NTNU

Centre for Autonomos Marine
Operations and Systems

NTNU AMOS

Centre for Autonomous Marine Operations and Systems

Annual Report 2020

Norwegian
Centre of
Excellence

The Research Council of Norway

OUR VISION

- Establish a **world-leading research** centre on autonomous marine operations and systems
- Create **fundamental knowledge** through multidisciplinary research
- Provide **cutting-edge interdisciplinary research** to make autonomy a reality for ships and ocean structures, unmanned vehicles and marine operations
- AMOS has license to create knowledge, competence and values in terms of innovations and entrepreneurships

NTNU AMOS will contribute to improved international competitiveness of Norwegian industries as well as to safety and protection of the marine environment

excellent – generous – courageous

Editors: Sigmund Bolme, Thor I. Fossen and Asgeir J. Sørensen

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DIRECTOR'S REPORT

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Creating competence, knowledge and innovations for a better world is the mission for NTNU AMOS.

On 12 March 2020, the Norwegian prime minister announced a lockdown of Norwegian society, following several other countries as a knock-down response to the pandemic outbreak of the COVID-19 virus. This was one of several wide-ranging decisions impacting Norway and the rest of the world.

Since the start-up in 2013, we at NTNU AMOS have advocated for the importance of a holistic and sustainable approach to develop competence, knowledge and innovations with relevance for:

- *global challenges* related to climate, energy, minerals, food, clean oceans and biodiversity;
- *value creation* in terms of oil and gas exploration, maritime transport, fisheries, aquaculture, offshore renewable energy, marine minerals, tourism, coastal infrastructure and urbanization; and
- *governance and knowledge-based management* of the oceans and coastal areas.

The year 2020 has been a game-changer in terms of the digitalization of work processes and interactions between organizations and people. During this year alone, the extent and pace in transition have probably been the same as the 10 preceding years together. 2020 is also recognized as the start of the decade towards a green shift in terms of zero-emission shipping, he ramp-up of offshore renewable energy, decarbonizing oil and gas operations and carbon capture storage in reservoirs, and may even by afforesting the seas use seaweed, energy conservations, clean oceans, etc. In addition, we are heading into the United Nations Decade (2021-2030) of Ocean Science for Sustainable Development – *The Science We Need for the Ocean We Want*.

Take-home messages from 2020 are underscoring the importance of *environmental sustainability*, *economic sustainability* and *social sustainability*, and that none of us are safe until all of us are safe. We – humans and other organisms – are dependent on functional ecosystems.

The targeted research areas at NTNU AMOS are well-aligned national and international strategies meeting these transformations. We are focusing on fundamental research within marine technology, control engineering and marine biology, leveraging ground-breaking results on autonomous marine operations and systems.

NTNU AMOS has two research areas: *Autonomous vehicles and robotic systems*, and *Safer, smarter and greener ships, structures and operations* organized into three projects:

- Project 1: Technology for the mapping and monitoring of the oceans;
- Project 2: Marine robotic platforms; and
- Project 3: Risk management and a maximized operability of ships and ocean structures.

In this context, it is important to enhance the impact and outcome by associated research projects and innovation activities. During 2020, NTNU AMOS scientists, together with fellows, have been instrumental in securing funding for several large research programs going from 5-8 years, such as:

- SFI Autoship: Will contribute to Norwegian players taking a leading role in the development of autonomous ships for safe and sustainable operations.
- SFI Harvest: Technologies for sustainable biomarine value creation. Pioneering the lower-trophic fisheries – Innovations to unlock the blue bioeconomic potential.
- SFI Blues: Enable Norwegian industry to create new types of floating stationary structures that satisfy the needs and requirements from renewable energy, aquaculture and coastal infrastructure.
- FME NORTHWIND: Will be at the cutting edge, working on innovations to make wind power cheaper, more efficient and more sustainable.
- NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS): Aim to become a world-leading research centre on autonomous underwater robotic operations with a focus on resident and collaborating autonomous underwater vehicles (AUVs), which are supported by subsea docking systems for energy charging and communication.

I am pleased to observe that the legacy of NTNU AMOS is well in place, while we still have two years more to run. In the annual report, selected highlights of in-depth technology development and projects, exemplifying cooperation between technology and science for ground-breaking research, are given.

It is with pride that I acknowledge that AMOS researcher groups are being recognized for their excellent research and innovation achievements. This year, the IEEE OES Autonomous Maritime Systems Rising Star Award for 2020 has been awarded to Martin Ludvigsen at the Department of Marine Technology and NTNU AMOS.

I would like to take this opportunity to thank all the colleagues, researchers, PhDs, postdocs and master's students, partners and collaborators for their efforts in *creating competence, knowledge and innovations for a better world*.

Keep up the spirit. NTNU AMOS is on track.

Sincerely,

Professor Asgeir J. Sørensen
Director NTNU AMOS

BOARD OF DIRECTORS

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The Board met twice in 2020 to review progress, consider management issues and offer advice on strategic directions for the Centre.

The Board was very satisfied with the performance and activities undertaken at NTNU AMOS during 2020. We found the results to be very impressive, particularly considering the global lockdown and travel restrictions that paused most physical interactions over the last year.

The Board confirmed that NTNU AMOS fulfiled the expectations as a Norwegian Centre of Excellence, while also acknowledging NTNU AMOS' remarkable track record in creating associated research projects, innovations and spin-off companies. We want to highlight that NTNU AMOS team members have been instrumental in the development of the newly awarded VISTA Centre for Autonomous Robotic Operations Subsea (CAROS), as well as three awarded SFIs and one FME. The inter-disciplinary nature of the centre, combining marine technology, cybernetics and marine biology, enabled the creation of new knowledge to the global scientific community, in addition to providing a significant added value to industry and society in general. The infrastructure that the Centre has access to provides an excellent research environment.

AMOS upheld the focus on the three project directions set out after the mid-term assessment in 2018:

- Technology for the mapping and monitoring of the oceans
- Marine robotics platforms
- Risk management and maximized operability of ship and ocean structures

In 2020, NTNU AMOS graduated 12 PhDs, of which two are female. Publication numbers include 99 journal papers in high-quality journals, as well as 67 conference papers, 11 book chapters and six plenaries. This shows that the NTNU AMOS team has been able to maintain their focus on publication and dissemination in a very special year.

The Board is also very pleased that key persons of AMOS have been recognized through awards. We proudly observe that Professor Martin Ludvigsen at the Department of Marine Technology and NTNU AMOS was awarded the IEEE OES Autonomous Maritime Systems Rising Star Award. The Board also wants to highlight the award “Årets DigIT-kvinne” presented to Professor Kristin Ytterstad Pettersen at the Department of Engineering Cybernetics, a Norwegian award that brings forward inspiring women who have contributedto new digital opportunities.

The board was also very pleased with the HSE performance of AMOS. There were few incidents and no near accidents. The HSE awareness in the centre management is very good, and there is a good system for risk assessment and training for laboratory and fieldwork.

The Board's Endorsement of the Annual Report

The main responsibility of the Board of Directors is to ensure that NTNU AMOS achieves its goals within the resources available, and within the research plan established by the Centre. As part of their duties, the Board members have discussed this Annual Report and endorsed it.

***MiniROV** with underwater hypespectral imager surveying seafloor in Kongsfjorden, Svalbard January 2020.*

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COMING HOME

Øyvind Smogeli is the COO and co-founder of Zeabuz, a company dedicated to the development of autonomous electrical passenger ferries for use in urban environments. An experienced researcher, Smogeli will join NTNU AMOS and the Department of Marine Technology (IMT) as an adjunct professor from January 2021.

Smogeli finished both his master's degree and PhD at IMT, and has previously been a visiting researcher at MIT. Since he graduated, he has worked for Marine Cybernetics followed by DNV, where his last position was to manage a research programme on Digital Assurance. In August 2020, Smogeli joined the team at Zeabuz before he became an adjunct professor.

Teaching

As a professor at NTNU, Smogeli will be involved with teaching and supervising Marine Technology students at IMT.
"I'll help in updating some of the courses on marine control systems, as we want to modernize them a little. I will also help teach some classes, and supervise PhD and master candidates."

"In a sense, it really feels like coming home. I am looking forward to being back at the Department of Marine Technology, and helping to build the future of Marine Technology studies at NTNU."

The position that Smogeli will fill is funded by Equinor. He will work at the intersection of marine technology, cybernetics and robotics, with a special focus on the assurance of autonomous systems. Already heavily involved in the TRUSST project through Zeabuz, Smogeli will also work on the Open Simulation Platform project for NTNU.

"I have had a running dialogue with Asgeir Sørensen about coming 'home' for some time now, and the timing is excellent considering the work I do work at Zeabuz," he says.

"One of the great things about this position is the synergies between what we do at Zeabuz and what NTNU AMOS is doing. The research being done on autonomy, for example through the ferries milliAmpere and milliAmpere II, is an example of excellent cooperation across research fields."

Building trust in technology

"Our grand vision is to create solutions that make our cities more sustainable and better places to live in. Working with cutting-edge technology is of course exciting, but the end goal is what really drives us. By revitalizing underutilized waterways, we can create smarter solutions for personal mobility and make it easier for citizens to travel within the cities, while decongesting roads and reducing emissions," says Smogeli.
But getting people to accept new technologies can be a challenge. At Zeabuz, they are highly aware that you need to create enthusiasm and know the needs of people if you want them to make use of new solutions.

"One of our big challenges is to create public trust in autonomous vehicles. Right now, the rules and regulations are lagging behind, and traditional assurance methods and tools are not quite adequate for the task, simply due to the complexity of these AI-powered software-intensive systems."

"Safety by design is a key term. We want to design systems that both are and, crucially, feel safe. This means that the physical system must be safe, but the

decision-making must also be as similar to that of a human as possible. The ferry should also be able to show its intentions to people onboard and to surrounding traffic. In short, it must feel like an actual person is steering the ship."

In order to manage this, Smogeli says, you need to find a balance between what is efficient and what feels safe. If it is too efficient and robot-like, people won't feel safe enough to use it, and if it is to slow, then people will have no incentive to choose that mode of travel.

"That balance is challenging to achieve, but we are confident that we are on the right track," he says.


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SINTEF OCEAN

THOMAS SAUDER RE-JOINS THE TEAM

From late 2020, NTNU AMOS and the Department of Marine Technology at NTNU have been strengthened by Thomas Sauder, who is joining the team as an adjunct associate professor. Sauder got his PhD in Marine Cybernetics at NTNU in 2018, and has already been involved with NTNU AMOS research for many years.

Since we last spoke you have worked for SINTEF Ocean; tell us a little bit about what you have been working on.
"Since my PhD in 2018, I have been working on various applications of hybrid testing: the testing of offshore wind turbines of course, but also the identification of nonlinear wave loads and the active truncation of slender marine structures, among others.
I have also been leading a group that works on the digital aspects of the Ocean Space Centre. It includes hybrid testing, but also automation, visualization, data and computational infrastructure, which are all central aspects to create a world-leading centre. I really hope that we will manage to implement our visions there."

How does NTNU AMOS fit into all of this?
"Control systems, sensor fusion and mechatronics are the core of hybrid testing. And at the same time 'classical' subjects like hydrodynamics, structural engineering, and more generally physics still play an extremely important role. This multi-disciplinary aspect is the DNA of NTNU AMOS."

Sounds exciting, what contributions do you see your research bringing to society at large?
"We know that the ocean will play an important role when it comes to energy harvesting and food production in the future. And it is a fundamental aspect of the Norwegian economy and competitiveness. My vision is that hybrid testing will contribute to the design of safer and optimized marine structures by: 1) increasing the precision of experimental techniques, and 2) extending the capabilities of our laboratories."

You are working on difficult research tasks, improving experimentation methods and developing new ways to test technology. Some might find this work daunting. What motivates you in your work?
"I am very motivated by going deep into challenges in various fields, such as control engineering and marine hydrodynamics, and then connect the dots to make something new. And I actually think that's one of the things a French engineer education makes us good at!"

You are already working on these issues at SINTEF. What made you decide to take on new tasks at NTNU as well?
"Since 2013, we at NTNU and SINTEF have been developing hybrid testing as a start-up. We have achieved high-quality results, and have become world-leaders in our field. I believe that we are now in a scale-up phase, where we should be consolidating all aspects of the methods, thinking about new applications, teaching and communicating more. This is far from an easy task, but I believe that this adjunct position can serve this purpose."

One of the most important tasks of any professor is to teach and train new generations of researchers. Are you looking forward to that and how are you prepared for this somewhat different challenge?
"I will be teaching a course dedicated to hybrid testing in the very near future and will need to prepare some material first, as it does not exist yet! I have not been teaching before, but have a lot of experience in communicating complex scientific concepts and ideas to customers, as that is an important part of our work at SINTEF. It will be a new experience, and I am very much looking forward to starting."

Professor Thomas Sauder in the Ocean Basin lab at Tyholt

ORGANIZATION, INTERNATIONAL COLLABORATORS, AND FACTS AND FIGURES

Organization

NTNU AMOS Board Members:

- Dean Olav Bolland, Chair, NTNU
- Vice Dean of Research Ingelin Steinsland, NTNU
- Dean Øyvind Weiby Gregersen, NTNU
- Vegar Johansen, SINTEF Ocean
- Kjetil Skaugset, Equinor
- Frank Børre Pedersen, DNV GL

NTNU AMOS Management:

- Asgeir J. Sørensen, Director
- Thor I. Fossen, Co-director
- Renate Karoliussen, Senior Executive Officer
- Sigmund Bolme, Higher Executive Officer, Communications
- Knut Reklev, Senior Engineer

NTNU AMOS Key Scientists:

- Jørgen Amdahl, Marine Structures
- Thor I. Fossen, Guidance, Navigation and Control
- Marilena Greco, Hydrodynamics
- Tor Arne Johansen, Optimization and Control
- Kristin Y. Pettersen, Motion Control
- Asgeir J. Sørensen, Marine Control Systems
- Geir Johnsen, Marine Biology

Senior Scientific Advisors:

- Odd M. Faltinsen, Hydrodynamics
- Torgeir Moan, Marine Structures

Innovation:

- Kjell Olav Skjølsvik, Innovation Leader

Research partners:

- DNV GL
- SINTEF Ocean
- SINTEF Digital
- Equinor
- Dept. of Marine Technology, Dept. of Biology and Dept. of Cybernetics at NTNU

Scientific Advisory Board:

- Randal W. Beard, Brigham Young University, USA
- Robert F. Beck, University of Michigan, ANN Arbor, USA
- Gianluca Antonielli, University of Cassio and Southern Lazio, Italy
- Torgeir Moan, NTNU, Norway
- Murat Acak, University of California, Berkely, USA
- David Mckee, University of Strathclyde, UK

International collaborators

Co-operation with international universities and research institutes occurs in the form of the two-way exchange of senior researchers and PhD candidates, the sharing of research infrastructure, and joint publications, regulated by a signed agreement. NTNU AMOS researchers are currently cooperating with these institutions:

- CNR-INM, Italy
- Eindhoven University of Technology, Netherlands
- Instituto Superior Técnico, Portugal
- Jet Propulsion Laboratory, NASA, USA
- National Academy of Sciences of Ukraine, Ukraine
- National University of Singapore
- Technical University of Denmark
- University of California, Berkeley, USA
- University of California, Santa Barbara, USA
- University of Cassino and Southern Lazio, Italy
- University of Delaware, USA
- University of Linköping, Sweden
- University of Michigan
- University of Porto, Portugal
- University of Rijeka, Croatia
- University of Zagreb, Croatia
- Woods Hole Oceanographic Institution, USA

Facts and figures

Personnel 2020

- 7 keypersons
- 15 adjunct prof/assoc.prof
- 31 affiliated scientists
- 2 Scientific Advisers
- 8 post docs/researchers
- 19 affiliated post docs/researchers
- 95 PhD candidates (incl. Affiliated)
- 3 administrative staff
- 2 Management
- 2 technical staff

- 3 graduated PhD candidates financed by NTNU AMOS
- 9 graduated PhD candidates associated to NTNU AMOS

Revenues (NOK)

•	Income	61 440 000
•	Costs	60 067 000
•	Year end allocation	1 373 000

Publications

- 99 refereed journal articles
- 67 refereed conference papers
- 10 book chapters
- 1 book
- 6 international keynote lectures

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MAIN RESEARCH AREAS AND PROJECTS

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The NTNU AMOS has two research areas:

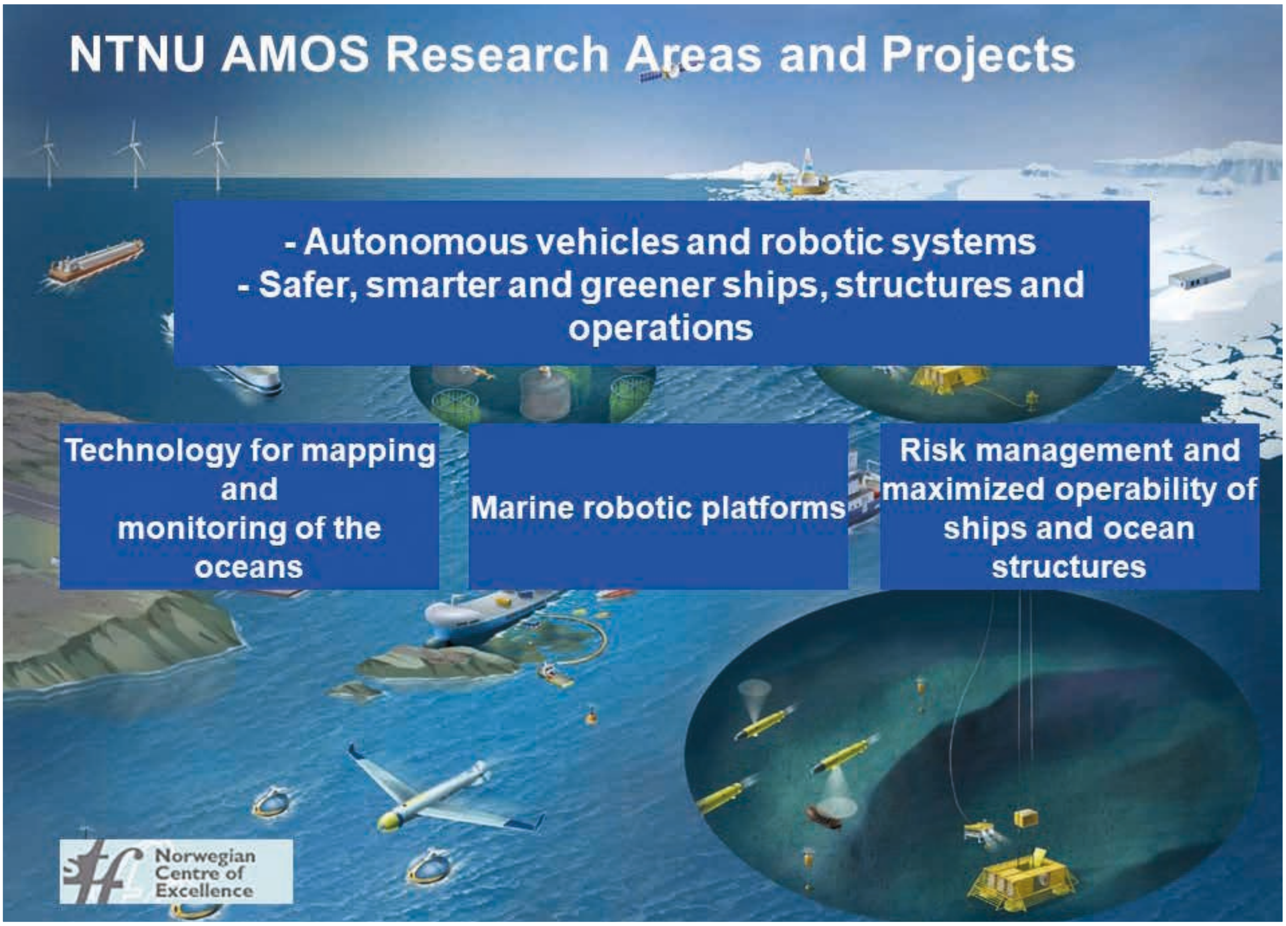
- **Autonomous vehicles and robotic systems**
- **Safer, smarter and greener ships, structures and operations**

Research at AMOS is organized as three major research projects

- **PROJECT 1: Technology for mapping and monitoring of the oceans.** Heterogeneous robotic platforms (underwater, surface, air and space) for mapping and monitoring the oceans in space and time.

