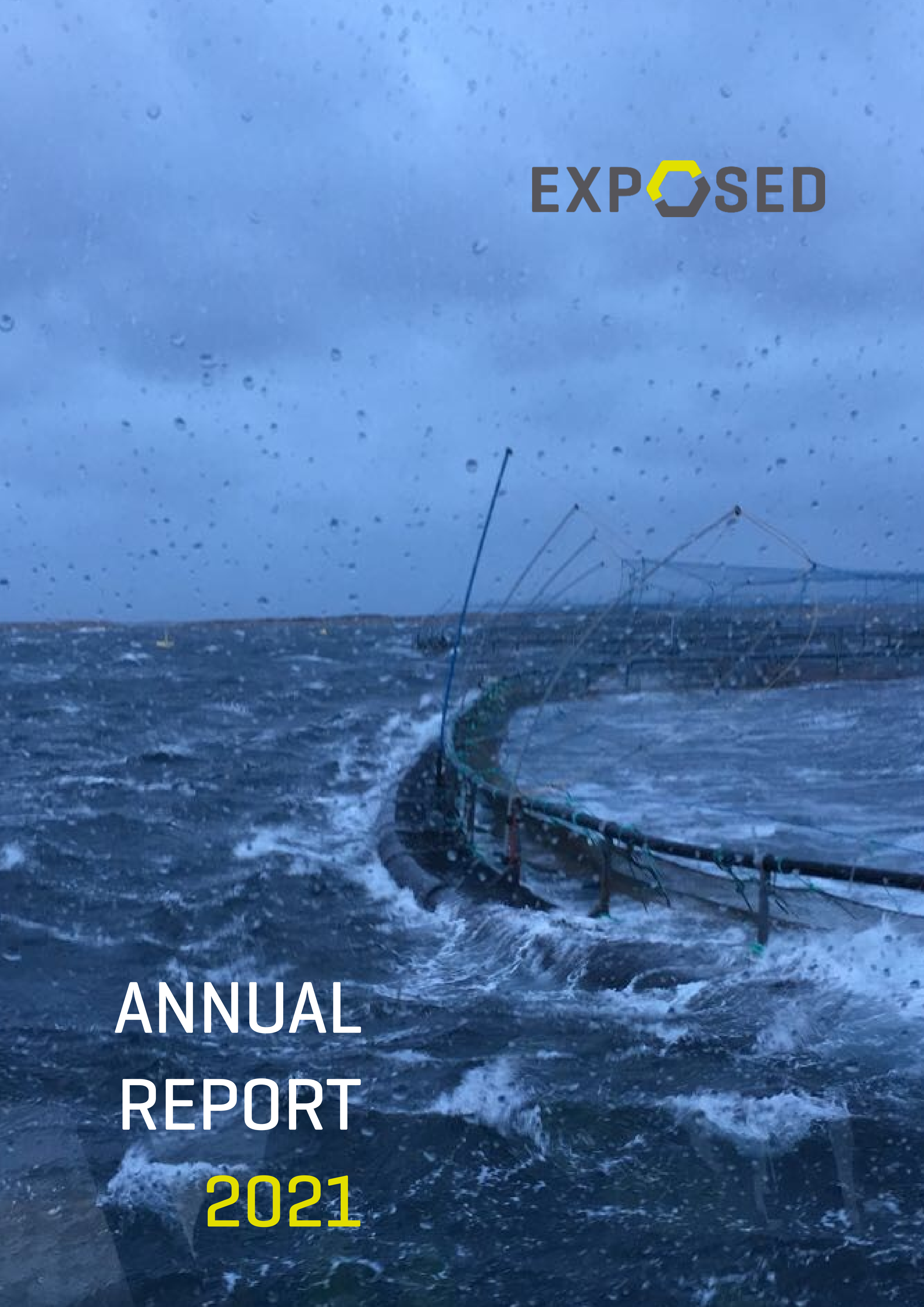


EXPOSED

ANNUAL REPORT 2021

CONTENTS

Centre host:
SINTEF Ocean
7465 Trondheim, Norway

Centre Director:
Hans V. Bjelland
hans.bjelland@sintef.no
(+47) 98829872

Photo front page:
Erlend Berg, Mowi

exposedaquaculture.no

SUMMARY

In 2021, the EXPOSED Aquaculture Operations Centre went on with ambitious research activities, at the same time as we developed a strategy to analyse the centre's general results.

The EXPOSED Aquaculture Operations centre brings together global salmon farmers, key service and technology providers, and leading research groups to develop knowledge and technology supporting robust, safe and efficient operations on exposed fish farms. EXPOSED is a Centre for Research-based Innovation (CRI) funded by our partners and the Research Council of Norway [1]. The CRI scheme encourages industrial innovative capability through long-term research in networks of research-performing companies and research institutions. The EXPOSED centre brings together global salmon farmers, key service and technology providers, and leading research groups with the aim of developing knowledge and technology to support robust, safe and efficient fish farming operations in exposed locations.

Currently, there is a strong innovation drive in the Norwegian aquaculture industry, aiming at novel production opportunities in new areas. Major investments are being made. Legislation and regulatory practices are reviewed to facilitate for the innovation. The centre partners are participating in this development, through R&D projects, in scientific and industrial fora, and in the public debate. We are also frequently contacted by foreign governments, industry, and researchers with requests to support similar developments abroad.

The application of new concepts for aquaculture production systems is growing rapidly in Norway, with various solutions. The solutions impact national strategies and regulation. The EXPOSED centre contributes with knowledge and technology and in 2021, we increased the dialogue with stakeholders. Established arenas for dialogue between centre partners were continued. In addition, we invited external actors to valuable communication relating to current and future needs, and how the centre can contribute.

As the EXPOSED centre's eight years started in 2015, the centre is at its final stage. Thus, our research projects the last years have emphasized on transforming knowledge into innovations for our industry partners and the wider aquaculture industry.

Several of the ongoing projects develop and demonstrate technologies and solutions linked to exposed farming operations, such as decision support systems, the use of robotic arms to compensate for the relative motions of vessels and cages, and underwater navigation and manoeuvring.

A large part of the PhD candidates working on projects linked to the centre have successfully defended their theses and are out making valuable contributions to industrial and academic work in the aquaculture industry.

sfi Centre for Research-based Innovation

[1] https://www.forskningsradet.no/en/apply-for-funding/funding-from-the-research-council/sfi/

VISION AND OBJECTIVES

EXPOSED aims to develop knowledge and technology to support **robust**, **safe,** and **efficient** operations on exposed fish farms.

Major parts of the Norwegian waters have been inaccessible to industrial fish farming due to their remoteness or exposure to unfavourably harsh wind, wave, and current conditions. The aim of the EXPOSED centre is to take advantage of Norway's strong position in the aquaculture, maritime and offshore sectors as a means of promoting safe and sustainable seafood production in exposed coastal and offshore areas. The industry requires technological innovation of autonomous systems, offshore structures and vessels to sustain aquaculture production under all conditions, and to enable more robust, safe, controlled and continuous operations.

EXPOSED brings together leading global salmon farmers, key service and technology providers, and leading research groups such as SINTEF, the Institute of Marine Research and the Norwegian University of Science and Technology (NTNU), including its affiliated Norwegian Centre of Excellence for Autonomous Marine Operations and Systems (AMOS).

Since the opening, there has been a significant industrial and political interest in the centre's research and innovation activities. This interest, driven in part by societal and regulatory developments, has promoted changes in the focus of partner innovation.

This increased interest has also generated enthusiasm among students, allowing the centre to recruit large numbers of MSc candidates and well-qualified PhD students.

Main objective

The main objective of the centre is to develop knowledge and technologies to support EXPOSED aquaculture operations, thus enabling a sustainable expansion of the fish farming industry.

Industry objectives

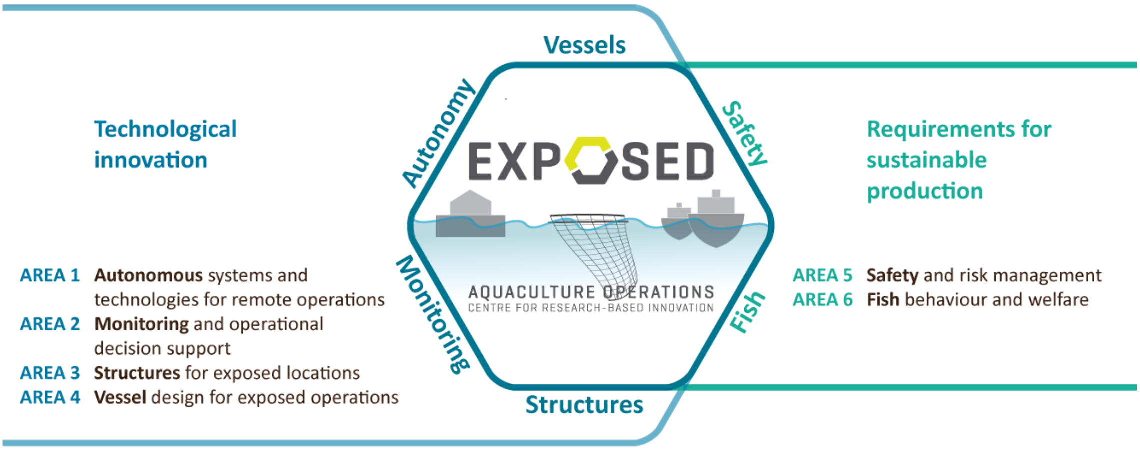
- To enable safe and profitable operations at exposed fish farming sites as a means of boosting sustainable seafood production.
- To develop new technologies that underpin Norway's leading global position in the aquaculture sector, its maritime expertise and technology.
- To help develop new technologies related to concepts identified in connection with development licences.
- To support innovation processes taking place at the centre's industry partners by facilitating access to relevant researchers.

Research objectives

- To conduct fundamental and applied research into key knowledge gaps related to exposed aquaculture operations by combining research fields linked to the aquaculture, maritime and offshore sectors.
- To build knowledge and expertise by the education of at least 20 doctorate, 5 post-doctorate and 70 MSc students.

RESEARCH STRATEGY AND PLAN

EXPOSED includes six core research areas aimed at addressing the challenges facing the industry.



Four of the six core research areas highlight technological innovation with the aim of promoting safe and reliable aquaculture operations:

Area 1: Autonomous systems and technologies for remote operations

Day-to-day work and periodic aquaculture operations must become less dependent on close human intervention.

Area 2: Monitoring and operational decision support

Severe weather conditions and remoteness hinder access and increase the need for robust monitoring and assessing of structures, systems, and fish welfare to support operational decisions.

Area 3: Structures for exposed locations

Aquaculture structures at exposed sites must be fully operational with respect to sea load response, personnel safety, and fish welfare.

Area 4: Vessels design for exposed operations

Vessels, onboard equipment, and logistical solutions must be designed to enable safe and efficient operations in exposed areas.

Two of the centre's research areas focus on key requirements for sustainable production:

Area 5: Safety and risk management

Exposed operations require improved risk management strategies and systems.

Area 6: Fish behaviour and welfare

The technologies and operational systems applied must ensure optimal fish performance and welfare under exposed conditions.

The centre research activities have usually been organised under the six research areas, although in the final stages of EXPOSED, more activities are performed in cooperation between research areas. Activities are fundamental research, additional industrial research, and an increased amount of demonstrators used to promote future innovations. Each research area involve PhD students or post-doctoral researchers. The centre runs several associated projects that carry out relevant research activities and involve other student candidates. The activities are presented in more detail below.

