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Report

Artifex Final Project Report

Unmanned surface vessel as a carrier of subsea and airborne vehicles for remote operation at fish farms (Artifex)

Original title in Norwegian: *Ubemannet overflatefartøy i samspill med undervanns- og luftbårne farkoster for fjernoperasjon av oppdrettsanlegg*

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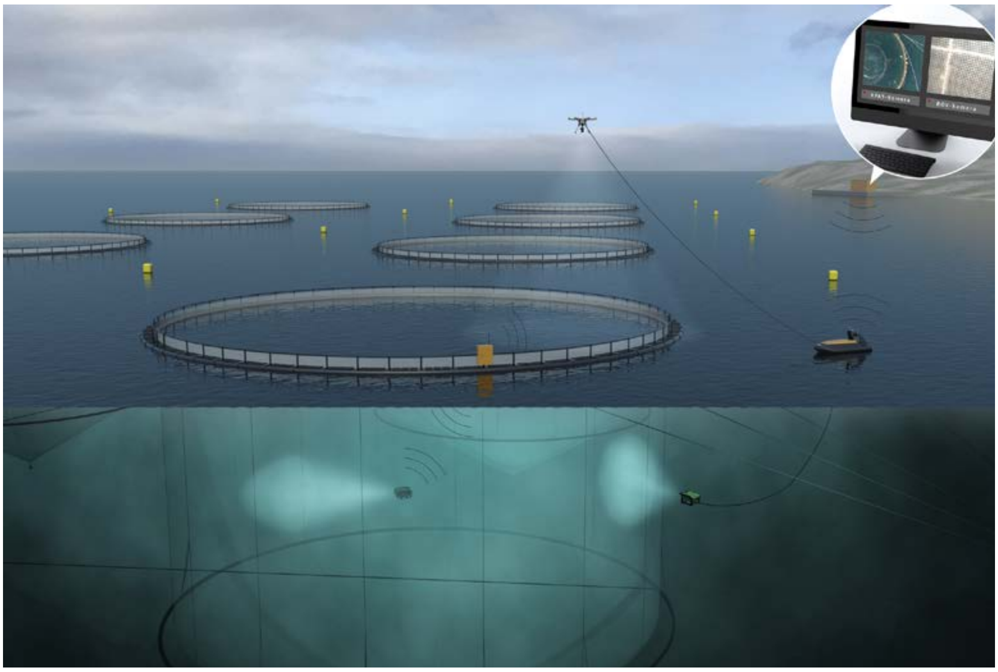

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ABSTRACT
This document summarises the results of the project named "Unmanned surface vessel as a carrier of subsea and airborne vehicles for remote operation at fish farms" (Artifex). The project has been carried out as a collaboration between the following partners: Maritime Robotics AS (project owner), Argus Remote Systems AS, Lerow AS, WavEC – Offshore Renewables, NTNU and SINTEF Ocean AS (project leader), and was supported by the MAROFF and HAVBRUK research programs of the Research Council of Norway. The report provides a brief overview of the followings: project background and objectives, overview of research and development results, assessment of the project implementation, dissemination, and exploitation of the results.

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Introduction

This document summarises the results of the project named "Unmanned surface vessel as a carrier of subsea and airborne vehicles for remote operation at fish farms" (Artifex). The project has been carried out as a collaboration between: Maritime Robotics AS (project owner), Argus Remote Systems AS, Lerow AS, WavEC – Offshore Renewables, NTNU and SINTEF Ocean AS (project leader), and was supported by the MAROFF and HAVBRUK research programs of the Research Council of Norway (RCN). The Artifex project explored new ways of executing operations at fish farms by combing remote control, unmanned surface vehicles, unmanned subsea robots and unmanned aerial vehicles. The project results and the outcomes from the developed technology show that: (1) inspection operations at fish farms (aerial, surface and subsea) can be rendered more systematic and more autonomous, from autonomy levels 1-2 to autonomy levels 3-4 according to [1]; (2) on-site manning of fish farms can be reduced, especially for inspection operations; and (3) several of the inspection tasks can be moved to remote operation centres. The report provides a brief overview of the followings: the project background, the project objectives, the project results, the assessment of the project implementation, and the dissemination and exploitation activities.

Background

Aquaculture and Fisheries are important global contributors to the production of seafood for human consumption, and in 2016 these industries produced in Norway more than 1.2 and 1.5 mill. t. of marketable fish meat, respectively [2]. Current state-of-the-art technologies and operations for sea-based aquaculture farms are highly dependent on manual labour and close human interactions with the process and cage structures while soon the fish farming industry will have to monitor and control the production process by employing autonomous vehicles for inspection and intervention tasks to reduce risk and costs and improve sustainability. Placing new farms in more exposed areas to increase production also highlights the need for operations that are more autonomous [3]. Inspection and intervention operations in fish farms bring extra challenges compared to the Oil and Gas industry with respect to the modelling and control of underwater vehicles operating in such challenging environment with flexible and deformable structures.

As an important step on introducing more autonomous operations in fish farms, the Artifex project developed technologies for future remote operations at fish farms by delivering solutions for regular remote inspection, maintenance, and repair operations without onsite personnel. An unmanned surface vehicle (USV) was envisaged as a platform for carrying a remotely operated vehicle (ROV) for underwater operations as well as a remotely piloted aircraft systems (RPAS) for airborne inspection tasks. The USV shall travel between different aquaculture sites and its land base.