- **PROJECT 2: Marine robotic platforms.** This project concerns the guidance, navigation and control of unmanned ships, underwater vehicles, aerial vehicles, and small-satellite systems, as well as optimization, fault-tolerance, cooperative control, and situational awareness; bio-mimics: bio-cyber-hydrodynamics, and multiscale and distributed systems for sensing and actuation are also included. The new emerging field of bio-cyber-hydrodynamics enables the development of novel concepts in marine robotics.

- **PROJECT 3: Risk management and maximized operability of ship and ocean structures.** The focus will be on the development of methods that maximize operability with improved risk management. This will be achieved by combining advanced numerical hydrodynamic and structural mechanical models for analysis, monitoring and control. Application areas include offshore wind turbines, aquaculture installations, oil and gas installations, coastal infrastructures, coupled multibody marine structures, marine operations, autonomous ships, inspections and installations.



Technology for mapping and monitoring of the oceans

Project manager: Prof. Tor Arne Johansen

Key Scientists: Profs. Asgeir J. Sørensen, Geir Johnsen, Thor Fossen

Scientists at NTNU: Profs. Martin Ludvigsen, Jo Arve Alfredsen, Lars Imsland, Fred Sigernes, Milica Orlandic, Annette Stahl, Rune Storvold, Martin Føre, Arne Fredheim, Nadia Sokolova, Francesco Scibilia, Roger Skjetne, Joao Sousa, Jørgen Berge, Steinar Ellefmo, Fredrik Søreide, Jo Eidsvik, Morten Alver, Egil Eide, Nils Torbjörn Ekman, Harald Martens

Other involved scientists: Autun Purser (AWI, Bremerhaven), Yann Marcon (AWI and Marum, Bremen), Bramley Murton and Alex Poulton (National Oceanography Centre, Southampton, UK), Duncan Purdie (University of Southampton, UK), Ilka Peeken (AWI, Germany), Christopher Mundy (University of Manitoba, Canada), Maxim Geoffroy (Memorial University, Canada), Finlo Cottier and Kim Last (SAMS, Scottish Association for Marine Science, Scotland), Igor Yashayaev and Erica Head (Bedford Inst Oceanography, Canada)

Research activities:

This project considers the modelling, mapping and monitoring of the oceans and seabed, including:

- hyperspectral imaging
- coordinated networked operations
- processing of payload data in real time and post-processing
- intelligent payload systems and sensor fusion
- big data analytics and machine learning
- adaptive sampling of spatial-temporal features from robotic vehicles

Main results

Advancing Ocean Observation with an AI-driven Mobile Robotic Explorer

Rapid assessment and enhanced knowledge of plankton communities and their structure in the productive upper water column is of crucial importance for ecosystem surveillance to help understand the impact of the changing climate on upper ocean processes. Enabling persistent and systematic observation by coupling the ongoing revolution in robotics and automation with artificial intelligence methods will improve the accuracy of predictions, reduce measurement uncertainty and accelerate methodological sampling with a high spatial and temporal resolution. Furthermore, progress in real-time robotic visual sensing and machine learning has enabled high-resolution space-time imaging, analysis and interpretation.

The AILARON project (Autonomous Imaging and Learning Ai RObot identifying plaNkton taxa in-situ) is an inter-disciplinary integrated effort for characterizing targeted plankton in-situ. AILARON is the first to apply the entire chain of imaging-classification-analysis-control to plankton taxa classification, especially onboard a mobile robotic platform. With the ability to monitor planktonic patches on a high spatio-temporal resolution onboard a robotic vehicle AILARON will provide a powerful and novel tool for biological oceanography with the equivalent of a microplankton robotic sniffer dog. The processing chain is guided by a human expert (as needed) via a communication link to shore to potentially alter her sampling preferences dynamically, thus ensuring the vehicle adapts on-the-fly. In doing so, it will provide an enhanced knowledge of plankton communities and their spatio-temporal distribution patterns, which has great importance for ecosystem surveillance and global change effects.

Figure 1: *Light Autonomous Underwater Vehicle (LAUV) following phytoplankton hotspots in the coastal waters near Munkholmen in Trondheimsfjorden*

The full AILARON system of imaging-classification-analysis-control workflow (Figure 3) is embedded on an LAUV (Figure 2), and is a continuous iterative process.

Imaging – A SilCam captures objects of an equivalent circular diameter >108 mm, in which the captured volume is 75.6cm^3 (45

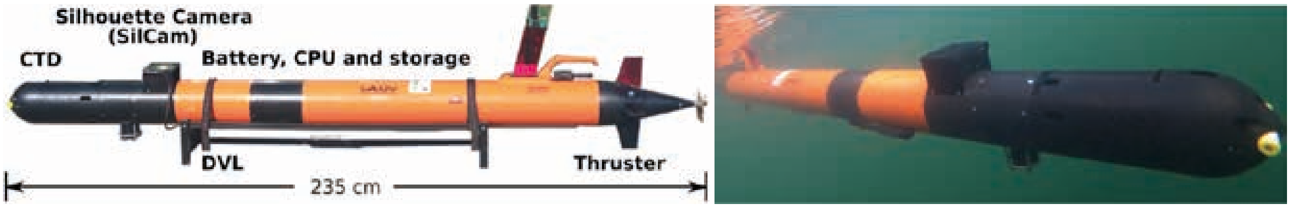


Figure 2: *The human-portable Light Autonomous Underwater Vehicle (LAUV) (Sousa et al., 2012) in Trondheimsfjorden, Norway, with a silhouette camera (SilCam), DVL (Doppler Velocity Log) and CTD (Conductivity, Temperature and Density) sensors used in* ***AILARON***

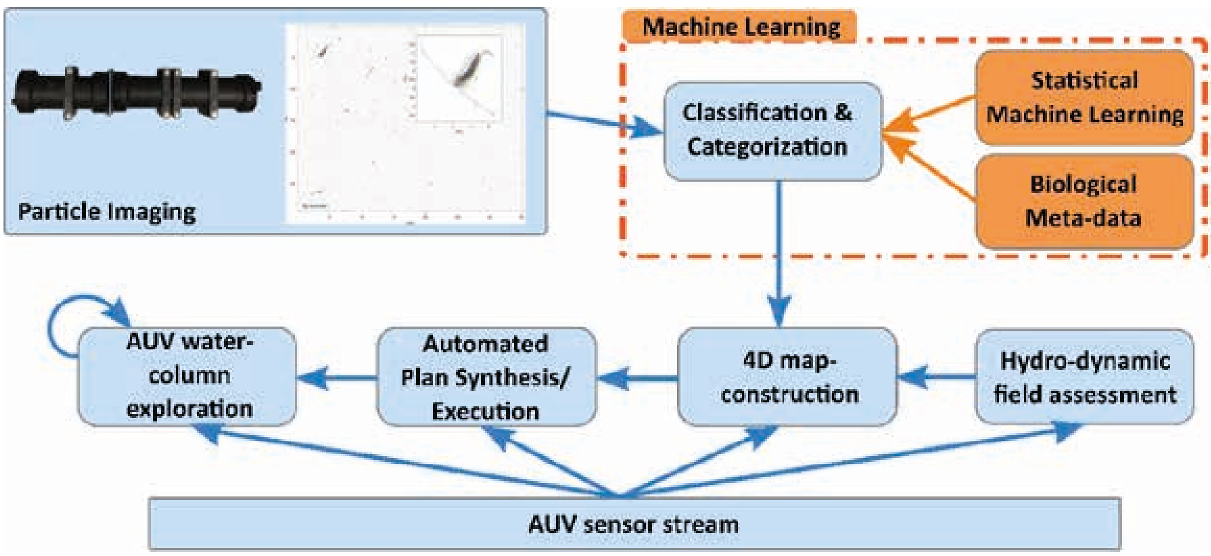


Figure 3: *System workflow and operation for* ***AILARON****. (Orange) arrows and boxes indicate offline operations used as pre-processing steps to generate the classifier for underwater operations. (Blue) arrows and boxes represent continuously running operations onboard the AUV, and include imaging, classification, sensor evaluation, estimation and plan execution. We focus on methods which facilitate the modules in the dashed red box.*

mm x 56 mm x 30 mm). The pixel resolution of the produced images is 27.5 μm. He captured images are in line with classes of planktonic organisms, such as, but not limited to: copepods (*Calanoida*) and diatom chains (*Thalassiosira spp*., *Chaetoceros spp.* and *Skeletonema spp*.).

Machine Learning – Time-series images, captured at 5 frames/ second are then fed into the DL-based image classification system, which in turn associates a probability measure indicating the likelihood that it belongs to a specific taxa. Table 1 contains example images from a database with a set of 7,728 individual planktonic images, representing seven different classes, manually tagged and classified by biologists. The inferred probabilities are logged along with spatial and temporal information for each detected particle in the image. The histograms of organism concentration in Figure 4 shows identified copepods and diatom chains at a >95% likelihood, taken at four metre intervals. The concentration is the amount of species (per litre) detected by the AUV in the water column. The cell number of diatoms is regulated by key environmental variables and the grazing pressure of zooplankton (e.g. copepods), which are affected by the size and species of prey and predator. Figure 5 shows that there were slightly lower copepod densities at a 10-20 metre depth, while higher numbers were found at the uppermost surface layer and a depth between 20-25 metres. At depths greater than 28 meters, no copepods were found. These findings exemplify a post-spring-bloom situation (in this case, April 23rd) in Trondheimsfjorden, Norway. Post-blooms of phytoplankton in this area are generally characterized by a decline in the number of diatoms. The organism concentration per group is then conveyed to the next step in the workflow to highlight community structure and spatial distribution in the water column. The output is a concentration estimate for each group, with corresponding uncertainty estimates provided by the probability distribution, median, mean and standard deviation. This, in turn, continuously updates a probability density map that shows community dispersion in 3D to generate a map of hotspots to direct an adaptive sampling process with the automated planning and execution engine.

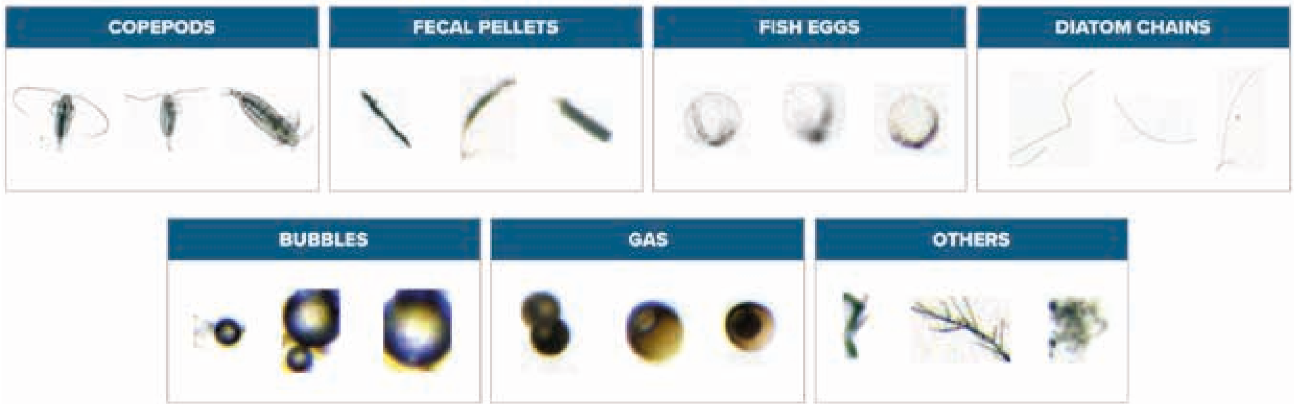


Table 1: *Instances of a labeled data set (Davies et al., 2018) of objects extracted from in-situ images and labeled manually by biologists as a prerequisite for the training process*

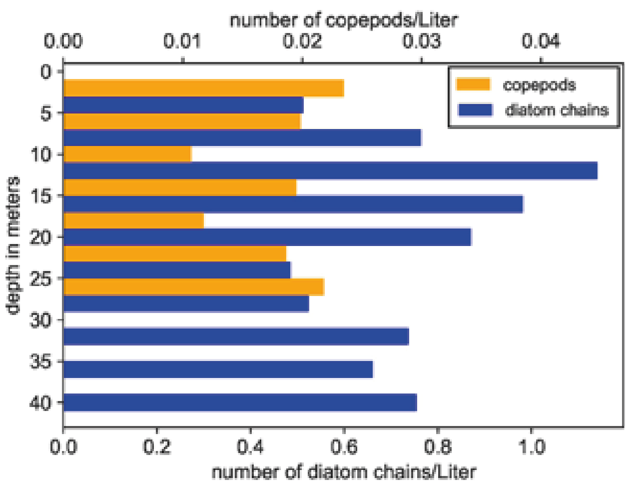


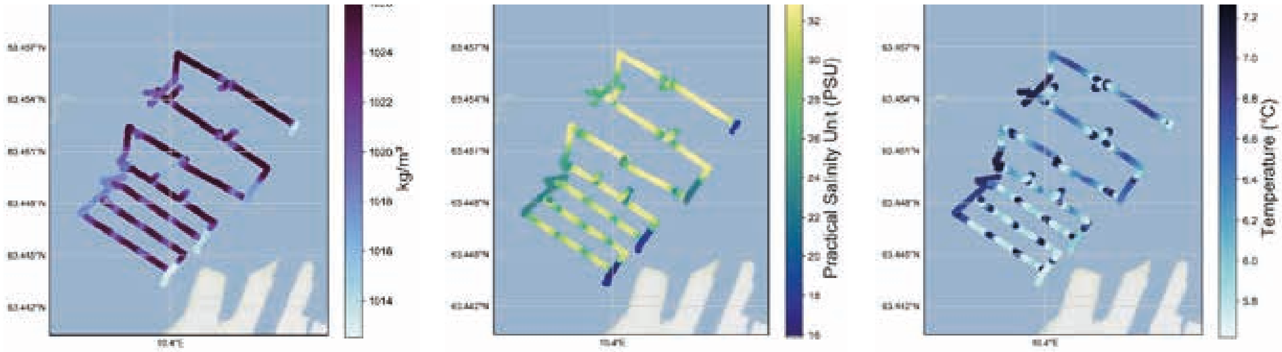
Figure 4: *Histogram of organism concentration for identified copepods and diatom chains at >95% likelihood, in Trondheimsfjorden, taken at 4-metre intervals, April 2020*

Hydrodynamics – To help predict the future positions of any observed plankton hotspots as they are advected with currents, a model of the local hydrodynamics is necessary. For these computations, the flow must be evaluated at arbitrary locations, both inside and outside the volume covered by the initial survey. From an initial survey, a set of velocity profiles are obtained using a DVL on the AUV. After discarding the measurements of poor quality, interpolation and extrapolation are used to create a local estimate of the currents at different depth layers. Once an estimate of the local hydrodynamics has been obtained from the initial survey, a Lagrangian particle transport model is applied, which predicts the temporal evolution of the plankton concentration in space and time. Numerical particles representing different types of plankton are seeded over the volume of the initial survey, with measured plankton concentrations. Each particle is individually transported through the current field, using a fixed or variable-time step integrator, applying a random walk to reflect the uncertainty in the measured currents, and optionally adding any active "swimming" behaviour according to the time of day and plankton type.

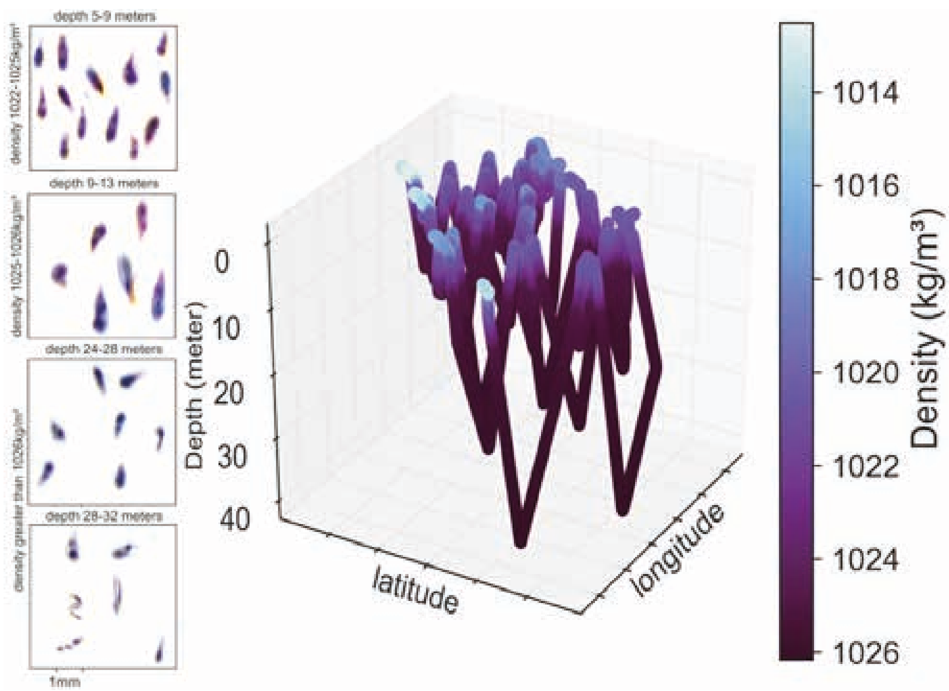
Automated Planning and Execution – The overall operational concept is for our AUV to adaptively visit planktonic hotspots as they advect in the water column after an initial fixed "lawn mower" survey. Such an adaptivity requires a deliberative decision-making given the sensor input, while projecting a future state for achieving stated goals or outcomes. Plan generation and execution embedded on a robot is continuous, dynamically adapting to the continuous sensory input from the robot's environment; this updates the internal plan representation, which in turn can alter future actions by replanning or planning synthesis. In enabling this continuous **sense**, **plan** and **act** loop, the robot can adapt to changing conditions in the real world, hence enabling a cognitive capacity that most robotic vehicles to date, fall short of. We use a mature onboard planning/execution software engine (Rajan et al., 2013; Fossum et al., 2019) that uses the input from classification to estimate a spatial probability density of the plankton-taxa classes as a spatio-temporal Gaussian Process (GP). The hydrodynamic model is used to project a hotspot location, which when visited by the vehicle utilizes a GP to systematically map an individual density field. The estimated GP and planned path are continuously updated as new measurements are gathered along a trajectory.