Figure 1. Research activities combine research areas, partners, and methods. PhD students and post-doctoral researchers take part in the project teams.

To further support research and innovation, the EXPOSED centre has initiated and encouraged **associated projects**, in addition to established centre-funded activities.

Associated projects typically involve one or more existing centre partners, and perhaps other external companies or research partners. The partners in those projects have varied depending on the main funding source (the Research Council of Norway/RCN, EU, or innovation-driven). The centre has entered into agreements with several projects with the aim of promoting mutual benefits and synergies.

The centre also has identified potential in collaborating with other centres and groups. EXPOSED has common activities and shares PhD students with NTNU AMOS and collaborates on PhD training with two maritime CRIs; the CRI Move (supporting the marine operations value chain) and the CRI Smart Maritime (supporting improved energy efficiency and harmful emissions reductions from the maritime sector). EXPOSED partners are also partners in and collaborate with the CRIs Blues and CtrlAqua (Centre for Closed-Containment Aquaculture).

Selected associated projects are listed in the table below.

Selected associated projects	Duration, project type and funding source	Host institution	Relevant current EXPOSED activity
ECHOFEEDING – Echo sounder technology for the appetite-led-feeding and welfare-monitoring of caged salmon	2017–2021 Researcher project (HAVBRUK2, RCN)	Institute of Marine Research	Area 6
FutureWelfare – Environmental requirements and welfare indicators for new cage farming locations and systems	2017–2021 Researcher project (HAVBRUK2, RCN)	SINTEF Ocean	Area 6
SalmonInsight – Unveiling links between salmon physiology and online monitored behaviour	2018–2022 Researcher project (HAVBRUK2, RCN)	SINTEF Ocean	Area 6
FASTWELL – Optimising feed withdrawal to safeguard fish welfare	2019–2022 Researcher project (HAVBRUK2, RCN)	Institute of Marine Research	Area 6
DEVELOP – Development licences as a driver for innovation in fish farming – effects on technology, industry and regulation	2021–2023 Researcher project (HAVBRUK2, RCN)	SINTEF Ocean	Areas 3 and 5
Opportunities and challenges with innovations in aquaculture production systems, Compareit	2021–2024 Collaborative and knowledge-building project (RCN)	SINTEF Ocean	Areas 3 and 5

ORGANISATION

Organisational structure

The organisation and operation of the centre is governed by a **Consortium Agreement**, which sets out the rights and obligations of the partners, as well as the roles and responsibilities assigned to the different sections of the organisation. A **General Assembly**, with representatives from all the consortium partners, elects a **Board** comprising seven member representatives from among the centre's partners. The Board is the operative decision-making body for the centre. In 2021, the Board members were as follows:

Board member	Affiliation
Alf Jostein Skjærvik (Chair)	SalMar
Bård Skjelstad	Aqualine (ScaleAQ)
Bjørn Egil Asbjørnslett	NTNU
Arne Fredheim	SINTEF Ocean
Berit Floor Lund	Kongsberg Subsea
Ole Folkedal	Institute of Marine Research
Kjell Emil Naas (observer)	Research Council of Norway

Figure 2. Group discussions at the EXPOSED-days in October 2021.

Hans V. Bjelland is the **Centre Director**, with responsibility for managing the centre on behalf of the host institution, SINTEF Ocean. Bjelland reports to the Board. The Centre Director, together with the **Management Group**, manages centre activities related to **projects**, **education** and **innovation**. The Management Group consists of a Research Manager for each of the six core research areas:

Management Group member	Role and responsibility
Hans V. Bjelland SINTEF Ocean	Centre Director
Esten Ingar Grøtli SINTEF Digital	Area 1
Jan Tore Fagertun SINTEF Ocean	Area 2
Heidi Moe Føre SINTEF Ocean	Area 3
Ørjan Selvik SINTEF Ocean	Area 4
Trine Thorvaldsen SINTEF Ocean	Area 5
Ole Folkedal Institute of Marine Research	Area 6
Kaja Haug/ Kristine Størkersen SINTEF Ocean	Scientific Coordinator

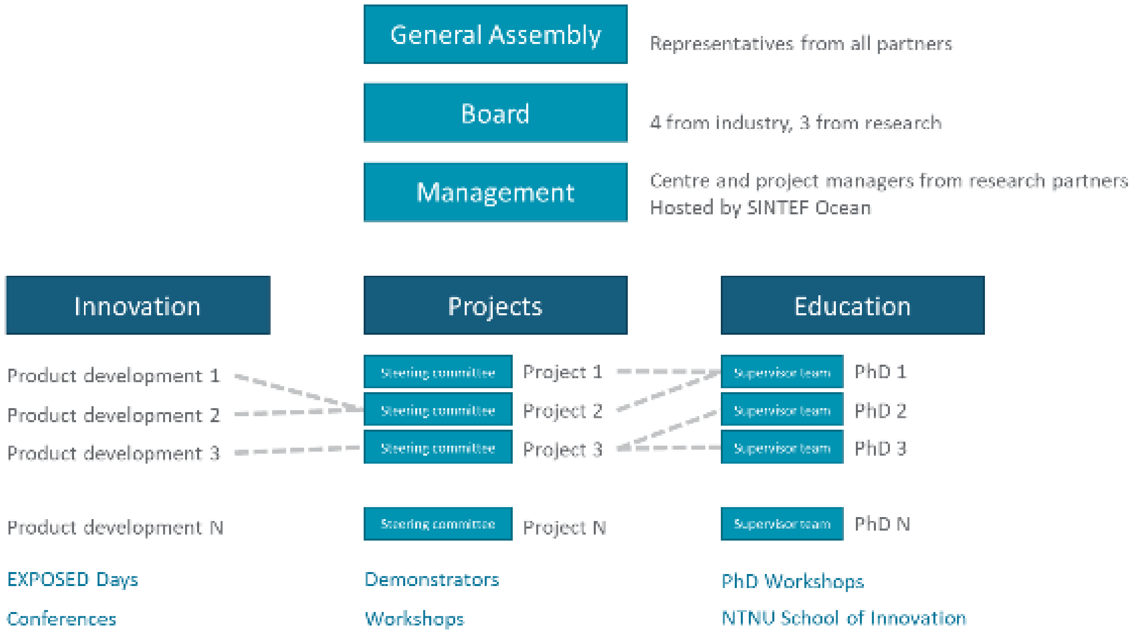


Figure 3. Organisational structure of the EXPOSED centre.

Projects are organised with a **Project Manager** and a **Steering Committee**. The Project Manager is responsible for carrying out the project, while the Steering Committee, headed by a representative of one of the industrial partners, focuses on the supervision of project progress and adherence to its objectives.

Education is implemented primarily via three departments at NTNU; Marine Technology, Computer and Information Science, and Engineering Cybernetics. In addition, some PhD and MSc students are educated at the University of Bergen, facilitated by a collaborative agreement with the Norwegian Institute of Marine Research. PhD students and post-doctorate researchers are assigned to related research areas. In addition, several other NTNU departments have been involved in MSc and bachelor's degree studies related to projects carried out at the centre.

Innovation is supported by several annual events. We organize at least two events for all partners, 'the EXPOSED-days', one in the spring and one in the autumn. PhD and post-doctorate researchers are invited to all events. In 2021, it was initiated a new line of phd/postdoc workshops. This year, we also have continued a video meeting series that was started in the first phase of the Covid-19 pandemic. All these events serve as arenas for innovation, presentation of research results, exchanges of ideas and the generation of new projects. Depending on the level of covid measures, meetings in 2021 have been arranged face to face, digitally, or as hybrid solutions.

The centre host, SINTEF Ocean, is located in Trondheim, and serves as a coordinating hub for activities performed at the centre. Several activities are also carried out in other parts of Norway, at partner locations and field sites.

Research facilities

The centre has access to an extensive research infrastructure, hosted by both its research and industry partners:

- **Full scale industrial fish farms with various levels of exposure.** These include the Aquaculture Engineering test site (SINTEF ACE) in the Hitra/Frøya area, as well as other locations in Mid-Norway, and more exposed farm facilities operated by Mowi, Cermaq and SalMar. The farms are equipped with measurement buoys and other instruments, integrated by a technical e-infrastructure and linked to a central and secure data access point for project partners. Experiments are being carried out at new farms in Norway and the Faroe Islands that provide access to even more exposed sites.
- **Vessel motion monitoring** is facilitated by the service provider and vessel operator AQS, and is used to study operational limits.
- **Scaled-down biological trials** on fish swimming capacity have been conducted under varying conditions at IMR's land- and sea-based facilities at Matre, which include two swim tunnels and a push cage.
- **Hydrodynamic laboratories** in Trondheim, and Hirtshals in Denmark offer a wide variety of scales and capabilities and is utilised as a resource for centre-financed activities.
- **A variety of simulation tools** developed by the centre's research partners have been used to model aquaculture systems and study the dynamics and interactions of structures and vessels, as well as the development of guidance systems for ROV and AUV systems.

Research partners

	Research area
SINTEF Ocean (SO). Conducts ocean space research and innovation activities for Norwegian and international industries. Our ambition is to maintain Norway's leading position in the fields of marine technology and biomarine research.	All
SINTEF Digital (SD). Provides research-based expertise, services and products ranging from robotics, microtechnology, communications and software technology, computational software, information, and security/safety systems.	1, 2, 4
NTNU's Department of Marine Technology (IMT). Carries out research in the field of marine technology. It hosts the Centre for Autonomous Marine Operations and Systems (AMOS), which is a Norwegian Centre of Excellence. AMOS has had key role within the EXPOSED centre.	1, 3, 4, 5
NTNU's Department of Computer and Information Science (IDI). Conducts research in computer and information science, including hardware-related research, intelligent systems and the social implications of information systems.	1, 2
NTNU's Department of Engineering Cybernetics (ITK). Conducts research in various fields associated with control theory, including mathematical modelling and simulation, autonomy, optimisation and automatic control. Together with IMT, ITK plays a major role in the Centre for Autonomous Marine Operations and Systems (AMOS).	1, 2, 6
Norwegian Institute of Marine Research (IMR). Norway's largest marine science centre, whose main task is to provide advice to the Norwegian authorities on aquaculture and related ecosystems.	6

SINTEF NTNU Norwegian University of Science and Technology HAVFORSKNINGSINSTITUTTET INSTITUTE OF MARINE RESEARCH AMOS

Partners

The EXPOSED centre brings together several leading global salmon farmers, key service and technology providers, and leading research groups.