The results from the Artifex project are yielding new products and services that are unlocking unmanned operations in aquaculture hence minimizing the risk for personnel and expanding the weather window for operations at remote and exposed sites. Elements of the Artifex platform can operate in potentially hostile environments where waves, current and wind interact with flexible floating structures, rendering the relative motion between the USV / ROV / RPAS and the structures very difficult to predict, especially at exposed sites [4]. The Artifex project builds on results from previous work executed from SINTEF Ocean, such as the MerdROV project (RCN project num. 217541) and the Sensodrone project (RCN project num. 226395).

Objectives

The main and secondary objectives of the Artifex project are:

Main objective
The project shall develop new robot technology and knowledge that facilitates operations for inspection, maintenance, and repair at fish farms without onsite personnel.

Secondary objectives

1. The technology developed by the project shall minimise the number of operators required to run remote operations at fish farms (ideally only one operator)
2. The project shall contribute to expand the operational weather window for safe operation and better monitoring of exposed aquaculture sites
3. The technology developed by the project shall enable the execution from remote of daily and periodic operations at fish farms such as: aerial visual inspection of the facility, net inspection, net cleaning, net repair, mooring line inspection, dead fish removal, and other light subsea intervention tasks.
4. The project shall deliver full scale demonstrations of USV, ROV and RPAS capabilities as well as demonstrations of remote-control capabilities from a land-based control centre. The demonstrations shall include as far as feasible, full-scale field trials at industrial fish farms.

Research and development results

The research and development results of the Artifex project are summarized in this section for each work package and task. The summary includes the list of produced deliverables per each task.

WP 1 Vehicle design and onboard equipment

Task 1.1 Seaworthiness

The requirements summarising the needs of the Artifex project were initially gathered and a catamaran-shaped vessel was chosen as the most suited since it allows for ROV deployment though a moonpool obtained between the two hulls. Thereafter a study was carried out to determine the seaworthiness of two types of hulls: (1) catamaran hull with symmetric side hulls, and (2) catamaran hull with vertical insides. The 3D models of the two hulls were created in the Orca3D® environment and their hydrodynamic and seakeeping performance were evaluated with the digital workbench ShipX®.

Heave motion at key locations on the vessel was evaluated at 2 m significant wave height (SWH) and at different wave periods to best estimate the operational window of the Artifex vessel. Such locations included the placement points of the ROV and the RPAS launch and recovery systems (LARS) since it was fundamental to minimise the relative motion between the vehicles and the mothership during launch and recovery. The results indicated that heave motion at the ROV and RPAS LARS locations at 2 m SWH can be minimised by (1) minimising the moments of inertia in pitch and roll by placing heavy equipment close to the centre of gravity (CG), and by (2) placing the LARS systems as close as possible to the CG of the vessel. Such measures could therefore make it possible successfully operate the Artifex system also at 2 m SWH.

Deliverable	Owners	Description
L1.1.1	SINTEF Ocean AS	**Project report** (restricted): *Artifex Hull Design, Powering and Seakeeping*
L1.1.2	Maritime Robotics AS	**Project report** (restricted): *Operational limits of catamaran USV platforms*

Task 1.2 ROV LARS and docking

A prototype of the launch and recovery system for the USV-carried ROV was developed in Artifex. The development process started with designing a LARS concept that could fit the catamaran hull from Task 1.1 and then a LARS operation was simulated in sea state conditions experienced at exposed aquaculture locations in Norway (i.e., up to 2 m in SWH and wave period of 6 seconds). Design improvements and operational inputs for the ROV LARS were derived from such simulations since they (1) helped assess the dynamic behaviour of the LARS in waves, and (2) helped assess sea loads, tether forces, and the relative motion between the ROV and the USV during launch and recovery.

The ROV LARS concept consisted of a 2 m long metal boom and a winch for tether management. The boom could pitch downwards, was equipped with proper counterweighs and its position was controlled by a metal wire system. At the tip of the boom there was a mechanical latch that connected the ROV to the boom and a pully that held the ROV tether in place. A shock absorber could be added to the pully to damp peak forces from waves and hence help reduce relative motion between the ROV and the LARS. The following sequences were defined for safe ROV launch and recovery:

- **Launch sequence:**
  1. The moonpool doors open.
  2. The boom is lowered until the ROV is submerged.
  3. The ROV vertical thrusters are activated pointing downwards.
  4. The latch opens and the ROV is now disengaged from the latch platform.
  5. The tether winch begins to unwind the tether and the ROV is moved to a safe depth (i.e., 3 m).
- **Recovery sequence:**
  1. The ROV is taken to a predetermined depth (i.e., 3 m) and to a horizontal position that coincides with the boom endpoint. The ROV auto-heading is set equal to the orientation of the USV.
  2. Tether winching is started at a constant speed and the ROV vertical thrusters are set to give thrust downwards to hold the tether in tension.
  3. A mechanical guiding system ensures automatic latching of the ROV.
  4. After latching, the winch speed is reversed briefly to slacken the tether.
  5. The boom is lifted and the ROV is taken out of the moonpool.
  6. The boom is stopped when its parking position is reached.
  7. The moonpool doors close.
- **Onboard ROV storage:**
  1. The ROV shall always be connected to the LARS, ready for deployment.
  2. The ROV system area inside the USV shall be kept dry.
  3. The moonpool shall have watertight doors.

The ROV LARS was tested at sea using a dummy ROV as a testbed. Maritime Robotics plans to further develop and commercialise the knowledge and technology generated in this task through products and consultancies.

