OTS-report.html

Subsea Tech

Figure A4: Subsea Tech with the mini Tortuga Hydro in the harbour of Stellendam.

Voordelta

Subsea Tech demonstrated the capabilities of the Mini Tortuga Hydro ROV in the Voordelta, producing camera mosaics, camera-based 3D models, and FLS imagery. A demonstration of the towed SSS behind the RHIB was also completed, and launch and recovery were successfully executed. The camera mosaics and 3D reconstructions can be used to document seafloor features and identify marine life on the seabed, while the FLS imagery provides information on the local seabed morphology including the distribution of reefs.

While the mission was completed, strong sunlight made the screens difficult to read and hindered system operation, and the small RHIB proved suboptimal for controlling the ROV.

Filename mission dashboard: SST-ROV-VD-report.html

Offshore Test Site

Subsea Tech demonstrated the capabilities of the Mini Tortuga Hydro ROV at the Offshore Test Site, generating a camera-based 3D model of the Egg reef cubes as well as collecting FLS imagery. Furthermore Launch and recovery were successfully conducted. The developed 3D models supports the visual documentation of reef cubes and seafloor structures, while the FLS imagery provides measurements of reef cubes size and information on local seabed morphology.

While the mission was completed, strong sunlight made the screens difficult to read and hindered system operation, and the small RHIB proved suboptimal for controlling the ROV.

Filename mission dashboard: SST-ROV-OTS-report.html

Seaber

Figure A5. Seaber in the Voordelta.

Voordelta

Seaber demonstrated the capabilities of the Marvel SCAN AUV and the Yuco PHYSICO AUV in the Voordelta, achieving autonomous waypoint following, conducting Side Scan Sonar (SSS) scanning with the Marvel SCAN AUV, and collecting water-property measurements with the Yuco PHYSICO AUV. Launch and recovery were successfully conducted from the RHIB.

The collected SSS data supports the detection of seabed features and the interpretation of possible reef presence, while the water-property measurements provide environmental context for the surveyed area. However, shallow water conditions in the Voordelta resulted in multipath effects and reduced sonar signal-to-noise ratio, making it difficult to clearly identify reef structures.

Filename mission dashboard: Seaber-AUV-VD-report.html

Offshore Test Site

Seaber demonstrated the capabilities of the Marvel SCAN AUV and the Yuco PHYSICO AUV at the Offshore Test Site, achieving autonomous waypoint following, conducting Side Scan Sonar (SSS) scanning with the Marvel SCAN AUV, and collecting water-property measurements with the Yuco PHYSICO AUV.

The SSS data provides seabed-acoustic information that can support the detection of the reef cubes and habitat characterization, while the water-property measurements allow characterization of the local water column. No significant operational issues were reported for the Offshore Test Site.

Filename mission dashboard: Seaber-AUV-OTS-report.html

H20 Drones

Figure A6: H2O Drones with the DeepTrekker Revolution at the offshore testsite.

Voordelta

H2O Drones demonstrated the capabilities of the DeepTrekker Revolution ROV in the Voordelta, collecting FLS and camera data, and performing launch and recovery from the RHIB. The collected FLS and camera data can be used for documenting seafloor features and identifying marine life on the seabed.

An encountered issue involved hardware problems with the autonomous navigation module which prevented demonstration of autonomous waypoint following and disabled georeferencing of the acquired data.

Filename mission dashboard: H20-ROV-VD-report.html

Offshore Test Site

H2O Drones demonstrated the capabilities of the DeepTrekker Revolution ROV at the Offshore Test Site, collecting FLS and camera data, and successfully executing launch and recovery from the RHIB. The collected camera and FLS data provide visual documentation of reef cubes and support interpretation of the surveyed area under offshore conditions.

An encountered issue involved hardware problems with the autonomous navigation module which prevented demonstration of autonomous waypoint following and disabled georeferencing of the acquired data.

Filename mission dashboard: H20-ROV-OTS-report.html

IQUA Robotics

Figure A5. IQUA Robotics at the Offshore Testsite.

Voordelta

IQUA Robotics demonstrated the capabilities of the SPARUS II AUV in the Voordelta, successfully performing launch and recovery, autonomous waypoint following, and collecting camera, FLS, and MBES data suitable for generating mosaics and a seafloor map. This data was acquired for all five predefined transects as well as for two larger rectangular grids.