	Industry partners	Contribution/role
MOWI	**Mowi.** The world's largest salmon and trout farmer with major operations in Norway, Scotland, Canada and Chile.	End user of technology and solutions
cermaq	**Cermaq.** The world's third largest salmon and trout farmer, with operations in harsh environments, including offshore northern Norway.	End user of technology and solutions
SALMAR	**SalMar.** The world's fourth largest salmon and trout farmer, operating large fish farms at exposed locations in Mid-Norway.	End user of technology and solutions
KONGSBERG	**Kongsberg Seatex, Kongsberg Maritime Subsea and Kongsberg Maritime. A s**upplier of technology and systems to the global maritime and offshore sector. Provider of knowledge and systems for communication, control, navigation, decision support, AUVs, etc.	Technology/solution provider
SCALE AQ	**Aqualine (ScaleAQ).** A major international supplier of aquaculture equipment and complete fish farms.	Technology/solution provider
møre maritime	**Møre Maritime.** A provider of maritime consulting, engineering and 3D modelling services.	Technology/solution provider
Anteo	**Anteo.** Operates and develops technical solutions and decision support systems for fish farming companies.	Technology/solution provider
ARGUS	**Argus Remote Systems. Carries out R&D on, and is a** manufacturer of, electrical ROVs.	Technology/solution provider
AQS	**AQS.** Service provider of fish farm inspection and maintenance services, as well as other operations, including delousing.	Service provider
marin design as	**Marin Design.** A provider of vessel designs and maritime consulting services.	Technology/solution provider
DNV	**DNV.** A leading classification society and certification body, and a recognized advisor to a wide range of industries.	Certification, classification and advisory services
MACGREGOR	**MacGregor Norway**. A leading provider of maritime system handling solutions and services to the offshore, fisheries, research and mooring sectors.	Technology/solution provider
SAFETEC	**Safetec.** An innovative partner that generates wealth in the field of safety management. Became a partner in the centre in March 2020.	Safety management and risk analysis

SCIENTIFIC ACTIVITIES AND RESULTS

The six research areas operated by the EXPOSED centre cover fundamental research, industrial research, applied studies, industrial activities, and the establishment of research infrastructure. Ten PhD students and three post-doctorate researchers were involved in these areas in 2021. Three of these PhD students defended their thesis during 2021. The following provides a brief description of the research areas, as well as their main results and innovation potential.

Area 1: Autonomous systems and technologies for remote operations

Area 1 is concerned with the development of tools and platforms for use during autonomous and remote operations with the aim of reducing the need for direct human intervention at exposed fish farm sites. In 2021 we focused on developing functionalities that enhance the autonomy of underwater vehicles used for net cage inspection, as well as contact-free operations using a vessel-mounted manipulator arm.

Net-relative navigation of an ROV in fish cages

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Sveinung Johan Ohrem / Walter Caharija	Argus Remote Systems, AQS, Kongsberg Maritime, SINTEF Digital and SINTEF Ocean	Fundamental

Aquaculture net cage inspection and maintenance are key fish farming operations, and inspection using autonomous underwater vehicles represents a promising technology. Our work has involved investigation of the use of laser camera triangulation for pose estimation that enables autonomous net-following by an autonomous vehicle. The 3D laser triangulation data are compared experimentally to a doppler velocity log (DVL) in an active fish farm. We have shown that our system is comparable in performance to a DVL in terms of distance and angular pose measurements. Laser triangulation is promising as a short distance ranging and net pose sensor for autonomous vehicles, which is inexpensive compared with acoustic sensors.

The estimation of the vehicle pose relative to the net pen enables the utilization of closed-loop control systems for autonomous operations that would relieve the ROV operator from continuous steering. One such method is autonomous net following where the ROV traverse the net with a constant speed and distance. Through the project, we have developed a mission control architecture for prioritizing the tasks of an ROV operating autonomously in a net cage. Through simulations, it is shown that the mission control architecture is able to keep track of the progression of an autonomous net inspection and direct the ROV to areas of the net which have not yet been inspected. Preliminary full-scale trials were conducted at SINTEF ACE (see Figure 3). The results were promising but highlighted a need for better filtering of measurements as measurement outliers can affect the performance of the mission control architecture.

Path-following is a fundamental part of many autonomous control systems such as autonomous net following. For path-following for holonomic vehicles such as ROVs, velocity control can be used to make the ROV follow the path independent of its heading. To ensure that the vehicle can follow the path, it is critical that the performance of the velocity control system is precise. For operations in exposed waters, this is even more important as the sea loads will be very heavy. Through our research, we have developed a velocity controller for ROVs that uses a mathematical model of the ROV and an adaptive estimation of the ocean currents to track the reference signals. Through full-scale trials at SINTEF ACE, it was shown that the performance of the proposed velocity controller was very good.

Dynamic positioning (DP) is one of the most important manoeuvres that an ROV is required to perform inside a fish cage. DP enables the operator to hold the ROV steady at one point while inspecting the cage for structural deformation, holes, or other damage to the net. Our research focuses on the development and full-scale testing of robust DP controllers that can be tailored to aquaculture operations because of their ability to adapt to unknown ocean currents and model uncertainties.

Main results 2021

- We have shown experimentally that laser triangulation can be used to navigate relative to a net cage. The signal quality is almost as good as that of a DVL, at less than 1/25th of the price.
- We have proposed a mission control architecture that can direct the ROV during an autonomous net inspection. The research resulted in a scientific publication: H. Ø. Karlsen, H. B. Amundsen, W. Caharija and M. Ludvigsen, "Autonomous Aquaculture: Implementation of an autonomous mission control system for unmanned underwater vehicle operations," Proc. MTS/IEEE OCEANS 2021: San Diego – Porto, 2021, pp. 1-10.
- We have developed a velocity controller for ROVs operating in the presence of ocean currents that has been tested in full-scale trials.
- We have shown experimentally that a backstepping DP controller can hold a ROV in position in the presence of currents and model uncertainties in a full-scale net cage.
- We have written an article describing our laser triangulation results that was published early in 2021: M. Bjerkeng, T. Kirkhus, W. Caharija, J. T. Thielemann, H. B. Amundsen, S. J. Ohrem and E. I. Grøtli, "ROV Navigation in a Fish Cage with Laser-Camera Triangulation", Journal of Marine Science and Engineering, vol. 9, no. 1, p. 79, Jan. 2021.

Innovation potential

Since the signal quality of laser triangulation is similar to that of a DVL, the technology has the potential significantly to reduce the cost of the autonomous control of underwater vehicles relative to the net cage.

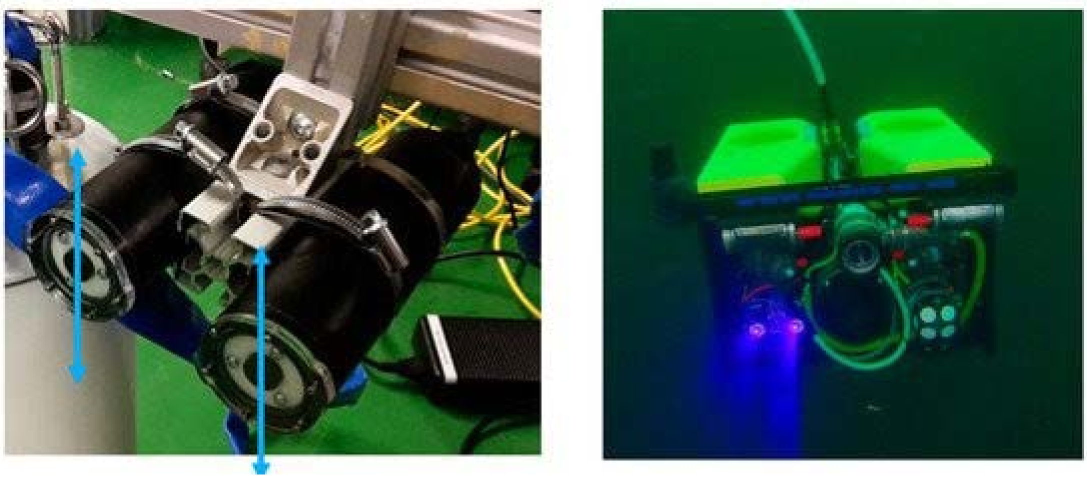


*Figure 2: **Left:** The lasers are mounted inside watertight tubes. Photo courtesy of SINTEF Digital. **Right:** The lasers mounted onto the ROV. The camera used is the on-board ROV camera, seen in the center of the ROV. Photo courtesy of SINTEF Ocean*

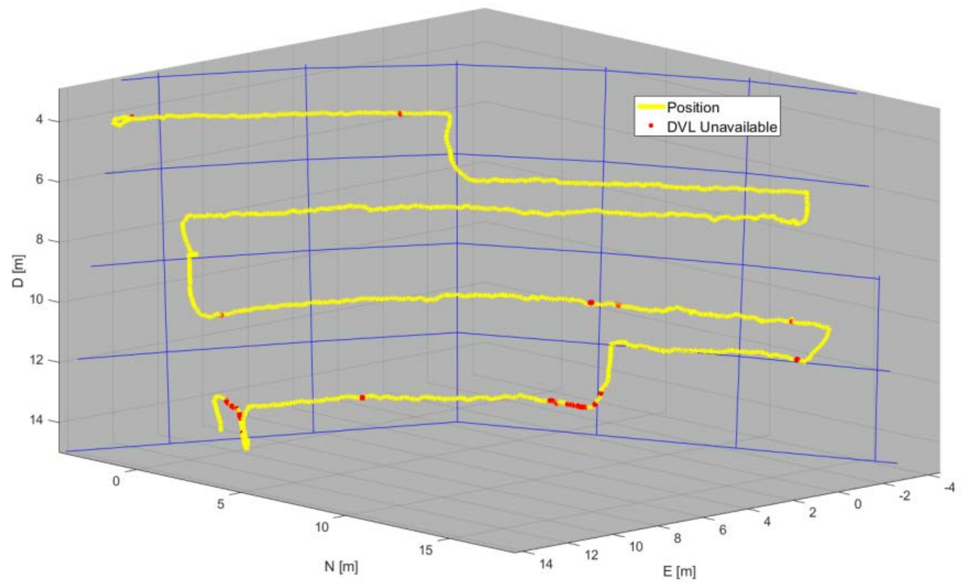


Figure 3: The ROV trajectory during net cage inspection using the autonomous mission control architecture in full-scale tests at SINTEF ACE Rataren.

Contact-free operations using a vessel-mounted manipulator arm

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Martin Gutsch	AQS, Cermaq, MacGregor, Mowi, Kongsberg Maritime, Kongsberg Seatex, Salmar, SINTEF Digital and SINTEF Ocean	Industrial

The main objective of this project was to simulate and demonstrate how service vessels can carry out aquaculture operations under different weather conditions without direct contact with the facility, except for the intended use and contact between the vessel's manipulator arm and the facility.

An initial version of a robot arm controller was used to improve the existing simulation model. An investigation of the sensors and instrumentation required to perform selected sets of work tasks, was carried out with the aim of establishing a test environment where it is possible to train machine learning algorithms (as a part of a PhD study) to perform tasks with the manipulator arm operating in automated mode.

One of the main milestones for 2021 was to prepare and perform a scaled experiment in the laboratory with a robotic arm mounted on a hexapod that emulated realistic wave motions, see Figure 4. To demonstrate the accuracy under different wave motions the robot arm was set to write "Exposed" on a whiteboard, see Figure 5.