Deliverable	Owners	Description
D1.2.1	SINTEF Ocean AS	**Project report** (restricted, in Norwegian): *Design and simulation of ROV-LARS for the Artifex USV* (Original title in Norwegian: *Simulering og design av ROV-LARS*)
D1.2.2	Maritime Robotics AS	**Project report** (restricted): *Sea trials of the Artifex ROV-LARS*

Task 1.3 Tethered RPAS

A prototype of the launch and recovery system for the USV-carried tethered multirotor RPAS was developed in Artifex. The choice of a tethered RPAS was dictated by the following advantages: (1) virtually unlimited flight time due to power-over-tether, (2) high and reliable bandwidth via tether connection, (3) possibility of fast recovery of the RPAS in case of emergency via fast tether retrieval, and (4) simplified regulation for aerial operations with tethered flying drones [5]. The development process started with designing a LARS concept that could fit the vessel superstructure from Task 1.1 and then a launch and recovery operation was conceived based on land tests executed with off-the-shelf drones.

The regulation on tethered unmanned aircrafts [5] requires the tensile length of the tether to be less than 50 m. The maximum operational height for the Artifex RPAS was therefore set to 40 m, and the maximum horizontal distance between the USV and the RPAS, when at its maximum operational altitude of 40 m, was set to 20 m. This allowed for a good top view of a single aquaculture net pen, assuming a field of view of 70 to 90 degrees for the RPAS camera, and requires a 45 m long RPAS tether, well within the regulation limits.

Airborne operations from the Artifex USV had to be adapted to the demanding maritime environment, especially the launch and recovery operation. Through several land tests it was determined that the best launch and recovery strategy is to keep the RPAS tether winch in retrieval mode, hence exercising a constant tension on the tether. The tension was such to allow for the RPAS, when activated, to easily overcome the winch pulling force and hence leave the USV. When recovering the RPAS, the multirotor positioned itself on top of the USV and reduced its vertical lifting force to allow for a gentle retrieval inside the USV superstructure housing. The LARS consisted of winch and a pully. The pully was placed in front of the winch on the USV deck so that the RPAS could be secured against the deck when parked and the tether could be kept in place during operation.

Maritime Robotics plan to further develop and commercialise the knowledge and technology generated RPAS-LARS development through products and consultancies.

Deliverable	Owners	Description
D1.3.1	Maritime Robotics AS	**Project report** (restricted): *Design and test of RPAS-LARS for the Artifex USV*

Task 1.4 USV integration and propulsion concepts

A geometrical model of the vessel was created in SolidWorks® to determine and visualise the best possible placement of all the vessel systems and the onboard equipment, i.e., the engines, the tanks, the waterjets, the generators, the control system computer, and the payload (ROV and RPAS). Placement of the heaviest elements has followed the guidelines established in Task 1.1. Different concepts for the type of propulsion to employ on the Artifex USV were evaluated including diesel propulsion and electric propulsion with batteries and back-up generators. Waterjets were chosen as the primary drives (one per hull) instead of propellers to enable the vessel to operate within a fish farm since waterjets, as opposed to propellers, do not pose any intrinsic risk of entanglement to the submerged mooring lines that populate the farm. Room was left in the fore part of the hulls to mount electric bow thrusters for improved manoeuvrability at low speeds. It was assessed that the two waterjets alone already give the capability to run almost-station-keeping manoeuvres by applying some of the control algorithms developed by Maritime Robotics.

The documentation and the material produced in this task were instrumental for the project owner Maritime Robotics to build several catamaran prototypes of different sizes, resulting in concrete products and commercial activities [6].

Deliverable	Owners	Description
D1.4.1	SINTEF Ocean AS Maritime Robotics AS	CAD drawings, datasheets, USV weight budget, USV energy budget and other production documentation
D1.4.2	Maritime Robotics AS	Prototypes

WP 2 Autonomous systems and operator interaction

Task 2.1 Operational analysis for autonomous system design

The tasks that the Artifex system shall execute were first defined and then analysed with the SEATONOMY methodology. The analysis represented a top-down design input to develop the Artifex sub-systems, and set the guidelines on how the different elements of the Artifex USV shall cooperate to achieve its operational goals.

The SEATONOMY methodology attempts to extend the iterative V-development model to autonomous systems [7] and concerns three key phases: (a) the operational specification phase that concerns the overall definition and description of the operations to be executed by the autonomous system; (b) the requirements specification phase (hardware and software); and (c) the verification and validation phase.

The SEATONOMY methodology was applied to the Artifex project in the (a) operational specification phase. Conventional requirements specification methods and verification and validation methods were subsequently applied in following iterative design phases.

Specific requirements were derived with the help of SEATONOMY for the following operations that were recognised as relevant for the USV-ROV-RPAS platform:

Inspection Operations (1)	Intervention Operations (2)
1.1. Net inspection for hole detection	2.1. Net repair to avoid escapes
1.2. Inspection of mooring lines	2.2. Cleaning of mooring lines
1.3. Inspection of fish cages from the air	

For each operation, the main objective was identified and split into several subgoals. This allowed for the operation to be sequenced in simpler steps and tasks iteratively, where each step and task was responsible for a given subgoal. High level requirements were thereafter defined for each step to achieve the correspondent subgoal. Such requirements cover: safety, operational modes, manoeuvres to be executed by each of the units (USV, ROV and RPAS), interactions and coordination between the units (USV, ROV and RPAS), communication and perceptions aspects and operator interaction.

Deliverable	Owners	Description
D2.1.1	SINTEF Ocean AS	**Project report** (restricted): *Operational Analysis and Design of Autonomous Vehicles*
D2.1.2	Maritime Robotics AS SINTEF Ocean AS Argus Remote Systems AS	Safety requirement specification, specification of autonomous modes, software architecture specifications, software interfaces, communication protocols

Task 2.2 USV operator interaction

The Artifex system requires a proper land-based control centre from where the operator is expected to monitor the execution of the operation and intervene in the process when required.