Sea state estimation from vessel motion responses: Smoothness and robustness using Bézier surface and L1 optimization

The complexity of the ocean environment is challenging for safe voyages and marine operations. An important consideration is thereby given to the sea states at the planning and operating stages for an offshore project. The wave spectra can be measured and detected by several measurement instruments. The article [P1-R2] presents nonparametric sea state estimation based on vessel motion responses (wave buoy analogy), and is summarized below:



(a) Density (kg/m³) (b) Salinity (PSU) (c) Temperature (°C)



(d) Density (kg/m³) and snapshots of detected plankton organisms, in this case mainly copepods, which is the dominant taxa with respect to biomass in distinct water layers.

Figure 5: *Data from an AUV mission in Trondheimsfjorden, Norway, April 2020*

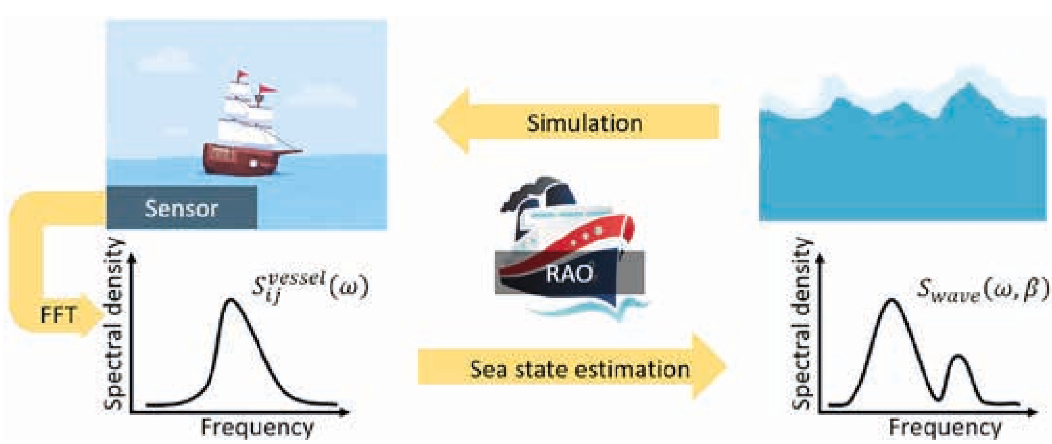


Figure 6: *Foundation of wave buoy analogy*

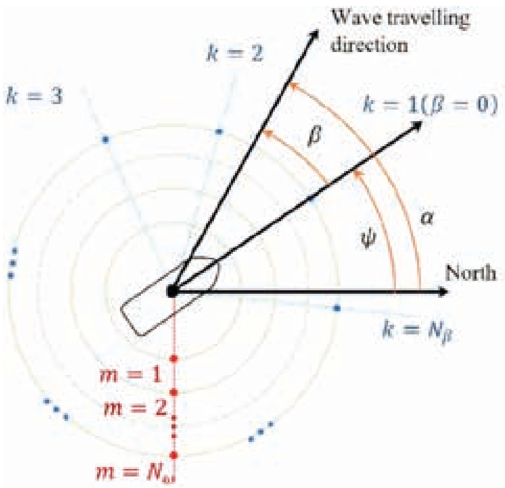


Figure 7: *Definition of angles and discretization of the wave field*

Because a vessel is asymmetric, as the cross-spectra of 6DOF vessel motions S_{ij}^{wave} are related to wave spectra S_{wave}. The relationship between the vessel motions and wave spectra are characterized by response amplitude operators (RAO), which are influenced by the hull geometry and can be calculated by well-known hydrodynamic formulas. After discretizing the directional spectrum concerning incoming wave direction β_k and wave frequency ω_m, respectively, a linear equation $b=Af$ is formulated according to the hydrodynamics with a tall matrix A, as shown in Figure 7. The vector of directional wave spectrum f can be solved as an inverse problem. However, the best-fit solution in this application does not always give a practical meaning. To help solve the problem, typical least square (LS) methods are adopted with additional implicit smoothness conditions existing in a spectrum. The research innovatively augments this classic setup in two aspects.

First, two-dimensional smoothness is achieved using the Bézier surface. Instead of considering the constant slopes between a node and its two neighbour nodes in the wave direction and frequency, respectively, the size of the smoothness scope in the discretized network can be arbitrarily selected (see Figure 8). The new smoothness condition is a more general form, in which a Bézier surface is the Cartesian product of two orthogonal Bezier curves. The classic constant-slope condition is a particular example of a Bézier curve with three nodes.

Second, the potential of sparseness in the ocean wave spectrum is realized through L1 optimization. The sparsity pattern of a wave spectrum with a threshold of 0.1 reveals the powerful components in the wave spectrum, see Figure 9. Converting from time-domain sampling, disturbances are noticed in the discretized motion cross-spectra, resulting in extra risks to the estimate results. Since L1 optimization is more robust to wild points, sparse regression is adopted in the inverse problem. The simulation results (e.g. in Error! Reference source not found.) verify that the L1 norm (1,1,1,1) has a much higher robustness against the disturbances and errors in the vessel response spectrum than the LS methods (2,2,2,2). The estimate given by the LS cost function (p_1,r_1,p_2,r_2)= (2,2,2,2) is risky. The estimates of L1 optimization (p_1,r_1,p_2,r_2)= (1,1,1,1) is "cleaner", thus showing a higher sparsity, with the energy in the estimated showing a better concentration.

Ocean Colour Hyperspectral Remote Sensing with High Resolution and Low Latency

The article [**P1-R3**] describes the hyperspectral imaging strategy, mission design and operations for the HYPSO-1 CubeSat. The mission is developed at NTNU, and is slated for launch in Q3 2021 to a 500 km altitude Sun-Synchronous Orbit. Based on current ocean colour remote sensing requirements and recommendations, the key objectives are to observe sporadic target areas in coastal regions (such as algal blooms), and quickly deliver tailored data products for use by in-situ robotic agents, operators and end users in the manner shown in Figure 11.

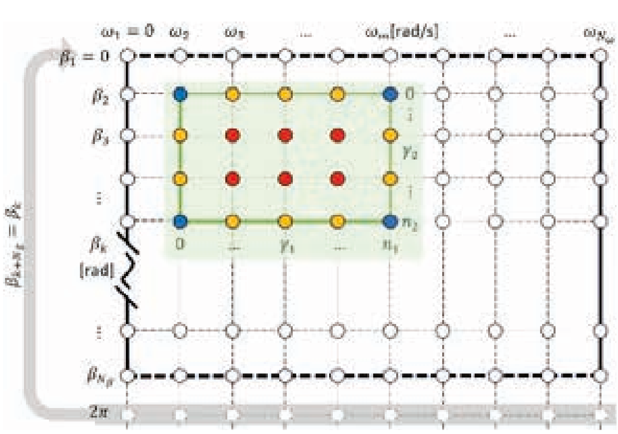


Figure 8: *Bézier surface in the discretized network*

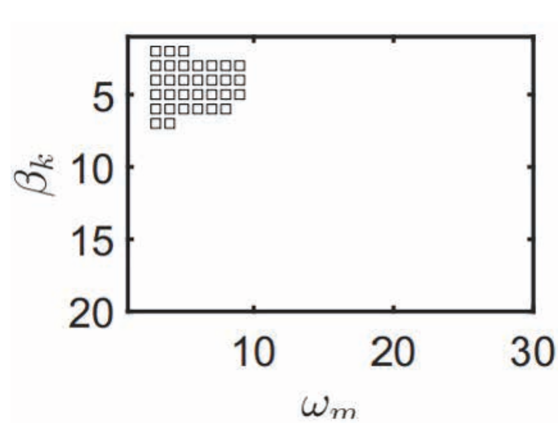


Figure 9: *Sparsity of a directional wave*

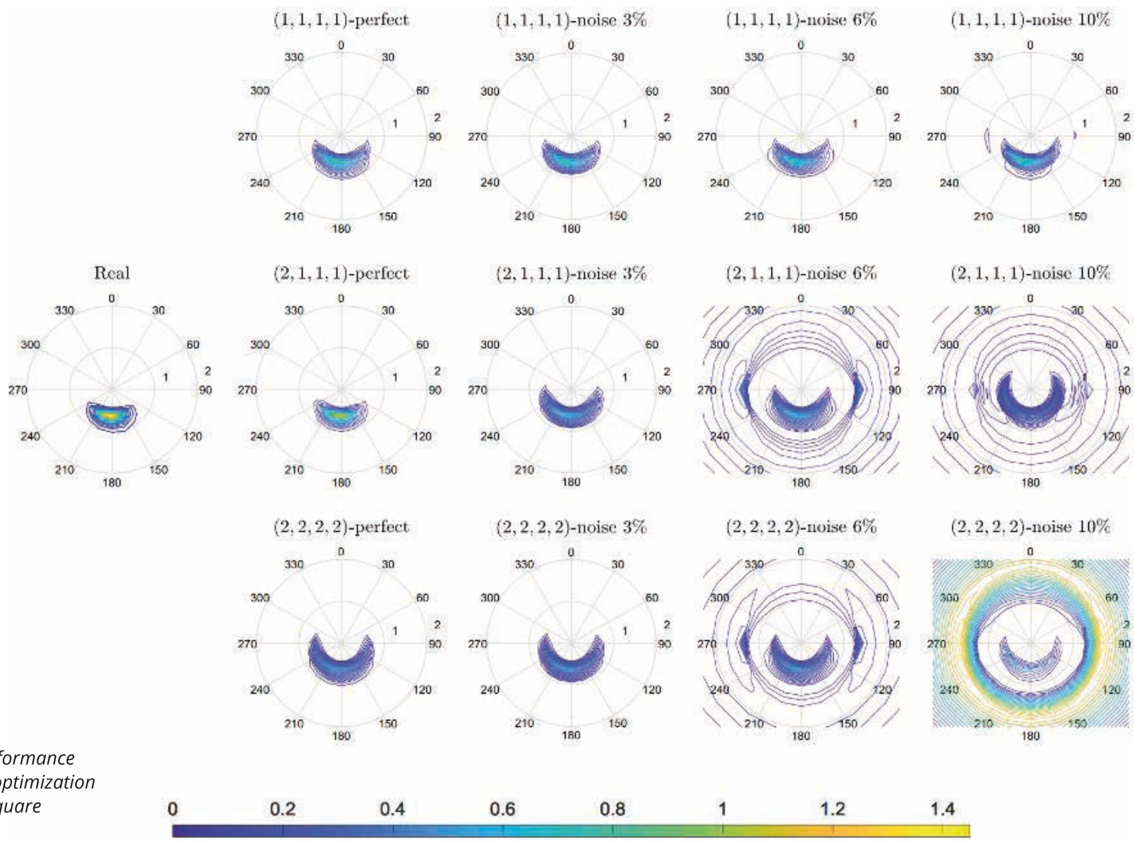


Figure 10: *The performance comparison of L1 optimization with classic least square methods*

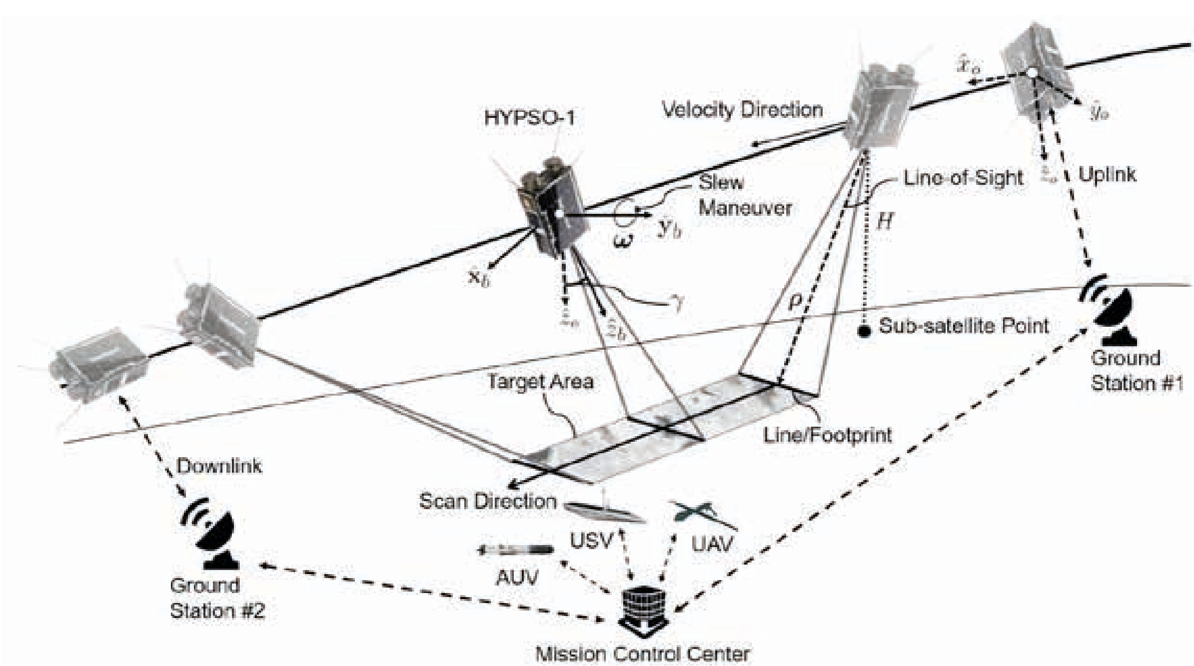


Figure 11: *Concept of Operations for HYPSO-1 mission in which uplink, observation and downlink shall happen in the same pass for use of high-quality data by operators and end users.*

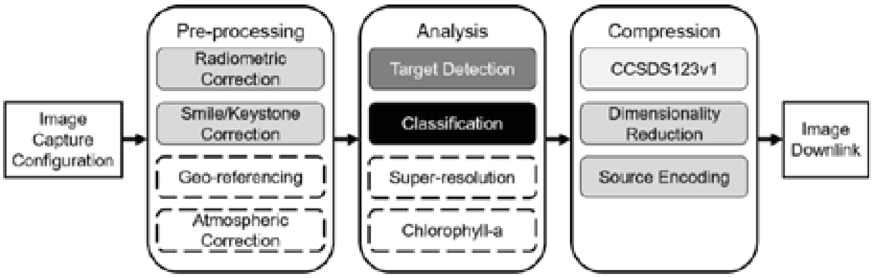


Figure 12: *Elements in the modular image processing pipelines with coloured blocks, meaning they are implemented, with dashed blocks being prospective algorithms to be uploaded. Post-launch updates and uploads are possible with our FPGA configuration.*

Push-broom Hyperspectral Imaging (HSI) Strategy

The theory-to-practice analysis on HYPSO's unique dynamic imaging strategy show that we can improve the image spatial and spectral resolution based on combining super-resolution image processing with fundamental principles in dynamical systems theory and relationships in the observation geometry, see Figure 11. A HSI with small optics constrained to fit into the small-satellite frame has evident challenges in obtaining adequate image quality. This challenge can be alleviated by utilizing the satellite's built-in control system to perform a slew manoeuvre, which moves the camera footprint against the satellite's velocity direction. The result is an increased amount of sequentially overlapping frames, which can then be processed to improve the spatial resolution and further increase the effective SNR in the image pixels.

Implementation of On-board Image Processing

Ocean colour processes with characteristic spectra, such as algal blooms, demand consistent monitoring at lower costs and a quick delivery of high-resolution data products after observation. For the latter, this demands on-board processing of the hyperspectral images in order for the big data to be sufficiently reduced to data that can be transmitted via radio communication without losing important information (i.e. pixel location and spectra of target). FPGA-implemented on-board processing elements are presented, which consist of compression with CCSDS123, dimensionality reduction, smile and keystone correction and target detection. Upon end-user requests and their acceptance criteria, the raw hyperspectral images can undergo all processing stages or each one selectively, with algorithms depicted in Figure 12.

For even more flexibility, the FPGA allows for configurability and post-launch uploads of more advanced image processing algorithms such as, for example, classification, super-resolution and geo-referencing.

Mission analysis

The HYPSO-1 mission can mitigate potential losses in aquaculture industry if it provides an early detection or warning of nearby harmful algal blooms before they reach the fish pens. The on-board processing capability saves the satellite's power budget by removing the bottleneck in limited radio communication resources. Moreover, this reduces the time to download the data to render a near real-time understanding of rapidly changing ocean colour events. We showcase a simulated operational scenario in which HYPSO-1 observes a 40 km x 40 km target area in Lofoten, and utilizes the nearby S-band ground stations at NTNU Gløshaugen, Kongsberg Satellite Services (KSAT) Svalbard and KSAT Spain. With the HSI capturing frames at 15 frames-per-second, and in combination with a slew manoeuvre to observe a 40 km x 40 km target area, the image pixel spatial resolution

Table 1: Main findings in the paper indicating imaging performance and latency of data

PARAMETER	VALUE
HSI spectral range	400-800 nm
HSI spectral resolution	3.3 nm
Swath Width	Up to 70 km
Spatial Resolution at nadir	423 m x 58.6
Spatial Resolution with slew manoeuvre	57.6 m x 58.6 m
Signal-to-Noise Ratio (sensed at Top-of-Atmosphere)	> 552 (with binning)
Nominal raw data size and downlink time	156.9 MB; 22 minutes
Losslessly compressed data size and downlink time	62.8 MB; 8.8 minutes
Reduced data size in target detection and downlink time	3.14 MB; 50 seconds

becomes approximately 57.6 m x 58.6 m instead of 423 m x 58.6 m using conventional nadir pointing. The attitude control and determination accuracy needs to be high for a consistent and uniform frame collection. When operating the HSI and satellite correctly, the results show that a delivery of custom data products to end-users is possible within some minutes while adhering to the image quality and latency requirements, see Table 1. Considering daily revisit times, even with a single satellite in polar orbit, HYPSO-1 is expected to provide data with a high spatial resolution at a higher temporal and spectral resolution than existing satellites for this kind of mapping.

Benthic communities on the Mohn's Treasure mound: Implications for the management of seabed mining in the Arctic Mid-Ocean Ridge

The Mohn's Treasure, described as an inactive sulfide mound, was discovered at a depth of 2,600 metres at the Arctic Mid-Ocean Ridge (AMOR) in 2002. In 2015, we conducted the first biological survey of Mohn's Treasure using remotely operated vehicle (ROV) photo transects and sampling. This site is covered by a thick layer of fine sediments, in which a hard substratum is only visible as rocky outcrops on ridges. The observed benthic community was typical of Arctic bathyal systems. A total of 46 species (identified as morphospecies) were recorded, with densities varying from 12.2 to 31.6 ind. m-2. The two most abundant phyla were Porifera and Echinodermata. The sediment is dominated by fields of the stalked crinoid Bathycrinus carpenterii, whereas areas of hard substratum were characterized by high abundances of several sponge species and associated fauna. Interest in commercial exploration and the exploitation of minerals from massive sulfide deposits is rising globally, and the AMOR is being targeted for mineral exploration within Norwegian waters. Gathering baseline ecological data from these poorly known sites is therefore urgent and essential if robust resource management measures are to be developed and implemented. In this article [P1-R4], the results of this ecological survey are discussed in relation to the designation of deep-sea vulnerable marine ecosystems (VMEs) and their implication in management and conservation of areas targeted by the emerging deep-sea mining industry, see also Figure 13.