The collected camera and FLS mosaics provide visual documentation of seafloor features, while the MBES map supports interpretation of seabed morphology and spatial structure. The only operational requirement noted during the Voordelta mission was that, in the presence of currents, transects needed to be defined parallel to the current direction. This mitigated the platform "crabbing" that occurs when survey lines are oriented perpendicular to the current, ensuring stable motion and consistent mapping throughout the survey.

Filename mission dashboard: IQUA-AUV-VD-report.html

Offshore Test Site

IQUA Robotics demonstrated the capabilities of the SPARUS II AUV at the Offshore Test Site, successfully completing launch and recovery, autonomous waypoint following, and acquiring camera, FLS, and MBES data for mosaic generation and seabed mapping.

The camera and FLS mosaics and the MBES map provide visual and acoustic documentation of the surveyed reef cubes. An operational limitation was observed: as the AUV maintained a safe standoff distance to avoid collisions, the mosaic quality remained high for the upper surfaces of the nature recovery blocks, but the lower segments appeared blurry due to the increased distance and limited visibility.

Filename mission dashboard: IQUA-AUV-OTS-report.html

Annex B: Detailed analysis of optical data

Introduction

This chapter contains examples indicating data quality collected by the participants in this project to support answers to the research questions of this study. In addition, some more background information on the AI model used is provided.

Optical data quality

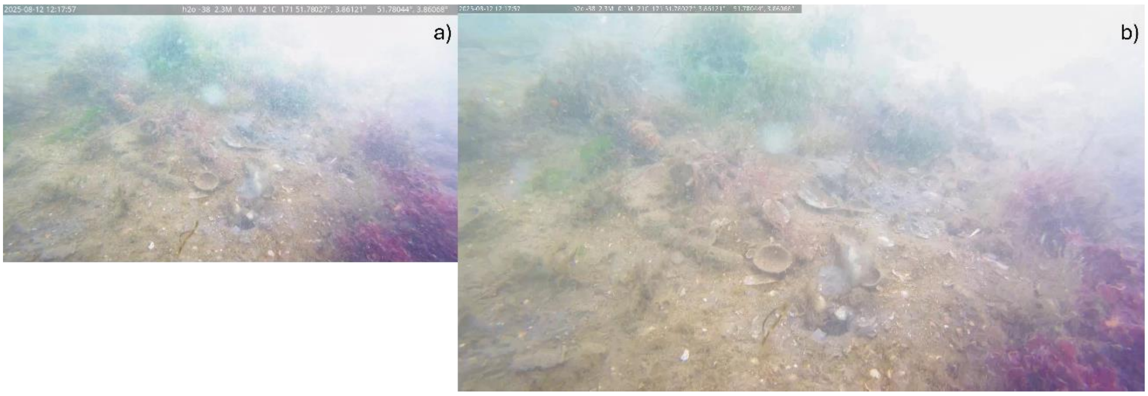


Figure B1. DeepTrekker in the Voordelta A) standard definition camera (848x480px) b) high definition camera (3840x2160px)

Figure B1 shows example frames collected by the DeepTrekker Revolution ROV with a standard definition camera (a) and a high definition camera (b). Both cameras were fixed at the forward looking position at ~45° to the seabed. High definition camera provides more details per frame, however water turbidity makes it challenging to see the advantages of a high definition camera.

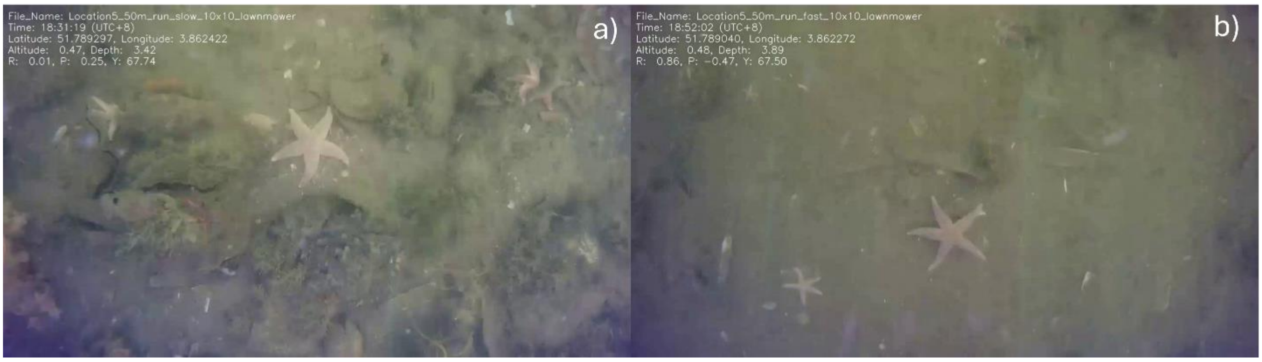


Figure B2. Frames selected from the video collected by the main camera of the Beex A.Ikanbilis HAUV in the Voordelta: a) lower speed; b) higher speed.

