

Final report

1. Project details

Project title	ACOMAR
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Name of the funding scheme	EUDP
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Project partners	SubC Partner A/S, TotalEnergies EP Danmark A/S, Siemens Gamesa Renewables Energy, EIVA, Mati2ilt, Sihm Højtryk, Aalborg Universitet.
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2. Summary

- *English version*

A challenge for constructions in water, for example offshore oil and gas platforms and wind turbine foundations, is marine fouling. The fouling settles permanently to the construction and thus increases both the thickness and roughness of the material. This causes an increased load and fatigue of the construction.

Cleaning of marine fouling is ineffective with the methods used today, with the help of large, free-flying ROVs, which carry a cleaning tool - often a high-pressure nozzle with water. The operation is manually driven. This applies to both control of the ROV and assessment of the amount and type of marine fouling. In addition, large ships are used to launch the ROV, which is extremely costly.

This project has focused on automating the control of the ROV in order to make the cleaning more efficient and relieve the ROV pilot. In addition, tests have been made of a number of different cleaning tools, in order to discover which technology and parameters are most optimal. It is common knowledge that underwater equipment is generally expensive. This project has largely focused on finding affordable solutions that are also easily accessible.

The setup of the entire system is scaled down to a footprint corresponding to 2 x 10-foot containers. This means that the solution can be used from a platform, without the need for a ship to launch from.

The current process for inspecting the extent of marine fouling is based on manual measurement of thickness and manual assessment of fouling-type. This process is significantly optimized using artificial intelligence, where synthetic data is used for training the algorithm. The data are generated from a virtual environment

which is easily expanded with new species of marine fouling and can be adapted to other operational conditions.

The system has been tested in a nearshore area and partially tested in an offshore environment. Further demonstration is expected to take place in an operational environment (offshore oil&gas platform) Q2 2024.

- *Danish version*

En udfordring for konstruktioner i vand, eksempelvis offshore olie og gas platforme og vindmøllefundamenter, er marinebegroning. Begroningen sætter sig permanent på konstruktionen og dermed øger både omfang og ruhed af materialet. Dette bevirker en øget belastning og udmattelse af konstruktionen.

Afrensning af marinebegroning er ineffektivt med de metoder som anvendes i dag. Dette er primært ved hjælp af store, fritflyvende ROV'er, som bærer et rensværktøj – ofte højtryksdyse med vand. Operationen er meget manuelt drevet. Dette gælder både styring af ROV'en samt vurdering af mængde og type af marinebegroning. Derudover anvendes store skibe til at søsætte ROV'en, hvilket er voldsomt omkostningsfuldt.

Dette projekt har fokuseret på at automatisere styringen af ROV'en med henblik på at effektivisere afrensningen og aflaste ROV piloten. Derudover er der lavet tests af en række forskelligere rensværktøjer, for at afdække hvilken teknologi der er mest optimal, og hvilke parametre teknologien fungerer bedst ved. Det er almindeligt kendt, at undervandsudstyr generelt er omkostningstungt. Dette projekt har i høj grad fokuseret på at finde prisvenlige løsninger, som ligeledes er let tilgængelige.

Setuppet til hele systemet er skaleret ned til et footprint svarende til 2 stk 10-fods containere. Dette betyder, at løsningen kan anvendes fra en platform, uden behov for et skib at søsætte fra.

Den nuværende proces for inspektion af omfang af marinebegroning er baseret på manuel måling af tykkelse samt manuel vurdering af type af begroning. Denne proces er væsentligt optimeret ved hjælp af kunstig intelligens, hvor syntetiske data er anvendt til træning af algoritmen. De syntetiske data er genereret fra en virtuelt miljø, som nemt udvides med nye arter af marinebegroning og kan tilpasses andre operationsforhold.

Systemet er testet i et nærkystområde og delvist testet i et offshoremiljø. Yderligere demonstration forventes at pågå i operationelt miljø (offshore olie&gas platform) Q2 2024.

3. Project objectives

Throughout many years the oil and gas (O&G) industry has faced problems with marine growth (MG) accumulating to the offshore constructions. The marine growth causes additional weight and increases the circumference and roughness of the structure, which result in increased wave load. Consequently, material integrity is affected as well as risk of increased overturning moment. To avoid these disadvantages, the operators within the O&G industry periodically remove the marine growth. Previously, cleaning of marine growth was carried out using divers. During the last two decades, ROVs have taken over the task, increasing safety significantly. However, this solution is still expensive, mainly due to large vessels required, and ineffective due to poor control of the ROVs.

The wind industry also faces the same problems caused by marine growth. Partly, the problem is currently overcome by over-dimensioning the foundations. However, Siemens Gamesa Renewables Energy (SGRE) predicts the problem will increase in the future, where super-optimization in design is required, and the wind industry will therefore also rely on periodically cleaning of the structures to stay competitive. This counts for both monopiles, jackets and floaters.



Figure 1 Due to additional loads and accessibility for inspection, it is important to remove MG.

1. Increased wave load on the structures due to larger diameters and more surface roughness.
2. Fatigue cracks and damages are very hard to detect without removing the MG / Biofouling. It is a huge safety and environmental risk if these damages are not identified and repaired.

The objective for this project is to gain knowledge from the O&G industry to be used in optimizing methods for marine growth removal, which can then be directly transferred to the wind industry, that has less experience with these operations. In this way, both industries will gain from this project, and the O&G industry will serve as user of (and help developing) the solution while the wind industry matures.

The main goals are to reduce emissions and costs of MG removal campaigns through a new set of disruptive tools. This will mainly be obtained due to increased automation of the cleaning solution, improved inspection tools and a compact setup that will obviate the need of large, resource demanding vessels, that the campaigns of today depend on. Furthermore, the solution will allow the wind industry to super-optimize foundation's design and thereby save significant amounts of steel.

A reduction in costs for operation and maintenance of the O&G platforms and in construction of wind farms, results in cheaper energy production, making the Danish market more competitive. Further, a significant reduction in steel consumption for production of wind turbine foundations, and avoidance of fuel consumption for large vessels during the MG removal campaigns, enhances the work towards reaching the 2030 goal of reducing greenhouses gases by 70% compared to 1990.

How it is done today

The challenges caused by marine growth is typically overcome either by

- oversizing the construction or,
- frequently removing the MG.

Within the O&G industry periodic MG removal campaigns are carried out as part of the maintenance programs. This is a requirement for both inspection of the structure and in consideration of design criteria for material fatigue and overturning moment. For the wind industry, MG removal is only carried out for specific inspection tasks, as the foundations are typically oversized to meet the additional loads due to MG.

Oversizing

The marine growth is taken into consideration during the design phase of the new foundations. This means that the foundation is designed to withstand the increased drag forces caused mainly by waves and also to withstand the extra weight impact from a maximum MG estimation.

Foundation oversizing significantly reduces the requirement for MG removal. However, it is necessary to ensure material integrity for the structure and such inspections require a clean structure. Therefore, marine growth removal is a part of operating a wind farm even though the structures are designed for maximum marine growth.

Removal of marine growth

Removal of marine growth is a mutual issue across offshore industries globally. According to project partner TEPDKs Subsea Department, MG removal is generally performed according to the process depicted in Figure 2.

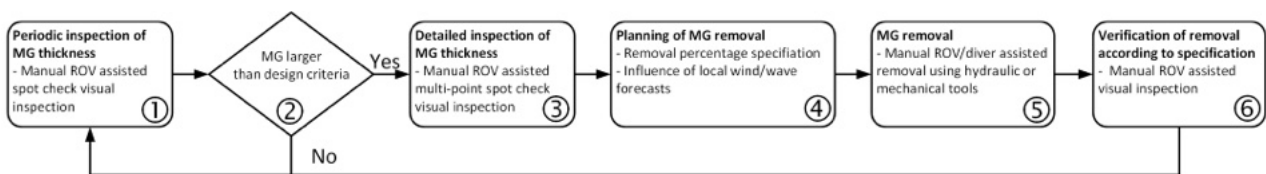


Figure 2 State-of-the-art marine growth and inspection process

Traditionally, the MG removal is initiated by a periodic rough spot check inspection (1). These inspections are performed using a manually controlled floating ROV mounted with a ruler to push into the marine growth in representative spots (see Figure 3). The layer thickness is assessed by reading off the measurements on the ruler manually by video transmission. Also, it is assessed what kind of marine growth is present. The inspection process is both laborious and affected by low visibility encountered in some weather conditions. This leads to significant uncertainties regarding MG estimation.

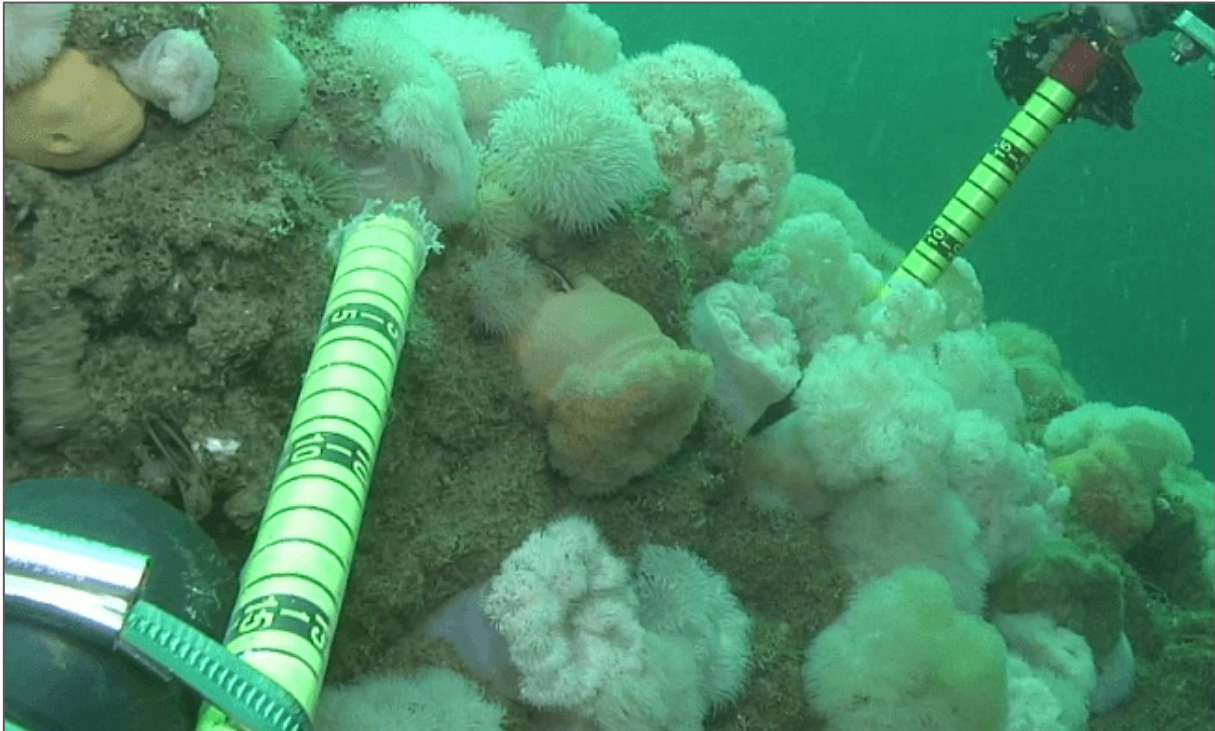


Figure 3 Manual ROV assisted marine growth inspection. A ruler is pushed into the marine growth.