The results from Task 2.1 determined to what extent and when the operator shall be involved in executing the identified operation. Based on this, a remote-control room equipped with a simulator has been designed and built by Maritime Robotics that provides the operator with the required situation awareness so that she/he is able to make sound decisions. Proper situation awareness also allows for dynamic replanning of operations. Emphasis was placed on (1) the required operator interaction during USV-RPAS tandem operations, (2) the tools for effective operation planning, (3) the tools for dynamic operation replanning, and (4) handling of failures and unexpected situations.

Deliverable	Owners	Description
D2.2	Maritime Robotics AS	Graphic user interfaces (GUI) and software for information analysis

Task 2.3 Interaction between the USV and the peripheral vehicles

The project developed solutions for path following and motion control of the Artifex USV. Based on Task 2.1 operational strategies were also realised for navigation, trajectory planning and motion control that take into account for the three units encompassing Artifex. Emphasis was placed on USV-RPAS tandem operations.

Such operations are very demanding since the system, after the USV has deployed the RPAS, must synchronise the USV motion with the RPAS motion to execute fast and detailed airborne inspections that may uncover specific locations that require further inspection/intervention on the surface and underwater. Combined USV-RPAS-ROV operations are envisaged for points-of-interest inspections/interventions where the USV shall hold its position and hence deploy the ROV and the RPAS.

Deliverable	Owners	Description
D2.3.1	Maritime Robotics AS	Coordination algorithms and strategies
D2.3.2	SINTEF Ocean AS Maritime Robotics AS	**Scientific publication**: IEEE/MTS Oceans 2022 conference, based on results from Task 2.1, Task 2.2 and Task 2.3

Task 2.4 Estimation of Structural Geometry

Methods for observing and recognizing fish farm structures from the airborne RPAS had to be developed to achieve autonomous operational ability for the Artifex system. Therefore, a study was executed to define a method for mapping the fish farms from digital images taken from the air.

Object detection algorithms were implemented to detect the different structures in the RPAS pictures that constitute a generic fish farm (i.e., cages, barges, and buoys). Triangulation methods where thereafter applied to determine the position of such structures with respect to the USV location. The proposed triangulation methods relied on the RPAS camera images as well as on the RPAS GPS position measurements. Once the position of the structures was determined, a digital map of the aquaculture site was generated.

The digital map was used to analyse the structural integrity of the farm and to define safe operational areas on the surface and underwater for the Artifex USV and the carried-on ROV, respectively. The safe operational areas were determined by dividing the sea surfaces in grid cells and the cells containing the structures were marked as not traversable. Safety lines were hence drawn around the occupied cells to generate no-go areas in the form of closed polygons, and the map could be updated on-line throughout the operation. An aerial drone inspection was executed within Artifex on the full-scale SINTEF ACE fish farm location *Korsneset*, and the techniques from Task 2.4 were tested on the gathered images.

Deliverable	Owners	Description
D2.4.1	SINTEF Ocean AS Maritime Robotics AS	Sensor systems, software framework and procedures for generating real-time maps of structural geometry
D2.4.2	NTNU	**Master Thesis**: G. V. Nybø, *Estimation of Structural Geometry*. Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, 2019.

WP 3 Airborne operations

Task 3.1 RPAS tether management

Based on the inputs from Task 1.3, Task 1.4 and Task 2.1, a tether management solution for the tethered RPAS was developed. The implemented solution relied on the tests as well as the launch and recovery procedure from Task 1.3, and entailed always holding the tether tense, i.e., the RPAS tether winch was always kept slightly in retrieval mode (at minimum). The solution made it possible to obtain safe and easy tether management since in normal operational conditions one could control the RPAS position and the tether length with the RPAS lifting power only, at the expense of marginally higher power consumption (the RPAS rotors must overcome the winch force in addition to gravity).

Deliverable	Owners	Description
D3.1.1	Maritime Robotics AS	Control strategy for RPAS tether management
D3.1.2	Maritime Robotics AS	**Technical note** (restricted): *Tether management strategy for the Artifex RPAS*

Task 3.2 RPAS navigation and motion control

Navigation systems and motion control systems for the RPAS were developed and integrated in Artifex based on off-the-shelf autopilot software for unmanned arial vehicles. The software had to be adapted for tethered operations as well as for safe launch and recovery. Findings from Task 2.1, Task 2.2, Task 2.3, Task 2.4 and Task 3.1 served as requirement inputs. Specific RPAS capabilities, such as the *follow me mode* or *hovering* over selected objects of interest were tested in full-scale at the SINTEF ACE fish-farm *Tristeinen*.

Deliverable	Owners	Description
D3.2.1	Maritime Robotics AS	Navigation and control systems for RPAS
D3.2.2	Maritime Robotics AS	**Technical note** (restricted): *Navigation and motion control for the Artifex RPAS*

Task 3.3 Sensor systems and data analysis for detailed inspection tasks

The task was combined with Task 2.4 and it focused on aerial inspection of sea-based aquaculture sites where it investigated algorithms for generating mosaics from aerial images captured by the Artifex RPAS. The purpose of the generated mosaics was to enable remote inspection of aquaculture farms by offering the level of detail required to detect deviations and changes from the previous state of the site under examination. Relevant mosaicking algorithms, visual simultaneous localisation, and mapping methods as well as structure from motion techniques were reviewed and evaluated for their application in the sea-based aquaculture context. The most promising techniques were applied to the images gathered during the aerial drone inspection of the SINTEF ACE fish-farm *Korsneset* executed in Task 2.4. Mosaicking algorithms based on feature detection were tested on the images and the results showed that it was possible to obtain a globally consistent mosaic with the required level of detail. The results also highlighted the importance of employing robust rectification and transformation of the images, accurate camera calibration and precise pose estimation. This task, together with Task 2.4, laid the groundwork for enabling remote arial inspection of sea-based aquaculture sites.