Figure B2 depicts sample frames collected by the Beex A.Ikanbilis HAUV at two different speeds, while all other settings remained the same. Lower speed (a) resulted in sharper frames compared to higher speed (b), however organisms with distinct shape like starfish remained recognizable in both cases. The speed influenced the duration of the survey transect and therefore the size of the recorded files. The video recorded at the slower speed is three times larger than the one recorded at the faster speed.

Figure B3 demonstrates example frames collected by the Beex HAUV with external camera (a) and main camera (b). Both cameras output frames with 720px resolution, external camera collected data with 8 fps, while the main camera at 10 fps. Despite the same resolutions in both cameras the resulting frames look different. This is caused by the different camera sensor sizes, lens types, and post-processing (e.g. contrast enhancement).

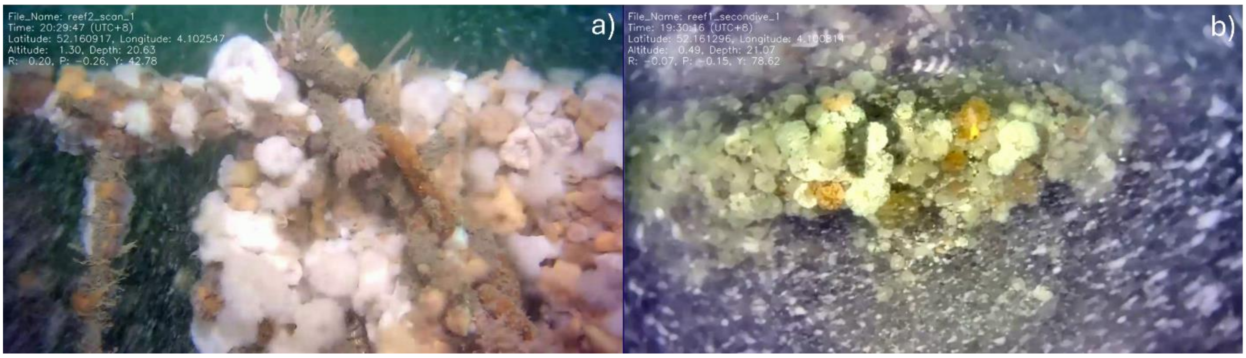


Figure B3. Frames selected from the video collected by the external and main cameras of the Beex A.Ikanbilis HAUV in OTS. a) external camera frames depicting a side of the Egg reef at range of ~0.5-0.6 m; b) a sample frame depicting a side of the Egg reef at range of ~1 m.

Figure B4 shows example frames collected by Lobster Robotics in the Voordelta at different altitudes in four different survey areas. The altitude of 0.5 meters provided the best frame quality; at 1 m altitude the sharpness and contrast of the frames is least optimal. Tether connecting the communication buoy and the AUV occasionally was present in the frames (Figure B4, a).