If the marine growth thickness is larger than specified maximum values (2), then a more detailed spot check inspection process is initiated to assess the requirement for marine growth removal (3). A cleaning campaign is planned based on the removal specification and weather forecasts (4). Marine growth is subsequently removed, usually ROVs are used for this purpose (5). Lastly, a verification of the removal process is performed manually with video transmission (6).

Today, the most common way to remove MG is using a conventional floating ROV mounted with a cleaning tool that removes the marine growth either mechanically (e.g. rotating brushes) or hydraulically (e.g. water jetting).

Disadvantages of ROV solution

Inhouse experience, market scan, conversations with skilled ROV operators and extensive inspection of video material from ROV operations has been conducted. The main challenges exposed using a floating ROV are

- Even for dedicated and experienced ROV operators, the cleaning efficiency is greatly reduced due to disturbances from the cleaning tool itself and the subsea environment (waves, tidal streams, umbilical forces).
- Non-adaptable in the splash zone (few meters below water level), which is difficult or even impossible, due to large wave loadings in this area and the natural limitations for an ROV at water level.
- Emissions to environment from supporting vessel.
- High costs for rental of supporting vessel (Dayrates in the order of 500.000 DKK including personnel capacity up to 50 persons) according to TEPDK and Hagland Shipbrokers[2].

Several competitive solutions to the floating ROV is in the market. In general, such solutions fix to the structure to maintain the optimum performance distance for the cleaning tool and clean in a controlled pattern. Often, they are launched from a platform or by rope access personnel. An example of such a solution is shown here:



Figure 4 Example of solution fixes to the structure (Robotic Crawler by SubC Partner)

Disadvantages of non-ROV solution

Unfortunately, these solutions that eliminate the downsides of the floating ROV concept, introduce other complications. The challenges to solutions that fix to the structures are

- Non-adaptable to diverging tube diameters.
- Much less flexible when it comes to relocation.
- Significant safety risk in case of installation by rope access personnel.

Especially for wind turbine generators (WTG) and transformer substations built on jacket structures it is important that the solution is manoeuvrable and not time consuming to relocate, as many relocations are required during the cleaning campaigns. Diameters diverge from approximately 300 mm to 6000 mm, which will require different tools if a fixed solution is chosen.

Planned innovation level

Based on the Conceptualization Phase (Phase 1) project, and experience from offshore cleaning jobs on both monopiles and jacket structures, it is considered optimal to

- Avoid use of high emission and expensive support vessels by designing a compact setup.
- Avoid fixation to the structure to maintain flexibility regarding relocation.
- Avoid dependency of tubular diameters.
- Avoid ineffective manual ROV operation.

Many obstructions are present such as joints, anodes, clamps, boat fenders, ladders etc. Figure 5 shows a transformer substation on a jacket structure showing the varying diameters, many joints and other obstructions. It clearly shows why it is important that the cleaning system is flexible to relocate.



Figure 5 Jacket structure showing complex geometry and obstructions

To enhance cleaning velocity, the key objective is to systematize the pattern of movement and keep a fixed distance to the target. Commercial ROVs are designed for multiple purposes, and cannot accommodate the compact size requirement needed. This solution is solely targeted marine growth inspection and removal for efficient operation and will be referred to as ACOMAR.

The movement will be regulated using advanced control algorithms which must take disturbances into account, such as forces generated by the waves, underwater streams, the ROV umbilical and the cleaning tool.

Automatic Control

The project will enable a transition from the existing manually operated to full-autonomous ROV. Several control elements need to be developed to achieve this goal. Specifically, this subsection deals with the automation of the processes “Planning of marine growth removal” and “Marine growth removal” as shown .

It should be noted that the control algorithms applied in this project are well-known in academia where numerous studies have focused on advanced automatic control for ROVs. However, limited attention has been given to real implementation of these methods on ROVs, especially in harsh environments which are present in off-shore scenarios. Therefore, in this project the focus will be on the implementation and practical investigation of these existing methods and algorithms (TRL 4 and above), as the methods previously only have been described and examined in theoretical analysis and by computer simulations.

Inspection

As opposed to the conventional inspection method, where a periodic initial inspection is carried out and then, later independently, a second detailed inspection is made, the innovation and ambition in this project is to automate and integrate both inspection campaigns into one single. Hence, this single inspection must both determine the need for a cleaning campaign and, if decided to go for a cleaning campaign, schedule where and how the cleaning will be carried out. The automated inspection process relies on control elements together with forecasts of wind, wave and tidal streams.

In addition, the current inspection method is based on samples carried out by divers are rarely representable for the complete examined construction. The new proposed solution is a sonar/vision-based approach where a system located on an inspection ROV is used to monitor all structures in a region at once in a single 3D image as illustrated in Figure 6. This image is compared to CAD drawings of the structure and images of the cleaned structures after the previous cleaning operation. In this way, the 3D image can determine the layer of marine growth and can both be used to determine if a cleaning campaign is needed and schedule where and how much cleaning must be carried out in a more detailed degree than the existing sample-based method.

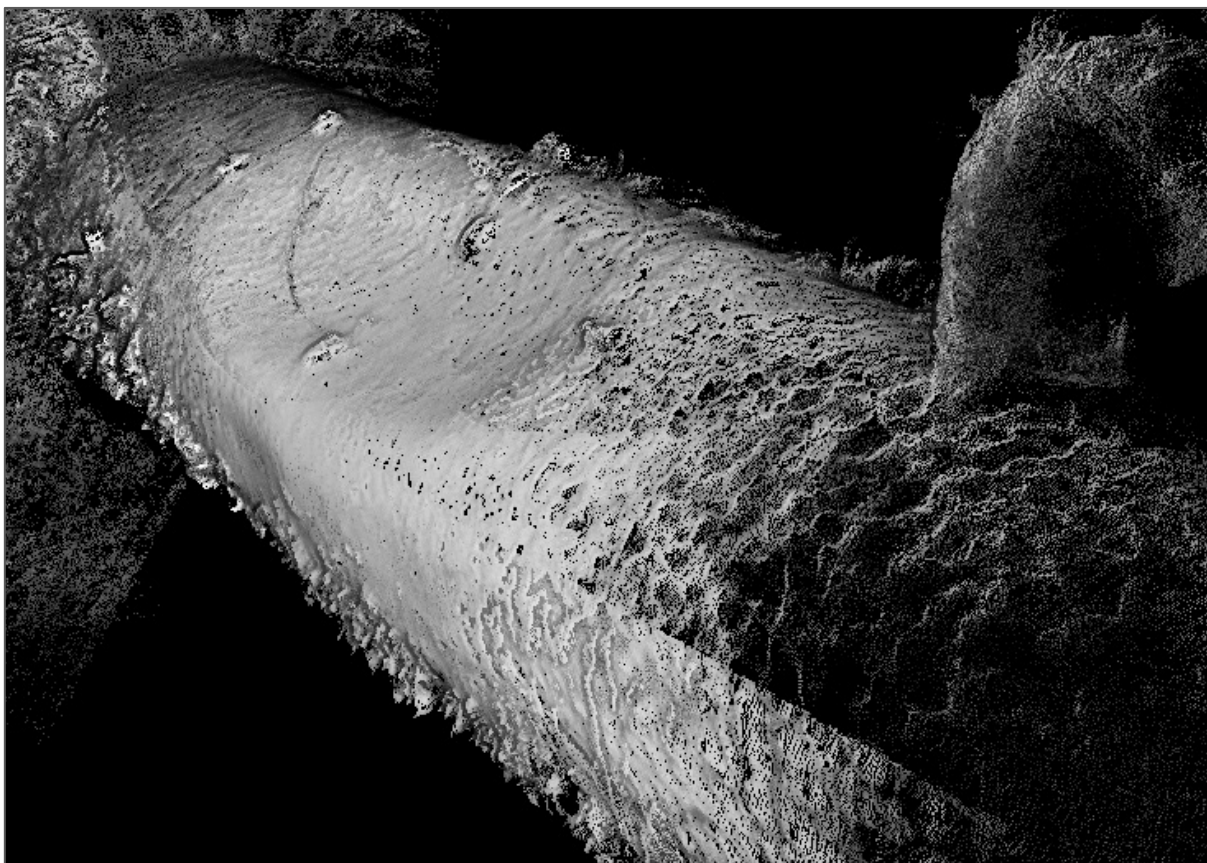


Figure 6 3D representation of submersed structure with marine growth

In summary, the new proposed inspection approach will:

- Remove the need for a second detailed inspection, as the accuracy of the initial periodic inspection is increased.
- The inspection time is reduced as the ROV can take photos from distance and does not need to physically touch the structure.

- In addition, the 3D maps can benefit the cleaning process by scheduling which structures need marine growth removal the most and even in details quantify how much cleaning is needed.
- Obviate the need for personnel to investigate video material and assess cleaning requirement.

Obviously, the quality of the 3D maps will determine how efficient and beneficial the new inspection approach will be.

4. Project implementation

The project has undergone substantial development. Despite encountering a few delays primarily attributable to the challenges posed by the Covid pandemic and a shortage of manpower at TotalEnergies, the project has successfully achieved all milestones. Moreover, a highly effective collaboration has been established among the project partners. The industry has expressed considerable interest in the project results, and both Aalborg University (AAU) and Energy Cluster Denmark (ECD) can attest that the ACOMAR project stands out as one of the most prominent endeavors in their respective portfolios.

The planning of the offshore test has represented a significant risk, given the fact that it is scheduled a year in advance leaving room for various unforeseen circumstances that may impede the successful completion of the test as per the original plans. Throughout the project, our approach has been solution-oriented, resulting in the successful testing of more components than initially envisioned, spanning different locations and environments. However, a final demonstration of the complete system in offshore environment was not feasible within the project period. This is planned to be carried out in Q2 2024.

As part of the project deliverables, the development of the frontend software was designated to be carried out internally. However, this task was underestimated in terms of both cost and manpower in the initial application. Following the recommendation of TotalEnergies, EIVA was brought into the project due to their pre-existing software solutions widely used in the industry, facilitating a more seamless integration into the ACOMAR system.

5. Project results

This section is divided into work packages concerning specific subjects of the project. Each work package section is introduced with a description of the associated work, described in the project application.

WP 1	Project management and dissemination
WP 2	Cleaning tool
WP 3	Control development
WP 4	ACOMAR Mechanical prototype
WP 5	Electrical and software integration
WP 6	Validation and demonstration
WP 7	Planning and inspection

For clarity, below is a drawing of the complete system setup referring to the associated work packages.