Phytoplankton community succession and dynamics using optical approaches

The phytoplankton in coastal regions are responding to constant environmental changes; hence, the use of proxies derived from *in situ* frequent time-series observations and validated from traditional microscopic or pigment methods can be a solution for detecting the rapid responses of community dynamics and succession. In this study, we combined in situ high-frequency (every 30 min from May to September 2017) optical and hydrographic data from a moored buoy and weekly discrete samplings to track phytoplankton community dynamics and succession in Mausund Bank, a highly productive region off the coast of Norway. Three hydrographic regimes were observed: a mixing period (MP) in spring, the onset of stratification (transient period, TP) in summer and a stratified period (SP) in fall, with occasional strong winds that disrupted the surface stratification in the beginning of September. A bloom dominated by the diatom *Skeletonema costatum* was observed in the MP due to

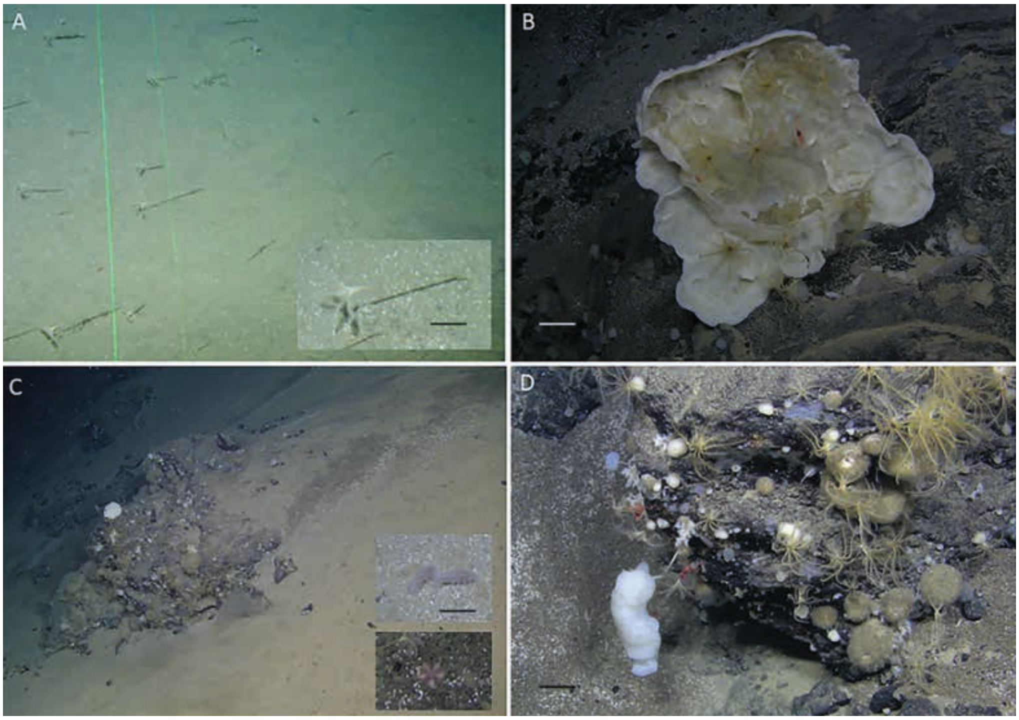


Figure 13: *Mohn's Treasure fauna. (**A**) Sedimentary plain at Site 1 with dense aggregations of the stalked crinoid* Bathycrinus carpenterii. *Insert: Close-up of one individual (scale bar = 2 cm). (**B**) Rocky outcrop with sponges and associated fauna on Site 2 (scale bar = 10 cm). (**C**) Site 3 was dominated by fine sediments with holothurians and asteroids, as well as rocky outcrops with sponges. The insert shows the holothurian Kolga species and the asteroid* Hymenaster pellucidus *(scale bar = 5 cm). (**D**) Site 4 was dominated by hard substrates with high abundance of filter feeders, in particular sponges (scale bar = 10 cm).*

an intense mixing and nutrient availability, while flagellates prevailed in nutrient-poor waters during the TP, followed by a bloom dominated by rhizosolenid diatoms (*Proboscia alata* and *Guinardia delicatula*) when stratification peaked. A mixed assemblage of diatoms (e.g. *Pseudo-nitzschia*), coccolithophores and dinoflagellates occurred during the SP, as strong winds reintroduced nutrients to surface waters. Through pigment (chemotaxonomy) and microscopic observations, for the first time in a coastal region we tested whether an "optical community index" derived from in situ measurements of chlorophyll a fluorescence (Fchla) and optical particulate backscattering (bbp) is suitable to dif- ferentiate between diatom versus flagellate dominance. Contrary to previous observations, in this article [**P1-R5**] we found a negative relationship between Fchla:bbp and diatoms:flagellate, possibly because of the influence of non-algal

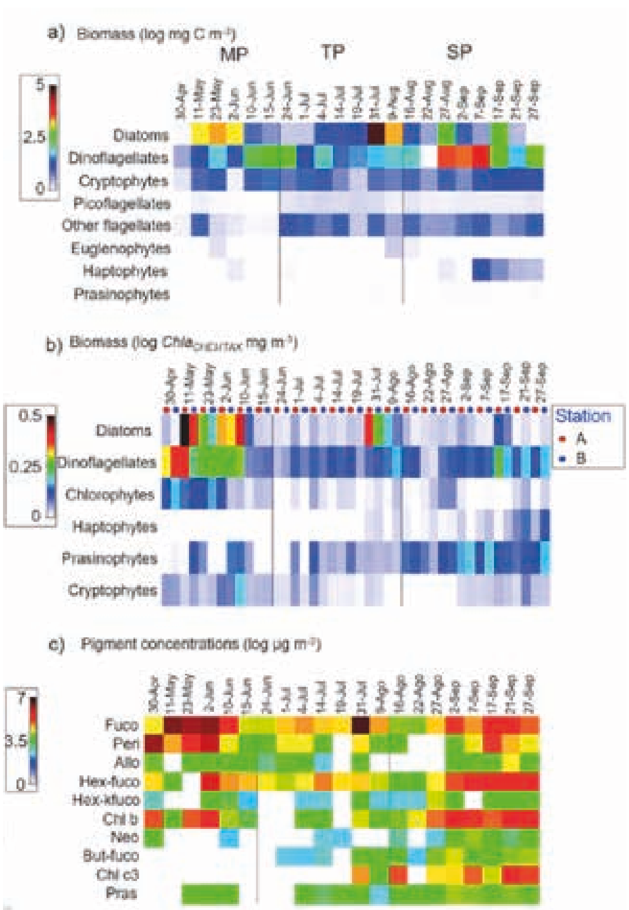


Figure 14: *Shade plot showing the phytoplankton biomass concentrations in terms of: a) carbon (derived from microscopic counts) and b) chlorophyll a from pigments estimations from CHEMTAX (*ChlaCHEMTAX*), in addition to c) pigment markers of phytoplankton groups from the upper 15 m at stations B only (a and c), or from stations A and B (b) from the end of April to the end of September 2017. All data were log-transformed to increase the importance of non-abundant groups/pigments. Vertical lines indicate periods of hydrodynamic forcing, defined as mixing (MP, mid-May to mid-June), transition (TP, mid-June to mid-August) and stratified period (SP, mid-Aug to mid-September).*

contribution (e.g. zooplankton, fecal pellets and detritus) to the bbp pool in highly productive systems, see Figure 14. This finding suggests that such a relationship is not universal, and that other parameters are needed to refine the optical community index in coastal regions.

Sensor-Carrying Platforms

Information and communication technology, autonomy and miniaturization in terms of, for example, micro-electro-mechanical systems, are enabling technologies with a significant impact on the development of sensors, sensor-carrying platforms, control systems, data gathering, storage and analysis methods. Sensor-carrying platforms are grouped in stationary devices such as landers and moorings to dynamic platforms, including marine robotics, ships, aerial systems and remote- sensing satellites from space. Lately, the development of low-cost small satellites with customized payload sensors and accessible mission control centres has also opened for a democratization of the space for remote sensing. The mapping and monitoring strategy may be carried out by each type of sensor-carrying platform suitable for the mission, see Figure 15. However, we see a quantum leap by operating heterogeneous sensor-carrying platforms for the most efficient mapping and monitoring in spatial and temporal scales. We are facing a paradigm shift in terms of resolution and coverage capabilities, as there have been several research efforts to improve the technology and methodology for mapping and monitoring of the oceans. Today, we see that the mapping coverage may be 100–1,000 times higher than the state-of-the-art technology six years ago. The entailed increase in data harvesting also creates new challenges in the handling of big data sets. There is an increasing need to update the oceanographic and ecosystem numerical model capabilities, taking full benefit of the ongoing shift in technology. The Arctic can truly be characterized as a remote and harsh environment for scientific operations, and even more demanding during the Polar Night due to the darkness. During winter operations, extreme coldness may also be a challenge dependent on the weather conditions. Enabling technology and proper operational procedures may be the only way to reveal and understand the processes taking place there. The spatial scale is enormous, and as several research campaigns have already taught us, the variability is huge, not only during the seasons but also over the years. This clearly also tells us the importance of prolonged presence. In this chapter, we will briefly present the various sensor-carrying platforms and payload sensors. We will also describe the philosophy behind integrated operations using heterogenous platforms, and why and how to bridge science and technology being successful in the development of autonomous systems for efficient and safe operations. Examples and experience from Arctic missions are presented in this article [**P1-R6**].

Marine Micro- and Macroalgae in the Polar Night

Microalgae have unique adaptions including low metabolic activity, utilization of lipid storage, and resting stage formation to survive the Polar Night. Some species are mixotrophic or heterotrophic and do survive periods that are not favorable for photosynthetic (autotrophic) growth, such as the Polar Night. In addition, the autotrophic and mixotrophic species seem to keep the key

Figure 15: *Adaptive sampling strategies*

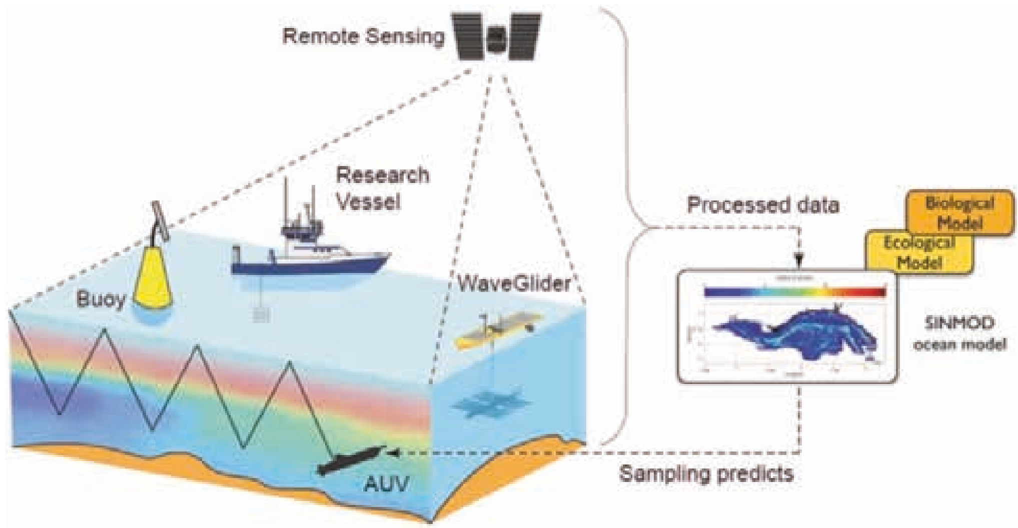
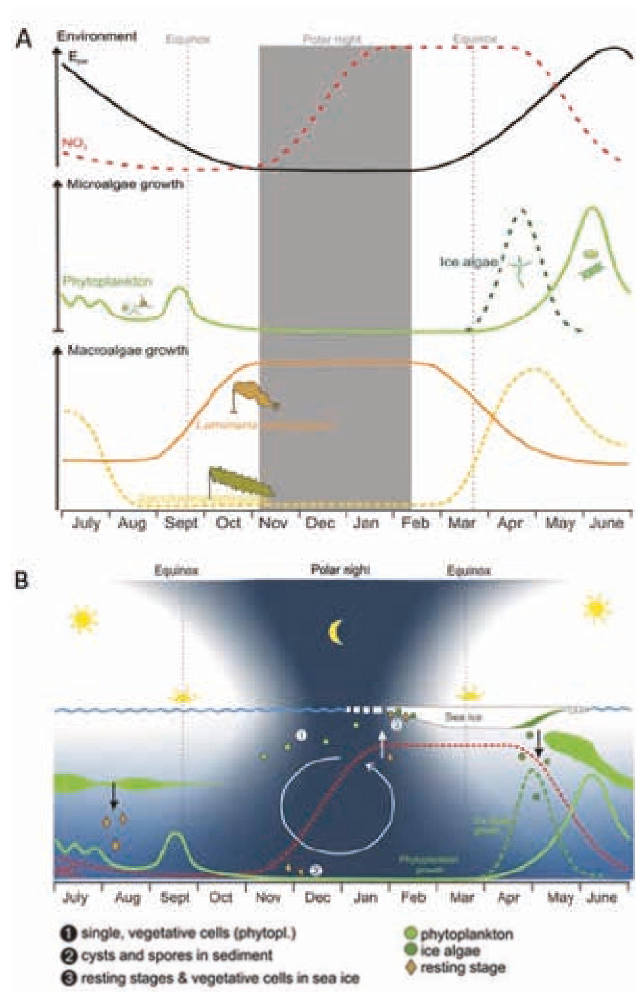


Figure 16: *(**A**) Seasonal variability of the limiting nutrient concentration (illustrated by the nitrate, NO_3, in the upper panel) and irradiance (EPAR) for algal growth (upper panel). Idealized seasonal growth curves for typical representatives of sea-ice algae and phytoplankton (middle panel), and for two kelp species (*Saccharina latissima *and* Laminaria solidungula*) with different growth strategies (lowest panel). (**B**) Distribution and state of microalgae during the Polar Night and the seasonal context throughout an entire year. During the Polar Night, microalgae can be found as vegetative cells in very low densities in the water column (1), as well as resting stages in surface sediments (2), or in either state inside sea ice (3). All three subgroups serve as seeding populations for the spring blooms initiated once there is sufficient light available. Non-stratified water masses are overturning during wintertime, replenishing the nitrate reservoirs (red-dotted curve) in surface waters, and thereby preparing the ground for next year's algal spring blooms.*



components of the photosynthetic apparatus intact during the dark period, which allows them to rapidly resume growth once light comes back in the spring. In contrast, some macroalgal species may act as "season anticipators", and utilize the winter darkness or early spring period as their major growth seasons. This chapter elucidates aspects of the ecology of micro- and macroalgae, with a focus on the dark season. It is comprised of six parts and starts with an introduction (the section entitled "Introduction") about Arctic marine micro- and macroalgae. The section "The Key Abiotic Environmental Variables Related to Micro- and Macroalgae" reviews the key abiotic environmental variables related to micro- and macroalgal growth and survival. The seasonal development of the different groups of microalgae is described in the section entitled "Microalgae", comprising phytoplankton, microphytobenthos and sea-ice algae. The section entitled "Macroalgae" introduces the three classes of macroalgae (phaeo-, rhodo- and chlorophytes), with information about biological variables, seasonal processes and habitats. Using selected examples, the section entitled "Ecophysiology of Algae in the Polar Night" [**P1-R7**] sheds light on the ecophysiology of microalgae and macroalgae in the Polar Night, see also Figure 16.

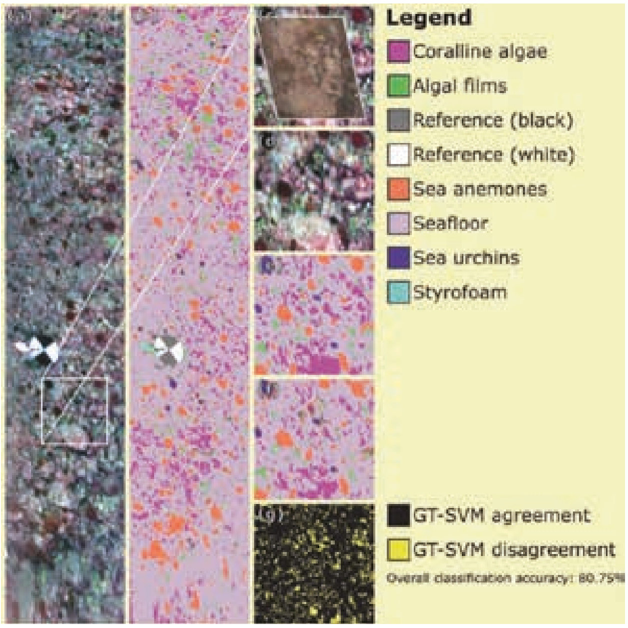


Figure 17: *Analysis of ROV-based underwater hyperspectral imaging (UHI) data from Kvadehuken, Kongsfjorden and Svalbard, during the Polar Night (January 2016). Panel (a) shows an RGB photomosaic representation (R: 490 nm, G: 550 nm, B: 620 nm) of one of the recorded UHI transects. The transect covered an area of approximately 5.90 × 1.15 m. Panel (b) shows the results of a support vector machine (SVM) classification of the same transect. Panels (c–g) correspond to a specific 60 × 60 cm subset area within the transect. The panels, respectively, show a dive-acquired photograph of the area (c; UiT, The Arctic University of Norway 2018), an RGB visualization of UHI data from the area (d), a manually labelled ground truth (GT) image of the area (e), the SVM classification results from the area (f) and a comparison of the GT image and SVM classification (g).*

Operative habitat mapping and monitoring in the Polar Night
The Polar Night has long been regarded as a period of no biological activity. As a logical consequence, environmental management has primarily been neglected in this period. We will use the Northguider accident in December 2018 as a case study for the need to prioritize operative habitat mapping and monitoring to provide a sufficiently knowledge-based environmental operative management. After the ship ran ashore in a remote location in the northern part of Svalbard, the entire crew was safely rescued and airlifted back to Longyearbyen within hours. However, the ship remained, potentially posing a threat to wildlife – not only wildlife expected to return in the spring, but also for the many organisms that we now know are present and active during the Polar Night. Even so, there is still a strong need to provide a necessary understanding of the dynamic marine biodiversity at the sea surface, the water column and the seafloor during the Polar Night, focusing on the threats for ecosystems and habitats. Please see the article [P1-R8] and Figure 17 for more information.

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Marine Robotic Platforms

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Key Scientists: Profs. Asgeir J. Sørensen, Thor I. Fossen, Tor A. Johansen, Marilena Greco and Geir Johnsen

Scientists at NTNU: Profs. Odd M. Faltinsen, J. Tommy Gravdahl, Martin Ludvigsen, Edmund Brekke, Ingrid Schjølberg, Roger Skjetne, Maarja Kruusmaa, Claudio Lugni, Kjetil Skaugset, Houxiang Zhang, Rune Storvold, Pedro De La Torre, Glaucia Fragoso, João Sousa, Annette Stahl, Nicole Aberle and Tor Nordam

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Research activities:

This project concerns the development of robotic platforms for autonomous marine operations and systems, including research on the following:

- Guidance, navigation and control (GNC) systems for autonomous ships, autonomous underwater vehicles, unmanned aerial vehicles and small-satellite systems
- Authenticated encryption of real-time GNC systems
- Dynamic optimization
- Fault tolerance
- Cooperative multi-vehicle control
- Situation awareness
- Bio-mimics: Bio-cyber-hydrodynamics
- Multi-scale and distributed systems for sensing and actuation
- Unmanned surface vehicles to estimate the effect of ambient light on zooplankton vertical migration during the polar night
- AUVs used to estimate phytoplankton blooms dynamics
- Mapping Historical Shipwreck in the High Arctic Using Underwater Sensor-Carrying Robots
- Advancing ocean observation with an AI-driven mobile robotic explorer (AUV)

Main results

Wave-Powered Surface Vessel for Persistent Ocean Observation

The AutoNaut, see Figure 1, is a five-metre ocean-going vessel equipped with a propulsion system that exploits waves to generate forward propulsion. Equipped with three deck-mounted solar panels, the AutoNaut uses the solar energy harvested on the on-board battery bank to support electrical steering, data collection and autonomous navigation capabilities. The vessel is equipped with a scientific payload sampling physical water properties, such as temperature, salinity, chlorophyll, oxygen concentration, wind and currents speed and direction.