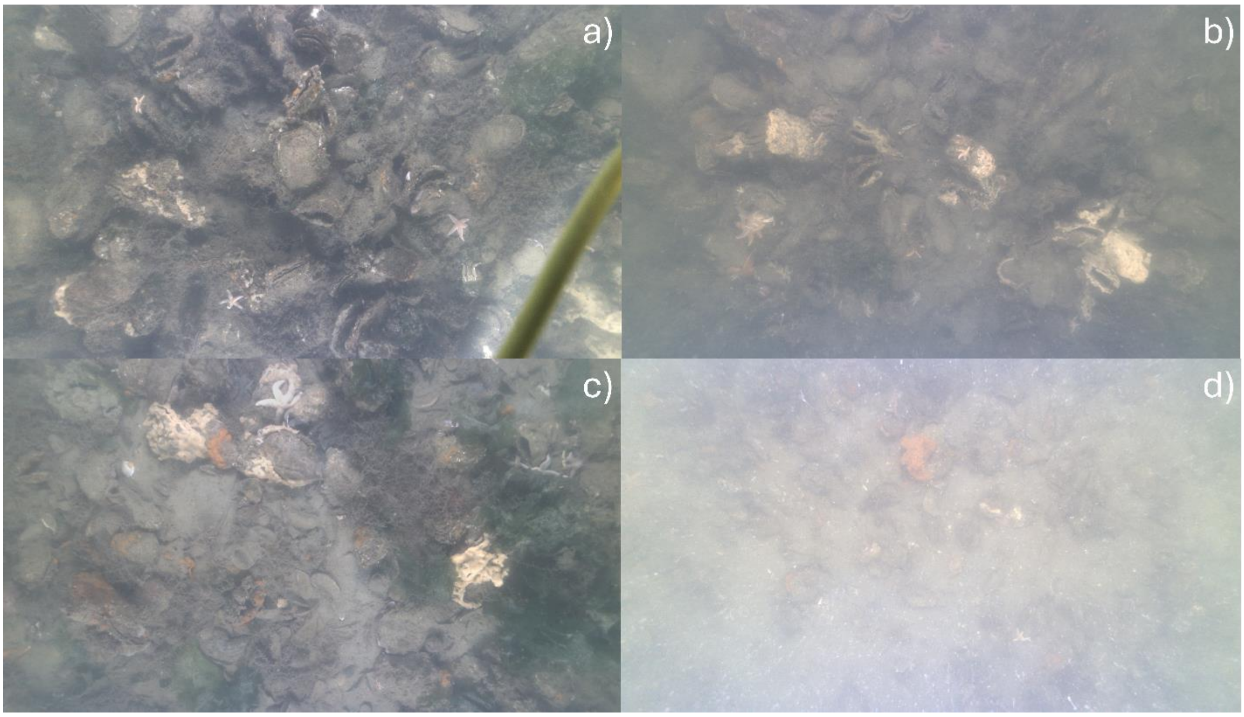


Figure B4. Raw frames collected by Lobster Robotics in Voordelta at a) while inspecting 5x5 survey area at 0.5 m altitude; b) in 'sand' location at 0.7 m altitude; c) at 'mussel bed' location at 0.5 m altitude; d) at location 'middle' at 1 m altitude.

AI applicability

This section provides extra information about the model that was used to test AI applicability of the data collected by the participants.

Grounding DINO is an artificial general intelligence model which has text features introduced in the detection pipeline (Liu et al., 2024). It is developed to deal with object detection tasks in open set scenarios via text prompt, this means that the model is able to detect the objects in the unseen data for which text description is given by human supervisor. Grounding DINO with Swin Base backbone was trained and evaluated on more than 15 million images from 7 datasets representing more than 1000 categories in various domains.
We used the variant with SwinB backbone for feature extraction; the model was optimized for faster and more efficient inference (Qint8).

Text prompts describing expected target objects were used to access GroundingDINO ability to detect target objects in a sample data collected by AUVs and ROVs in the test sites, confidence was set to 0.01.

Annex C: Rugosity calculation

Rugosity calculation method

Seafloor surface irregularity strongly links to the habitability and biodiversity potential. It therefore provides meaningful information for ecological monitoring. This irregularity can be measured by the so-called rugosity parameter which is defined, for a given area, as:

$$\text{Rugosity} = \frac{\text{Three-dimensional surface area}}{\text{Two-dimensional projected area}}.$$

By definition, the rugosity for a completely flat surface is 1 while a more complex surface has the rugosity value higher than 1.

There are several advantages of applying the rugosity metric in our study. First, the definition of the rugosity is defined mathematically. This provides a quantitative metric to measuring the seafloor surface complexity. Second, the method is compatible with the data obtained by acoustic and optical sensing of the seafloor, such as the spatially dense point-cloud data provided by the MBES or the 3D surface reconstruction by stereo cameras.

Practically, a point-cloud dataset contains coordinates in (X,Y,Z), where Z represents the surface elevation or the depth. A 3D surface is reconstructed by connecting nearby points by triangulation, connecting nearby points by small triangles. These triangles form a 3D mesh. The 3D surface area, the nominator of the rugosity formula, is calculated by summing the area of all triangles. The 2D projected area in the denominator is calculated by repeating the same process, keeping only (X,Y) coordinates and omitting the Z component.