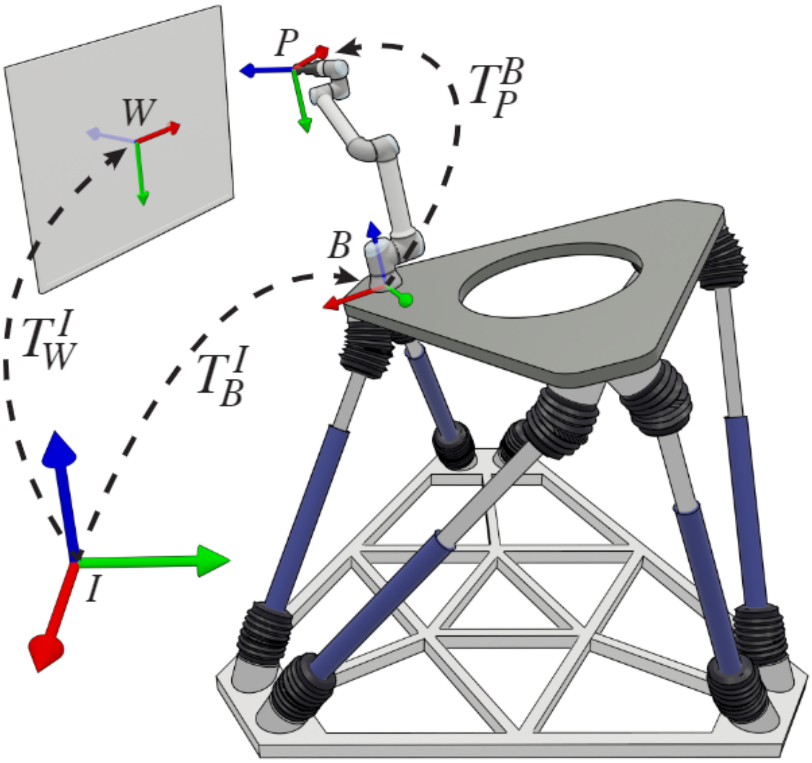


Figure 4: Experimental setup of robotic arm mounted on hexapod.

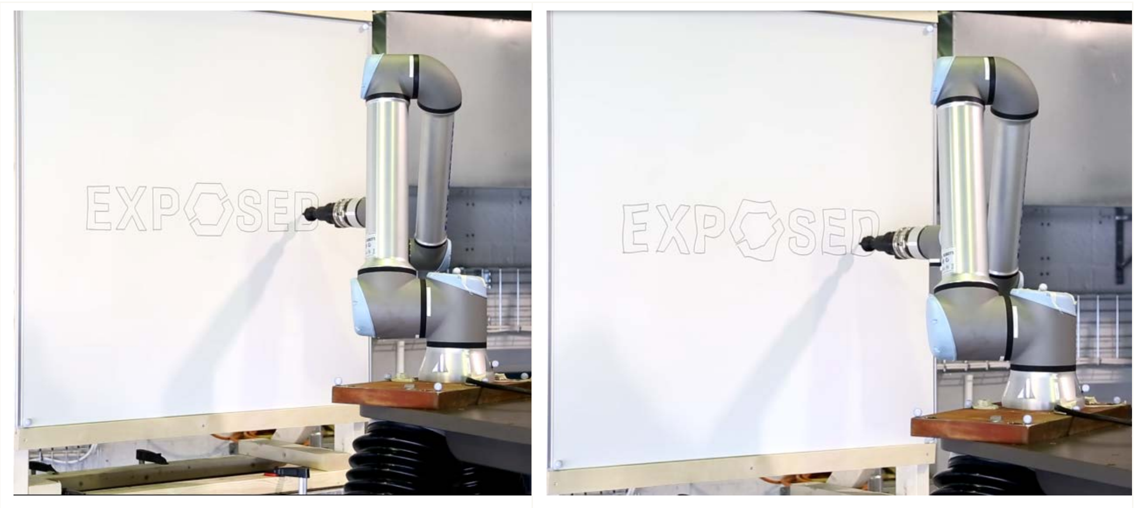


Figure 5: Snapshots of robot arm motion compensation performance test for vessel motions at sea state Hs=0.5m, Tp=6s (left) vs. Hs=2.0m, Tp=9s (right)

Main results 2021

- Demonstrated in a lab experiment how a robotic arm controller was performing when following a predefined trajectory, writing the Exposed logo on a whiteboard, while exposed to wave motions simulated by the hexapod.
- Vessel motions of the Service Vessel *AQS Loke* were simulated with SIMO for different environmental conditions.
- The motions of the base of the robot arm on the main deck were used as trajectory to be followed by the hexapod.
- The motion compensation capability of the experimental setup was demonstrated for the autumn conference, investigated, and discussed for a scientific publication.

Innovation potential

Contact-free operations will enable the operator to perform:

- Flexible operations with reduced risk for injury to humans and fish, and damage to cage structures (due to mooring loads).
- Operations at larger sea-states.

The used lab-setting provides a safe environment to develop, test and train algorithms for innovative operational tasks in selected environmental conditions.

Figure 6: At the EXPOSED-days in October 2021 – watching the live transmitted demonstration of the robot arm from SINTEF at Tyholt.

Area 2: Monitoring and operational decision support

Area 2 focuses on data that are relevant to fish farm operations in exposed conditions. Such data are required for the validation of numerical simulations, which may provide decision support for whether a certain operation should be carried out at a given site. Projects linked to Area 2 develop the knowledge that is needed to create systems for data acquisition, digital twin technologies and decision support tools. This knowledge helps operators to improve fish welfare, reduce the risks to personnel, fish and equipment, and generate value by means of reduced operating costs and higher quality end products.

Data acquisition

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Jan Tore Fagertun	Aqualine (ScaleAQ), Cermaq, Kongsberg Seatex, Mowi, Salmar and SINTEF Ocean	Fundamental

The main aim of this project was to generate further knowledge in the field of data acquisition systems used in fish farming operations in exposed waters.

The aims of one of the activities were to systemize acquired data and make them available to the centre partners and other interests linked to the centre for further research. A further activity focused on improving logging times taken from the monitoring system with the aim of reducing downtime. The results of this work were presented to the partners during a video conference.

Main results 2021

- Data on waves, currents, water and air parameters from Buholmen were acquired most of the year. The only remaining Seawatch buoy in SFI Exposed functioned satisfactorily until the mooring broke early December 2021. It has not been in operation since. Data from Buholmen has been systematised to display the findings.
- A new, smaller buoy (wave measurements only) was acquired in the latter half of 2020 and tested at Tristeinen in February to June 2021. The small buoy has been supplemented with two more. The test indicated satisfactory results for the wave measurements compared to a Seawatch buoy.

Innovation potential

- New and emerging systems for open ocean and coastal monitoring are under development. Data acquisition, combined with numerical simulations, provide a deeper understanding of environmental conditions and how these affect people, the fish, infrastructure and wider society. Data acquisition tools represent a key component of these new systems, and the development of buoys, as well as submerged and mobile systems, make a major contribution.
- Development of decision support tools by use of fusion of measured data, historical data and forecasted data increase the value of digital twins. The digital twin technology may be used both for integrity management and as decision support. Integrity management can be use of measured and historical data combined with numerical simulations for fatigue status as well as rest capacity evaluations. Further digital twin with use of forecasted data may serve as decision support for planning, executing and aborting operations.
- Onshore data requires connection by means of either wired or wireless networks. 5G mobile networks, combined with compact data shipment, provide a foundation for the 'live' (real-time) presentation of sea conditions, fish behaviour and facility structure responses.
- Studios and screens for the presentation of simulated and/or monitored data is developed and adapted to the needs of operators, design developers and the verification bodies.

Digital twin of an exposed fish farm

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Biao Su	DNV, Salmar and SINTEF Ocean	Fundamental

The main aim of this project was to further develop the existing simulation software and model of an exposed fish farm. Work focused on fish farm equipment responses such as floating collar movement, loads on bridles and mooring systems, and deformations of the nets. Input data consisted of environmental conditions that were simulated based on monitoring results from an integrated wave/current buoy, combined with recorded weather conditions.

The simulation model was developed using artificial sensors employed for simulation validation with reference to real sensors installed at a specified site. To reflect the motions measured, the model was modified by adjusting the environmental conditions. In this way, the model may be used as a means of presenting, or 'measuring' actual environmental conditions.

Main results 2021

- A complete model of a fish farm cage was modelled, and a generalized interface has been developed to set up the digital twin model and fetch real-time sensor data (from Piscada cloud).
- The simulation was validated based on monitored conditions, responses, and loads.
- The model was shown to be a means of presenting environmental conditions, once it has been calibrated with reference to the measured responses and loads.
- The digital twin has been further developed to include 48-hour weather forecast data (wind, wave and current) automatically fetched from the MET (Norwegian Meteorological Institute) web service, which can be used for effective early warnings and operational planning.
- Preliminary results were presented in a video conference, where a use case was also demonstrated.

Innovation potential

- The use of digital twins provides insights into responses to environmental conditions at fish farms for the benefit of operators, design developers and service providers.
- The technology improves our knowledge of such responses, generating data that can be used for the planning of maintenance activities and the selection of cages, floaters, mooring systems, etc.
- This technology may expand the operational windows by providing more accurate information, thus reducing uncertainties.
- The technology thus can enhance operational performance and decision making.
- The technology may improve the future design of fish farms.

Decision support system for operational planning

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Eivind Lona	Anteo, MacGregor, Mowi and SINTEF Ocean	Industrial

The main aim of this project is to demonstrate the use of automated data acquisition combined with established operational limitations for wellboat operations, to provide decision support and aid in the risk management of vessel operations at aquaculture sites. The project develops a demo user interface for decision support in planning of wellboat operations. The proposed solution will demonstrate the use of automated data acquisition (location specific weather forecasts), combined with established location specific weather limitations for wellboat operations, in a user interface that will give an overview of future acceptable weather windows at the various aquaculture sites in a specific production area.

Further, the project aims to demonstrate how established weather limitations, weather forecasts and operation specific parameters (transit time, loading capacity, operational time, etc.) can be used to establish a route plan for a set of wellboats.

Main results 2021

The project has relied on the use of environmental monitoring devices to determine operational limitations defined by parameters such as wave height, current and wind conditions. Due to both a lack of equipment, and downtime of existing equipment, on the farms selected for the project, the acquisition of relevant operational data was not started in 2021. The project has engaged in a discussion regarding which vessel types and operations would be most suited to this tool, resulting in a decision to shift focus from service vessels to well boat operations.

Innovation potential

Increased knowledge of operational limitations, combined with systematic and automated data acquisition, has the potential to contribute to the development of a decision support and risk management tool for use in vessel operations.

Figure 7: Bård Skjeldstad explaining Scale's methods for innovation, at EXPOSED-days October 2021.

Area 3: Structures for exposed locations

Fish farming at exposed sites require robust and reliable structures which facilitate safe and efficient production. To improve precision in design of fish farming structures, research area 3 have focused on establishing updated and precise load models for net structures. In addition, definitions and methods to quantify of exposure has been suggested.

Hydrodynamic loads on fish farms

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Heidi Moe Føre	AQS, Aqualine (ScaleAQ), Cermaq, DNV, Kongsberg Maritime, Mowi, NTNU, Salmar and SINTEF Ocean	Fundamental

Increased precision in structural design is important for exposed structures, with estimation of hydrodynamic loads on nets as a central topic. Nets for fish farming are the main source of hydrodynamic loads acting on a conventional fish farm and has a large impact on total loads on new designs utilizing netting for containment of fish. Today, both load coefficients for nets and measured netting dimensions are given with relatively high uncertainties. Empirical formulas for estimation of drag and lift loads on nets were established about 30 years ago, and there is a need to adjust these according to current and new net materials, and more precise solidity measurements. During 2020 and 2021, new empirical formulas have been developed based on results from towing tank tests of net panels with a wide range of solidities in 2019 and 2020. New knowledge for both netting materials with high solidities and scaled netting commonly applied in model tests have been established, and the work on scaled netting continues in 2022. In 2021, the load models have been implemented in a numerical simulation tool and validated.