Deliverable	Owners	Description
D3.3.1	SINTEF Ocean AS	Software framework and procedures to generate photomosaics of fish farms
D3.3.2	NTNU	**Project report**: E. Ujkani, *Sensor systems and data analysis for detailed inspection tasks*. Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, 2018.

WP 4 Subsea operations

Task 4.1 ROV tether management

A control system has been developed to adjust the length of the tether connecting the USV to the ROV using an automated winch. The system ensures (1) sufficient tether slack in relation to the pull forces arising from the ROV and the waves, and (2) low entanglement risk by minimising the amount of tether released. This is achieved by always keeping the tether at a minimum tension. The tether loads on the ROV and the USV have been estimated by developing mathematical models that account for the forces exercised by the ocean current on the tether. A numerical model has been developed for the winch system as well, and extensive simulations that combined models of the USV, the winch, the LARS, the tether, and the ROV have been performed to test, optimise, and validate the tether management controller. This was done in parallel with the development of the ROV LARS in Task 1.2. A prototype of the winch system has been built and tested in full scale and is now a standard product offered by Argus Remote Systems to its clients [8].

Deliverable	Owners	Description
D4.1.1	SINTEF Ocean AS	Control system software prototype for tether management
D4.1.2	SINTEF Ocean AS	Validation logs and videos from simulations. The results are integrated and discussed in D1.2.1 (Project report: *Design and simulation of ROV-LARS for the Artifex USV*)
D4.1.3	Argus Remote Systems AS SINTEF Ocean AS	Winch prototype
D4.1.4	Argus Remote Systems AS	**Project report** (restricted): *Argus Artifex winch and the theory behind it*
D4.1.5	Argus Remote Systems AS	**Product documentation and datasheet**: Argus Mini Winch Standard / Extended (Winch for ROV-umbilical)

Task 4.2 ROV navigation and motion control

Control systems, remote control, and autonomy

A navigation and motion control system has been developed for safe and accurate navigation and control of the ROV to perform inspection operations, intervention operations, and safe launch and recovery. Within Artifex, a high level of autonomy has been achieved for navigation in aquaculture net pens with minimal requirements for operator interaction (autonomy level 3, according to [1]). This has been accomplished by:

1) Equipping the vehicle with a full set of sensors that include: a compass, a gyro, a depth sensor, a Doppler velocity log (DVL) and an ultrashort baseline (USBL) underwater positioning system.
2) Developing a control system for autonomous net pen traversing.
3) Implementing a standard dynamic positioning (DP) control system for station keeping purposes.
4) Developing an adequate graphic user interface (GUI) that accounts for: the relevant ROV operational modes (i.e., manual, net following and station keeping), the required level of operator interaction and the required software architecture to achieve ROV remote control from land.

Combinations of net traverses and DP proved very useful during operations in fish farms as they allow the ROV to stop and hold its position if e.g., the operator detects a hole in the net. This has rendered inspection operations significantly more systematic. Inputs from Task 2.1 were instrumental during the development process and the system has been successfully tested and validated in full scale at SINTEF ACE location *Rataran*. Argus Remote Systems greatly benefited from the development process since it provided valuable inputs for improvements of their offered ROV solutions, such as the Argus Mini ROV [9].

Deliverable	Owners	Description
D4.2.1	SINTEF Ocean AS	GUI for aquaculture operations, control system software, software for autonomous operations, IT architecture for remote control
D4.2.2	NTNU	**Master Thesis**: H. B. Amundsen, *Robust Nonlinear ROV Motion Control for Autonomous Inspections of Aquaculture Net Pens*. Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, 2020.
D4.2.3	NTNU SINTEF Ocean AS	**Scientific publication**: H. B. Amundsen, W. Caharija, and K. Y. Pettersen, *Autonomous ROV inspections of aquaculture net pens using DVL*, IEEE Journal of Oceanic Engineering, 2021 (submitted, under minor revision).

Deliverable	Owners	Description
D4.2.4	NTNU SINTEF Ocean AS	**Project report**: TDT4290 Customer Driven Project Report, Aqueous GUI, Group 11, Department of Computer Science, Norwegian University of Science and Technology, Trondheim, Norway, 2018.
D4.2.5	NTNU SINTEF Ocean AS	**Project report**: TDT4290 Customer Driven Project Report, Aqueous GUI, Group 11, Department of Computer Science, Norwegian University of Science and Technology, Trondheim, Norway, 2019.
D4.2.6	Argus Remote Systems AS	**Product documentation and datasheet**: Argus Mini ROV

Modelling

The developed ROV motion controllers had to prove functional in harsh weather as well. Therefore, the validation of such controllers required detailed modelling of environmental disturbances and their interaction with the structures before their operational deployment in such a harsh environment. The project has therefore developed simulation tools to identify the sea condition that is closest to the operational limit of the ROV and its motion control system. This was accomplished by integrating the following into numerical simulations: (1) weather data from the SINTEF ACE *Tristeinen* fish farm, (2) a complete net pen structure and (3) the ROV model provided with its motion control system.

Deliverable	Owners	Description
D4.2.7	SINTEF Ocean AS	Software and simulation tools to identify the operational limits of the ROV in the aquaculture context when operating close to net pen structures
D4.2.8	NTNU	**Master Thesis**: L. T. Haug, *Hydrodynamic Study of ROV (Remotely Operated Vehicle) Operations at Net-based Fish Farms*. Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 2020.
D4.2.9	NTNU SINTEF Ocean AS	**Scientific publication**: L. T. Haug, M. Greco, B. Su, and W. Caharija, *Hydrodynamic Study of ROV Operations at Net-based Fish Farms*, Ocean Engineering, 2021 (to be submitted).