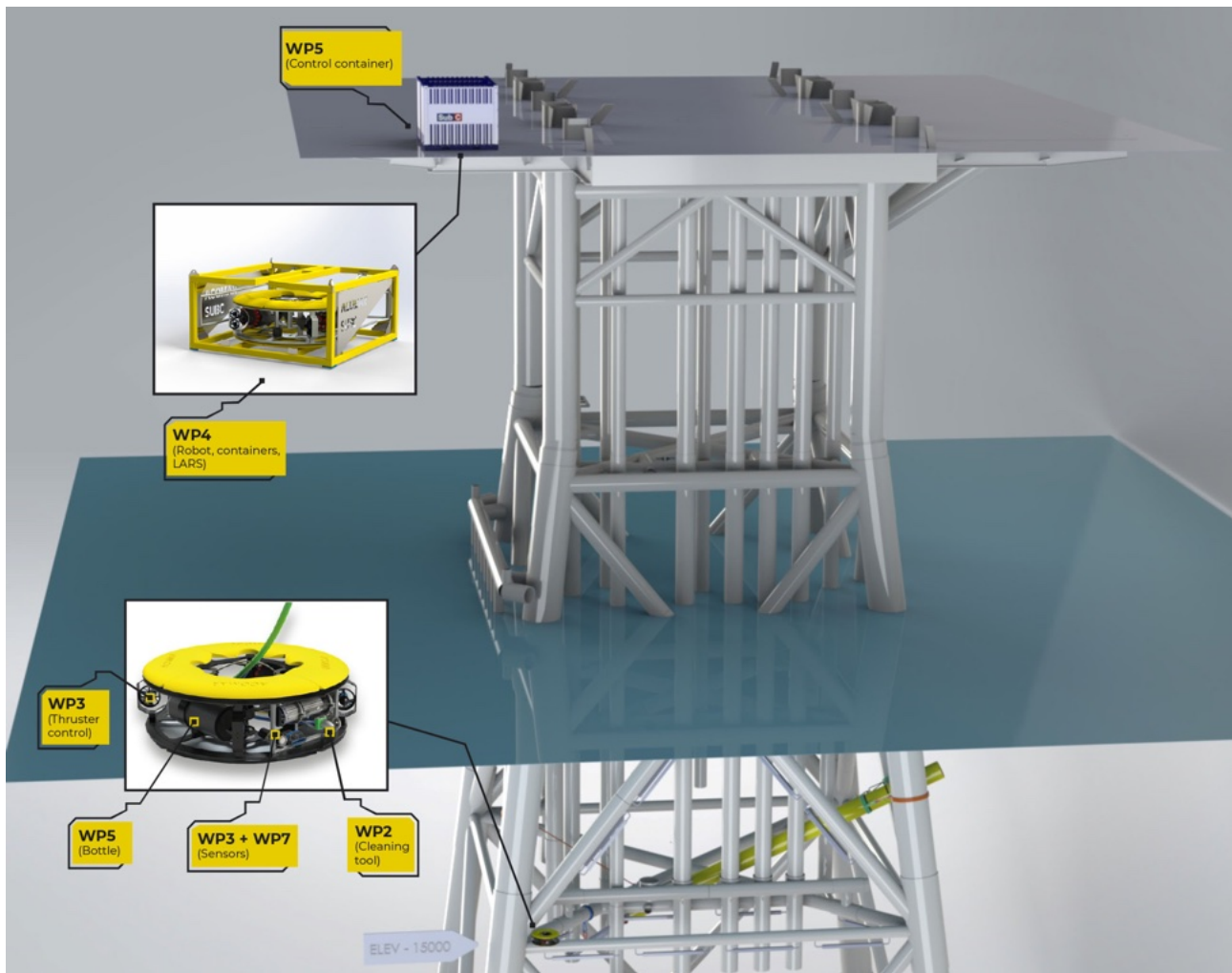


Figure 7 Complete system referring to associated work packages.

WP1 Project management and dissemination

“All dissemination activities in this project will be coordinated through ECD. The task include dissemination in relevant media, including EnergyWatch, Erhverv+, ECD newsletters, yearbook and relevant conferences such as High Tech Summit, Wind Energy Denmark, Offshore Wind Europe and ECD annual innovation summit. Focus of this task is to highlight the new technological development as well as the project partners’ competences within energy storage.”

The ACOMAR system has not been used commercially yet, however there has been some positive effects from the project work relating spin-off work:

- SubC has used knowledge from the ACOMAR project to produce their own 180-degree view camera. This has been used commercially for inspection of caissons at a port in Denmark.
- SubC has fabricated an inspection and cleaning ROV (the Coala) in cooperation with a world leading O&G company. The Coala is based on knowledge gained during the ACOMAR project. Based on the

interest of this tool, it is deemed feasible that the two ROV's (Coala and ACOMAR) will be suitable to use in pairs, as the Coala neutralise some of the downsides of the ACOMAR and vice versa. As the Coala is already commercialized, it is expected that it may open doors to further testing and training of the ACOMAR.

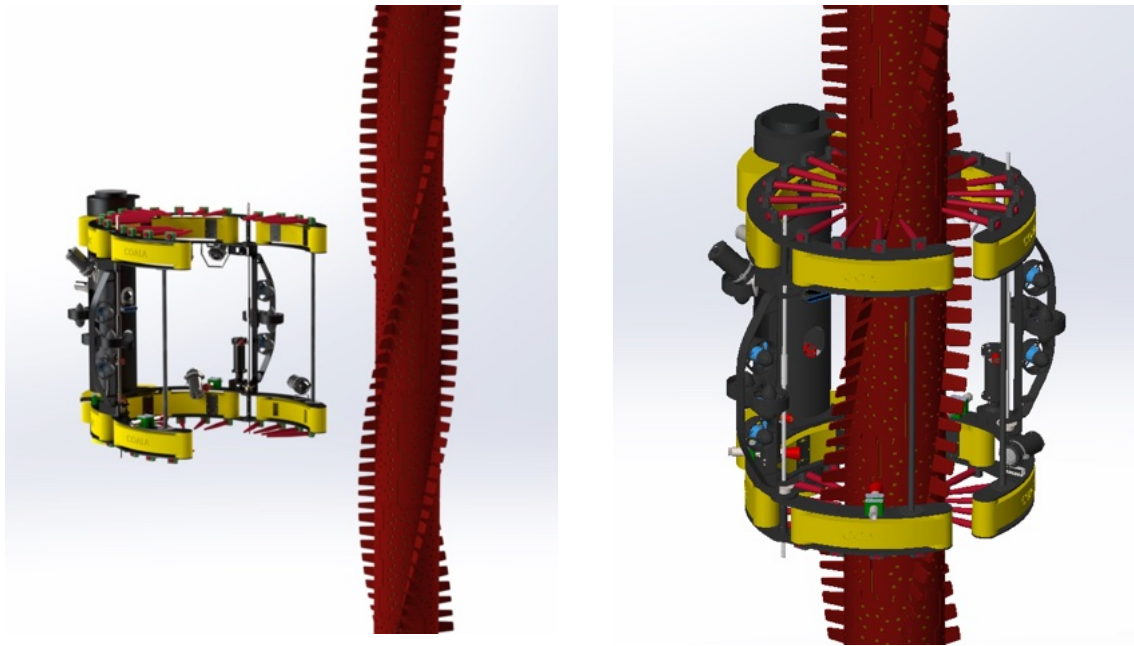


Figure 8 Coala free flying (left) and attached to the structure (right). Tether not shown.

Briefly explained, the Coala can hook up to the same system as ACOMAR. Like ACOMAR, it is free flying in the water. Once the structure (pipe) is reached, it attaches. This means that the Coala stays in place, and therefore it can carry three water jet nozzles, as opposed to one nozzle on the ACOMAR system. This means that for longer pipe stretches without severe obstructions, the Coala will be faster doing inspection and cleaning. The disadvantage of the Coala is that it is diameter dependent and not able to handle complex structures.

The project has received quite much attention compared to the norm experienced by Energy Cluster Denmark. That is that there has been interest from both written media, but also potential customers who wanted to hear more about the project's results. Also, the project participants were interviewed for national radio DR P4, and there has been contact from stakeholders in the marine (ship) industry, where marine growth removal is also a severe problem.

In general, all milestones have been achieved, and dissemination goals have been easy to fulfil, as there has been great demand for interviews and information regarding the project.

In Q1 2024 it is planned to have a webinar hosted by Energy Cluster Denmark, where stakeholders will be invited for a presentation of the project results.

The ACOMAR Project has been communicated through a substantial number of platforms. Please see Section 8, Appendices.

WP2 Cleaning tool

“SubC will test and compare efficiency of relevant cleaning tools. An electric powered tool is preferred to obtain the compact setup that will allow to eliminate the supporting vessel. Many different tools are in the market, and various methods will be considered for testing, i.e. rotating brushes, scrapers, FlexiClean, cavitation jetting and water jetting.

It is deemed possible to retrieve tubulars containing marine growth as the Tyra Field is currently being redeveloped and some platforms demolished and brought onshore. In such case, tests will be conducted at SubC site. Another possibility is to perform the test in the nearby dock. SIHM HØJTRYK A/S will assist in testing hydraulic tools for comparison.

The tests for WP2 were carried out at Port of Esbjerg, where the sheet pile walls are covered with marine growth.

A test setup consisting of tool container (pump, HPU etc.), control container (camera screens etc) and a structure to carry the cleaning tools was designed and fabricated. Velocity of the cleaning tool and distance to the sheet pile wall was measured during all the tests, and effects of various flow and pressure was monitored via camera and subsequent inspections. The test setup was also supported by SIHM HØJTRYK A/S, both on the equipment and knowledge side, but also in regards to high pressure pump unit (HPU) and water jetting cleaning tools.



Figure 9 Test setup with tool container, control container and structure to carry the cleaning tool.

Various tools were tested, including FlexiClean, rotating brush, cavitation jet and water jet.



The rotating tools were not found feasible for the job. The tests showed that the structure was not acceptably cleaned. Further, these tools induced significantly more noise to the system than the water jet and cavitation jet. Various water jet nozzles were tested and compared. Not all of them performed acceptably, but some of them were definitely feasible. The cavitation lance, water jet nozzles, and different high pressure equipment was provided by SIHM HØJTRYK A/S.



Figure 10 Poor performing water jet nozzle (left) vs. well performing water jet nozzle (right) after one run.



Figure 11 Well performing water jet nozzle after four runs.

Also, a comparison was made on water jet vs. cavitation jet on a fragile material, which showed that the cavitation solution could be beneficial in some situations where more delicate surfaces should be cleaned.



Figure 12 Cavitation technology to the left. Water jet to the right. Shows that cavitation technology is more gentle to surface material.

Ultimately, WP2 lead to a substantiate decision on choice of cleaning tool as well as optimum settings for the tool (distance, pressure, flow, velocity).

WP3 Control development

“This work package dealt mainly with the design and development of control solutions for automation operations. Sensor technologies were selected in this work package to comply with the designed algorithms. In connection to the choice of sensor technology, a failure analysis was conducted to aid in the subsequent incorporation of fault tolerance in the control algorithms. Lastly, the algorithms were designed to achieve full-autonomous robust operation tested in realistic offshore environments.”

The description in this section is based on the results documented in Scientific papers. The main contributions of the work package can be summarized to be: Sensor selection for autonomous operations and environmental condition monitoring, digital twin (simulation model) for realistic offshore operation simulations, control algorithm design, implementation and testing, thruster fault analysis, and science frame integration in the final robotic solution.