Main results 2021

- The new load models for netting materials have been implemented in a numerical analysis software and tested. Test results imply that we may have succeeded in our goal to produce more accurate load estimates for fish farm nets, especially for relatively high solidities (including biofouling).
- To validate this new load model, resulting loads and response from numerical analysis have been compared to results from physical model tests of nets performed in a flume tank (Figure 7). Here, net cylinders, representing a simplified net cage model were applied. The cylinders had different solidities.
- Drag forces calculated during numerical simulations applying the new load model compared well with measured drag forces from model tests, especially for the higher solidity netting materials, while total lift forces were in some cases dissimilar. The reasons for deviations in lift loads are not fully understood and could be both due to variations in local geometry and challenging technical conditions for load measurements.
- A parameter study varying the relationship between drag and lift forces and different net inclination angles was conducted. This study indicated that applying formulas derived from net panel tests in analyses of full net models may require some adjustments to account for fluid-structure interaction effects. The study showed that the estimated total drag forces were dependent on the lift formula and vice versa, due to changes in net cage deformation.

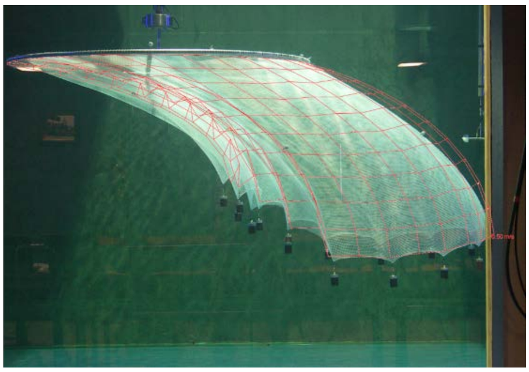


Figure 8: Validating numerical model (red grid) through comparison with physical model test (Photo: SINTEF Ocean).

Innovation potential

- Updated numerical methods for design of fish farms, and improved model test methods and results benefit innovations in fish farming technology.

Exposure level

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Heidi Moe Føre	AQS, Aqualine (ScaleAQ), Cermaq, DNV, Kongsberg Maritime, Mowi, NTNU, Salmar and SINTEF Ocean	Fundamental

Fish farming at exposed sites introduce additional challenges in structural design and operation of farms. There are several research questions that need to be answered: What determines if a site is exposed? What are important factors from a technological point of view? Can exposure level be quantified, and can limit values be established?

We answer these questions from a technological perspective, bearing in mind that this will also be of relevance to e.g. fish growth and welfare.

Main results 2021

- Through this work, we suggest relevant definitions of exposed aquaculture: Exposed aquaculture is culturing of animals or plants at exposed locations. Exposed locations are not sheltered or protected by the surroundings, i.e. they have potentially high environmental loads (in some or all directions). The main environmental loads are hydrodynamic loads from waves, current, and wind loads. We consider both extreme values for design, and operational condition for daily and occasional fish farming activities and operations.
- Waves and water currents are identified as the most important exposure factors for fish farms, affecting loads on and movements of the structures. Combining horizontal velocity contributions from water currents and waves at a given depth (e.g. 5 m) into a horizontal exposure velocity is suggested as a possible measure of exposure.
- Exposure velocity may be given in a polar coordinate system indicating frequency and direction (exposure velocity rose), with different colour bands for given velocity intervals (Figure 8). The highest triangle represents the most common direction of the exposure velocity.

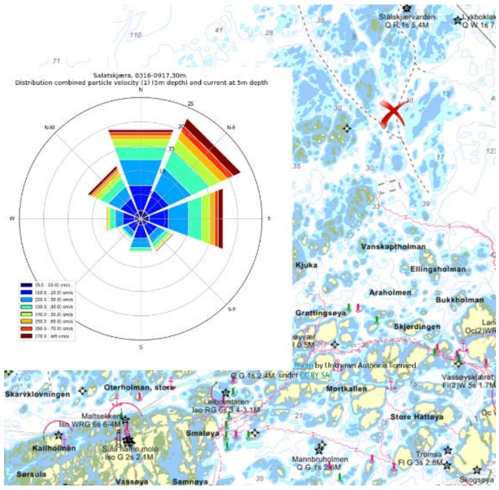


Figure 9: Exposure velocity rose, based on wave and current measurements at a given location on the outer coast of Trøndelag.

Innovation potential

- Defined exposure levels and limits will benefit regulation of the aquaculture industry and may be a useful tool for exposed innovations and planning of exposed operations.

Area 4: Vessel design for exposed operations

Harsh environmental conditions demand new approaches to the design of vessels performing aquaculture operations close to fish cages. Increased wave heights, wind velocities, and current conditions complicate interaction between the vessel and cage structure for both the crew and the structural integrity of the facility. The focus of research in area 4 is directed towards expanding operational weather windows using contact-free systems and an understanding of the interactions taking place between vessel thrusters and fish cages. New contact-free systems that replace the need for personnel to work in hazardous areas on the fish cage are intended to contribute to enhanced operability and safety in aquaculture operations.

Development of a numeric tool to simulate contact-free aquaculture operations

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Martin Gutsch	AQS, MacGregor, Mowi, Salmar and SINTEF Ocean	Industrial

Development of a net-element algorithm in SIMO to be able to simulate movements of fish cages, together with motions of rigid bodies such as vessels, in the same operational condition using irregular waves. This is a prerequisite for being able to perform simulations of operational aquaculture scenarios to investigate operating limits as planned in Research Area 1, Task 2.

Main results 2021

- Development of a net-element code within SIMO allowing cage motion simulations in irregular waves.
- Verification of simulation results against FH-Sim.

Innovation potential

- Enables researcher to perform a complete aquaculture operational investigation, simulating vessel motions and cage motions together in the same environment of waves, wind and current.

Concept study for the contact-free transfer of fish

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Eivind Lona	Aqualine (ScaleAQ), AQS, Cermaq, MacGregor, Marin Design, Møre Maritime and SINTEF Ocean	Industrial

The aim of this project is to perform a concept study for contact-free operations between vessels and aquaculture cages, with a focus on addressing technical and operational challenges. Contact-free operations may involve the use of a thruster-assisted station that has to avoid physical contact with the cages. A further aim of the project is to study the feasibility of introducing a higher degree of automation to the crowding and transfer of fish.

Main results 2021

- The project was launched at the end of 2021 and will continue during 2022.

Innovation potential

- A concept for contact-free operations may expand operational weather windows and contribute to reduced operational downtime at exposed locations.
- Increased levels of automation may enhance levels of personnel safety and reduce the risk of fish escapes resulting from manual handling operations.

Area 5: Safety and risk management

It is crucial for aquaculture operations in exposed areas that the safety of personnel is assured and that the fish, material assets and the environment are protected. The safety barriers employed may be human, technical, or organisational, and must be based on thorough knowledge and assessments of the different risks. Two main projects were selected in area 5 in 2021, addressing a guide for emergency preparedness and holistic risk management with de lousing as a case.

Risk management for exposed aquaculture

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Trine Thorvaldsen	Mowi, AQS, Salmar, Cermaq	Fundamental

Delousing is a relevant case for studying holistic risk management, because fish farmers must consider and handle several hazards when planning and conducting operations. In this work, hazards related to the following risk dimensions has been assessed: personnel, environment/escape, fish health and welfare, structures/farms/vessels, and food safety (Yang et al. 2020). This work had a particular focus on fish health and welfare, through interviews with fish health personnel, operators, and managers. In a workshop, the different risk dimensions were discussed based on a step-by-step description of non-medicinal methods for de lousing. Hazards and measures before, during and after delousing was identified. Discussions showed that fish health and welfare are highly important. During operations personnel often work night and day and the weather is monitored continuously. A new challenge is that some slaughterhouses do not have a "waiting pen" for fish to be slaughtered, which in turn may affect the logistics. Slaughter vessels are also more common than before, which demands a longer weather window when operations are planned.

Main results 2021

- Results show that a holistic approach considering all risk dimensions are highly important in risk management for delousing operations.

Innovation potential

- A holistic risk management that considers different risk dimensions and how they interact may be useful to increase safety in operations and may rationalise the overall follow-up of the management systems.

Emergency preparedness

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Trine Thorvaldsen	Safetec, DNV, Salmar, Mowi, Cermaq, MacGregor, Anteo, Scale AQ	Fundamental

The aim of this project was to develop an emergency preparedness guide for exposed aquaculture. This work built on previous activities in the centre (assessing relevant literature, regulations, emergency preparedness plans, interviews with fish farm employees, and workshops). Workshops were used for experience transfer from other industries, and for defining relevant hazards and accident situations (DFU) and scenarios for the guide. The authorities have stated that increased distance from shore, increased numbers of fish, increased automatization and more demanding logistics are key factors that must be considered during the design of emergency preparedness strategies at exposed sites. Dialogue meetings with authorities were conducted to discuss risks for coastal versus offshore sites. Topics included regulations, performance requirements, coordination of emergency preparedness. The foundation for the guide has been established through this work, and will be finalized in 2022.

Main results 2021

- Emergency preparedness may be improved by focusing on systematisation, simplification and the clear delegation of responsibility, the involvement of personnel and targeted training.

Innovation potential

- An industry guide for the establishment of a holistic emergency preparedness strategy for exposed offshore aquaculture sites will be available in 2022.

Area 6: Fish behaviour and welfare

Knowledge of fish behaviour and physiology under exposed conditions is crucial for understanding the limitations and potential linked to safeguarding fish welfare. Such understanding is important for site selection, production planning, facility construction design and operational procedures. Moreover, the regulatory authorities are reliant on science-based advice on fish coping thresholds in exposed environments. Fish swimming capacity in strong currents and coping strategies under high-energy wave conditions are of particular concern. Research area 6 addresses fundamental biological questions of fish welfare under exposed conditions, and development of novel methods and analytical tools for welfare assessment.

Standard measurement of fish welfare

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Ole Folkedal	Cermaq DNV, IMR, Kongsberg Maritime (Subsea), Mowi, NTNU, Salmar, SINTEF Digital, SINTEF Ocean and University of Melbourne	Fundamental

The main aim of this project is to develop standard tools and protocols for the assessment of salmon behaviour and energetics in exposed farms. The relationships between salmon tail-beat frequency, swimming speed, metabolic rate and heart rate, as measured in detailed laboratory studies, have been scrutinized in order to generate standard curves. Both tail-beat frequency and swimming speed can be assessed visually at farm locations, which enable easy read-outs of valuable information concerning swimming parameters and coping strategies in response to water current speeds and wave energies. While visual observations provide functional 'snapshots' of a given situation, the tagging of individual fish can provide continuous data and more detailed levels of understanding. For this reason, technological and analytical development to implement tail-beat frequency and swimming speed as proxies in fish tags have been conducted, and successfully tested in fish experiments. Further testing, involving forced swimming trials using larger groups of fish, and at full-scale at exposed sites, will enable the full validation of the tools and protocols used for the assessment of salmon coping abilities under exposed conditions.

Observation of fish size distribution is important in monitoring growth among farmed fish. A 3D range-gated camera was tested in salmon sea cages. A robust algorithmic pipeline consisting of detection, tracking and fish length estimation showed an accuracy in the order of 1% vs. manual measurement, both for individual fish length and the population distribution (Risholm et al., 2022).