Figure 1: *AutoNaut operating in the Trondheimsfjord.*

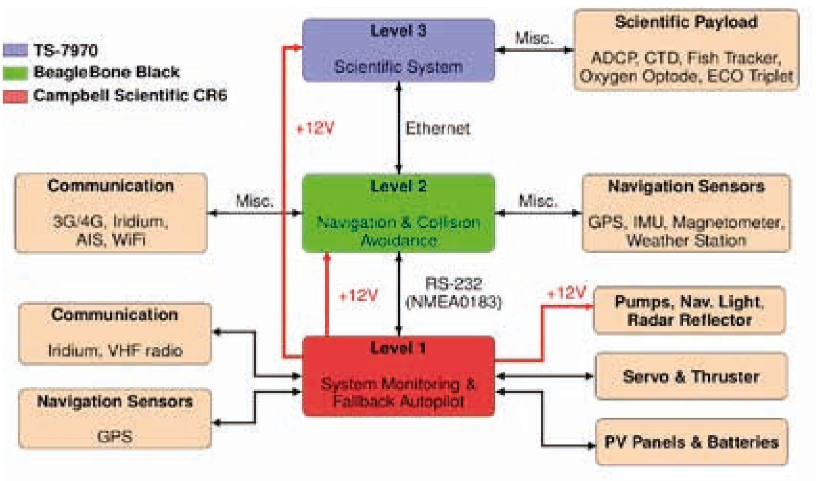

Figure 2: System architecture

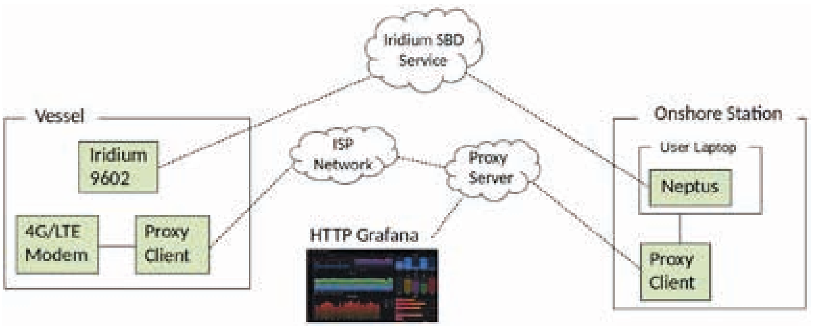

Figure 3: Communication architecture

Sustainable, persistent open ocean observation

The abilities to propel and power itself enable continuous operations for weeks, making the AutoNaut a persistent and sustainable observational presence in the ocean. This transforms current ocean monitoring methods, so far mostly based on ship-based operations and measurements. The conventional observations methods are not continuous, cause substantial release of CO_2, disturb the boundary layer significantly and are not cost-effective, and therefore limited in scaling across space and time.

Control system architecture

NTNU purchased the vessel in 2017, and implemented a customized system architecture, as shown in Figure 2. The control and communication systems were tested on a number of field exercises in 2018 and 2019, mainly in the Trondheimsfjord.
In 2020, the focus moved towards sensor data collection and management, and open ocean testing. Several automatic routines (Figure 3) were implemented in order to trigger underwater sensors, and process, store and dispatch data depending on the available communication link (radio, 4G/LTE, Satellite), [**P2-R1**].

Fish Tracking in Nordfjord

iIn May 2020, the AutoNaut was involved in a week-long mission whose objective was the study of Atlantic salmon smolt migration in western Norway (Figure 4). The mission consisted of persistent navigation along a narrow fjord approximately 100 km long. The vessel was equipped with an acoustic hydrophone able to pick up acoustic underwater signals emitted by tagged salmons. The exercise presented a new methodology in the field of acoustic telemetry, and proved the benefits of employing wave-powered vehicles in the study of fish migration processes.

Open Ocean Experiments

Two main operations took place during the summer of 2020. Both started in Mausund (Frøya, Trøndelag), and involved long-term missions whose goal was observing navigation performances in the open ocean. The first deployment lasted three days, in which the vehicle navigated up to 40 km far from the coast, and continuously collected water-related data. Data compression and dispatch routines were successfully tested, with an IoT platform enabling biologists and oceanographers to observe sampled physical properties as the mission evolved (Figure 5). The second deployment saw the vehicle engaged in a two-week long operation. The primary purpose of this exercise was to observe

Figure 4: *Fish detection timestamping*

Figure 5: *Open ocean experiments*

the durability of the developed system architecture and of the vessel itself. Autonomous navigation and communication proved to be robust and reliable. The vessel covered several hundreds of kilometres in two weeks, and proved to have a good capability for coping with strong currents, wind and high waves, typical of the open ocean.

Contacts: Alberto Dallolio and Professors Jo Arve Alfredsen and Tor Arne Johansen.

Subsea collision avoidance

Avoiding collisions is an essential goal of the control system of autonomous vehicles.
At AMOS, we have developed a reactive algorithm for avoiding moving obstacles in a three-dimensional space, and shown how the algorithm can be applied to an underactuated underwater vehicle, including theoretically, through numerical simulations and full-scale experiments [P2-R2].

The algorithm

The algorithm is based on maintaining a constant avoidance angle to the obstacle, which ensures that a guaranteed minimum separation distance is achieved. The algorithm can thus be implemented without any knowledge of the obstacle shape.
The avoidance angle is designed to compensate for obstacle movement, and the flexibility of operating in 3D can be utilized to implement traffic rules or operational constraints. We exemplify this by incorporating safety constraints on the vehicle pitch and by

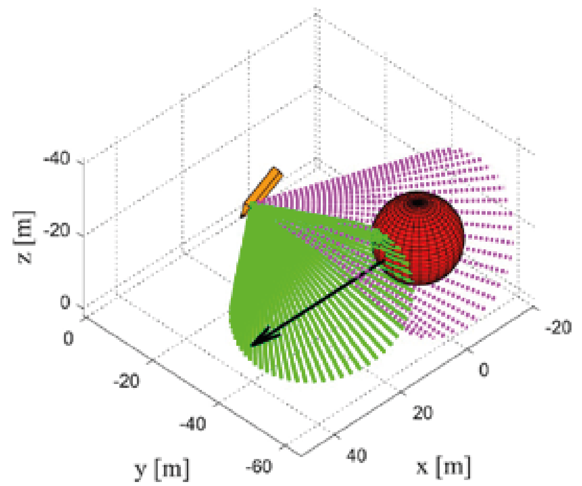

Figure 6: The extended vision cone (dotted magenta) is compensated for the velocity of the obstacle (black arrow) to create the compensated vision cone (solid green).

***Figure 7:** The Hugin HUS vehicle.*

distance to the obstacle is kept, the algorithm creates an extended vision cone from the vehicle to the obstacle, and compensates this cone for the obstacle velocity. The flexibility offered by operating in a 3D space is then utilized when choosing a safe direction along this cone to avoid the obstacle. The algorithm is only required to know the vision cone from the vehicle to the obstacle, as well as the obstacle velocity, and not the complete obstacle shape. Hence, algorithm implementation is kept simple, using measurements that are readily available on most platforms.

The underactuation of the vehicle induces a sway and heave movement while turning. To avoid uncontrolled gliding into the obstacle, we account for this movement using a Flow frame controller, which controls the direction of the vehicle's velocity, rather than just the pitch and yaw.

We have been able to prove, and have derived explicit conditions under which it is ensured that the resulting manoeuvre is safe and successful.

Simulations and experimental results

The theoretical results are verified through numerical simulations, and through full-scale experiments on the Hugin HUS autonomous underwater vehicle (Figures 7-8). Whereas the simulations illustrate the performance of the system under ideal conditions, the experiments further strengthen the results by demonstrating the performance of the proposed algorithm when applied to a case with unmodeled disturbances and sensor noise, and by showing how the modular nature of the collision avoidance algorithm allows it to be applied on top of a commercial control system.

Contacts: Martin Syre Wiig and Kristin Y. Pettersen

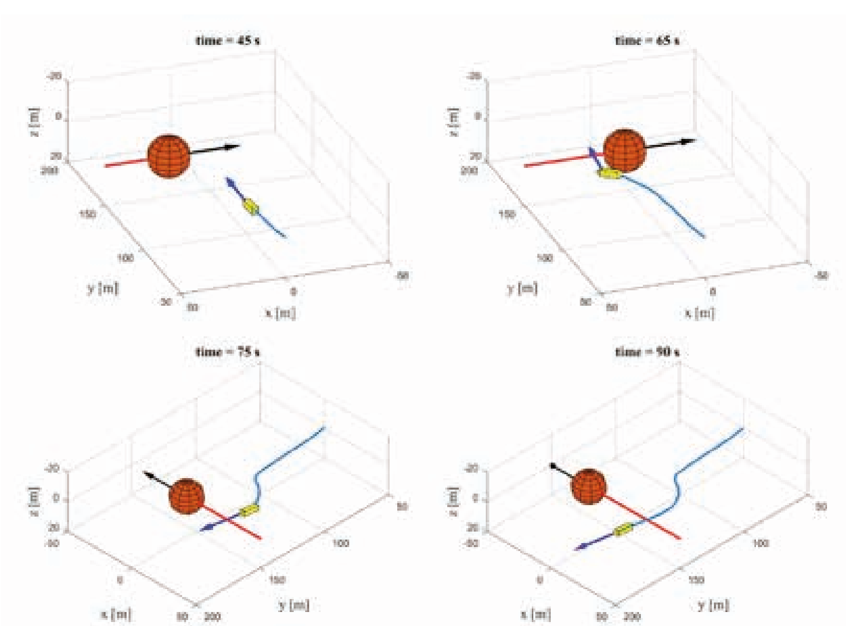

***Figure 8:** Snapshots from an experiment in which the obstacle crosses horizontally in front of the AUV.*

Mapping the Historical Shipwreck Figaro in the High Arctic Using Underwater Sensor-Carrying Robots

In 2007, a possible wreck site was discovered in Trygghamna, Isfjorden, Svalbard by the Norwegian Hydrographic Service. Using (1) a REMUS 100 autonomous underwater vehicle (AUV) equipped with a sidescan sonar (SSS) and (2) a Seabotix LBV 200 mini-remotely operated vehicle (ROV) with a high-definition (HD) camera, the wreck was identified in 2015 as the Figaro: A floating whalery that sank in 1908. To the best of our knowledge, the Figaro is currently the northernmost wreck in the world to be investigated by archaeologists. Because the wreck is protected by law as an underwater cultural heritage (UCH) site, only non-intrusive methods could be used during surveys. In this study, we demonstrate how using multiple complementary remote sensing techniques can be advantageous with respect to acquiring a holistic overview of a recently discovered wreck site. In January 2016, the wreck was revisited, and a full photogrammetric survey of the site was conducted with a Sperre Subfighter 7500 medium-class ROV. In addition to stereo camera images, HD video and underwater hyperspectral imagery was also obtained from the wreck site. In terms of data analysis and interpretation, in the current study the emphasis was put on the photogrammetric 3D model and the underwater hyperspectral imagery. The former provided an excellent general overview of the Figaro wreck site, whereas the latter supplied detailed information from a 14.65-m2 sub-area situated on the top of the wreck. By analysing classified underwater hyperspectral imagery in context with supplementary information from the 3D model, the levels of biofouling associated with different marine archaeological substrate types were assessed. Our findings suggest that strongly protruding archaeological objects support significantly higher levels of biofouling than their surroundings, and consequently that high-density biological assemblages could serve as proxies for identifying human-made artefacts on the seafloor [**P2-R4**].

Contacts: Aksel Mogstad, Øyvind Ødegård, Asgeir Sørensen, Geir Johnsen

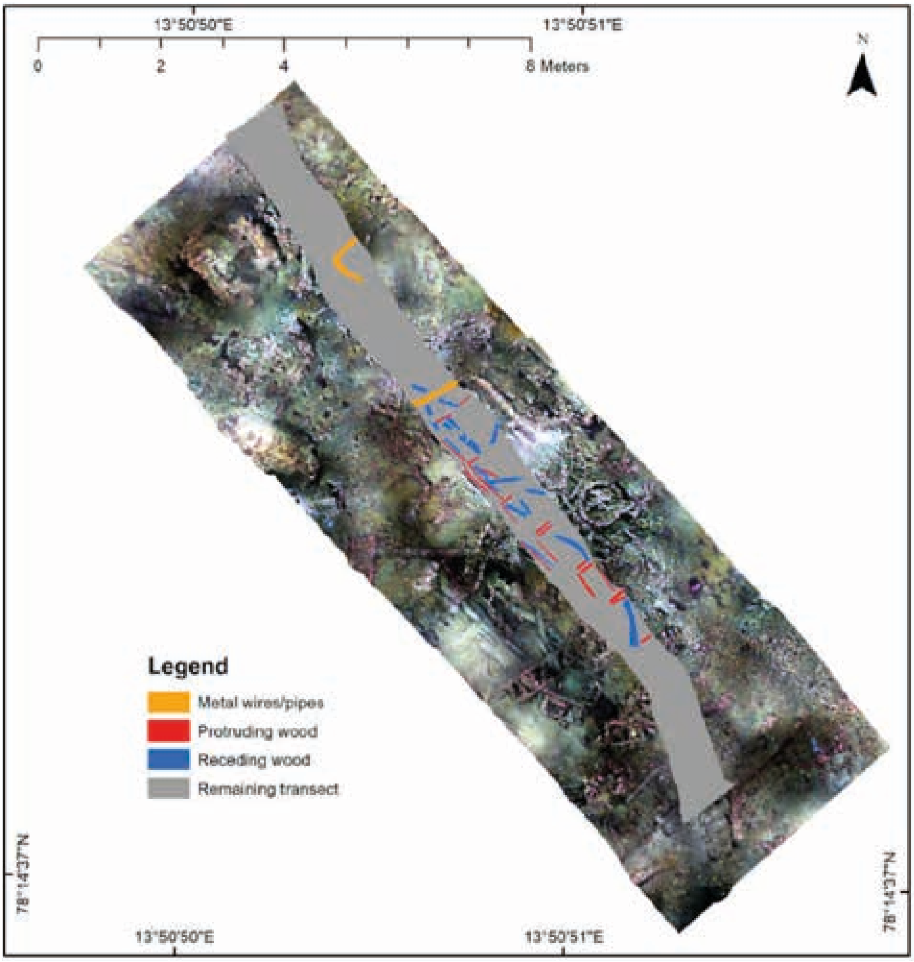

Figure 9: *Regions of interest (ROIs) corresponding to different marine archaeological substrate types in the analysed underwater hyperspectral imaging (UHI) ROV transect from the Figaro wreck site. The background image is a contrast-enhanced subset of the Figaro orthophoto; Mogstad et al. (2020).*

Advancing ocean observation with an AI-driven mobile robotic explorer (AUV).

Rapid assessment and enhanced knowledge of plankton communities and their structure in the productive upper water column is of crucial importance to understand the impact of the changing climate on upper ocean processes. Enabling persistent and systematic observation by coupling the ongoing revolution in robotics and automation with artificial intelligence methods will improve the accuracy of predictions, thereby reducing measurement uncertainty and accelerating methodological sampling. Furthermore, progress in real-time robotic visual sensing and machine learning has enabled high-resolution space-time imaging, analysis and interpretation. We describe a novel mobile robotic tool for upper water-column biota to enable intelligent on-board sampling to autonomously target specific mesoplankton taxa. Such a tool will accelerate the time-consuming process in asking, "Who is there?", and aid the advancement of oceanographic observation.

AILARON (Autonomous Imaging and Learning Ai RObot identifying plaNkton taxa in-situ) is an inter-disciplinary integrated effort for characterizing targeted plankton in-situ. Our AUV uses a camera to image microorganisms in the photic zone, process imagery in-situ, categorize and classify based on Machine Learning, generate a probability density map and uses an advanced AI-based controller to return to the most coherent "hotspots" with respect to species of interest over the survey volume.

Contact: Aya Saad, Annette Stahl, Geir Johnsen

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P2-R3. **I.-L. Borlaug, K.Y. Pettersen and J.T. Gravdahl**, "Tracking control of an articulated intervention AUV in 6DOF using generalized super-twisting: Theory and Experiments", IEEE Transactions on Control Systems Technology, 2020.

P2-R4. **A. Mogstad, Ø. Ødegård, S.M. Nornes, M. Ludvigsen, G. Johnsen, A. J. Sørensen, J. Berge**, "Mapping the historical shipwreck Figaro in the high Arctic using underwater sensor-carrying robots", Remote Sens. 12, 2020, 997. https://doi:10.3390/rs12060997.

P2-R5. **A. Saad, A. Stahl, A. Våge, E. Davies, T. Nordam, N. Aberle, M. Ludvigsen, G. Johnsen , J. Sousa, K. Rajan**, "Advancing ocean observation with an AI-driven mobile robotic explorer". Oceanography (in press), 2020.

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- Skal lære roboter å samarbeide under vann. By Sigmund Bolme, Gemini 19.10.2020.

Plenary lectures at international conferences:

- **Pettersen, Kristin Ytterstad**. Snake robots. Hendrik W. Bode *Lecture at the 59th IEEE Conference on Decision and Control*, Jeju Island, Republic of Korea, 14-18 December, 2020.
- **Sørensen, Asgeir J.** Step change in ocean and Arctic research capabilities using autonomous marine robots, Science, 29 January 2020, Arctic Frontiers, Tromsø, Norway.

Figure 11: *Subsea charging and docking plate in the Trondheimfjord.*

PROJECT 3: Risk management and maximized operability of ships and ocean structures

Project manager: Prof. Jørgen Amdahl

Key Scientists: Profs. Asgeir J. Sørensen, Thor I. Fossen, Tor A. Johansen, Marilena Greco.

Scientists at NTNU: Profs. Odd M. Faltinsen, Torgeir Moan, Ingrid B. Utne, Morten Breivik, Edmund Brekke, Marta Molinas, Roger Skjetne, Ekaterina Kim, Trygve Kristiansen, Zhen Gao, Erin E. Bachynski, Josef Kiendl, Lars Imsland, Claudio Lugni, Martin Slagstad, Pål Takle Bore, Zhengru Ren, Mathias Marley, Einar Ueland, Sven Are Tutturen Vernø, Andreas Reason Dahl.

Other involved scientists: Adjunct Profs. Kjetil Skaugset, Kjell Larsen, Ulrik D. Nielsen, Oleksandr Tymokha, Vahid Hassani, Trong Dong Nguyen, Giuseppina Colicchio, Tord Hansen Kaasa, Laxminarayan Thorat.