Task 4.3 Intervention tools

The Artifex project contributed to develop a subsea manipulator arm to make it possible for the ROV to execute light intervention tasks in the aquaculture domain. The design was based on per-existing prototypes and the following requirements were set:

1. Lift and hold payload of up to 8 kg when fully extended.
2. Feature the size, the dexterity, and the speed of a human arm (i.e., 65 cm of length).
3. Perform precise movements with seven degrees of freedom.

Such requirements were defined to ensure the flexibility, the accuracy and the mobility that are needed to perform tasks that are currently accomplished by divers, such as net repair, as well as fastening and installation of ropes and equipment underwater.

The robotic arm development within WavEC was co-funded by the OCEANERA/0001/2016 EU grant (Kraken Project, [10]), where the Artifex project heavily contributed to develop the watertight electrical motors that drive the arm joints. Electrical motors were chosen as actuators and had to be developed specifically for the arm due to the demanding performance requirements. The design team was furthermore forced to minimise the size of all watertight casings to make it possible for the arm to achieve all the movements and trajectories necessary to behave like a human arm. Therefore, each individual actuator was placed in its own watertight casing. A full-scale prototype was developed, and laboratory tests were successfully executed.

Deliverable	Owners	Description
D4.3.1	WavEC	Prototype of robotic arm
D4.3.2	WavEC	**Project report** (restricted): *Artifex final report: A Robotic Arm Manipulator for Offshore operations*

WP 5 Testing and validation

Two validation activities were performed: one concerning the airborne and subsea operations, and one concerning ROV LARS validation.

Airborne and subsea operations

It was shown that it is possible to perform a complete arial inspection of a standard aquaculture facility using commercial drones. The field trial was carried out at the SINTEF ACE *Tristeinen* industrial fish farm facility. A commercial drone was deployed from the SINTEF ACE workboat *Torra* and kept in *follow me* mode at different hights and distances, among them 30 m in height and 20 m in distance to resemble an Artifex RPAS inspection (Task 1.3 and Task 2.3). Detailed video material was taken to assess the structural status of the fish farm (Task 2.4) and to generate detailed photomosaics of the facility to detect deviations and changes from the previous state of the site under inspection (Task 3.3).

After the arial inspection was successfully executed, the boat was docked to a fully operational fish cage and the Argus Mini ROV from SINTEF ACE was deployed inside the cage. A net pen inspection was performed with the ROV that made use of the technology developed in WP 4: a large portion of the net pen was therefore successfully inspected by autonomous net traverses. Station keeping was used to have the ROV stationed at a location that had to be further inspected.

ROV LARS validation

The ROV LARS was mounted on a catamaran prototype and was tested successfully in sheltered harbour waters using a dummy ROV as a testbed. The launch and recovery sequence defined in Task 1.2 was optimised and tested at different speeds.

Deliverable	Owners	Description
D5.1	SINTEF Ocean AS	Airborne and subsea operations demonstration: validation logs, summary, media material (video)
D5.2	Maritime Robotics AS	ROV LARS demonstration: validation logs, summary, media material (video)

Additional activities, results, and deliverables

The project also featured a market analysis concerning the demand for USVs of the Artifex type in the aquaculture sector, in Norway and abroad. The analysis focused on what the Artifex concept could bring to the end-user. Furthermore, it has been assessed whether the Artifex USV may be relevant to other industries as well (i.e., oil & gas, offshore wind, and coastal monitoring). The market analysis consisted of a PEST-analysis (Political, Economic, Societal, Technological) and interviews with relevant personnel involved in aquaculture operations. The analysis was performed together with Lerow AS, an aquaculture service company that was part of the Artifex consortium.

The PEST-analysis identified several factors that may increase the demand for the Artifex concept within aquaculture, while the interviews show that several technological solutions that Artifex developed are very relevant to the needs of the personnel involved in aquaculture operations.

Deliverable	Owners	Description
AD1	SINTEF Ocean AS Lerow AS	**Project report** (restricted): *Market analysis for the Artifex concept in the aquaculture sector* (Original title in Norwegian*: Behovsanalyse for ARTIFEX fartøyet i havbruk*).

Deliverable	Owners	Description
AD2	SINTEF Ocean AS Lerow AS	**Project report** (restricted): *PEST analysis - Factors of relevance to technologies such as remote control and autonomy in aquaculture* (Original title in Norwegian*: PEST analyse - Ytre faktorer for relevans for realisering av fjernstyrte og autonome servicefartøy i havbruk*)

Achievement of the project objectives

The Artifex project achieved it primary and secondary objectives to a great extent:

Achievement of the main objective

Main objective: The project shall develop new robot technology and knowledge that facilitates operations for inspection, maintenance, and repair at fish farms without onsite personnel.

Achievements in Artifex: The project has developed robot technology that can render inspection operations at fish farms (aerial, surface and subsea) more systematic and more autonomous, from autonomy levels 1-2 to autonomy levels 3-4 according to [1], hence limiting the requirements for on-site manning and potentially transferring more tasks to remote operation centres.

Achievement of secondary objectives

1 **Secondary objective:** The technology developed by the project shall minimise the number of operators required to run remote operations at fish farms (ideally only one operator)

Achievements in Artifex: The USV/RPAS/ROV control systems that were developed and tested in Artifex present high level autonomy features (autonomy levels 3-4 according to [1]), hence reducing the need for operator interaction. This reduces the number of operators required as well as the workload on those that are required to safely operate the Artifex system.