Main results 2021

- A tag that records the heart rate of a tagged fish has been used in several experimental trials with post-smolt Atlantic salmon, and has shown to be a suitable welfare indicator (Hvas et al., 2020a; 2021a). It has been useful in the description of heart rate both during, and in recovery following, a critical swimming speed test (Hvas et al., 2021b), and is a robust indicator of post-surgical recovery (Hvas et al., 2020a; Føre et al., 2021). Diurnal patterns in heart rate of large caged salmon correspond with day length over seasons, and confirmed the ~24 h recovery time as observed in the lab study by Hvas et al. (2020a) after handling stress (Warren-Myers et al., 2021).
- A Doppler shift-based technique for the measurement of free-swimming fish using acoustic telemetry tags has been developed and evaluated (Hassan et al., 2021).
- The experimental testing of compass fish tags has been carried out in sea-caged salmon, and demonstrates potential for the recording of fish orientation in opposing water currents and the effects of waves on behaviour (Warren-Myers et al. in prep.)
- Experimental testing of activity tags to measure tail beat frequency has been carried out in a pilot trial and found highly functional for its purpose (Warren-Myers et al. in prep).
- A description of a 3D range-gated camera and analytical system for length estimation

of free-swimming salmon (Risholm et al., 2022).

Innovation potential

- Innovative methods for measuring swimming speed and tail-beat frequency using fish tags are important tools for the evaluation and documentation of coping abilities in strong water currents.
- Documented standards for the observation and scoring of fish welfare in exposed environments.

On-site monitoring of fish welfare

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Ása Johannesen	Cermaq, Fiskaaling, IMR, Kongsberg Maritime (Subsea), Mowi, NTNU, Salmar, SINTEF Digital, IMR, University of Melbourne and SINTEF Ocean	Fundamental

The main aim of this project is to observe and understand fish behaviour and welfare in exposed environmental conditions, and to develop novel analytical tools for the automatic classification and detection of fish swimming behaviour.

Production cycles at exposed sites in the Faroe Islands have been monitored using cameras and echo sounders to monitor fish interactions with waves and currents (Johannesen et al., 2021, 2022). Fish have been sampled periodically in order to assess welfare indicators. The results show that wave parameters, currents, and time of day influence fish behaviour and their vertical distribution. During the day, hydrodynamic conditions exert a stronger influence on vertical distribution than during the night. In weak currents, fish generally move further down in the water in response to taller waves, while stronger currents generally cause them to move upwards regardless of wave conditions. Salmon show strong horizontal preferences, mostly occupying the portions of the cage exposed to currents, while waves cause salmon to disperse from the exposed side of the cage to the more sheltered side. The results highlight important coping mechanisms in salmon towards exposed conditions and suggest that salmon should be provided with sufficiently deep cages to enable escape from wave forces and net deformations.

The use of echo sounder observations of farmed fish is a highly effective method for continuous monitoring their spatial distribution and density, as well for recording individual fish parameters such as size, swimming speed and direction. The method offers a huge potential for detection of behavioural anomalies, although full utilisation depends on the development of analytical tools and methods. A transformer-based approach (EchoBERT) was developed for the automatic detection of behaviour in caged salmon (Måløy, 2020). This approach interprets the spatiotemporal dynamics in echograms through attention mechanisms as means of classifying fish behaviour. The results from analysing group behaviour of salmon in sea cages, including successful detection of a disease outbreak, show that EchoBERT has a major potential. This is supported by recent development of similar deep learning models and testing on new data sets (Måløy et al., submitted).

Cage technologies used to farm salmonids are thought to have changed in both size and location in coastal environments, yet remarkably little data exists to explain these major developments. Using satellite images, sea-cage features of the salmon farming industry was tracked over time for the major global production regions (McIntosh et al., 2022). Farm size has increased by 30–220% from 2005 to 2020, and an average farm in 2020 has 12 cages of 32 m in width and is less than 400 m from shore. Supersizing farms has implications for fish welfare, production and farm impacts.

Main results 2021

- The following papers have been published:
- Description of salmon behaviour in relation to waves and current at an exposed site (Johannesen et al., 2022).
- Updated models from that of Måløy et al. (2020) for automatic behaviour detection in caged salmon based on hydroacoustic data (Måløy, et al. submitted).
- Description of development in salmonid cage technology (2005 to 2020) based on satellite images. Farm and cages sizes increased

significantly. Salmon farming remains close to the coast, with farms on average sited a few hundred metres from the nearest land (McIntosh et al., 2022).

Innovation potential

- Knowledge of salmon spatial requirements in high-energy wave environments must be considered under construction and planning new farm sites.
- Implementation of EchoBERT and newer models as observation tools in exposed farms is required to evaluate the model(s) potential for automatic classification and detection of behaviour linked with water current speeds and waves.
- Characterising cage technologies in use across the major farming regions may allow for management practices to be critically analysed to improve fish welfare and production and reduce farm biosecurity threats and environmental impacts.

Swimming capacity and basal physiology in Atlantic salmon and cleaner fish

PROJECT MANAGER	PARTNERS INVOLVED	TYPE OF RESEARCH
Malthe Hvas	Cermaq, IMR, Kongsberg Maritime (Subsea), Mowi, and Salmar	Fundamental

The aim is to investigate basal physiological responses that are of relevance in exposed fish farming, where the focus is on different types of swimming capacities and how they are modulated by environmental and biological factors. A recent review paper summarized current knowledge and proposed welfare guidelines regarding biological limits at exposed sites. One of several concerns at exposed sites are periods without feeding, and the impacts on fish of such periods have been assessed in detail. In brief, salmon that fasted for up to four weeks exhibited mild metabolic constraints and normal critical swimming speeds (Hvas et al., 2020b; 2021b). The impacts on acute stress responsiveness and subsequent recovery rate were minor. Salmon fasted for two months showed full compensatory growth and no detectable short or long-term effects on fish welfare (Hvas et al,. 2022). A highly relevant question that has recently been addressed concerns the duration which salmon can sustain a high swimming velocity. Salmon exhibited impressive endurance by maintaining speeds at 80-85% of their critical swimming speed for the full experimental protocol duration of 72 hours (Hvas et al., 2021c). The energetic cost of parasite infection is rarely quantified, where a recent study investigated the cost of sea lice infestation in salmon. Sea lice at the mobile life-stages imposed a noticeable increase in salmon standard and maximum metabolic rates, revealing an energetic cost and a compensatory mechanism towards parasite infestation in salmon (Hvas and Bui, 2022). Effects of experimental protocols for assessment of fish metabolism requires attention to achieve relevant answers.

An experiment addressing effects of protocol length and photoperiod on metabolic rates in ballan wrasse found that the conventional 24 h respirometry protocol can overestimate the standard metabolic rate vs. protocols of longer duration. Moreover, the metabolism of ballan wrasse was not affected by alternating light conditions, as found for e.g. salmon, suggesting an adaptation to lower costs of living in this species (Hvas, 2022).

Main results 2021

- A description of metabolic rate response to feed withdrawal (Hvas et al, 2020b), the effects of fasting on swimming capacity, blood parameters and stress recovery in Atlantic salmon (Hvas et al., 2021b) and long-term growth and welfare effects of long-term fasting (Hvas et al., 2022). Feed withdrawal is interpreted as a minor concern.
- A review of fish welfare in offshore salmon aquaculture (Hvas et al., 2021d).
- A description of sustained swimming capacity in Atlantic salmon (Hvas et al., 2021c). This paper is highly relevant to the estimation of salmon coping ability towards strong current conditions lasting over days (e.g. storms).
- Quantification of the energetic response of sea lice infestation in salmon (Hvas and Bui, 2022).
- A description of ballan wrasse metabolism and improved protocols for assessment of fish metabolism (Hvas, 2022).

Innovation potential

- The knowledge acquired during this project is highly relevant to fish welfare risk assessments in the context of site selection, production planning, construction designs and operational procedures.
- Salmon is a dynamic species with high degree of coping ability also in exposed conditions.

Figure 10: From the EXPOSED-days in October 2021. Heidi Moe Føre presents the results of Research Area 3, including the gilded drag coefficient formula. This formula was also published presented at international meetings.

INTERNATIONAL COOPERATION

Exposed fish farming still generates significant interest around the world.

The potential of exposed fish farming and the research carried out by the EXPOSED centre has also in 2021 generated interest in many countries, including Scotland, the Faroe Islands, Chile, Australia, China, South Korea and Japan.

Since joint analyses of comparable fish welfare data from Norway and the Faroe Islands have been so successful, we in 2021 continued the post-doctoral collaboration with the research organisation *Fiskaaling* in the Faroe Islands.

The University of Melbourne in Australia also continued their cooperation with the EXPOSED partners in the *Area 6: Fish behaviour and welfare*.

Other current projects that involve international partners and funding include 'Echofeeding', which studies echo sounder technology for the appetite-led-feeding and welfare-monitoring of caged salmon, 'FlexAqua', which addresses aquaculture operations with reliable flexible shielding technologies for infestation prevention in offshore seas and coastal areas, and 'SalmonInsight', which reveals links between salmon physiology and online monitored behaviour.

In 2021, we extended the collaboration with Memorial University in St. John's, Newfoundland, and had exchange activities between Norway and Canada.

Researchers from the EXPOSED centre worked closely with other partners of the International Council for the Exploration of the Sea (ICES) and particularly in the working group on Open Ocean Aquaculture (WGOOA).

The host institution, SINTEF Ocean, and its partner DNV, participated in studies in the Blue Economy Cooperative Research Centre in Australia (cooperation started in 2019).

The global pandemic still hindered several planned conferences and events where the EXPOSED centre would have presented results or chaired sessions on relevant topics. However, some of our researchers attended the Aquaculture Europe Conference in Madeira in October 2021. Our researchers have also contributed with presentations on webinars held by various international organisations, such as the European Aquaculture Technology and Innovation Plattform (EATIP) where the centre director held a key note on *Offshore Aquaculture – Trends and developments*.

RECRUITMENT

In the second last year of the EXPOSED centre and when the society slowly opened in the aftermath of the covid pandemic, the centre focused on providing new and old recruitments with arenas for discussion, learning and dissemination.

As EXPOSED will end in 2023, most PhD students and research activities are well underway, but some persons were still recruited in 2021. Three PhD students defended their thesis in 2021. One new PhD student was recruited (Wai Yen Chan, see image), and one of the finalized PhD students was recruited as postdoc in EXPOSED. Another EXPOSED student (Hans Tobias Slette, see image) was recruited as researcher in SINTEF Ocean for Research Area 4.

The active students and postdoc researchers were invited to all events in EXPOSED, and we established a student network to advance collaboration, knowledge sharing and industrial insights. Several PhD project research results were presented and discussed as part of the EXPOSED video meeting series.

Figure 11: EXPOSED-student Hans Tobias Slette started working as researcher at SINTEF Ocean in 2021.

Figure 12: Wai Yen Chan started as PhD student at NTNU in 2021.

COMMUNICATION AND DISSEMINATION ACTIVITIES

EXPOSED takes pride in good communication, to the public, other stakeholders, and the centre partners.

To support cross-disciplinary innovation and effective internal communication, we arranged several meetings and events in 2021. As always before, the EXPOSED-days served as a meeting place to promote innovation, present research results, exchange ideas and generate new projects.

In 2021, the awareness of the EXPOSED centre partners became more holistic. Since the centre will be finalized in 2023, the focus has shifted from promotion of individual research results, to communication of overarching findings and final results of the centre.

The main communication channels used by the centre have been:

- Research activities and meetings between partners in the Research Areas.
- Attendance at Norwegian and international conferences and other fora. For example, we had a dedicated session at the Norwegian industry conference Aqua Nor.
- Articles in relevant scientific, trade and popular science media.
- Video meetings for partners and invited actors to present results, discuss industry challenges, changes in regulation, etc.
- The website http://exposedaquaculture.no/. In 2021, we started rebuilding the website from a "news based" site, into a long-lasting display of research results. We want it to present information about the centre to all interested actors in the years after the centre is finalized.