It is known that global positioning systems do not work underwater, as water attenuates radio waves. Therefore, other sensors must be used for localization. The most similar approach to GPS localization is acoustic positioning systems (APS). However, sound has a much lower traveling speed underwater (approx. 1500 m/s) compared to light in air (299792 km/s). This results in delays in the position calculated by APS, when working on large distances. If the locator and receiver is positioned 750 m from each other, it will result in a 0.5-1 second delay (0.5 seconds for each direction, depending on the configuration), on top of that, there is the processing time. Therefore, it has been important to determine the maximum allowed time-delay for which the vehicle can be stabilized within an acceptable distance from the structure. An input-output controllability analysis has been conducted, which showed that the maximum allowed delay for surge (the direction pointing towards the structure while cleaning) is 0.69 seconds to obtain good control performance. This means that

APS would not be suitable as feedback for the distance controller, furthermore, the APS relies on line-of-sight between the transducer and the receivers, which can be hard to maintain within jacket structures.

To overcome these challenges, the objective of this project has been to identify onboard sensors, that can be used for localization relative to a structure. Two different sensor technologies that provides distance measurement, namely a sonar and a structured light system (SLS) has been investigated. The sonar chosen is Oculus M3000d from Blueprint Subsea. The SLS is made by combining a line-laser and a Intel RealSense camera (Stereo depth camera) by Intel RealSense, which also give the possibility to provide a depth image. These sensors has been installed on a frame, that can be detached from the vehicle to perform calibration and tests, without the need of the vehicle itself. The frame can be seen in Figure 13.

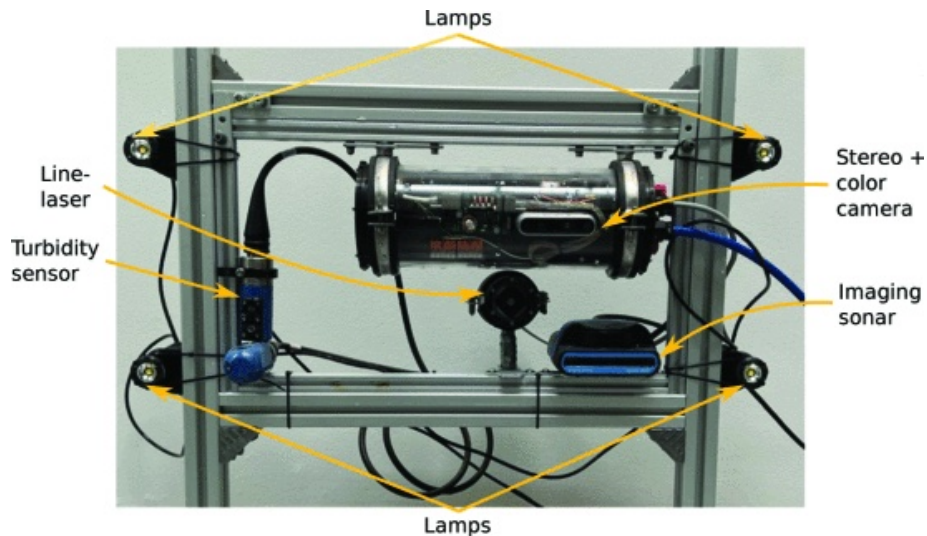


Figure 13: Sensor frame for the ACOMAR

The performance of these sensors has been evaluated in the laboratory under varying light and turbidity (using kaolin to control turbidity) at Aalborg University Esbjerg. The outcome of the test (See Figure 14) has shown that sonar is not affected by turbidity, which was also expected.

Tech	0.3 FTU	1.0 FTU	1.4 FTU	2.1 FTU	6.0 FTU
Stereo	>200.00 cm	>200.00 cm	170.00 cm	170.00 cm	63.00 cm
SLS	>200.00 cm	103.00 cm	NA*	103.00 cm	43.00 cm
Sonar	>200.00 cm	>200.00 cm	>200.00 cm	>200.00 cm	200.00 cm

* The SLS algorithm were not tested at 1.4 FTU, however it is expected to be at same limit as 1.0 FTU and 2.1 FTU.

Figure 14: Maximum range for the distance measurement based on results.

However, both the stereo camera and the SLS is highly affected by turbidity as seen in Figure 15, which must therefore be considered risk for invalid measurements while cleaning, as debris from the removed marine growth can result in increased turbidity. To measure the turbidity, a turbidity sensor has also been installed on the frame, while a conductivity sensor is installed to measure the salinity level, as this can affect the sonar.

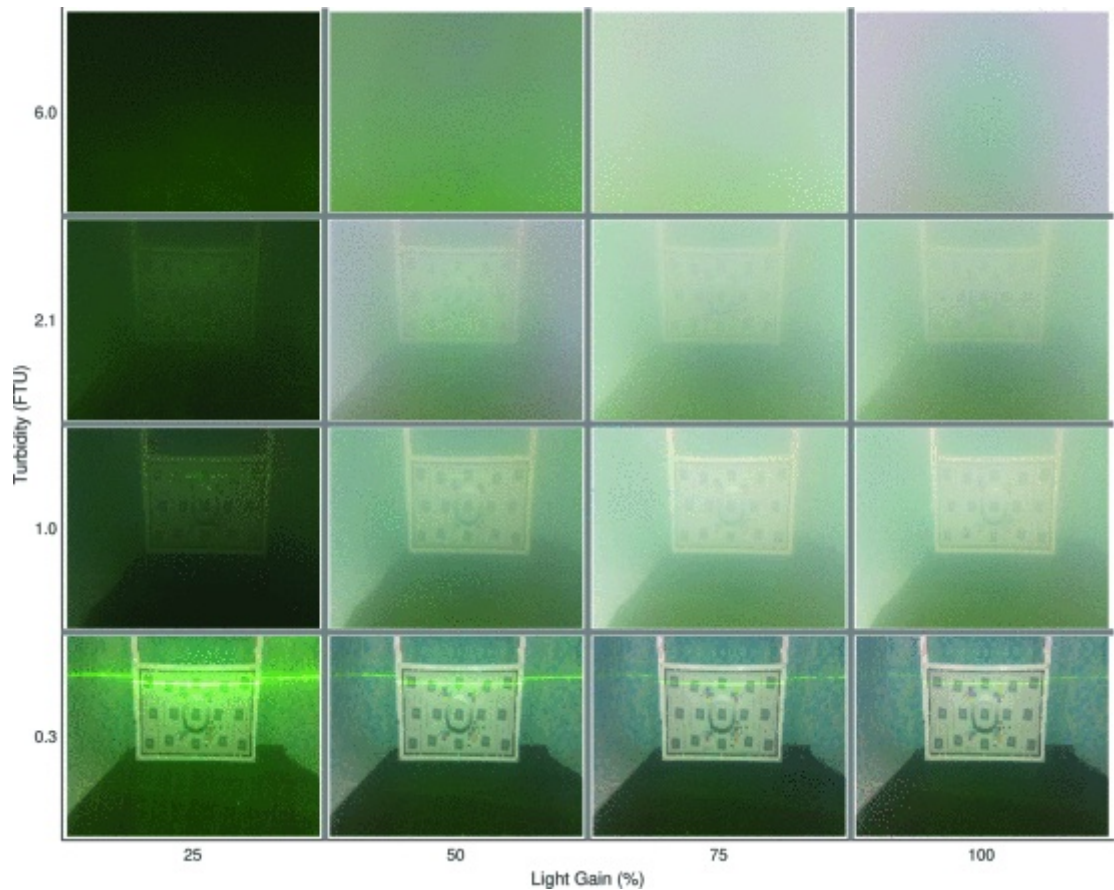
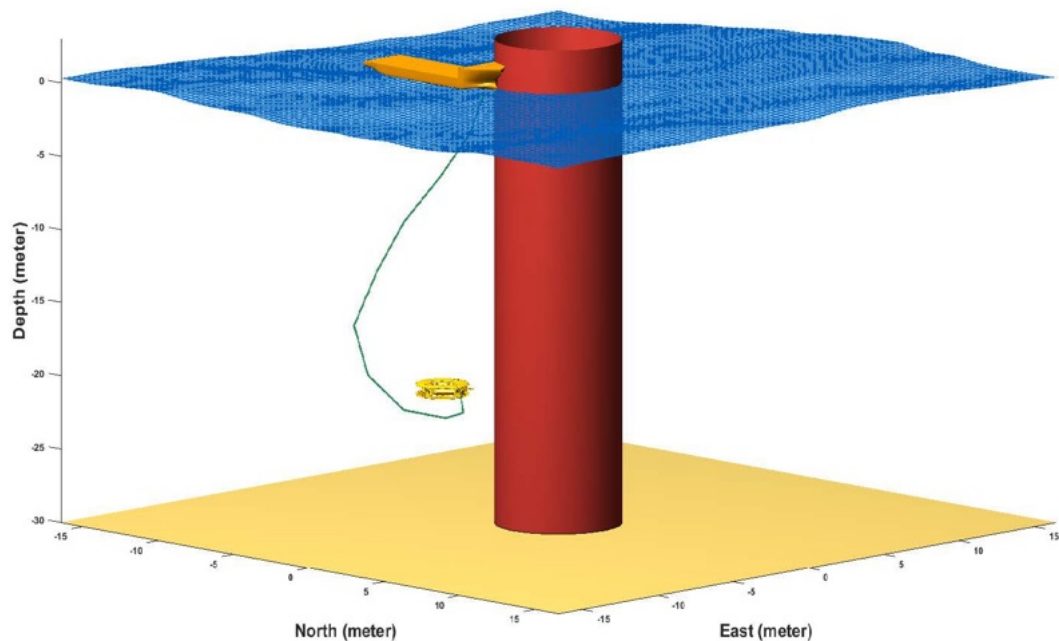


Figure 15: Color images at 1.7 m distance to target.

Additional to the sensor frame, a doppler velocity log (DVL) has been installed to measure the velocity of the vehicle, this is both used to measure the position of the vehicle, but also aid the distance measurement system. Both a fiber-optic gyroscope (FOG) and a micro electro-mechanical system (MEMS) inertial measurement unit (IMU) has been installed to measure the orientation (attitude) of the vehicle. A pressure sensor is used to measure the depth, while GPS system is installed to provide the location while surfaced.

A digital twin of the ACOMAR has been developed and implemented in offshore simulation model, which includes waves, current, tether, tool and the interaction between them. This purpose of this simulator is to allow for evaluating ROV designs and fast testing of control algorithms. The final control algorithm is based on a nominal nonlinear controller with a disturbance estimator, and a safeguarding controller which ensures that the ACOMAR is kept predefined safe set. The safeguarding controller is based on adaptive control barrier functions.



The final control structure includes:

- An asymptotically stable nominal controller based on Lyapunov analysis.
- A safeguarding controller based on adaptive control barrier functions ensures that the robot stays in the optimal cleaning region and punishes the robot when hitting the structure.
- An estimator is designed to continuously estimate the disturbances (waves, current, the tether, and the cleaning tool) and actively use it in the controller.
- The key idea of the control structure is to mitigate disturbances, enforce safety, and optimal cleaning performance.

The operation range of the ACOMAR with the controller is determined based on a comprehensive simulation study where 240 scenarios are evaluated. The evaluation is based on how well the ACOMAR can keep an optimal distance to the structure while cleaning in an offshore environment. The optimal distance is determined based on the results of WP2. The operating range is illustrated in the heatmap shown in Figure 16.