Rugosity from MBES data

BeeX and IQUA Robotics provided point-cloud MBES data. An example rugosity calculation based on a point-cloud dataset obtained at the VD location by BeeX is shown in Figure C1. The triangulated 3D mesh is shown by the coloured surface and the black outline indicates the boundary of the 2D projected area. The rugosity of this point cloud example is 1.49.

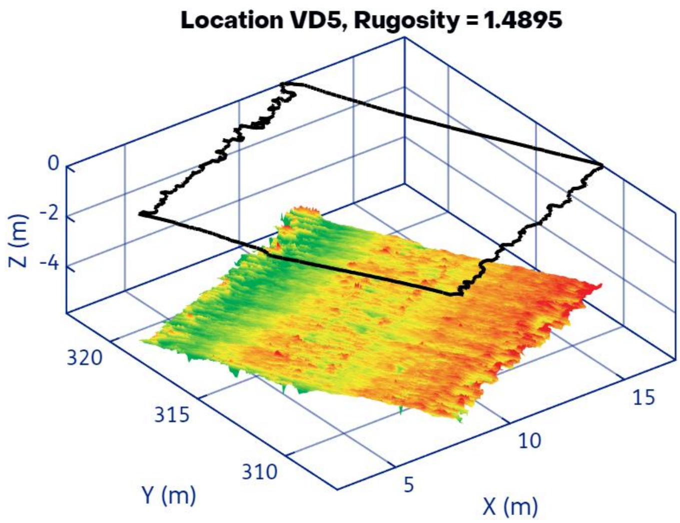


Figure C1: Bathymetry plot of the VD site surveyed by the MBES onboard the BeeX HAUV and the corresponding rugosity value.

A periodic stripe pattern is observed in the 3D surface reconstruction of the seafloor surface from the MBES point-cloud data. This is likely an artefact caused by a combination of the ROV motion and the high uncertainty at high beam angle along the swath edges. This suggests that an extra data preparation step may be required to minimize this artefact. To demonstrate, we applied a heuristic wavelength filter (cutoff wavelength of 0.2 m and angle of 22 degrees) to the point cloud data and recalculated the rugosity. The triangulated 3D mesh before and after applying the high-pass filter are compared in Figure C2. Qualitatively, we see a slightly weakened periodic patterns. However, we observed a rather minimal change in the rugosity value after applying the filter. Further fine-tuning the wavelength filter is beyond our scope.

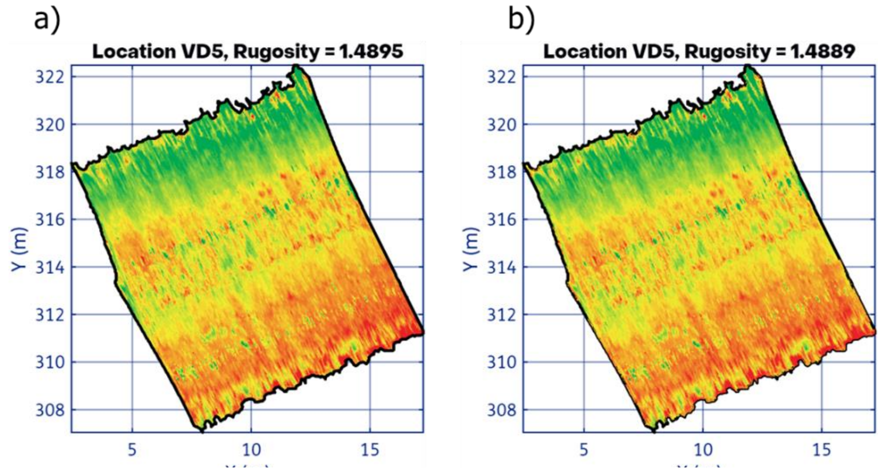


Figure C2: Bathymetry plot of the VD site surveyed by the MBES onboard the BeeX ROV and the corresponding rugosity value. a) Before applying a high-pass filter; b) After applying a high-pass filter.

The example rugosity calculation results of the point-cloud depth data from the MBES of IQUA Robotics at the VD location is shown in Figure C3. MBES dataset from IQUA Robotics is provided for a relatively larger variation of area sizes, each with varying point-cloud spatial densities. Furthermore, the bathymetry maps show relatively less periodic stripe patterns due to the platform movement and sound-speed uncertainties. This could be caused by many different factors, including the different platform and environmental conditions during the survey.