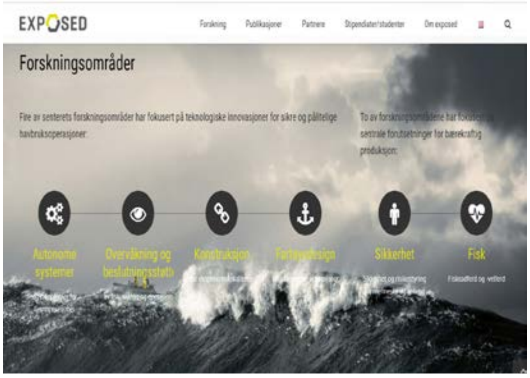


Figure 4. The EXPOSED website is under re-construction and aim is to display the centre's results for present and future audiences.

The EXPOSED Catalogue is popular among the partners, and is an internal, living document that aims to boost the accessibility of the knowledge generated by the centre and promote future innovation. The catalogue provides an overview of completed projects, as well as links to relevant articles, memos, associated projects and personnel.

Figure 5. The EXPOSED Catalogue.

PUBLICATIONS

EXPOSED makes every effort to register all its dissemination activities in the Current Research Information System in Norway (Cristin). We refer to the website https://www.cristin.no/app/projects/show.jsf?id=536331. Scientific papers are listed below.

Journal papers

2015 – journal paper

Utne, I.B., Scjølberg, I. and Holmen, I.M., 2015. Reducing risk to aquaculture workers by autonomous systems and operations. *Safety and Reliability of Complex Engineered Systems. CRC Press, Switzerland*.

2016 – journal papers

Bui, S., Dempster, T., Remen, M. and Oppedal, F., 2016. Effect of ectoparasite infestation density and life-history stages on the swimming performance of Atlantic salmon Salmo salar. *Aquaculture Environment Interactions*, *8*, pp.387-395.

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2017 – journal papers

Hvas, M., Folkedal, O., Imsland, A. and Oppedal, F., 2017. The effect of thermal acclimation on aerobic scope and critical swimming speed in Atlantic salmon, Salmo salar. *Journal of Experimental Biology*, *220*(15), pp.2757-2764.

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Mathisen, B.M., Aamodt, A. and Langseth, H., 2017. Data driven case base construction for prediction of success of marine operations. CEUR Workshop Proceedings.

Vilsen, S.A., Sauder, T. and Sørensen, A.J., 2017. Real-time hybrid model testing of moored floating structures using nonlinear finite element simulations. In *Dynamics of Coupled Structures, Volume 4* (pp. 79-92). Springer, Cham.

2018 – journal papers

Eidsvik, O.A.N., Haugaløkken, B.O.A. and Schjølberg, I., 2018, June. SeaArm-A Subsea Multi-Degree of Freedom Manipulator for Small Observation Class Remotely Operated Vehicles. In *2018 European Control Conference (ECC)* (pp. 983-990). IEEE.

Eidsvik, O.A.N., Haugaløkken, B.O.A. and Schjølberg, I., 2018 SeaArm - A Subsea Multi-Degree of Freedom Manipulator for Small Observation Class Remotely Operated Vehicles. In *European Control Conference 2018 Limassol, Cyprus.*

Faltinsen, O.M. and Shen, Y., 2018. Wave and current effects on floating fish farms. *Journal of Marine Science and Application*, *17*(3), pp.284-296.

Haugaløkken, B.O.A., Jørgensen, E.K. and Schjølberg, I., 2018. Experimental validation of end-effector stabilization for underwater vehicle-manipulator systems in subsea operations. *Robotics and Autonomous Systems*, *109*, pp.1-12.

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Conference papers

2016 – conference paper

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2018 – conference papers

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Sandøy, S.S., Matsuda, T., Maki, T. and Schjølberg, I., 2018, May. Rao-Blackwellized Particle Filter with Grid-Mapping for AUV SLAM Using Forward-Looking Sonar. In 2018 OCEANS-MTS/IEEE Kobe Techno-Oceans (OTO) (pp. 1-9). IEEE.

2019 – conference papers

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Vilsen, S.A., Sauder, T., Føre, M. and Sørensen, A.J., 2018, June. Controller analysis in real-time hybrid model testing of an offshore floating system. In *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection.

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Føre, H. M., Endresen, P. C., Norvik, C., Lader, P. F., Hydrodynamic Loads on Net Panels With Different Solidities. International Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2020. August 3-7, 2020, Virtual, Online.

Mathisen, Bjørn Magnus; Bach, Kerstin; Meidell, Espen; Måløy, Håkon; Sjøblom, Edvard Schreiner. FishNet: A Unified Embedding for Salmon Recognition. I: 24th European Conference on Artificial Intelligence, 29 August–8 September 2020, Santiago de Compostela, Spain – Including 10th Conference on Prestigious Applications of Artificial Intelligence (PAIS 2020). IOS Press 2020 ISBN 978-1-64368-101-6. pp. 3001-3008

2021 – conference papers

Caharija, Walter; Dalseg, Esten Solem; Haugaløkken, Bent Oddvar Arnesen; Stahl, Annette. Echosounder tracking with monocular camera for biomass estimation. Oceans 2021; 2021-09-20 - 2021-09-23 OCEAN NTNU

Føre, H.M., Endresen, P.C., Bjelland, H. V., 2021. Load coefficients and dimensions of Raschel knitted netting materials in fish farms. Proceedings of the ASME 2021 40th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2021. June 21-30, 2021, Virtual, Online.

Karlsen, H. Ø., Amundsen, H. B., Caharija W. and Ludvigsen M., "Autonomous Aquaculture: Implementation of an autonomous mission control system for unmanned underwater vehicle operations," Proc. MTS/IEEE OCEANS 2021: San Diego – Porto, 2021, pp. 1-10.

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Mathisen, B.M., Bach, K., and Aamodt, A. Using extended siamese networks in a cbr system to provide decision support in aquaculture operations. *ICCBR 2021, 3001 Accepted in Applied Intelligence.*

Doctoral theses

2018 – doctoral thesis

Shen Y. 2018. Operational limits for floating-collar fish farms in waves and current, without and with well-boat presence. Doctoral thesis at NTNU, 2018:367

2019 – doctoral theses

Hvas, Malthe. 2019. Physiology and welfare of Atlantic salmon and cleaner fish in exposed aquaculture. Doctoral thesis at University of Bergen. ISBN 9788230845271

Vilsen, Stefan A. 2019. Method for Real-Time Hybrid Model Testing of Ocean Structures Case Study on Slender Marine Systems. Doctoral thesis at NTNU, 2019:166. ISBN 978-82-326-3930-4

2020 – doctoral theses

Haugaløkken, Bent O. A. 2020. Autonomous Technology for IMR Operations in the Norwegian Aquaculture. Doctoral thesis at NTNU, 2020:9. ISBN 978-82-326-4384-4

Sandøy, Stian S. 2020. Acoustic-Based Probabilistic Localization and Mapping for Unmanned Underwater Vehicles in Aquaculture Operations. Doctoral thesis at NTNU, 2020:208. ISBN 978-82-326-4765-1

2021 – doctoral theses

Jónsdóttir, Kristbjörg Edda. 2021. Current flow processes at fullscale Atlantic salmon farm sites. Doctoral thesis at NTNU, 2021:133. ISBN 978-82-326-5910-4

Mathisen, Bjørn Magnus. 2021. Using similarity learning to enable decision support in aquaculture. Doctoral thesis at NTNU, 2021:236. ISBN 978-82-326-5625-7

Hassan, Waseem. 2021. Fish on net: Acoustic Doppler telemetry and remote monitoring of individual fish in aquaculture. Doctoral thesis at NTNU, 2021:259. ISBN 978-82-326-5327-0

PERSONNEL

Key researchers	Institution	Main research area
Hans V. Bjelland	SINTEF Ocean	Decision support systems and aquaculture operations
Ingunn Marie Holmen	SINTEF Ocean	Safety and risk management
Trine Thorvaldsen	SINTEF Ocean	Safety and risk management
Heidi Moe Føre	SINTEF Ocean	Materials science
Per Christian Endresen	SINTEF Ocean	Aquaculture structures
Jan Tore Fagertun	SINTEF Ocean	Aquaculture structures, field measurements and e-infrastructure
Ørjan Selvik	SINTEF Ocean	Vessel design
Martin Gutsch	SINTEF Ocean	Marine operations
Eivind Lona	SINTEF Ocean	Aquaculture structures
Frode Oppedal	Institute of Marine Research	Fish behaviour and welfare
Ole Folkedal	Institute of Marine Research	Fish behaviour and welfare
Esten Ingar Grøtli	SINTEF Digital	Autonomous systems
Trine Kirkhus	SINTEF Digital	Optical measurement systems and data analysis
Pål Lader	NTNU, Department of Marine Technology	Aquaculture structures
Jørgen Amdal	NTNU, Department of Marine Technology	Marine structures
Bjørn Egil Asbjørnslett	NTNU, Department of Marine Technology	Marine operations and systems
Ingrid B. Utne	NTNU, Department of Marine Technology	System safety engineering, risk assessment, and maintenance management of marine systems
Stein Haugen	NTNU, Department of Marine Technology	Risk monitoring and analysis
Agnar Aamodt	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Kerstin Bach	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Helge Langseth	NTNU, Department of Computer and Information Science	Intelligent systems and decision support
Martin Føre	NTNU, Department of Engineering Cybernetics	Telemetry and biological modelling
Jo Arve Alfredsen	NTNU, Department of Engineering Cybernetics	Telemetry and biological modelling

PhD students with financial support from the centre budget

Name	Nationality	Period	Gender [M/F]	Topic
Bjørn Magnus Mathisen	Norwegian	Q3 2015 – Q4 2021	M	Monitoring and operational decision support
Pål Takle Bore	Norwegian	Q1 2015 – Q3 2018	M	Intelligent aquaculture structures
Ingunn Marie Holmen	Norwegian	Q1 2016 – Q2 2021	F	Safety and risk management
Bent Arnesen Haugaløkken	Norwegian	Q3 2016 – Q3 2021	M	Remotely-controlled and automated underwater vehicles
Malthe Hvas	Danish	Q2 2016 – Q2 2019	M	Physiology and behaviour of salmon in strong water currents
Waseem Hassan	Pakistani	Q4 2016 – Q4 2021	M	Acoustic fish telemetry for real-time fish performance monitoring in aquaculture
Håkon Måløy	Norwegian	Q2 2018 – Q2 2022	M	Recognizing ecological behaviour patterns using deep learning
Hans Tobias Slette	Norwegian	Q3 2018 – Q3 2021	M	Methods and models for marine system design of vessels and vessel operations in exposed aquaculture
Muhammad Mukhlas	Indonesian	Q4 2018 – Q4 2022	M	Closed cage aquaculture structures in waves and currents
Martin Slagstad	Norwegian	Q4 2019 – Q4 2022	M	Advanced and rational analysis of steel fish farms in exposed waters
Sverre Herland	Norwegian	Q3 2021 – Q3 2024	M	Reinforcement learning for contact-free operations
Wai Yen Chan	Chinese	Q3 2021 – Q3 2024	F	Computer vision for maritime situational awareness purposes