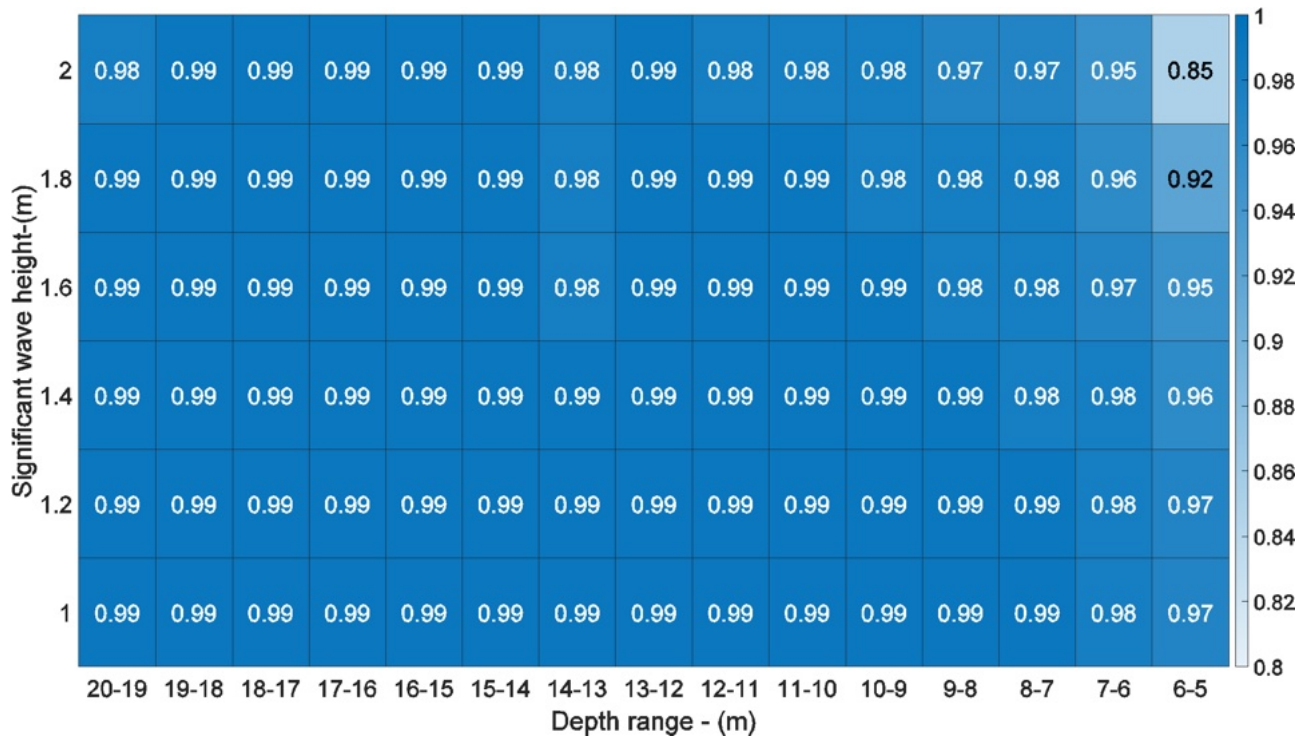


Figure 16 Heat map of operating range of the ACOMAR robot. Above 0.95 is considered acceptable.

A total of 14 propellers were damaged on the offshore campaign in 2022 caused by marine growth. Some of the propellers are shown in Figure 16.

Several tests have been performed on the propellers. The goal has been to detect incipient propeller faults from the data. The initial idea was to develop an algorithm to determine the efficiency degradation of each propeller such that it could be used in control algorithms. Several frequency analysis tools have been used; however, it has not been possible to determine the remaining efficiency online. It has been possible to predict whether the propeller has been damaged or not by training a Gaussian maximum likelihood classification (GMLC) algorithm based on quadratic discriminant analysis (QDA). The QDA algorithm is able to predict the state of the propellers in three categories with an accuracy of 70-90%. The three classes are undamaged, damaged, and severely damaged.

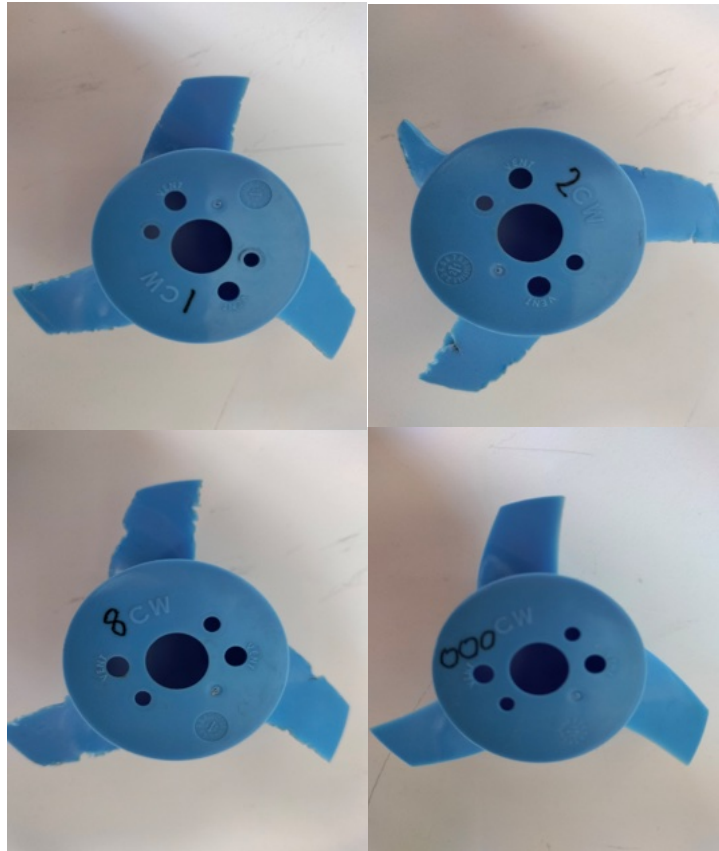


Figure 17 Shows some damaged propellers from an offshore cleaning campaign.

It was observed that the sensors, both optical and acoustic solutions, worked better during inspection and open-water operation than during cleaning operations where the sensors were disturbed by the cleaning tool (water jet). The water jet disturbed the acoustic signal from the sonar by the overlapping noise frequency, and both the marine growth and water jet bubbles challenged the optical camera and laser. This can be seen in Figure 18. Test conducted with COALA performed at the same location, indicated that relocating the sensors used for distance measurements can reduce these issues to an extent, where the distance measurements can be used for feedback while cleaning.

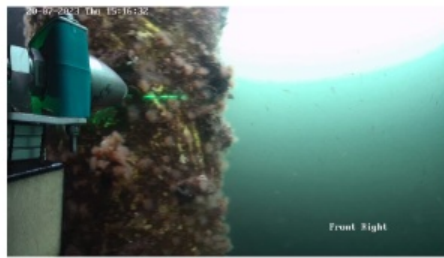


Figure 8. RGB Image from ACOMAR

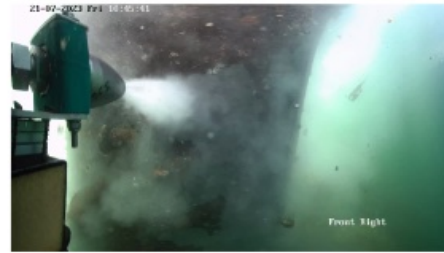


Figure 27. RGB Image

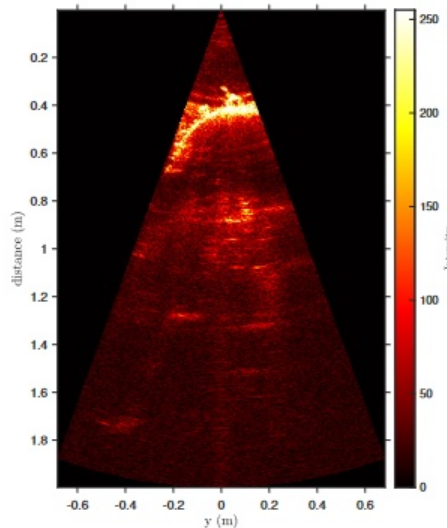


Figure 10. Sonar Image from ACOMAR

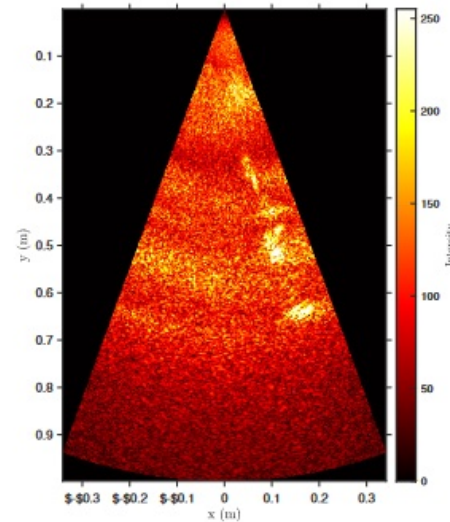


Figure 29. Sonar Image

Figure 18: From unpublished paper, the tests were conducted at Ensted Oil Terminal.

WP4 ACOMAR mechanical prototype

“All mechanical parts of the robot will be designed and build by SubC in consideration of the interfaces to implementation of software and hardware for inspection and control. The design will comply with standards for the offshore industry and will be based on experience from similar tasks. Great emphasis will be put on size of the setup to comply with the desire to operate the system from the offshore facilities. This WP will result in a prototype robot, full functional for both contact and floating operation. The parts and assembled mechanical parts will continuously be tested on SubC site during development to detect potential failures as soon as possible in the process. When WP2 is completed, the chosen cleaning tool will be implemented on the robot and the system tested in this WP.”

The feasibility study resulted in the decision to design a free flying robot to make it as flexible as possible for use. As the robot is primarily designed for station keeping more than forward motion, and to avoid inappropriate disturbances from a tether, the robot has a torus shaped frame to center the attachment of the tether, which also allows for a balanced placement of the thrusters.

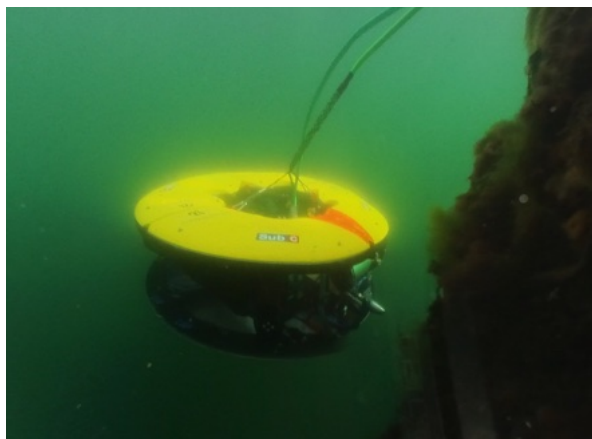


Figure 19 ACOMAR is torus shaped and tether attached in center.

Thruster size is based on simulations, and great emphasis is placed to find components with low costs and as little maintenance requirements as possible. After tests and in cooperation with the thruster vendor, the thruster blades have now been fabricated in a more resistant material.

A general problem is to operate in the splash zone due to the large force effects from waves. In the feasibility study it was suggested to have a telescopic arm for cleaning in the splash zone to allow the ACOMAR to stay further below the water surface. However, it would require an inappropriate scale up of the ACOMAR to withstand the forces from cleaning with a telescopic arm. This compromise was not acceptable, as it was of great importance to keep the ACOMAR as small as possible. This means that ACOMAR is not operable in the surface unless the weather is very calm.