This dataset shows different observations regarding the rugosity calculation. First, the rugosity value increases for the finer point-cloud spatial resolution. For example, for the same area with spatial point-cloud spacings of 10 cm and 5 cm, the rugosity values are 1.06 and 1.16, respectively. Secondly, due to the greater survey area, there is large local variation of the seafloor surface complexity and bathymetry values as shown in the bottom subfigures in Figure C3. The rugosity value calculated using the method described so far, where all provided points are taken at once, might not provide a meaningful insight into sub-areas with locally higher rugosity values. To focus on more localised rugosity calculation, we then apply a sliding square window of 1 x 1 m with an overlap of 50% to the area and calculate the rugosity for the subset of points in this square area. The resulting local rugosity values are shown in Figure C4. It can be observed that the point cloud data with the overall rugosity value of approximately 1.2 can have a variation of the local rugosity value ranging from 1.0 to 1.6, depending on the local depth variations.

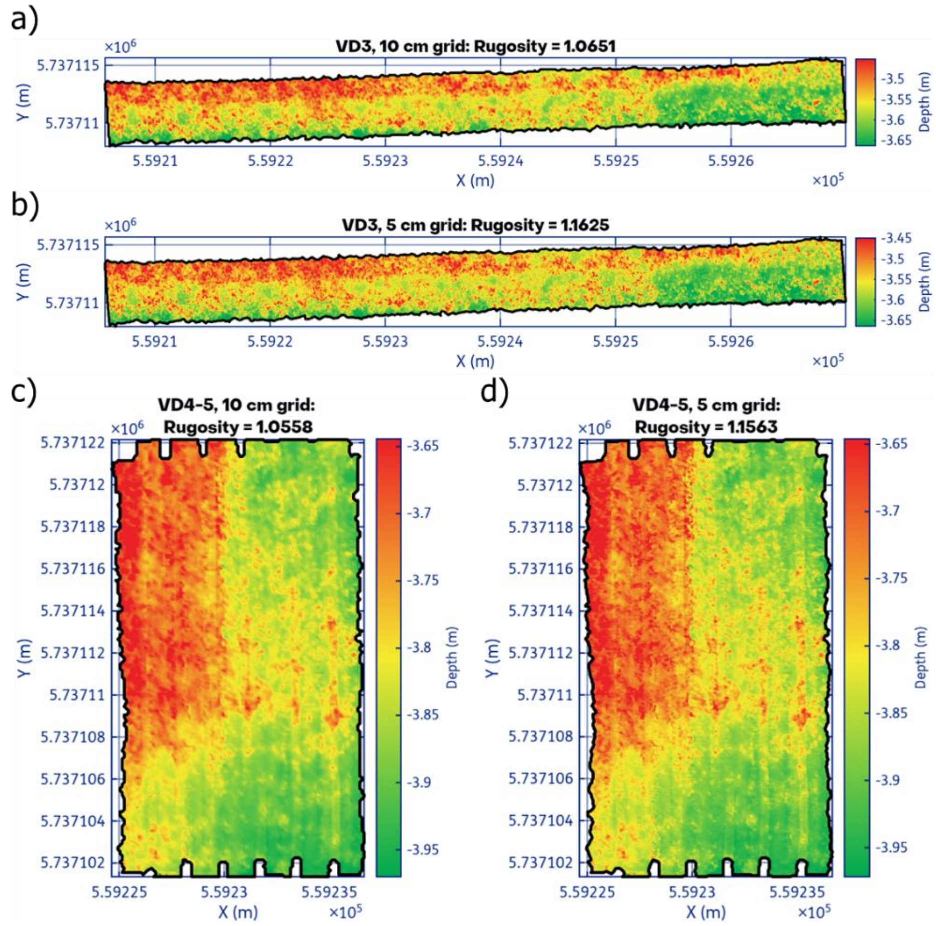


Figure C3: Bathymetry plot of the Voordelta (VD) site surveyed by the MBES onboard the IQUA Robotics AUV and the corresponding rugosity value. a) Survey VD3, grid spacing 10 cm; b) Survey VD3, grid spacing 5 cm; c) Survey VD4-5, grid spacing 10 cm; d) Survey VD4-5, grid spacing 5 cm.