Relevant research activities, carried out this year, dealt with:

- Numerical studies relevant for semi-flexible and rigid closed fish farms in waves
- Experimental analysis for closed and semi-closed fish farms in waves
- Theoretical investigations of resonant three-dimensional nonlinear sloshing in a square base basin
- Numerical study on the influence of viscosity and non-linearities in wave-induced motions of a semi-displacement platform relevant for offshore wind farms
- Uncertainties of ship speed loss evaluation under real weather conditions
- Parametric roll resonance for a fishing vessel with and without forward speed
- Experimental and numerical study of hydrodynamic loads and motions of a damaged midship section in waves
- Experimental and theoretical study of slamming induced hydroplastic structural response
- Development of novel methods and solution strategies for problems involving free-surface flows and steep-wave propagation
- Determination of impact energies from drifting ice features in stochastic sea
- Assessment of structural damage to platform columns form ice impact
- Assessing the potential for design improvements for large monopile wind turbines through load-mitigating control
- Design and analysis of mooring systems for semi-submersible floating wind turbines in shallow water conditions (water depth of 50-100 m)
- Dynamic analysis of novel gearbox configurations for offshore wind turbines
- Fully coupled numerical modelling of the hydraulic blade pitch actuator on a SPAR floating wind turbine during fault conditions
- Estimating uncertainties in hydrodynamic model testing of floating wind turbines
- Reviewing the state of response analysis tools from a reliability perspective

Highlights

Closed fish cages in the sea are proposed as a new concept in marine aquaculture, replacing the conventional net cages in order to meet ecological challenges related to fish lice and escapes. Several types of closed cages have been suggested, and they are categorized according to structural properties such as flexible membrane structures (fabric), semi-flexible structures (glass fibre) and rigid structures (steel or concrete). In order to be able to develop safe and reliable structures, more knowledge is required on the seakeeping behaviour of closed cages in waves, and on the structural response to the wave loads. For this purpose, a linear theory of a 2D semi-flexible closed fish cage in waves (see Fig. 1) has been developed and used to assess the importance of hydroelasticity (coupling between structural and hydrodynamic problems) [P3-R1]. The stress in the curved beam part of the closed fish cage was examined for increasing and decreasing stiffness relative to a reference composite structure; one stiffer and two softer cases have been analysed (see Fig. 2).

The results in regular waves indicate that to use the quasi-static assumption in structural stress calculation is conservative within the given frequency range for all examined stiffnesses and

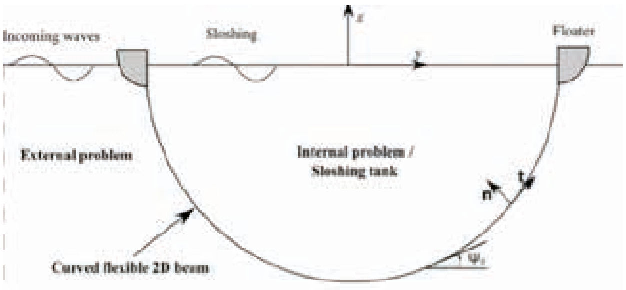

Figure 1: *Illustration of the 2D semi-flexible closed fish cage in waves.*

frequencies, except for frequencies very close to the second sloshing frequency. Close to this, a localized peak can be observed in the coupled hydroelastic results for all the examined stiffnesses. The structural stress in irregular seas was also examined, thus showing no indication of increased stress close to the second sloshing frequency. However, this is not a surprising result since the stress peak is very localized in frequency, and the accumulated effect on the stress standard deviation is therefore small.

We also continued our investigation on **violent sloshing phenomena in closed partially filled cages/tanks** using an analytically oriented approach. The last effort examined a square base basin under three-dimensional, non-parametric cyclic tank forced motions (combined sway, pitch, surge, roll and yaw) [**P3-R2**]. We were able to prove that there exists an asymptotic equivalence between the steady-state resonant waves due to sway, surge, roll, pitch and yaw, and those excited by a suitable horizontal elliptic orbital tank motion. The asymptotically equivalent waves possess the same stability properties. This means that, instead of making an exhausting search of all possible periodic non-parametric excitation scenarios, one can investigate the steady-state wave regimes and their stability versus the following three input parameters: the angular position, $0 \le \gamma \le \pi/4$, the semi-axes ratio, $0 \le |\delta_1| \le 1$ and the direction (counter- or clockwise) of the equivalent orbit. From the analysis, circular orbit causes stable swirling waves, but may also excite stable nearly-standing waves. The orbit direction does not affect the wave-amplitude response curves for wall-symmetric and diagonal angular positions, whereas the latter is not true for oblique-type elliptic forcing. When the semi-axes ratio $|\delta_1|$ changes from 0 to 1, the response curves exhibit astonishing metamorphoses that significantly influence the frequency ranges of stable nearly-standing/swirling wave modes and irregular (chaotic) sloshing.

Motion predictions of floating bodies in extreme waves represent a challenging problem in marine hydrodynamics. For this reason, many seakeeping models have been formulated over the years in order to predict wave-induced motions using simplified flow theories, usually based on potential-flow assumption. However, neglecting viscous effects in the wave-induced forces might greatly underestimate the energy dissipated by the system. This problem is particularly relevant for unconventional floating bodies at resonance. In these operating conditions, the linear assumption is no longer valid and conventional Boundary Element Methods, based on potential flow, might predict unrealistic large responses

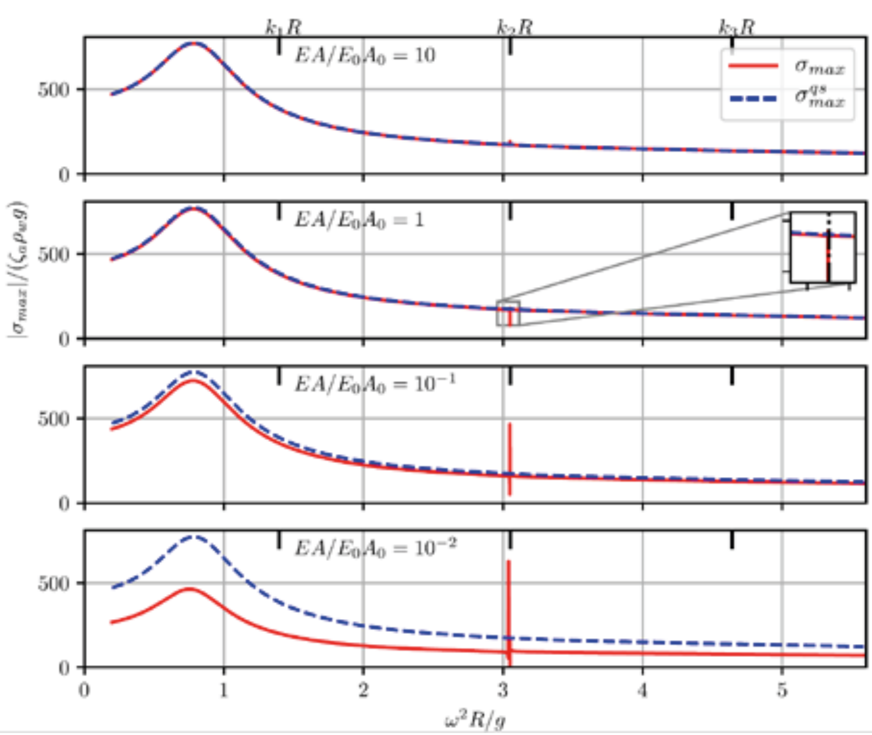

Figure 1: *Transfer function of the maximum stress in the circular beam part of the cage for varying stiffness EA. E0A0 is the stiffness of the reference composite structure.* $|\sigma_{max}|/\zeta_a\rho_w g$ *is the maximum nondimensional stress at a given non-dimensional squared incident-wave frequency* ω^2R/g *found from a full hydroelastic analysis, and* $|\sigma^{qs}_{max}|/\zeta_a\rho_w g$ *is the maximum non-dimensional stress found from a quasi-static analysis. Here,* ζ_a *is the incident wave amplitude,* ρ_w *is the water density, R is the cage radius, and* k_nR *are non-dimensional squared natural sloshing frequencies.*

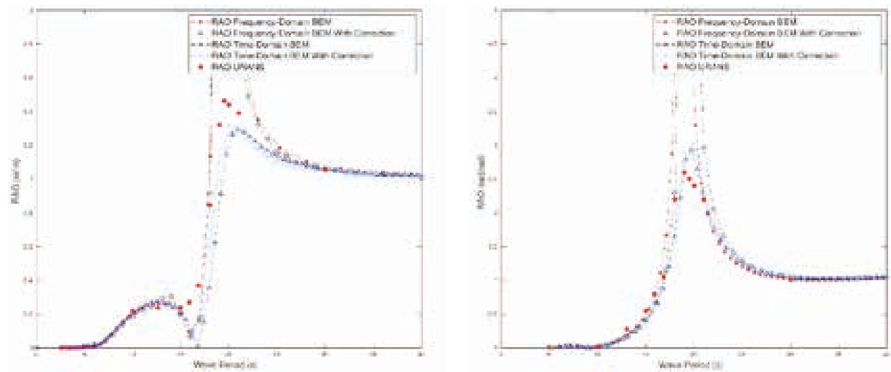

Figure 3: *RAOs obtained from codes A, B and C (see the text for their definition). The RAOs are referred to the COG and a complete transformation matrix composed of Euler angles is implemented in B and C simulations. For codes A and B, the results are provided both without and with a viscous damping correction equal to the 6.25% and 6.6% of the critical damping in heave and pitch, respectively. These values are in the expected range of the viscous damping for semi-submersible platforms.*

if not corrected with empirical viscous damping coefficients. We examined these aspects for **a semi-submersible platform** to be used **in an offshore wind farm, requiring operability even in extreme meteorological conditions** [P3-R3].

Three different seakeeping models of increasing complexity, namely, (A) a frequency-domain BEM, (B) a partly nonlinear time domain BEM, and (C) a non-linear fully viscous model based on the solution of the Unsteady Reynolds Averaged Navier-Stokes equations (URANS) were employed to estimate the heave and pitch Response Amplitude Operators (RAOs) of the platform (see Fig. 3). When the motions are relatively small (RAO≤1), all codes predict the same motions, only requiring the use of URANS near the resonance and cancellation periods. In particular, near the natural frequency of the system, the potential flow models highly overestimate the wave-induced motions. This is because vortex-shedding and subsequent damping effects are not included, while they can be captured directly by code C (see e.g. Fig. 4). Viscous corrections can be included in the potential-flow solvers, but their entity need to be estimated according, for instance, to previous experimental measurements. On the other hand, the examined high-fidelity fully viscous model with a non-linear free surface is 175 times more expensive than code B, and 700,000 times more expensive than code A. Therefore, its use for the RAO prediction is justified only when incoming waves induce motions at the resonance frequency.

A correct assessment of the ship speed loss in conditions of operation is becoming increasingly important for ship owners, as well as ship designers. We are witnessing an increasing concern for the environment and awareness of the necessity to preserve it as much as we can. The ship speed drop in the real environmental conditions can cause increased fuel consumption, as well as increased emissions of CO2 and other greenhouse gases (GHGs) from ships. A decrease in the ship speed in real conditions is a consequence of the added resistance due to the impact of weather conditions, and due to aggravated propeller working conditions. Moreover, the solution estimation of this problem is

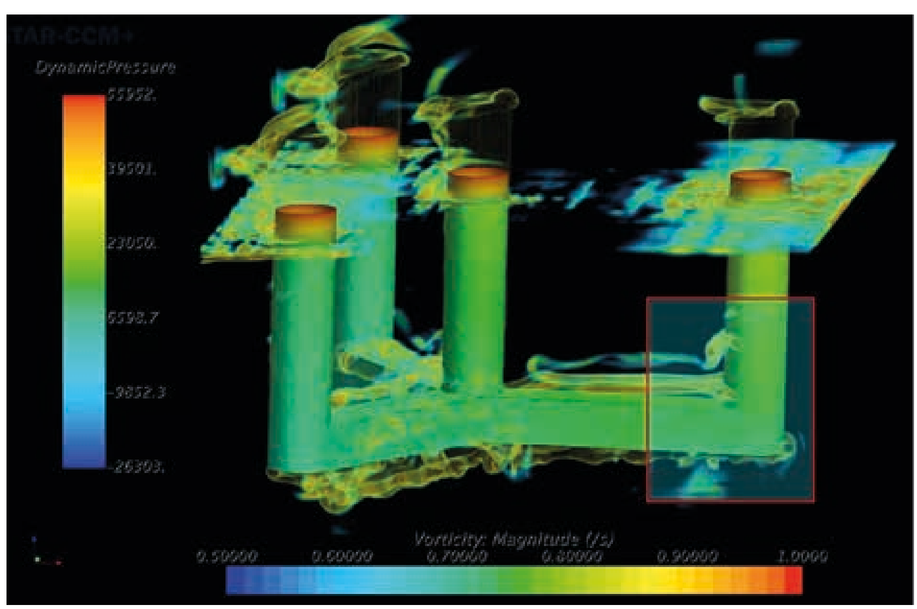

Figure 4: *Results from code C: Vortex sheets are shed at the platform edges. Flow confinement between the columns introduces perturbation to the vortex sheet development.*

very much affected by human factors. With concerns for safety, the ship master can make a judgment that, under certain adverse weather loads, it is necessary to slow down or change the ship's course to moderate or bypass the worst condition. In addition, the loading condition of the ship is constantly changing, which governs the basic parameters of the ship: the mass and mass moment of inertia, draft and trim and, consequently, the ship's behaviour at sea. All these parameters affect the assessment of ship speed; hence it is necessary to be conscious of their influence on the final value.

At the same time, they cannot be predicted with absolute certainty, so we carried out a dedicated analysis to estimate the impact of weather and operational uncertainties on the actual speed of the ship in real operating conditions [P3-R4]. The relevant results for a S175 Containership in head and in following sea states are given in Fig. 5. This provides the involuntary-speed reduction as a function of the significant wave height considering the effect of different voluntary-speed reduction criteria on the attainable ship speed. For both the head and following sea, the ship master would reduce the main engine power at the weather condition of an approximately 3 m significant wave height and a wavelength that is approximately half the ship's length. In head-sea waves, the variations of limit acceleration values have an evident impact on the estimated ship speed. Due to a stricter limiting rms value of 0.1 g, the estimated speed varies up to 4 kn. The effect of considering the propeller-emergence criterion is visible, but the attainable ship speed value is not sensitive to the variation of the limiting values of this criterion. In the following sea, voluntary speed reduction would primarily happen due to propeller emergence. The analysis exhibits a low sensitivity of the attainable ship speed on criteria limit variations, e.g., deck wetness and propeller emergence.

Our analysis on scenarios involving large wave-induced ship motions and their consequences continued. The occurrence and features of **parametric roll (PR)** were studied for a fishing vessel in regular head-sea waves [**P3-R5**]. PR is an instability and

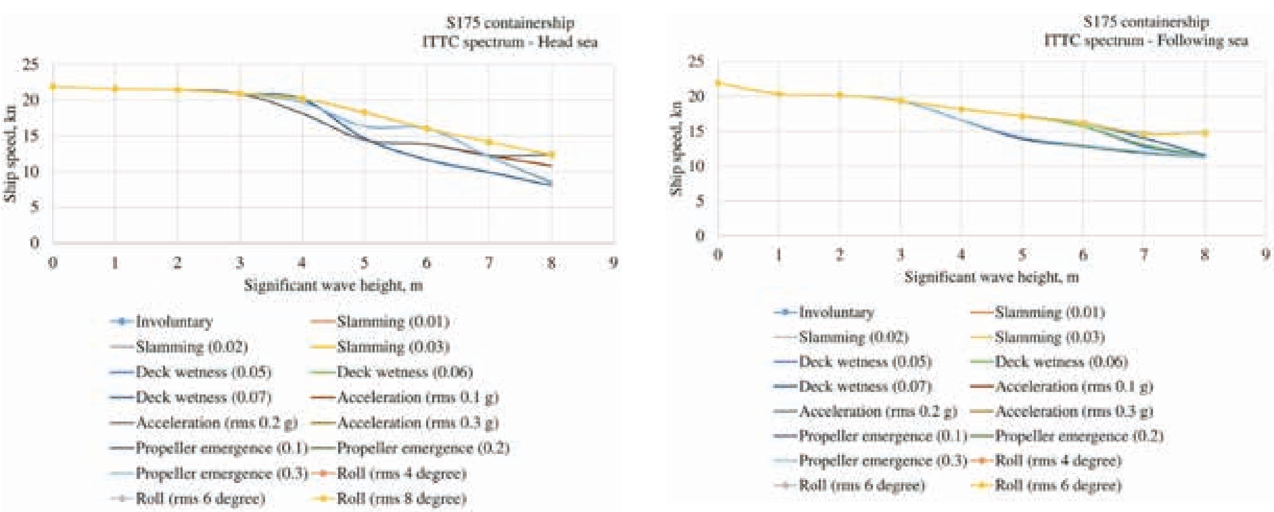

Figure 5: *Speed loss in head (left) and in following (right) sea for a S175 containership with individual causes.*

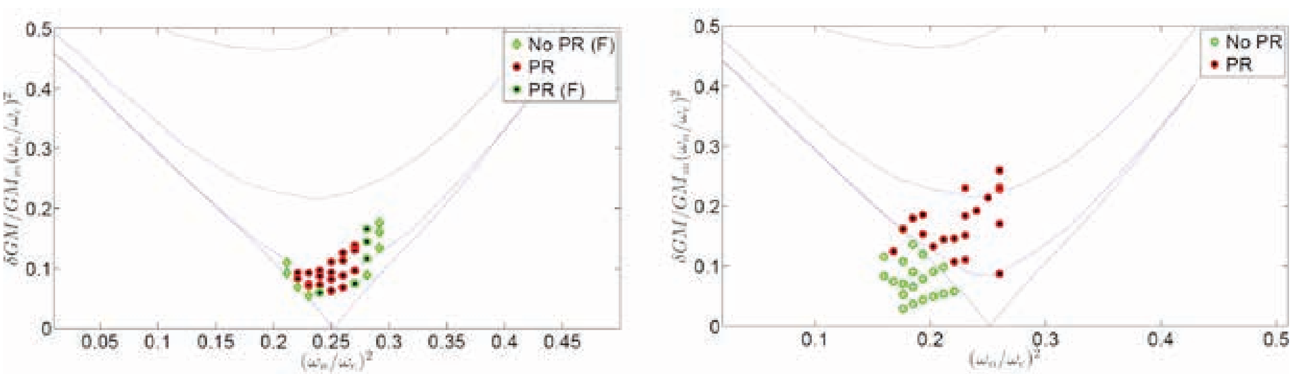

Figure 6: *Mathieu instability diagram for uncoupled roll (solid lines) and experimental cases (symbols) at Fn=0 (top) and Fn = 0.09 (bottom). PR = parametric roll in the experiments. No PR = No parametric roll in the experiments. Here,* ω_n *= roll natural frequency,* ω_e *= encounter frequency,* GM_m *= mean transverse metracentric height,* δGM *= amplitude of change in metacentric height.*

resonance phenomenon that can lead the roll to reach very high oscillation amplitudes at its natural frequency, depending on the damping level involved. In the worst cases, it is responsible for vessel capsize. Our analysis was based on numerical and experimental studies on a typical Norwegian fishing vessel with a blunt hull and small length-to-beam ratio. Experimentally, we analysed model tests previously performed (within a collaboration with SINTEF Ocean and CNR-INM) on the SFH112 fishing vessel on a 1:10 scale in regular head-sea waves with different wave frequencies and steepnesses. The tests were performed without and with forward speed, with a corresponding Froude number Fn = 0.09 and 0.18. Numerically, a blended method was developed based on a 6-DOF 3D hybrid method, in which the radiation and diffraction potentials were computed for a zero forward speed by a linear frequency-domain potential-flow solver (WAMIT), and used in the Salvesen-Tuck-Faltinsen strip theory to obtain speed-dependent loads. The method includes the convolution integrals for the effect of a radiation free-surface memory effect and nonlinearities in the Froude-Krylov and restoring loads. Use of the weak-scatterer hypothesis in radiation and diffraction loads has also been considered. The numerical simulations exhibited a good agreement with the experimental results. For cases near the instability border of a 1-DOF Mathieu-type instability diagram, the physical and numerical predictions were different in terms of parametric roll occurrence. The instability borders for the experimental cases were also different from the instability borders of 1-DOF Mathieu-type instability diagram (see Fig. 6):

The instability region for the experiments and 6-DOF simulations cover a wider range of frequency ratio, while the threshold value of a metacentric height variation amplitude to have parametric roll seems to be lower than predicted by the 1-DOF Mathieu instability diagram. The results also show that the instability region for the cases with forward speed shifts to the lower frequency ratios (natural roll frequency-to-encounter frequency ratio) compared to the cases without forward speed. The results show that the simulations without this weak-scatterer hypothesis tend to underestimate the occurrence and severity of parametric roll, particularly in longer and steeper waves.