The ACOMAR body frame is prepared with several additional holes for easy mount of supplemental sensors etc. Further, a “science frame” is mounted on the front to ensure uniform calibration of sensors.

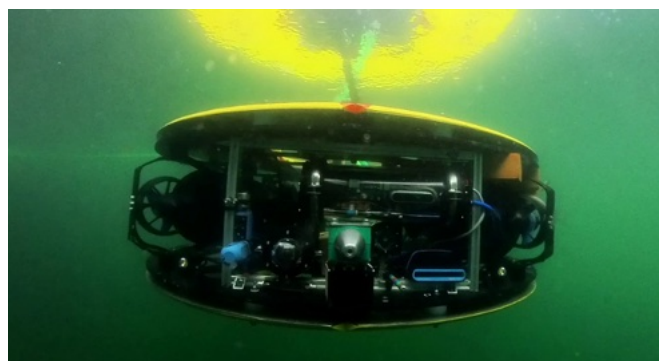


Figure 20 Science frame mounted to ensure uniform calibration.

WP2 established the necessity of a hydraulic cleaning tool, and the tether is therefore twofold with a high-pressure water hose and a cable for data and power. The tether is dimensioned to the smallest possible diameter, as wave forces to the tether is a severe challenge to control the robot. Though it was not possible to use the electrical cleaning tool, the complete setup of the system has been kept to a footprint of 2 x 10 feet containers, which fulfils the aim to launch the system from a platform.

The two containers consist of a control container which is basically a control room from where the robot can be operated, and the operation can be monitored. The other container contains the high-pressure unit for water jetting as well as other utility and spare and maintenance materials. Further, a frame for launch and recovery of the system is fabricated.

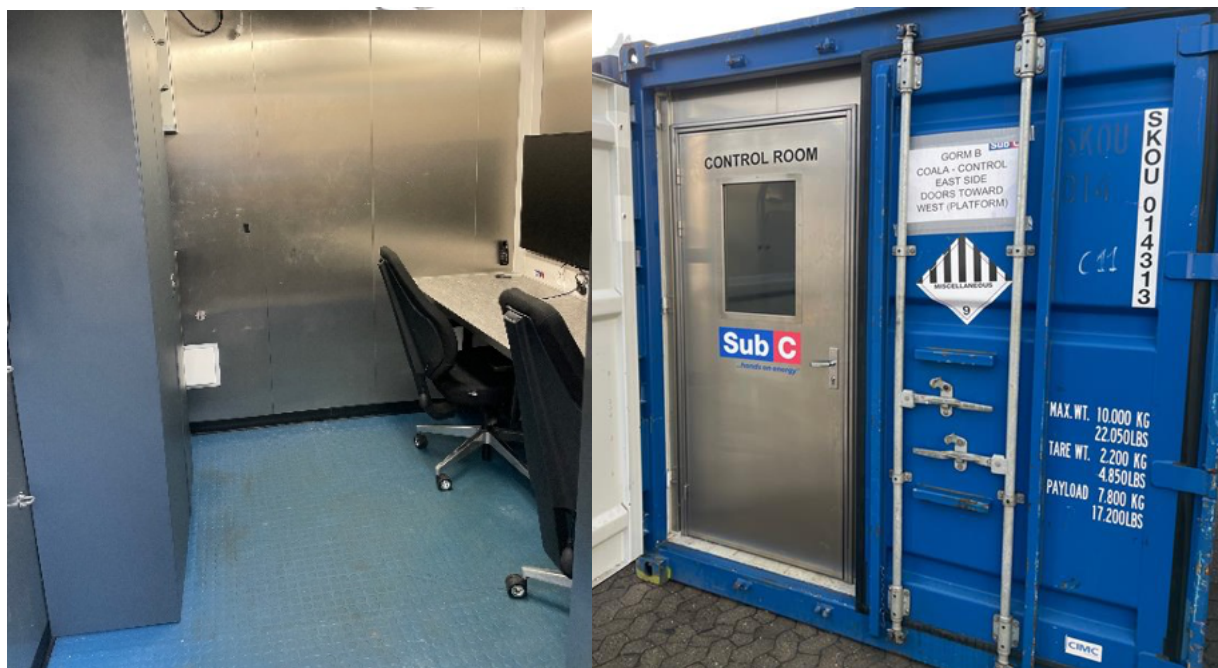


Figure 21 Control container.



Figure 22 Tool container.



Figure 23 Launch and recovery system.

Dimensions and requirements of the ACOMAR and LARS system:

Table 1 ACOMAR ROV parameters

Description	Value	Unit
Volume	135	L
Height	50	cm
Ø	150	cm
Mass	135	kg

Table 2 ACOMAR LARS parameters

Description	Value	Unit
Height	80	cm
Footprint	2 x 2	m
Mass	250	kg
LARS criteria Significant wave height	≤ 2	m
LARS criteria Wind	≤ 20	knots

Table 3 ACOMAR utility parameters

Description	Value	Unit
Footprint (2x 10 feet)	13,38	m ²
Power connection	400 x 63	V & A
Power consumption	43,64	kW
Water supply pressure	≥4	bar
Water supply flow	30	L/min

Table 4 Crane requirements (from platform)

Description	Value	Unit
Minimum outreach over platform	18	m
Minimum lifting height over handrail	15	m
Heave compensation	No	-
Lifting capacity, deployment	500	kg
Lifting capacity, container	5	ton

The system consisting of the two containers and LARS system has been tested from an oil & gas platform in the Danish North Sea and is ready for commercialization.

From the project owners in the wind industry, it is deemed possible that the system could also be operated from a wind turbine, though it could be a challenge to deliver fresh water for the cleaning. However, it is worth discussing whether it will actually make sense to operate the system from the wind turbines, as it may not be feasible to relocate the system from turbine to turbine. Another possibility is to operate the system from vessels that has other operations going on in the area.

WP5 Electrical and software integration

“The focus of this work package is designing and implementing the electrical and software components while considering the control algorithms from WP3 and the mechanical design from WP4. During the process of integrating the control algorithm in the robot, the robot and the control algorithm will be refined to finalize physical and computational constraints. In addition, the sensor and software considerations for the 3D mapping in WP7 must be implemented in this work package.

All sensor data will be stored in the operational unit (located topside during cleaning and inspection campaigns) in a time-series database. The operational unit will be designed according to the size and mobility requirements described in chapter 1.3. Moreover, the operational unit will be the main human-machine-interface (HMI) and computational unit.

All electrical components will be designed in accordance to different work environments offshore, this includes ACOMAR, the umbilical, and the operational unit.”

The electrical design of the ACOMAR has been focusing on dividing power electronics and control electronics in decoupled systems. The insulator between the topside power supply and the ACOMAR is the power supplies onboard the robot. Power is transmitted from the topside at 370V to enable the transmission to handle peak power of 15 kW. Onboard the ROV to pressure bottles house the electronics. The main bottle houses:

- 1 x power supply for 48, 24, 15, and 5V (600W).

- 3 x Gigabit ethernet switch POE

- 1 x Pressure sensor

- 1 x PWM generator for light control

- 1 x Onboard computer

To supply power for the thruster used to maneuver ACOMAR around the input voltage must be transformed to 24V. This is done in the power conversion bottle, which houses:

- 2 x 3200 W power supply 370 V in, 24 V out

- 10 x ESC with temperatur sensor (Motor controller) (2 spare)

- 1 x fuse board on 24 V.

The design and selection of components have been focused on off-the-shelf components to ensure a stable supply chain and cheap components. This choice comes at a cost of the size of components, but this is deemed reasonable as it also enables components to be changed as better components become available.

The control algorithms, data storage and sensor integration are facilitated by using the open-source ROS (Robot Operation System) framework. Off the shelf sensor technology with available ROS integration packages has been the main choice for the ACOMAR. This enables a high degree of modularization which has been the main driver in shifting from prototype testing on a commercial small scale ROV (BlueROV2) to the actual ACOMAR. Both AAU and SubC partner has greatly benefitted from the modular design approach (see Figure 24) developed in this project. AAU is now employing a similar design and implementation strategies when educating engineering students on subsea robotics. From a commercial perspective, this approach has also fostered a significant decrease in in development cost and time for the COALA robot.

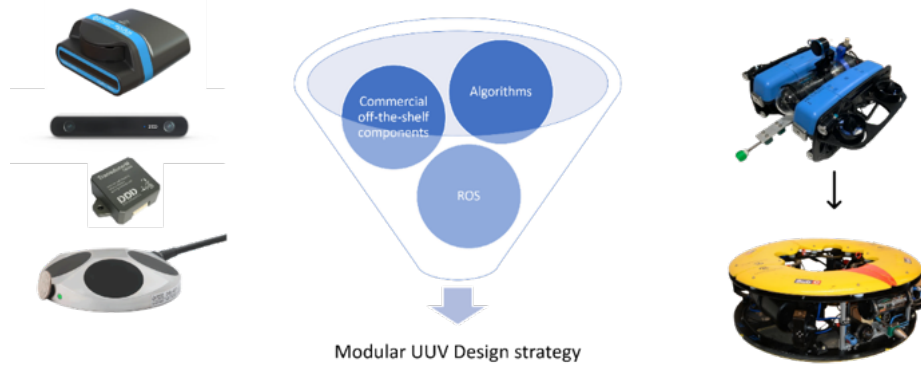


Figure 24 Modular design strategy developed through the ACOMAR project

EIVA NaviSuite Mobula software (see Figure 25) is a plug-and-play ROV control and inspection software, allowing operators to plan and perform inspections efficiently – and enabling automation. The software provides high-performing features focusing on automated steering and inspection, as well as delivering advanced, high-quality data visualisations. In the ACOMAR project the Mobula software was used for user interface and sensor configuration platform for the ACOMAR ROV – making it possible to watch real-time high-quality data displays and overlays. The user interface is configurable to suit the individual user and offers simultaneous data displays for increased situational awareness. The main development for the project include Mobula integration on the ROV and adjusting data communication with the control and sensor software.

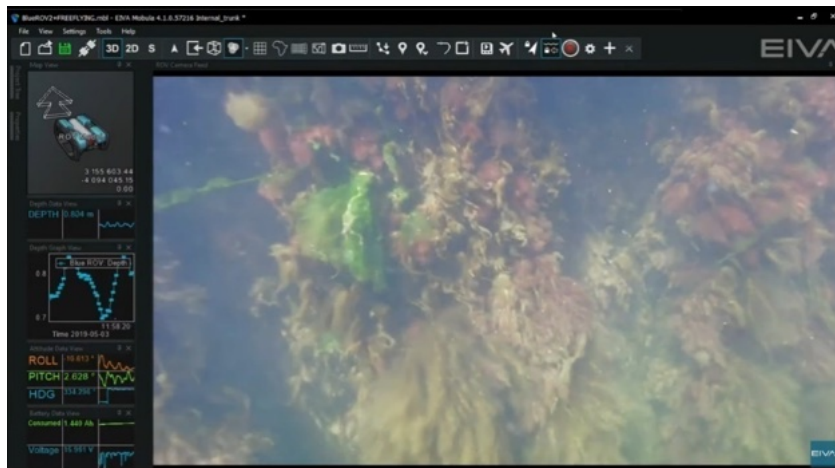


Figure 25 Mobula interface to the ACOMAR

WP6 Validation and demonstration

“This WP will take the integrated system through TRL 6 and 7 and will be carried out simultaneous with WP4 and WP5.