2 **Secondary objective:** The project shall contribute to expand the operational weather window for safe operation and better monitoring of exposed aquaculture sites

Achievements in Artifex: Several of the developed solutions such as the ROV LARS system, the ROV control system and the USV hull, were developed with requirements to withstand seas of up to 2 m SWH.

3 **Secondary objective:** The technology developed by the project shall enable the execution from remote of daily and periodic operations at fish farms such as: aerial visual inspection of the facility, net inspection, net cleaning, net repair, mooring line inspection, dead fish removal, and other light subsea intervention tasks.

Achievements in Artifex: The robotics solutions developed in Artifex, such the ROV controls system, the RPAS GNC system as well as the USV control system were implemented over modular TCP/IP solutions that allow for remote operations. Furthermore, within Artifex, Maritime Robotics further developed its remote-control room concepts.

4 **Secondary objective:** The project shall deliver full scale demonstrations of USV, ROV and RPAS capabilities as well as demonstrations of remote-control capabilities from a land-based control centre. The demonstrations shall include as far as feasible, full-scale field trials at industrial fish farms.

Achievements in Artifex: Numerous demonstrations were performed in full-scale at the SINTEF ACE facilities, such as the ROV and RPAS demonstrations. The USV as well as LARS capabilities for both the ROV and the RPAS were otherwise demonstrated in sheltered waters outside the Maritime Robotics premises.

Assessment of the project implementation

The progress in the second year of the project was lower than planned since some of the partners experienced busy periods and lack of resources to commit to Artifex in 2017 and early 2018. The project period was therefore extended by one year. The scope and complexity of the activities in WP 1 turned out to be greater than expected with a lot of resources spent on analysing, designing, and simulating the ROV LARS, a fundamental part of the Artifex concept. The work in WP 2 focused mainly on the operational analysis of the tasks that the Artifex platform shall execute. WP 2 also benefited from pre-existing knowledge held by the project owner Maritime Robotics on multivehicle operations. The scope of WP 3 proved to be smaller than expected thanks to the availability of off-the-shelf technology that helped developed the RPAS system as well as envisage and test several airborne inspection scenarios. The activities in WP 4 proved more demanding than expected: technology for autonomous subsea inspections in aquaculture net pens was at its novelty at project start (autonomy level 2 with technology readiness level 4-5 according to [1] and [11], respectively) and therefore considerable resources were spent on producing the required enabling software and hardware to reach autonomy level 3 with technology readiness level 6-7. Several field trials have been performed in WP 4 in addition to the development of advanced control systems, software, and IT architecture for remote operations. The closing field validation and demonstration activities in WP 5 were delayed by one more year due to the covid-19 outbreak that limited the access to the field test facilities.

Overall, the project was executed by a small team of SINTEF researchers with close links to the industry partners and NTNU. Typically, at least two project meetings per year were held together with partners to present new results and discuss the project progress.

Impact, dissemination, and exploitation of the results

Artifex generated significant impact and results in several domains.

Table 1, Scientific impact and scientific dissemination: Artifex contributed to expand fundamental knowledge in the fields of control system technology, oceanic engineering, autonomous systems, robotics, and hydrodynamics.

ID	Task	Description
1	Task 1.2 Task 4.1	The method and the results from the project report *Design and simulation of ROV-LARS for the Artifex USV* (D1.2.1) contain significant novelties that are of relevance to a large audience within the marine control scientific community. A scientific publication is being considered.
2	Task 2.1 Task 2.2 Task 2.3	The method applied in the project report *Operational Analysis and Design of Autonomous Vehicles* (D2.1.1) contain significant novelties that are of relevance to a large audience within the scientific community working on autonomous systems. A scientific publication is being considered.
3	Task 4.2	The net following algorithm represents a significant scientific achievement for subsea autonomous navigation in aquaculture net pens. A scientific paper has been therefore submitted the IEEE Journal of Oceanic Engineering (D4.2.3)
4	Task 4.2	The methods used to identify the sea condition that is closest to the operational limit of the ROV and its motion control system as well as the results of the analysis are of significant novelty to the hydrodynamics scientific community. A scientific paper is therefore in the process of being submitted to the Ocean Engineering scientific journal (D4.2.9)
5	Task 4.3	The solutions employed to design specific watertight light electrical motors for the robot arm and the placement of them so to properly balance the weight, are rather unique (D4.3.2). Some of the results could be published soon.

Table 2, Impact on education: Artifex supported 4 master thesis activities at NTNU and participated with 2 projects, one in 2018 and one in 2019, to the course TDT4290 Customer Driven Project given by the Department of Computer Science of NTNU to its 4th year students.

ID	Task	Description
1	Task 2.4	Master Thesis (D2.4.2): G. V. Nybø, Estimation of Structural Geometry. Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, 2019. Advisor: Associate Professor Annette Stahl, Co-advisor: Research Scientist Walter Caharija.
2	Task 3.3	Project report (D3.3.2): E. Ujkani, Sensor systems and data analysis for detailed inspection tasks. Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, 2018. Advisor: Associate Professor Annette Stahl, Co-advisor: Research Scientist Walter Caharija.
3	Task 4.2	Master Thesis (D4.2.2).: H. B. Amundsen, Robust Nonlinear ROV Motion Control for Autonomous Inspections of Aquaculture Net Pens. Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, 2020. Advisor: Professor Kristin Y. Pettersen, Co-advisor: Research Scientist Walter Caharija.
4	Task 4.2	Master Thesis (D4.2.8): L. T. Haug, Hydrodynamic Study of ROV (Remotely Operated Vehicle) Operations at Net-based Fish Farms. Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 2020. Advisor: Professor Marilena Greco, Co-advisors: Research Scientists Walter Caharija and Biao Su.
5	Task 4.2	TDT4290 Customer Driven Project (D4.2.5), Aqueous GUI Department of Computer Science, Norwegian University of Science and Technology, Trondheim, Norway, 2018.
6	Task 4.2	TDT4290 Customer Driven Project (D4.2.6), Aqueous GUI Department of Computer Science, Norwegian University of Science and Technology, Trondheim, Norway, 2019.