PhD students with financial support from sources outside the EXPOSED centre

Name	Nationality	Period	Gender [M/F]	Funding	Topic
Kristbjörg Edda Jónsdóttir	Norwegian	Q3 2016 - Q3 2019	F	Strategic research project at SINTEF Ocean	Dynamics of water flow and turbulence in large-scale aquaculture sea cages
Stian Sandøy	Norwegian	Q3 2016 - Q3 2019	M	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)	Sensor fusion for autonomous underwater inspection of aquaculture structures
Yugao Shen	Chinese	Q3 2013 - Q3 2016	M	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Limiting operational conditions for a well boat
Stefan A. Vilsen	Danish	Q1 2014 - Q1 2018	M	NTNU AMOS – Centre for Autonomous Marine Operations and Systems	Hybrid model testing of marine systems
Eirik Svendsen	Norwegian	Q3 2018 - Q3 2022	M	SalmonInsight (HAVBRUK2, RCN)	Links between salmon physiology and online monitored behaviour

Postdoctoral researchers with financial support from the centre budget

Name	Nationality	Period	Gender [M/F]	Topic
Ása Johannesen	Faroese	Q3 2018 – Q3 2021	F	Fish behaviour and welfare in waves
Malthe Hvas	Danish	Q3 2019 – Q4 2022	M	Physiology and behaviour of salmon in strong water currents
Bjørn Magnus Mathiesen	Norwegian	Q4 2021- Q1 2023	M	Monitoring and operational decision support

Postdoctoral researchers with financial support from sources outside the centre

Name	Nationality	Period	Gender [M/F]	Funding	Topic
Xue Yang	Chinese	Q2 2017 - Q1 2019	F	Reducing risk in aquaculture – improving operational efficiency, safety and sustainability (HAVBRUK2, RCN)	Operational risk assessment

Master's students

Name	Gender [M/F]	Period	Affiliation	Topic
Lene Erdal	F	Q1–2 2016	Industrial Economics and Technology Management, NTNU	Shared value creation in an industry context – assessing how governmental policies can contribute to increased corporate sustainability in the Norwegian aquaculture industry
Marianne Wethe Koch	F			
Fredrik Lindahl Roppestad	M	Q1–2 2016	Department of Computer Science, NTNU	Decision support for predictive maintenance of exposed aquaculture structures
Niklas Bae Pedersen	M			
Helene Nordtvedt	F	Q2 2016	Department of Production and Quality Engineering, NTNU	Development of a risk model for fish farming operations
Alexander Wallem Berge	M	Q1–2 2017	Department of Marine Technology, NTNU	Fleet scheduling of service vessels used in a more exposed Norwegian aquaculture industry
Henrik Theodor Ramm	M			
Marius Gyberg Haugland	M	Q1–2 2017	Department of Marine Technology, NTNU	Use of clusters in a route generation heuristic for distribution of fish feed
Sondre Thygesen	M			
Simen Aleksander Haaland	M	Q1–2 2017	Department of Marine Technology, NTNU	Semi-closed containment systems in Atlantic salmon production – comparative analysis of production strategies
Jens Kristian Hole	M	Q1–2 2017	Department of Marine Technology, NTNU	*Risiko-basert design av fartøy og merde for eksponert havbruk* (Risk-based design of vessels and cages for use in exposed aquaculture settings)
Hanne Hornsletten	F	Q2–3 2017	Department of Marine Technology, NTNU	Optimization model aimed for the aquaculture industry for fleet composition and routing of well boats

Name	Gender [M/F]	Period	Affiliation	Topic
Henrik Håkonsen	M	Q1–2 2017	Department of Marine Technology	Emergency preparedness and response in aquaculture
Marte Tuverud Kamphuse	F	Q1–2 2017	Department of Marine Technology, NTNU	Modeling of seaborne transport of fresh salmon. Inventory routing with continuous time formulation for a perishable product
Runar Stemland	M	Q1–2 2017	Department of Marine Technology, NTNU	assessment of service vessel operability in exposed aquaculture. An exploratory approach combining vessel response and discrete event simulation
Arne Jacob Eide	M	Q1–2 2017	Department of Marine Technology, NTNU	Analysis of ocean farming's steel cage concept subjected to environmental loads
Lars Sunde Gjengseth	M	Q1–2 2017	Department of Marine Technology, NTNU	Rational analysis of Nordlaks' 'Havfarm' aquastructure concept for exposed waters
Nikolai Hanevik	M	Q1–2 2017	Department of Marine Technology, NTNU	Analysis of ocean farming's steel cage concept in very exposed waters
Vegard Holen	M	Q1–2 2017	Department of Marine Technology, NTNU	Ultimate limit state analysis of 'Havfarm'
Ole-Johan Nekstad	M	Q2–3 2017	Department of Marine Technology, NTNU	Modularization of aquaculture service vessels – an approach to the implementation of operational flexibility
Erik Andreas Næstvold	M	Q1–2 2017	Department of Marine Technology, NTNU	*Simuleringsmodell som beslutningsstøtte for valg av tiltak mot lakselus på lokalitetsnivå* (Simulation model as decision support for selection of site-specific measures against salmon lice)
Adrian Stenvik	M	Q1–2 2017	Department of Marine Technology, NTNU	Fleet size and mix in the Norwegian aquaculture sector. A stochastic fleet renewal problem with an uncertain future
Vetle Skavraker Evju	M	Q1–2 2017	Department of Marine Technology, NTNU	Competitiveness in construction of offshore fish farms – assessment of cost and strategic aspects
Ronja Eide Lilienthal	F	Q1–2 2017	Department of Marine Technology, NTNU	Discrete event simulation of a multimodal downstream supply chain for future Norwegian aquaculture
Ragni Rørtveit	F			
Odin Dybsland	M	Q1–2 2017	Department of Marine Technology	*Risikostyringsverktøy for oppdrettsnæringen* (Risk management tool for the aquaculture sector)
Solveig Sæbø	F	Q1–2 2017	Faculty of Science and Technology, UiT	*Integrering av ytre miljørisiko i HMS-arbeidet - En casestudie av et fiskeoppdrettselskap* (Integration of HSE-related external environment risk – case study using an aquaculture company)
David Williams	M	Q3 2016 – Q2 2017	Department of Marine Technology, NTNU	Extreme loads on a feeding barge
Yuyang Zang	F	Q1–2 2018	Department of Marine Technology, NTNU	Experimental and numerical investigations of global motions and slamming loads on an aquaculture feed barge
Øyvind Haug Lund	M	Q1–2 2018		

Name	Gender [M/F]	Period	Affiliation	Topic
Trym Sogge Sjøberg	M		Department of Marine Technology, NTNU	Evaluation and comparison of operability and operational limits of service vessel designs in exposed aquaculture
Gøran Bredahl Woll	M	Q1–2 2018	Department of Technology and Safety, UiT	*Sertifiserer de seg sikrere? – En casestudie av frivillige miljøsertifiseringers innvirkning på sikkerhetsstyringen i oppdrettsnæringen* (Does certification make them safer? – A case study of voluntary environmental certifiers' influence on safety management in the aquaculture sector)
Loenard O. Cheri	M	Q3 2017 – Q1 2018	Department of Physics, UiO	Net-relative localization algorithm for fish cage inspection operation
Erling Nilsen	M	Q3 2017 – Q3 2018	University of Agder	Effect of ploidy on oxygen uptake and swimming performance in the lower end of the thermal niche of Atlantic salmon.
Amalie Almenning Bu	F	Q1–2 2019	Department of Marine Technology, NTNU	AIS-Data for increased insight into navigational impacts post-installation of man-made structures at sea
Katarina Staalesen	F	Q1–2 2019	Department of Marine Technology, NTNU	Exploring the digital twin concept for a rigid aquaculture cage – insight through structural analysis and sensor application
Roald Hartvigsen	M	Q1–2 2019	Department of Marine Technology, NTNU	Inventory management, scheduling and routing in fish feed distribution
Hanne Buan	F	Q1–2 2021	Department of Marine Technology, NTNU	Simulation-based analysis of salmon encounters with delousing operations
Mats W. Langseth	M	Q1–2 2021	Department of Marine Technology, NTNU	Strategic planning in Norwegian aquaculture: A decision-support system for fleet size and mix problems with processing vessels
Carina Nygård	F	Q1–2 2021	Department of Marine Technology, NTNU	An investigation of methods and value of information in routing of priority-based operations – using a rule-based routing method tested with discrete event simulation
Jørn Larsen Ringvall	M	Q1–2 2021	Department of Marine Technology, NTNU	Mobile slaughterhouses at sea – do stun-and-bleed vessels meet Norwegian salmon farming requirements?
Vilde Xiu Drønen	F	Q3 2021 – Q2 2021	Department of Marine Technology, NTNU	Guidance and navigation principles for autonomous ROV missions in an aquaculture context
Henning Ødeby Karlsen	M	Q3 2021 – Q2 2021	Department of Marine Technology, NTNU	Autonomous Aquaculture: Implementation of autonomous mission control for unmanned operations
Kenny Hoang Nguyen	M	Q3 2021 – Q2 2021	Department of Engineering Cybernetics, NTNU	Cybernetics control of unmanned surface and subsea vehicles operating at exposed fish farms in the presence of time-varying environmental disturbances
Kyrre Haugland	M	Q3 2021 – Q2 2021	Department of Engineering Cybernetics, NTNU	Cybernetics smart and resilient sensor fusion and bathymetric SLAM for future autonomous aquaculture

Name	Gender [M/F]	Period	Affiliation	Topic
Esten Solem Dalseg	M	Q3 2021 – Q2 2021	Department of Engineering Cybernetics, NTNU	Smart and resilient visual tracking for future autonomous aquaculture
Lindis Rokseth	F	Q3 2021-Q2 2022	Department of Industrial Economics and Technology Management (IØT)	Personal safety and automated aquaculture operations
Ingeborg Sofie Gumdal	F	Q3 2021-Q2 2022	Department of Industrial Economics and Technology Management (IØT)	Personal safety and automated aquaculture operations

Figure 13: Centre director Hans Bjelland wish the partners and guests welcome to the EXPOSED-days of fall 2021.

STATEMENT OF ACCOUNTS

Name	Funding		Cost
Research Council of Norway	10 795	(51.4 %)	-
Host institution (SINTEF Ocean)	1 450	(6.7 %)	9 025
Research partners*	4 006	(19.1 %)	7 630
Enterprise partners**	4 718	(22.8 %)	5 231
Public sector partners	-	-	-
Equipment	-	-	-
Total	**20 987**		**21 866**

(All figures in NOK 1000)

* IMR, SINTEF Digital, NTNU IMT, NTNU IDI, NTNU ITK, Fiskaaling (Faroe Islands), University of Melbourne

** Mowi, Cermaq, SalMar, Kongsberg Seatex, Kongsberg Maritime Subsea, Kongsberg Maritime, Aqualine (Scale AQ), Møre Maritime, Safetec, Anteo, Argus Remote Systems, AQS, Marine Design, DNV and MacGregor Norway

Centre for Research-based Innovation

The Research Council of Norway

EXPOSED

AQUACULTURE OPERATIONS

CENTRE FOR RESEARCH-BASED INNOVATION

SINTEF Ocean • Mowi • Cermaq Norway • SalMar Farming • Kongsberg Maritime Kongsberg Seatex • ScaleAQ • Marin design • Møre Maritime Argus Remote Systems • DNV • SINTEF Digital • Institute of Marine Research Anteo • Norwegian University of Science and Technology • AQS • MacGregor Norway • Safetec Nordic

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