Onshore test of the integrated system (robot, control software, sensors, inspection tool etc.) will be conducted at SubC’s test facility (basin). When all risks are assessed and mitigated to widest extent, and improvements are implemented, the offshore demonstration will be conducted. In summary, WP6 include all the major on-shore and offshore experimental work. In the final stage of the project TEPDK provides a 14 days offshore trip where it is possible to test and demonstrate the complete prototype. This is a crucial part of the project as it will allow the project to reach TRL 7.”

Testing has been carried out during the whole project as expected. This includes continuous testing in the test tank at SubC facility. The tank was lined with “fake grass” to imitate the offshore surroundings, as some sensor equipment reacted inexpedient to the metal walls of the tank.

Also, several tests have been made at Port of Esbjerg, when larger area or more offshore-like conditions were required. Due to very poor visibility at the Danish west coast, tests were carried out at Port of Fredericia, where sight is more similar to offshore.

In 2021 an offshore trip to join a planned underwater campaign was planned to collect initial data for further analysis and use in WP3 and WP7. Due to Covid19, it was not possible to accomplish this. Instead, it was arranged for one of Totals contractors to mount a bottle containing relevant sensors to an ROV that were planned for a campaign. Unfortunately, a valve to the bottle had been opened during the operation and the bottle not sealed correctly, which caused flooding of the bottle and ultimately no useful data collection. This incident set back the progress for the concerned work packages.

In 2022 the setup was tested on the Gorm field in the Danish North Sea. At that point most of WP4 was complete, except the correctly sized thrusters, where 6 smaller thrusters replaced two large thrusters due to delivery time. This turned out to be fatal, as it caused the power to switch off due to surge of the smaller thrusters. It was deemed too risky to proceed the testing with the ACOMAR. Instead, most of the equipment was installed on the Coala, which operates on the same system and hooks up to both control and tool container. In this way it was still possible to retrieve important data, and ultimately, both LARS-system (launch and recovery system) as well as utility systems were tested and found applicable. Only smaller updates required.

In 2023 an offshore test was planned to demonstrate the ACOMAR. Unfortunately, this offshore trip was cancelled due to more essential maintenance in the oil and gas field. To compensate for the cancelled offshore trip, it was arranged to carry out testing at Port of Aabenraa, where there is a larger depth and acceptable sight. Further, there is a pier, which may constitute a part of an offshore structure. However, testing in a port does not reflect real offshore conditions, and a final offshore test would have been desired to demonstrate the system sufficiently, for both technical and commercial reasons.

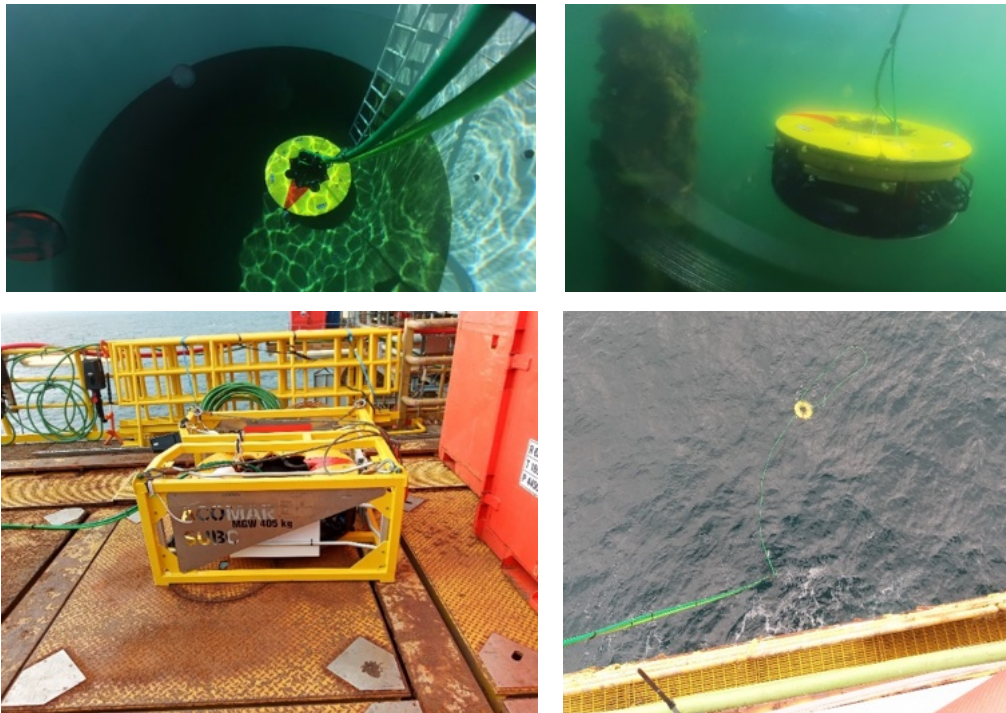


Figure 26 Test basin (upper left), Test harbour (upper right), Test North Sea (lower left and right).

WP7 Planning and inspection

“The focus of this WP is to conduct steps needed for automating the inspection and planning process. Firstly, an investigation should be performed on which sensor technologies should be applied to ensure a reliable construction of a 3D model of the subsea structure to overcome the visibility issues that can be encountered using state-of-the-art methods. The chosen sensor technologies are then fused to generate a 3D representation of the marine growth. It will also be investigated if a classification of marine growth can be performed from the 3D sensor data of the subsea structure. Lastly, an algorithm is designed such that the information from the obtained 3D models including forecasts for e.g. wind and weather can be used for planning and generating set points for a cleaning campaign.”

The task of inspection marine growth on offshore structures has involved the exploration of a plethora of sensor technologies and methods. While the original intent was to recreate the structure with a 3D point cloud, it became evident that marine growth can be detected and classified using methods that do not rely on a 3D point cloud of the structure. The investigated sensor technologies for 3D point cloud generation relied on either Time-of-Flight, stereo/monocular camera or sonar, where the latter two showed the most promising results in a wide range of conditions. Machine learning based on optical images was chosen to be a viable approach for classifying marine growth.

The main issue concerning images used for machine learning is the significant effort in manual labelling which was economically out-of-scope the project. Also, the conditions in which the images are taken cannot be controlled in the offshore environment leaving the machine learning model to be non-robust to a wide set of operating conditions. Hence, the main technical outcome of the work package is a solution (see Figure 27) utilizing images generated from a virtual subsea environment allowing for full control of conditions such as turbidity, sunlight, marine snow and debris, water type etc. Additionally, the virtually generated images are inherently labelled on a pixel-to-pixel scale yielding a high-quality training data set for the machine learning model. The

developed machine learning model has been validated on spot checks on images evaluated for marine growth showing larger accuracy than manual categorization. The model needs further validation on a full inspection campaign.

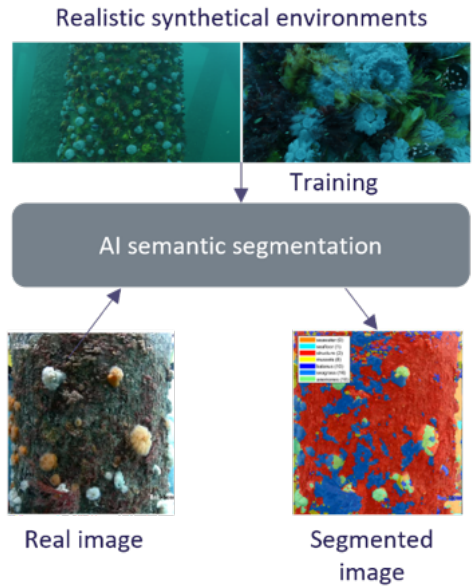


Figure 27 Machine learning approach to marine growth classification using virtual images

Other than the classification of marine growth, the thickness is important for assessing if a structure needs cleaning. A thickness estimation method has been developed based in acoustic (sonar) data. Figure 28 shows an example where the method has been employed for an inspection where the ACOMAR has moved along a subsea structure. As for the classification method, the thickness estimation need further validation in an inspection campaign.

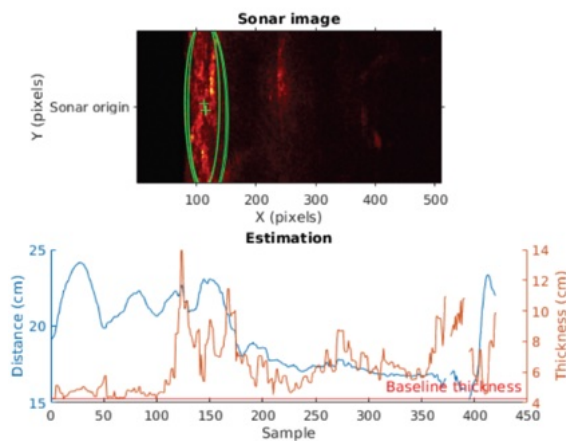


Figure 28 Thickness estimation using acoustic data. The green oval indicates the thickness of the marine growth. The plot shows the thickness from an inspection using the ACOMAR where it moves along a subsea structure.

The planning algorithm for cleaning structures has been developed. While trivial from an algorithmic perspective, the success relies heavily on the inspection and thickness estimation data. The planning algorithm needs further testing on an offshore cleaning campaign.

6. Utilisation of project results

SubC Partner will be the service provider and also the owner of the overall ACOMAR solution. As described previously, parts of the system are ready and qualified for commercialization, and SubC Partner has gained sufficient experience handling these parts of the system. For results on the station keeping and, derived from that, cleaning velocity, it is preferred to have more extensive training and data to verify that this system is superior to the known solutions. The goal is to demonstrate the lower TRL-parts of the system to the customers, preferably in smaller scale projects. This could for example be alongside a SubC job with the Coala-robot.

On the contrary, the inspection part of the project has come so far, that it is ready for commercialisation. Currently an agreement is being made to demonstrate the classification algorithm on data collected by a customer.

The project has led to permanent employment of 2 engineers at SubC Partner, as well as a partly employment at a period of 6 months after the project (Project Phase 3) in cooperation with Aalborg University. Further it has led to a very strong cooperation between Aalborg University and the project partners in general. Students at AAU regularly utilize the facilities at SubC partner for testing student projects on subsea robotics.

From an academic perspective, the project as set AAU Energy Campus Esbjerg on the forefront of national research on subsea robotics. An important area emphasized by the current need for surveillance of critical subsea infrastructure. Several of the topics addressed in this project are at the cornerstone of succeeding subsea surveillance.

On a short term it is not expected to add further private investments (more than the Project Phase 3), until the setup is sufficiently demonstrated and there is a clear commitment from an end user.

Competitors are mainly multinational companies carrying out a broad range of subsea inspection and maintenance activities (Boskalis, Fugro, Subsea7, Technip, OceanTech etc.). However, the companies listed as competitors here, could potentially be business partners in the future. The most common solution is using a conventional working class ROV and water jetting for marine growth removal. In general, the setup used is quite conservative with limited development during many years. Though the use of ROV have proven advantageous compared to human divers, the users still find the solution too time consuming and insufficient for the splash zone area, and technologies customised for improvements in the offshore industry are continuously developed.