Table 3, Commercial exploitation: Artifex contributed heavily to product and technology development for commercial purposes.

ID	Task	Description
1	Task 1.2	Maritime Robotics plans to further develop and commercialise the ROV-LARS technology through products and consultancies.
2	Task 1.3	Maritime Robotics plans to further develop and commercialise the RPAS-LARS technology through products and consultancies.
3	Task 1.4	The documentation and the material produced in this task were instrumental for the project owner Maritime Robotics to build several catamaran prototypes of different sizes, resulting in concrete products and commercial activities [6].
4	Task 4.1	A prototype of the winch system has been built and tested in full scale and is now a standard product offered by Argus Remote Systems to its clients [8].
5	Task 4.2	Argus Remote Systems greatly benefited from the development process since it provided valuable inputs for improvements of their offered ROV solutions, such as the Argus Mini ROV [9].
6	Task 4.3	The solutions employed to design specific watertight light electrical motors for the robot arm and the placement of them so to properly balance the weight, are rather unique. A patent is under consideration for some specific design aspects by WavEC.

Table 4, Dissemination through presentations and lectures: Artifex results were presented on several occasions on the national and international level. The table below lists some of them.

ID	Description
1	W. Caharija “Robotics and automation for sea-based aquaculture” Guest lecture to high school students of the ISIS Jožef Štefan in Trieste, Italy, January 8, 2021.
2	W. Caharija, S. J. Ohrem, H. B. Amundsen, L. M. Sunde “Autonomy, cybernetics and remote control for vessel-based operations in exposed aquaculture”, presented at Havbruk 2020, Norway, June 2020 (digital conference). Original title in Norwegian “Autonomi, kybernetikk og fjernstyring for fartøysbaserte operasjoner i eksponert havbruk”.
3	W. Caharija, E. Kelasidi, M. O. Pedersen, N. Blöcher, L. M. Sunde, H. Bjelland, M. Føre, C. Schellewald, K. Frank “Autonomy and remote-control technology in sea aquaculture activities”, Tekna's annual Seabed Mapping and Survey conference, Geilo, Norway, March 2019.
4	W. Caharija, E. Kelasidi, L. M. Sunde, H. Bjelland, M. Føre, C. Schellewald, E. Svendsen, K. Frank, B. Venås “Autonomy and remote-control technology in sea aquaculture activities”, presented at BTS 2018, Biograd na moru, Croatia, Oct. 2018.
5	E. Kelasidi, W. Caharija, E. I. Grøtli, M. Føre, L. M. Sund “Design of autonomous robots for sea-based aquaculture with SEATONOMY”, presented at AQUA 2018, Montpellier, France, Aug. 2018.
6	W. Caharija and M. Føre “ARTIFEX and CageReporter – autonomy and remote control in future aquaculture”, presented at Havbruk 2018, Oslo, Norway, April 2018, Original title in Norwegian “ARTIFEX og CageReporter – Autonomi og fjernstyring i fremtidens havbruk”.
7	W. Caharija, L. M. Sunde and A. Fredheim “Unlocking exposed locations for sea aquaculture activities with autonomy and remote-control technology”, presented at Arctic Frontiers, Tromsø, Norway, Jan. 2018.

Table 5, Dissemination through popular science articles: Artifex results were disseminated through several websites and popular science magazines.

ID	Year	Description
1	2021	nortekgroup.no, user story, "A DVL enhancing autonomous navigation for ROV net inspections on fish farms", https://www.nortekgroup.com/knowledge-center/userstory/autonomous-navigation-for-rov-net-inspections-on-fish-farms
2	2019	The Fish Site, "Self-farming aquaculture? It's closer than you think…", https://thefishsite.com/articles/self-farming-aquaculture-its-closer-than-you-think
3	2018	iLaks.no (in Norwegian), "SINTEF-ingeniør: – Det er alltid behov for folk på merdkanten. Elektronikk og sjøen likar ikkje kvarandre", https://ilaks.no/sintef-ingenior-det-er-alltid-behov-for-folk-pa-merdkanten-elektronikk-og-sjoen-likar-ikkje-kvarandre/
4	2018	fiskerioghavbruk.no (in Norwegian), "Slik kan robotikk trygge og effektivisere oppdrettsnæringen", https://www.fiskerioghavbruk.no/fiskeri-og-havbruk/slik-kan-robotikk-trygge-og-effektivisere-oppdrettsnaeringen-2/#
5	2018	Tekfisk (in Norwegian), "Lager oppdrettsnæringens «Kinderegg»", https://www.tekfisk.no/havbruk/lager-oppdrettsnaringens-kinderegg-/8-1-60555
6	2018	Fiskeribladet (in Norwegian), "Forsker spår færre folk på merdkanten", https://www.fiskeribladet.no/nyheter/forsker-spar-farre-folk-pa-merdkanten/8-1-58101
7	2016	Fish Farming Expert, 2016-4, "Futuristic farming"

Table 6, Project exploitation: the Artifex results are utilized and/or extended in several ongoing projects at SINTEF Ocean.

ID	Project
1	SFI Exposed (RCN 237790)
2	Netclean 24/7 (RCN 296392)
3	RACE Fish Machine Interaction (SINTEF Ocean, internal funding)
4	An underwater robotics concept for dynamically changing environments (RCN 313737)
5	PerformFish, EU H2020

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