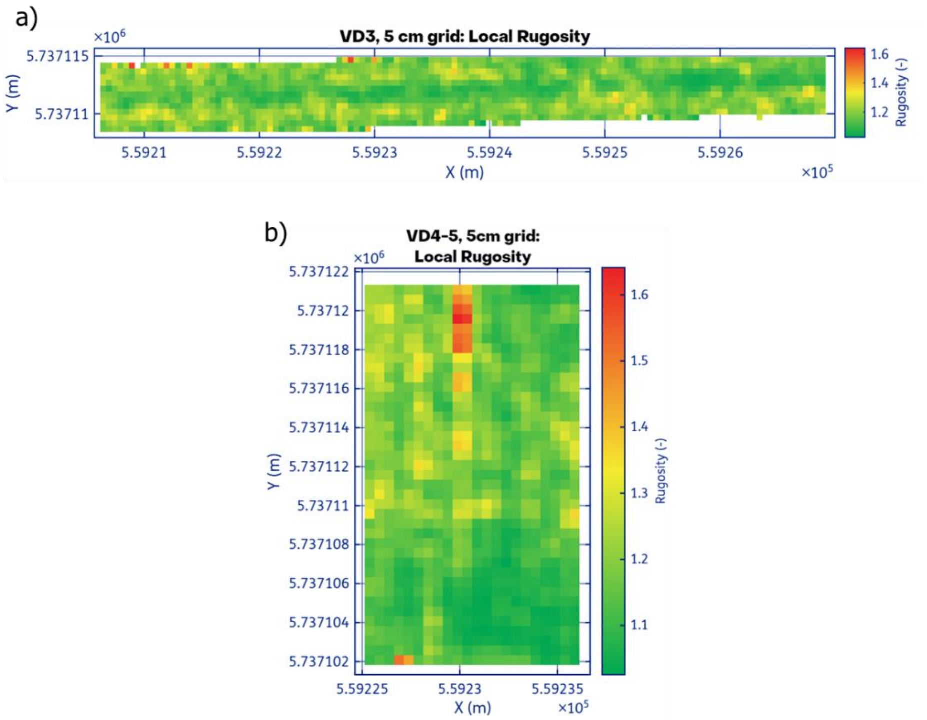


Figure C4: Local rugosity values calculated by a 1 x 1 m sliding window technique with an overlap of 50% for the MBES dataset from IQUA Robotics AUV at the Voordelta (VD). a) Survey VD3; b) Survey VD4-5, both with grid spacing 5 cm.

Rugosity from stereo-camera data

Lobster Robotics provided a digital 3D model of the VD survey for an area of 5 x 5 m constructed using stereo camera data. This dataset is visualized in Figure C5. This dataset was already provided in a 3D mesh format rather than only the point cloud as for the MBES data. The data also has been provided in a much higher resolution (point spacing less than 1 cm) than that of the MBES point cloud. Due to the different data format, the rugosity calculation was done in the CloudCompare software. The resulting rugosity value of this area is 1.45.

The rugosity value calculated from the stereo-camera data is higher than that derived by the MBES data for the VD area. This is expected based on our earlier observation from the MBES data that the higher point-cloud resolution would result in a higher rugosity value.