Flooding in ships is a complex phenomenon often resulting from damage due to collision, grounding or rough weather. A large number of ship collisions in recent years have led to a loss of lives and hazardous cargo spills/loss, thereby motivating our research effort in addressing the challenges of a damaged ship in waves. We analysed experiments previously performed on a damaged ship section in waves, with a focus on the effect of sloshing and piston mode resonance (for the internal water) on the ship-section behaviour [P3-R6]. The model is a midship section with a rectangular damage opening on the side. Freely floating tests in regular beam-sea waves were carried out on the model in intact and damaged conditions. Free roll decay tests were also performed to understand the effect of floodwater on the roll natural period and roll damping of the model. A linearized strip theory method based on viscous flow has been implemented to cross-check and complement the experimental results; this method can estimate the damaged ship motions with reasonable accuracy. The effect of wave steepness, wave period, initial loading condition, damage-compartment division about the centre plane (symmetric/asymmetric flooding), damage-opening size and air compressibility in the damaged compartment have been examined. The results demonstrate an occurrence of sloshing and piston mode resonances, with their influence on damaged ship motions in waves being highlighted. The initial loading condition of the ship section determines the equilibrium flooding state and, therefore, the sloshing and piston mode resonance frequencies of the flooded water. The damage-opening size primarily affects the roll damping behaviour of the section. Air compressibility in the airtight compartment acts as a coupled spring system with the floodwater, and restricts the free-surface motion in the damaged compartment. Cases of transient flooding for a damaged section have also been examined, in which the freely floating model moves in beam-sea waves, and subsequent flooding takes place. An example of the main stages of transient flooding is shown in Fig. 7.

As the roll motion increases and gradually reaches a steady-state condition, the freeboard height of the opening relative to the external wave decreases and water starts entering the damaged opening. This inflow of water increases the model weight towards the damaged compartment, and therefore increases the mean roll moment. The model attempts to recover by rolling to the other side, but the increase in the roll moment towards the damaged side, combined with a reduction in metacentric height due to the free surface in the compartment, further increases the roll motions. As a result, the magnitude of the roll angle towards the damaged side increases over time, and the model takes in more floodwater. The initial flooding may be slow for some incident wave periods until when a sudden abrupt flooding occurs with sudden large transient motions. The effect of wave steepness, incident wave period and the initial intact stability of the model have been examined for this scenario.

Understanding fluid structure interaction during violent wave impact is important for the appropriate design of ships and ocean structures. Within a collaboration with SINTEF Ocean, we investigated the problem in which a flat plate is dropped onto a flat free surface [P3-R7]. This is an idealized scenario to study the details of slamming, which is a phenomenon inducing large, local pressures of a short duration on the structure. Most research in the area has examined linear elastic structural responses to such impacts, but hydrodynamic responses during large, plastic deformations of engineering structures remain under-explored. These represent the focus of our research. A setup for an experimental drop test was designed for this purpose, with an equal emphasis on the hydrodynamical and structural mechanical aspects. Dual cameras were used to monitor the deforming plate from above during impact, and its deformation was tracked using a three-dimensional digital image correlation, 3D-DIC, technique. The complex hydrodynamics of the impact was captured using a high-speed camera from below. An example of extracted and analysed data is shown in Fig. 8:

The experimental results for a flat impact showed a large air pocket under the deforming plate. The material properties of

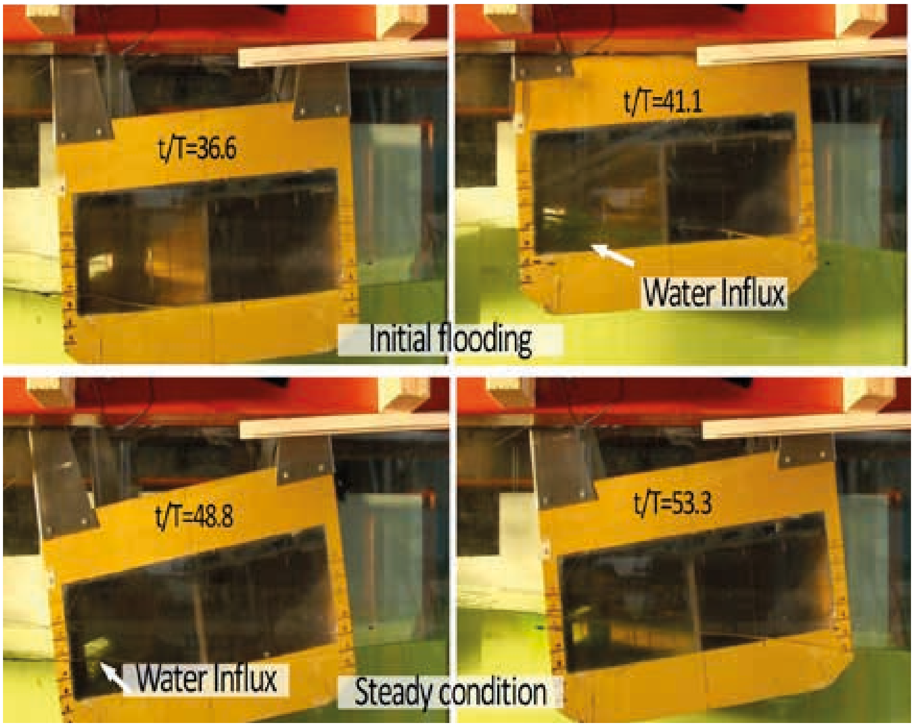

Figure 7: *Sequence of flooding as it occurs over time for the model in beam-sea regular waves with period T=0.9 s and steepness kA=0.066. Time increases from left to right, and from top to bottom.*

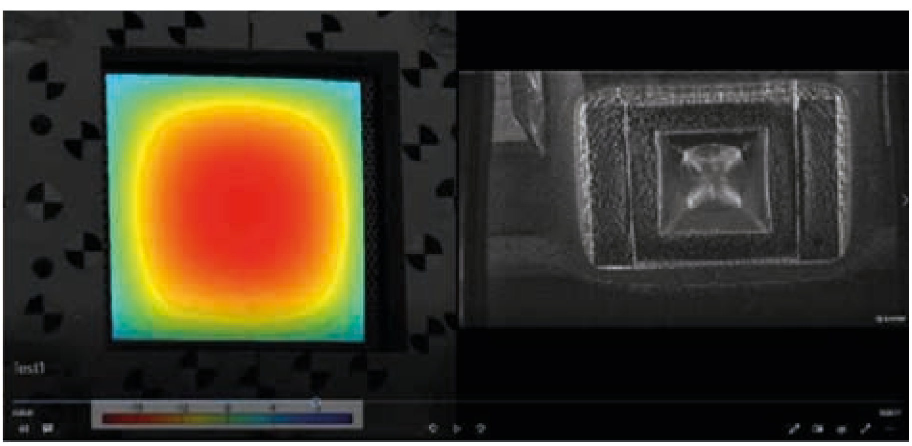

Figure 8: *Example of analysed data. The coloured plot on the left shows the instantaneous deflection of the plate extracted using the 3D-DIC technique, with the image to the right showing the corresponding details of the flows of air and water beneath the plate.*

the plate were documented through separate tests. Hydroelastic theories were offered to account for large deformations, and validated against the experimental results. Analytical hydroplastic theory shows that the maximum deflection is approximately equal to the velocity of the impact times the square root of the ratio of the added mass to the plastic membrane capacity of the plate. An important source of error between the theory and the experiments was the effect of a deceleration of the drop rig on the deflection of the plate. This error was estimated using direct force integration and Wagner's theory.

The development of novel advanced hydrodynamic methods to deal with complex free-surface flows is also part of our research interest. Within a collaboration with the Harbin Engineering University, an upgraded harmonic polynomial cell (HPC) method has been proposed, named as a high-order Harmonic Polynomial Method (HPM), to solve the Laplace equation with complex boundaries [P3-R8]. The concept of "irregular cell" (see sketch in Fig. 9) is proposed for an accurate discretization of the Laplace equation, for fluid regions where it is difficult to construct a high-quality stencil:

An advanced discretization scheme has also been developed for an accurate evaluation of the normal derivative of potential functions on complex boundaries. The resulting method can avoid the drawback of distorted stencils, i.e., possible numerical inaccuracy/instability. Furthermore, it can involve stationary or moving bodies on the Cartesian grid in an accurate and simple

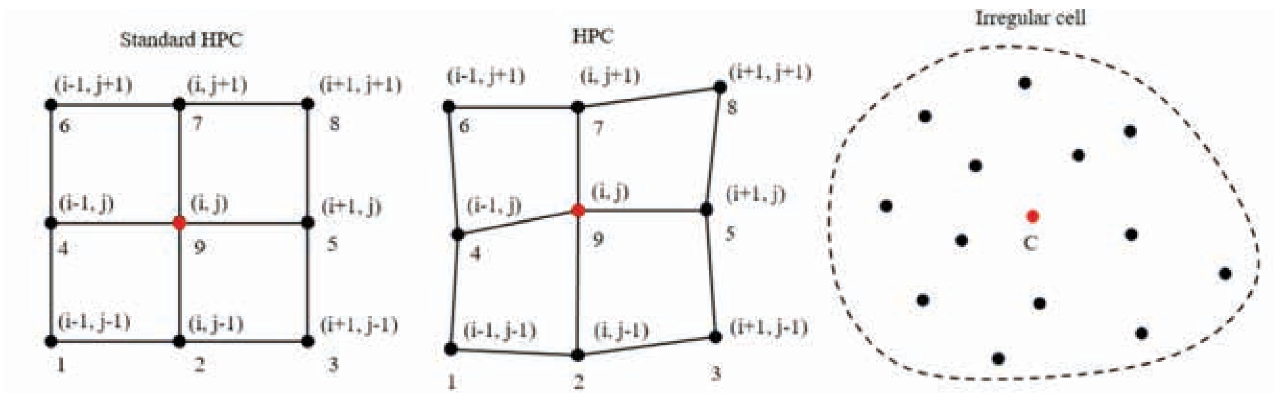

Figure 9: *Example of cells used for discretizing the Laplace equation by harmonic polynomials .*

way. With the proper free-surface tracking methods, the harmonic polynomial method has been successfully applied to the accurate and stable modelling of highly-nonlinear free-surface potential flows with and without moving bodies, i.e., sloshing, water entry and plunging breaker (see example in Fig. 10).

Floating glacial ice features of various sizes pose a substantial threat to the structural integrity of offshore structures and ships operating in ice-prone regions. Relatively small ice features, e.g., bergy bits and growlers, are of major concern because they are more susceptible to large wave-driven oscillatory motions, more difficult to detect by marine radars and more difficult to handle with present ice management operations, especially in extreme sea states. In collaboration with the centre for research-based innovation - SAMCoT (Sustainable Arctic Marine and Coastal Technology) - the wave-driven oscillatory motion and mean drift speed of small glacial ice features, and their potential impacts with a floating offshore structure, were studied (P3-R9). The numerical model is capable of efficiently calculating the relative motion between the ice and the structure and to sample a sufficient number of impact events from which statistical information is obtained. The statistical information concerns the distributions of the impact location and associated impact velocities. On this basis, the kinetic energy for given impact scenarios can be quantified for a subsequent assessment of structural damage. A case study was conducted for a 10-m wide glacial ice feature drifting under the influence of surface waves towards an offshore structure. It was found that the overall impact location and impact velocity were best fitted by the Normal and Weibull distributions, respectively. The impact velocity increased, and the impact range was more dispersed in high sea states, see Figure 11:

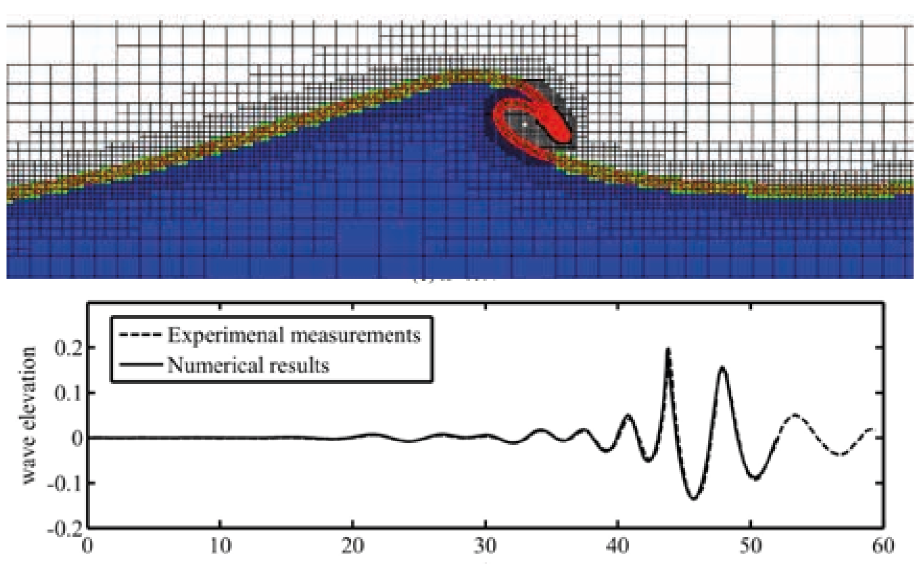

Figure 10: *Example of HPM results. Top: Numerical free-surface profile of a plunging wave and the corresponding grid system. The red circles denote the markers on the free-surface boundary. Bottom: Numerical free-surface elevation compared to wave-probe measurement (from Dommermuth et al., 1988) as a function of time (in seconds) at distance x=9.17 m from the wavemaker.*

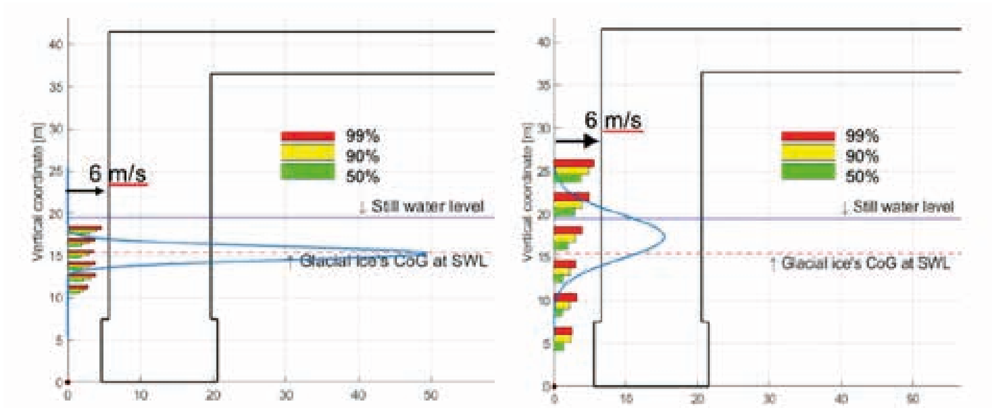

Figure 11: *Impact probability and velocity distributions in two sea states. Left: Hs = 4.98 m, T_p = 6.5 s, Drift velocity 1.62 m/s. Right: H_s = 9.8 m, T_p = 14.8 s, Drift velocity 0.98 m/s. Bars correspond to cumulative percentage at various height.*

An accidental limit state (ALS) **assessment of the structural damage** caused by impacts from ice features with a different local sharpness was carried out by means of a nonlinear finite element analysis, taking ice-structure interaction into account (P3-R10). A critical local ice sharpness was identified, which caused maximum penetration of the stiffened panels in the platform column for a given demand for energy dissipation, see Figure 12. Using the identified critical ice sharpness, the energy dissipation and maximum penetration was analysed for various impact locations on the platform column. In addition to normal ice impacts, oblique impact scenarios were also simulated, in which the glacial ice feature slid along the contact plane with different initial indentations of the panel.

On the basis of the above-mentioned work, an executive summary was prepared for the Petroleum Safety Authority of Norway. A framework was constructed in which the accumulated knowledge was presented in line with existing design standards. Detailed design formulations in the format of recommended practices were also developed (P3-R11).

Monopile wind turbines remain the most commonly installed substructures for offshore wind turbines, even as the industry moves toward larger turbines and deeper water. These trends contribute to an increase in the first natural period of the structure: an increase in turbine size results in a larger top mass and a higher hub height, while deeper water contributes to an increase in the free length. Furthermore, the increasing water depth, and increase in monopile diameter required to support larger turbines, result in increased wave loads, which can contribute significantly to fatigue in the monopile and tower. A key challenge is to reduce the cost of the support structure while maintaining sufficient safety margins for the fatigue life.

The global load effects that govern the design against fatigue depend strongly on the wind turbine's blade pitch and generator torque closed-loop control. Moreover, load effects related to the ultimate limit state and serviceability limit state also depend on control settings, such as the cut-out wind speed. Load-mitigation strategies have been developed for reducing the fatigue-inducing load effects, but these strategies may increase wear of the drivetrain or blade pitch actuator components – or reduce the power output or degrade the power quality. However, designers must also account for the significant uncertainties related to the soil-structure interaction. The first natural period is sensitive to the local conditions, which are often poorly predicted during design.

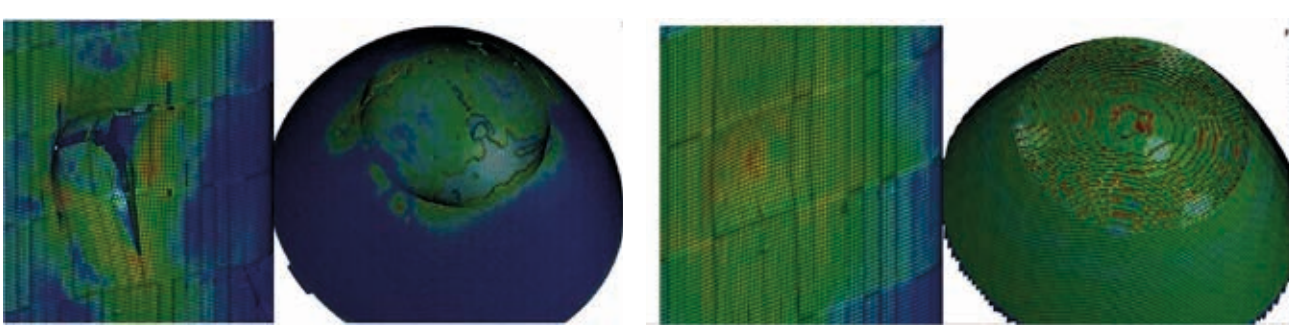

Figure 12: *Distribution of structural damage to column front panel and ice front crushing for two different ice front curvatures. Left: Ice curvature radius 3.6 m. Right: ice curvature fradius 1.8 m. Critical curvature w.r.t penetration is 2.4 m.*

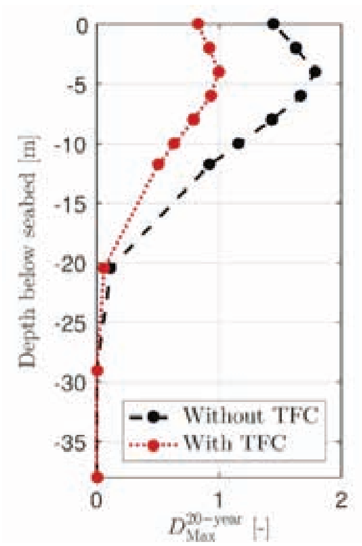

Figure 13: *Influence of tower feedback control (TFC) on the fatigue damage below the mudline for a 10 MW monopile wind turbine [P3-R12].*

We have therefore proposed and assessed a strategy for the post-installation adaptation of control strategies for offshore wind turbines, considering a case study with a 10 MW monopile in a 26-m water depth [P3-R12]. The objective is to optimize the use of existing control strategies by mitigating their adverse side-effects at the wind farm level. Two load mitigation strategies are considered: tower feedback control, which modifies the blade pitch command via an auxiliary control loop, and provides both damping and stiffness to the fore-aft bending mode; and peak shaving, which reduces the aerodynamic efficiency in near-rated conditions in order to reduce the maximum thrust force.