The conceptualization phase revealed shortcomings in all the investigated technologies. The ones that are easy to relocate (floating devices) are ineffective in striking the target. The ones that are effective in striking the target, are fixed to the structure which makes them diameter dependent and time consuming to relocate. This project aims toward a solution that obliges the best of the two strategies – being able to relocate fast and overcome obstacles, while effectively striking the target. Common for all the competitors are that they primarily operate ROV's from large vessels or use less flexible solutions clamped to the structure.

This project has succeeded in disrupting the manual method in both controlling the ROV, classification of marine growth (species, hardness and thickness) and the level of documentation, previously based on manual assessment.

However, it requires first movers to take it to market. Thorough knowledge says that there is quite a conservative approach in the industry, partly due to the complications that offshore work imposes in general, and subsea work in particular. It is commonly known that a clear entry barrier is reaching contacts at an organizational level that has the authority to implement new technologies.

It is expected that the ACOMAR will require more thorough testing and hours in the offshore environment before a potential customer will rely on this technology solely. As this is also a strong request from the project team, the aim is to prove the ACOMAR during a campaign where ACOMAR is not operating as the main technology. This could be in connection with other subsea campaigns using SubC Partners robotic solutions Coala or Crawler. Or it could be in cooperation with other service providers' campaigns, where ACOMAR could be introduced on a commercially favourable solution.

The ACOMAR may not be able to always completely replace the current ROV solutions, depending on the scope of the campaign being carried out. There may very well be other tasks during the campaign, for which the ACOMAR is less feasible. In such cases, it is important to demonstrate that ACOMAR will prove more efficient in marine growth cleaning and inspection, and therefore will be used as a supplement.

Currently SubC Partner is in contact with oil & gas field operators and service providers from the Mexican Gulf. They have been visiting SubC Partner's facility in 2023 to understand the products and services offered, which may ultimately result in an inspection campaign in 2024. This could very well be a step on the way to have the ACOMAR introduced.

Further, SubC Partner has a dialogue with oil & gas field operators in Qatar and Scandinavia regarding marine growth cleaning and inspection, which could also include the ACOMAR.

The project is based on a collaboration between the wind and oil & gas industries, which is quite uncommon. For this project it has been emphasized by the stakeholders in the wind industry, that they could take advantage of the knowledge gained from the oil & gas industry during decades. This means that the wind industry can be prepared to overcome the challenges of marine growth before the problem has occurred, and the methods to do so will be well tested and "on the shelf". It also means that they can include the various scenarios during the design phase, which effectively makes them more competitive.

Introducing a setup at a size that can be deployed from an offshore platform decreases the dependence of large DP2 vessels commonly used in the oil & gas sector, and thereby decreases emissions induced by such an operation. Also, the ability to do AI supervised inspections and estimations significantly decreases the time spent for assessments and offers the possibility of inspection and cleaning immediately after. This reduces the time spent on the operation in general, and thereby lowers energy production costs.

7. Project conclusion and perspective

In broad terms, the project has developed as expected, although it has not been possible to conduct tests in relevant environments to the extent hoped for. However, thorough testing has been carried out both in test basin, in various harbours and offshore. A complete system has been developed with the aim of scaling it down to the point where it can be launched from a platform, thereby eliminating the need for a larger vessel. This has been achieved with a setup equivalent to 2 x 10-foot containers.

Knowledge has been gained regarding the most effective cleaning tools and the settings under which they operate most optimally. Overall, the design and selection of components have been focused on off-the-shelf components to ensure a stable supply chain and cheap components. This choice comes at a cost of the size

of components, but this is deemed reasonable as it also enables components to be changed as better components become available.

One of the main objectives with the ACOMAR is automating the cleaning and inspection task. This has prompted a study of several sensor technologies and control strategies. To reduce complexity of the sensor demand, the navigation control algorithm was designed to rely only on onboard sensors such as acoustic front facing sonar and several optical methods. The sensors provide reliable results, yet, during cleaning the high pressure water jet has shown to cause significant disturbances. Despite challenges during cleaning operations, relocating sensors showed promise in overcoming these disturbances. Regarding the automation of the inspection task, an approach based on virtual environments and acoustic sensors has been investigated. The initial results are promising and needs further validation in an offshore cleaning campaign.

As mentioned in results from WP5, the development of a highly modular design approach for ROVs software and hardware has been directly utilized in educating engineering students, research and by SubC Partner. From an academic and educational perspective, the implementation and testing time has been reduced to a level where students and researchers are able to design and validate advanced control and sensing methods on a short time scale. This is especially suitable for strengthening student learning during semester projects where the AAU employs the problem-based learning approach. From an industrial perspective, the development of the modular design approach has aided in efficient development of the COALA ROV.

As mentioned in Section 6, the most important step forward is to gain more experience handling the robot and implement findings experienced while training. Also, it is important to prove the advantages of the system in comparison to the currently used systems. This step is planned for Q1+Q2 of 2024, as Aalborg University and SubC Partner will proceed the cooperation for a 6 month period with the aim to train and optimise the system.

8. Appendices

8.1 Communication of the project

Video (Youtube/LinkedIn)

ACOMAR Project Video, Sep 2020

ACOMAR Testbassin SubC

ACOMAR Test Fredericia Harbour, Jun 2023

ACOMAR Results (To be released after project closure)



Online

Søfart.dk: Ny undervandsrobot til høst af begroninger offshore testes på land

Tekniskfokus.dk: Ny undervandsrobot testes på land

Elek-data.dk: Ny undervandsrobot testes på land

DKVindkraft.dk: Innovationsprojekt: Ny robot kan spare offshore industrien for millioner

DKHavenergi.dk: Innovationsprojekt: Ny robot kan spare offshore industrien for millioner

Energy-Supply: Ny undervandsrobot testes på land. Fjerner begroninger på havvindmøllefundamentterne

JV.dk: Stor fremgang: Tab i virksomhed i Esbjerg er forvandlet til millionplus

Maskinmesteren: Autonom ROV fjerner selv begroning på offshore installation

Energy.aau.dk: Robotic lawnmower of the sea



The screenshot shows the Energy Supply website with a main article titled "Ny undervandsrobot testes på land: Fjerner begroninger på havmøllefundamentterne". The article features a photo of the SubC submersible in a basin. To the right, there is an advertisement for LP Kolding A/S Stainless Steel Solutions, a section for "MEDLEMMERNES EGNE NYHEDER" (Member's Own News) listing various updates, and a footer with contact information.

Print

- Erhverv+ Syd: Undervandsplæneklipper vil spare millioner for virksomheder (sektion 1, s. 3)
- Erhverv+ Fyn: Undervandsplæneklipper vil spare millioner for virksomheder (sektion 1, s. 14)
- Erhverv+ Vest: Undervandsplæneklipper vil spare millioner for virksomheder (sektion 1, s. 7)
- Jern Og Maskinindustrien: Undervandsrobot skal nappe algerne (sektion 2, s. 4)
- [TekniskNyt April 2022 \(Side 18\)](#)
- Maskinmesteren, Sep 2023



Figure 29 Maskinmesteren Sep 2023

The project has been presented at following exhibitions/conferences

- ACOMAR Project Result Webinar (Expected Q1 2024 – After project closure)
- EIVA Demo Days 20.09.23, Århus (DK)
- Wind Europe, 25-27 April 2023, Copenhagen (DK)
- Oceanology International, 14-16 February 2023, San Diego (USA)
- IEEE IPAS Genova + Best presentation Award Dec 2022
- IFAC TDS Montreal Okt. 2022
- IFAC CAMS Copenhagen Sep. 2022
- IEEE AUV Singapore Sep. 2022
- R22 Robotfair in Odense, Mar. 2022
- IEEE OCEANS Chennai Feb. 2022
- Interview SubC på DR P4 radio, 2021
- Theme day on Green transition in the energy sector on Aalborg University, Mar. 2021 (DK)
- Webinar, Focus on Energyproduction, Nov. 2020



Academic outcome

15 papers

4 Journal papers (MDPI & Elsevier)

Study abroad at NTNU Dept. of Marine Technology

9. Scientific papers

1. F. F. Sørensen, M. von Benzon, S. Pedersen, J. Liniger, Kenneth Schmidt and S. Klemmensen, "Experimental Filter Comparison of an Acoustic Positioning System for Unmanned Underwater Navigation", IFAC-PapersOnLine vol. 55, no. 36, pp. 25-30, 2022. 17th IFAC Workshop on Time Delay Systems TDS 2022. doi: 10.1016/j.ifacol.2022.11.328.
2. F. F. Sørensen, M. von Benzon, J. Liniger, and S. Pedersen, "A Quantitative Parametric Study on Output Time Delays for Autonomous Underwater Cleaning Operations", MDPI Journal of Marine Science and Engineering, vol. 10, no. 6, pp. 1-26, 2022. doi: 10.3390/jmse10060815.
3. F. F. Sørensen, M. von Benzon, S. Pedersen, J. Liniger, and C. Mai, "Fault Tree Analysis of Sensor Technologies for Autonomous UUV Navigation", IFAC-PapersOnLine vol. 55, no. 31, pp. 484-490, 2022. 14th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles CAMS 2022. doi: 10.1016/j.ifacol.2022.10.474.
4. F. F. Sørensen, C. Mai, M. von Benzon, S. Pedersen, and J. Liniger, "Optical and Acoustic Imaging Comparison in a Controlled Underwater Environment", In Proceedings of OCEANS 2023 - Limerick. Limerick, Ireland, 2023. doi: 10.1109/OCEANSLimerick52467.2023.10244506.
5. F. F. Sørensen, C. Mai, O. M. Olsen, J. Liniger, and S. Pedersen, "Commercial Optical and Acoustic Sensor Performances under Varying Turbidity, Illumination, and Target Distances", MDPI Sensors, vol. 23, no. 14, pp. 1-23, 2023. doi: 10.3390/s23146575.
6. M. von Benzon, F. F. Sørensen, J. Liniger, and S. Pedersen, "Integral Sliding Mode Control for a Marine Growth Removing ROV with Water Jet Disturbance", in 2021 European Control Conference (ECC). pp. 2265-2270, doi: 10.23919/ECC54610.2021.9655050.
7. S. Pedersen, J. Liniger, F. F. Sørensen, and M. von Benzon, "On Marine Growth Removal on Offshore Structures", in Proceedings of OCEANS 2022 - Chennai. Chennai, India, 2022, pp. 1-6. IEEE. doi: 10.1109/OCEANSSChennai45887.2022.9775498.
8. J. Liniger, A. L. Jensen, S. Pedersen, H. Sørensen, and C. Mai, "On the Autonomous Inspection and Classification of Marine Growth on Subsea Structures", in Proceedings of OCEANS 2022 - Chennai. Chennai, India, 2022, pp. 1-7. IEEE. doi: 10.1109/OCEANSSChennai45887.2022.9775295.
9. C. Mai, J. Liniger, A. L. Jensen, H. Sørensen, and S. Pedersen, "Experimental Investigation of Non-contact 3D Sensors for Marine-growth Cleaning Operations", in Proceedings of 2022 IEEE 5th International Conference on Image Processing, Applications and Systems (IPAS), Genova, Italy, 2022, pp. 1-6. IEEE. doi: 10.1109/IPAS55744.2022.10053020
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