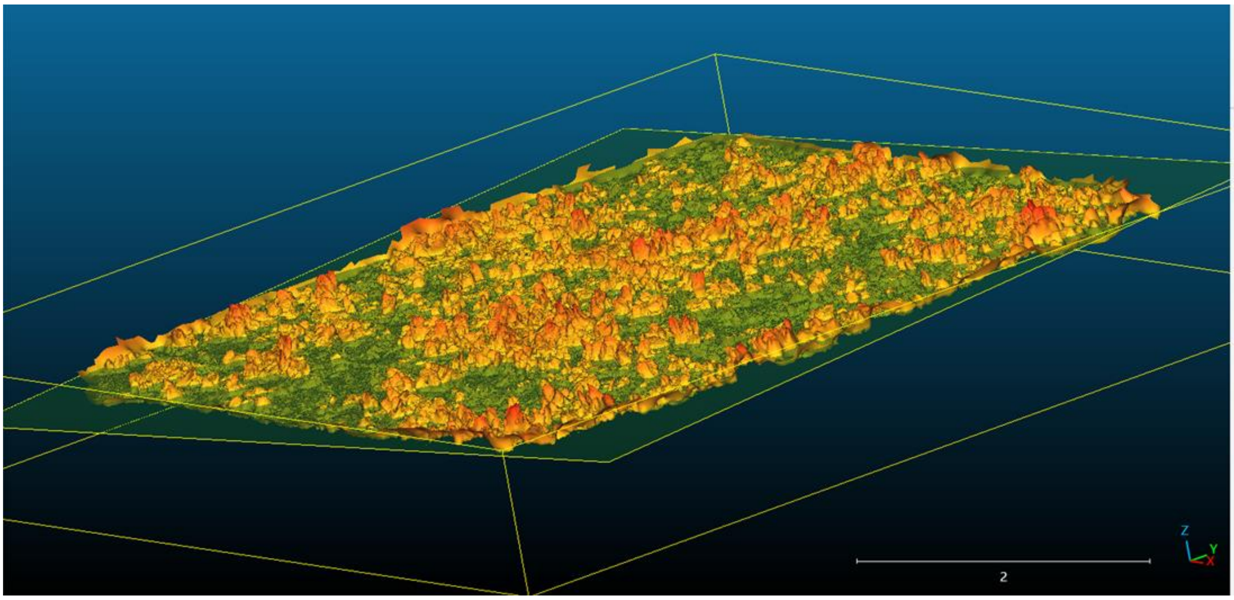


Figure C5: 3-D model constructed by a stereo-camera survey of the Voordelta site using Lobster Robotics AUV. The corresponding rugosity value is 1.45.

Meaningful insights could be obtained by comparing the (local) rugosity value calculated by the stereo-camera 3D model and the MBES point-cloud data from a given area. To better match the point-cloud resolution and the rugosity value between the MBES and the stereo-camera data, an MBES system with a higher frequency (approximately 1.2 MHz) would be required. Within the scope of this project there is unfortunately no overlapping stereo-camera and MBES datasets from the same area. This is therefore a recommendation for future survey campaigns where the rugosity is of high interest. On the other hand, if only the relative change in the rugosity value is of interest, such as for reef presence detection, the present MBES model or the qualitative evaluation of the FLS data might already suffice.

Annex D: Reef object localisation accuracy

Several companies provide georeferenced images from their FLS, SSS, and MBES. These images could be used to assess the localisation accuracy of specific objects. This localisation accuracy indicates the ability of the UUVs to (re)visit specific survey locations for long-term repeated monitoring.

Given the known ground-truth GPS coordinates of the reef objects at the OTS provided in Table 2.2. We compare the centre location of the reef objects indicated in the georeferenced images with the ground-truth location. For this, we use the map visualisation in the mission dashboard to estimate the distance offset between the indicated GPS coordinates of the reef objects and their ground-truth GPS coordinates as visualised, for instance (Figure D1). The resulting distance offsets are summarised in Table D1.

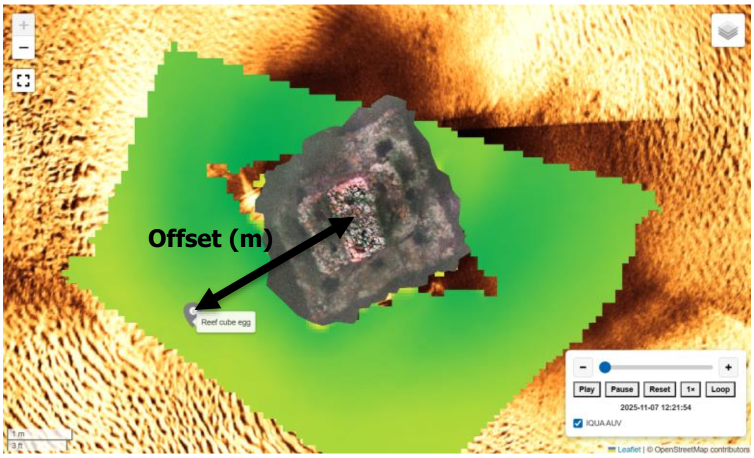


Figure D1. Example reef object offset estimation from the map visualization in the mission dashboard.

Table D1. Distance offsets between the reef object GPS coordinates and the reef object locations indicated in the georeferenced images.

Company	Reef objects					
	Reefcube mussel		Reefcube egg		WERC dock	
	Sensor data	Offset (m)	Sensor data	Offset (m)	Sensor data	Offset (m)
BeeX	FLS	8	FLS	5	FLS	1.5
Lobster	n/a	n/a	Camera	1.5	Camera	2
Seaber	SSS	20	SSS	15	SSS	10
IQUA Robotics	FLS, MBES	1	FLS, MBES, Camera	2	FLS, MBES	3

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