For the studied case, the application of tower feedback control (TFC) could reduce the fatigue utilization by 43% for an individual turbine over its lifetime (Figure 13), at a cost of 25% increase in the damage equivalent loads in the pitch actuator bearings. However, these trade-offs are sensitive to the uncertain soil parameters. Nonetheless, a study of 10,000 field realizations shows that there are clear trends which can be used as criteria for an event-triggering of TFC (Figure 14).

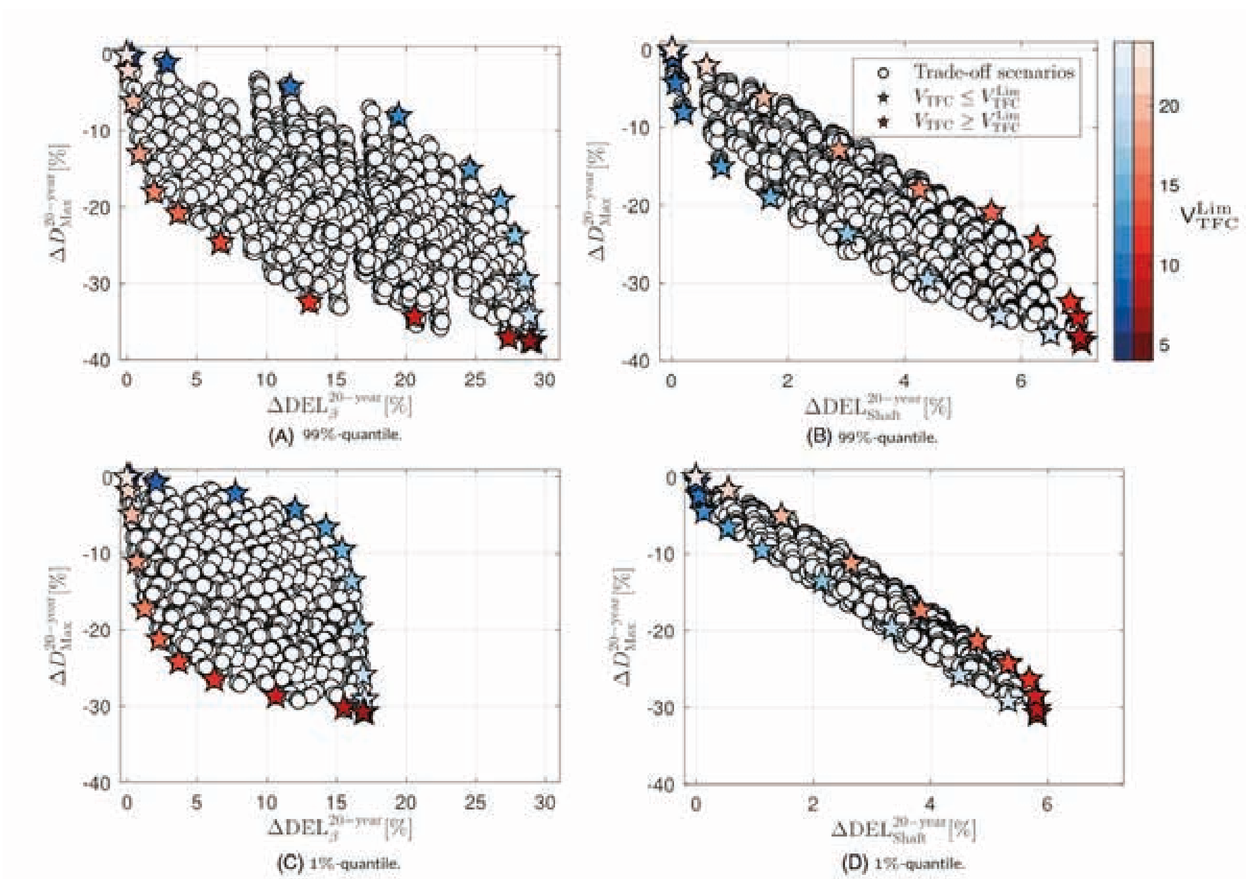

Figure 14: *Tradespaces considering mean-wind-speed-triggered tower feedback control. The results show 1% and 99% quantiles in the distribution of the natural period. $\Delta D_{Max}^{20\text{-}year}$ indicates the change in fatigue utilization for the support structure. The change in the damage equivalent loads for the pitch actuator bearings and main shaft are denoted $\Delta DEL_{\beta}^{20\text{-}year}$ and $\Delta DEL_{shaft}^{20\text{-}year}$, respectively. [P3-R12].*

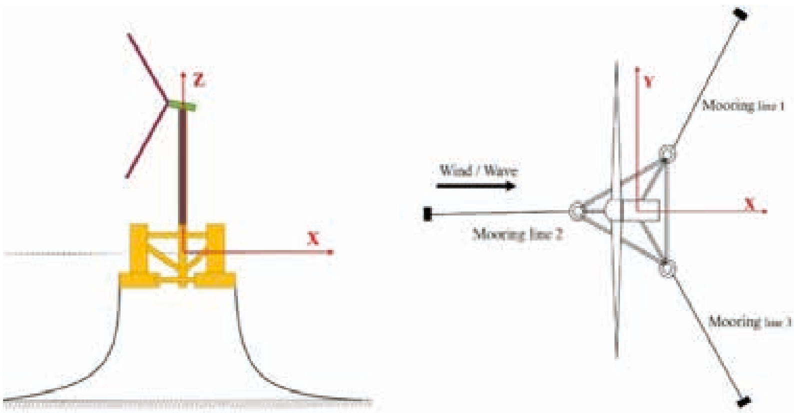

Figure 15: Left: Illustration of a 5MW semi-submersible floating wind turbine; Right: Mooring system configuration

In the proposed two-stage control adaptation, an improved knowledge of the true structural natural period is used (based on structural monitoring). Thus, some turbines in a farm will have an increased use of the TFC, whereas others will not require the application of load-mitigating controls. With perfect knowledge of the natural frequency of each turbine, one could then equalize the support structure fatigue life over a range of natural periods. Even with uncertainties related to identification of the true natural period, one can reduce the adverse side-effects of load-mitigating control, while harvesting its benefits in terms of reduced support structure costs at the farm level.

Similarly, peak shaving can be applied to reduce the serviceability utilization – specifically related to the maximum allowed pile-head rotation – at a cost of reduced power production. Given that the support structure represents approximately 20% of the cost of offshore wind energy, any loss in power production must be justified by a fivefold reduction in cost. The present results suggest that it is unlikely that sufficiently large cost reductions can be obtained to justify a significant application of peak shaving. The proposed two-stage post-installation controls adaptation therefore led to a significant reduction in the application of peak shaving.

Floating wind turbines might be economically competitive when compared to bottom-fixed wind turbines for offshore areas with a water depth beyond 50-100m. However, the mooring system represents a technical challenge for such water depth. On the one hand, the mooring system should be designed to provide a sufficient horizontal stiffness to cope with the wind speed-dependent large mean thrust force from the turbine, as well as the low-frequency resonant motions of the floating wind turbine due to both wind and wave loads, while on the other hand, to allow wave-frequency motions of the floater. Seven mooring concepts designed for a 5 MW semi-submersible floating wind turbine (see Fig. 15) at a 50-m water depth are compared with the purpose of identifying structurally reliable and economically attractive solutions [P3-R13, P3-R14]. The concepts are made of different mooring line materials (chain and synthetic fibre rope), mooring components (clump weight and buoy) and anchors (drag embedment anchor and suction anchor), see Fig. 16. For fibre rope mooring systems, a numerical model of the nonlinear tension-dependent stiffness of synthetic fibre rope based on the experimental data, and an iterative procedure, were developed and implemented in SIMA for global response analysis of the semi-submersible floating wind turbine. The performance of the seven mooring concepts is compared with respect to mooring line characteristics and tension responses, as shown in Fig. 16 as one example. The comparison indicates that combining clump weights and buoys will help reduce the stiffness nonlinearity and the large tension in a pure catenary mooring system, whereas the use of fibre rope will provide a more cost-competitive solution:

The **gearbox and drivetrain** remain critical components for offshore wind turbines. Compared to land-based wind turbines, larger non-torque loads may enter the gearbox due to wave-induced and wind-induced motions; hence, the demands for reliability are more stringent due to the inherent difficulties in accessing the turbines. Furthermore, as the industry moves toward larger wind turbines, there is a need for new analysis methods and designs.

Increases in turbine size result in more structural flexibility for the components in the nacelle, such as the bedplate. Traditional global analysis methods assume that the bedplate is rigid. For a 10 MW drivetrain, considering the flexibility in the bedplate could reduce the first tower fore-aft bending natural frequency by almost 9% [P3-R15]. The mode shapes of the drivetrain are illustrated in Figure 17, and clearly show the interaction between tower and bedplate modes. By applying a decoupled analysis method, in which the global responses are first calculated in an aero-hydro-servo-elastic tool, and the local analysis of the drivetrain is carried out separately, it has been shown that the bedplate flexibility contributes to a significant increase in the standard deviation of the axial force in the planet carrier bearing in the first stage of the gearbox. The flexibility of the bedplate implies that the drivetrain resonances can also be seen in axial loads. A model with approximately 15 modes of the bedplate is recommended as a compromise between accuracy and computational cost [P3-R15]:

A more compact gearbox layout for the same 10 MW wind turbine was also proposed [P3-R16]. Compared to a conventional layout,

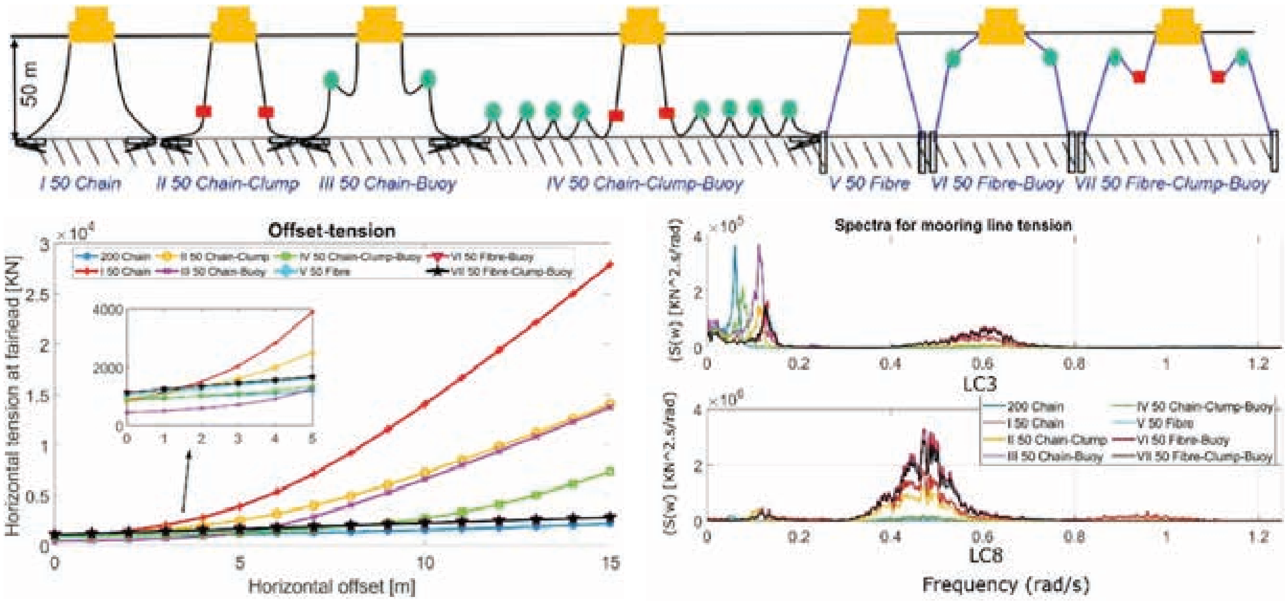

Figure 16: *Top: Illustration of seven mooring systems designed for 50 m of water depth. Bottom-left: Mooring line characteristics. Bottom-right: Tension spectra of mooring line 2 for two load cases (LC3: Operational condition, mean wind speed of 12m/s, significant wave height of 3.2m and spectral peak period of 10.1s; LC8: Parked condition, mean wind speed of 40m/s, significant wave height of 9.8m and spectral peak period of 13.0s).*

the compact layout can offer a weight reduction of approximately 5% (for the gearbox alone), and a halving of the volume. The smaller volume may provide further weight reductions for the surrounding structure. The compact gearbox is more suited to floating applications, due to better load-sharing and less sensitivity to rotor pitching moments. Additionally, the compact gearbox is less sensitive to errors in the tangential pin position. On the other hand, access to the gearbox is more challenging due to its compact form.

Faults in wind turbine components (for example, a blade pitch actuator) may induce the rotor load imbalance and therefore significant responses of support structures, especially floating support structures. A detailed numerical model [P3-R17, P3-R18] for a hydraulic pitch actuator, both with/without valve faults, has been developed and coupled to a global load/response analysis model of a spar floating wind turbine in Simo-Riflex for integrated dynamic analysis (see Fig. 18). Four different valve faults were considered and simulated, including circuit shortage (VCS), excessive friction (VEF), slit lock (VSL) and wrong voltage applied (VWV). These valve faults represent different dynamics of the hydraulic pitch actuator and lead to undesired changes of blade pitch angle, which eventually alter the aerodynamic loads on the blades and the global responses of the spar wind turbine.

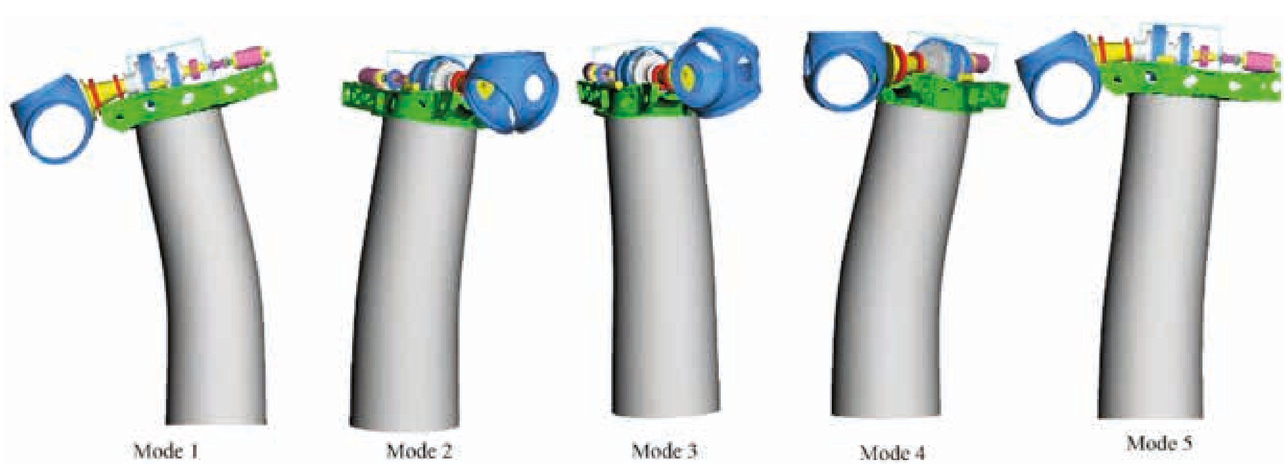

Figure 17: *Eigenmodes of a 10 MW drivetrain with a flexible bedplate [P3-R13].*

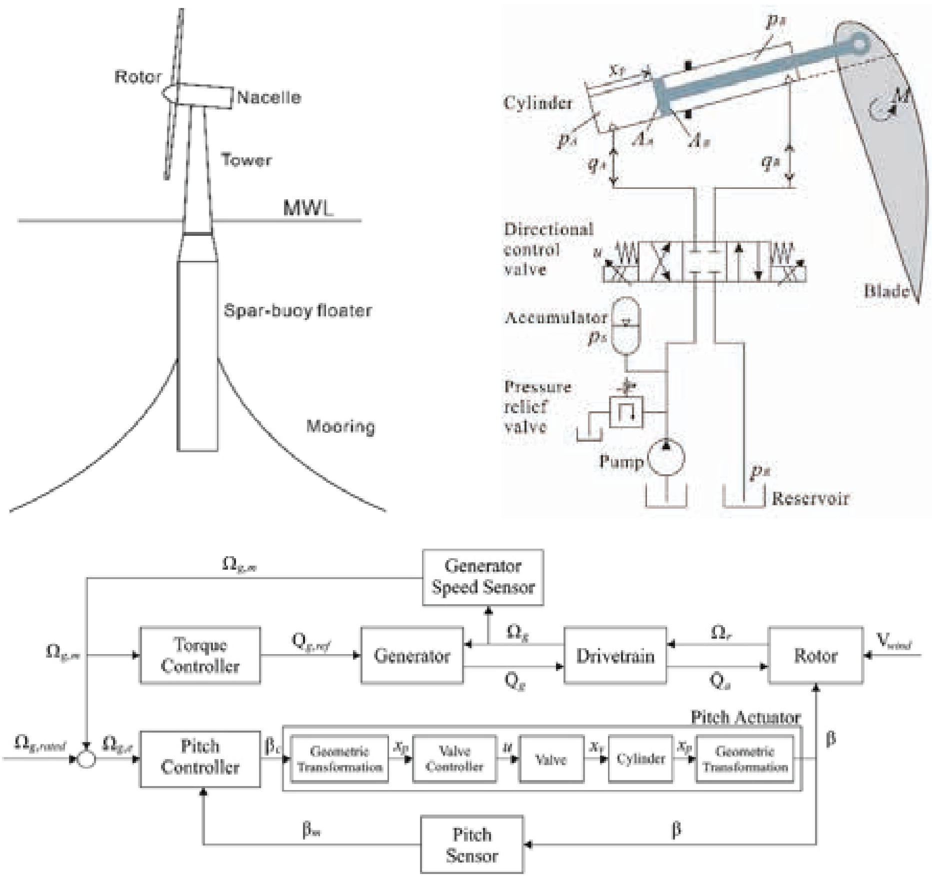

__Figure 18:__ Top-left: Illustration of a spar floating wind turbine; Top-right: Sketch of the hydraulic blade pitch actuator, Bottom: Simulation and control diagram

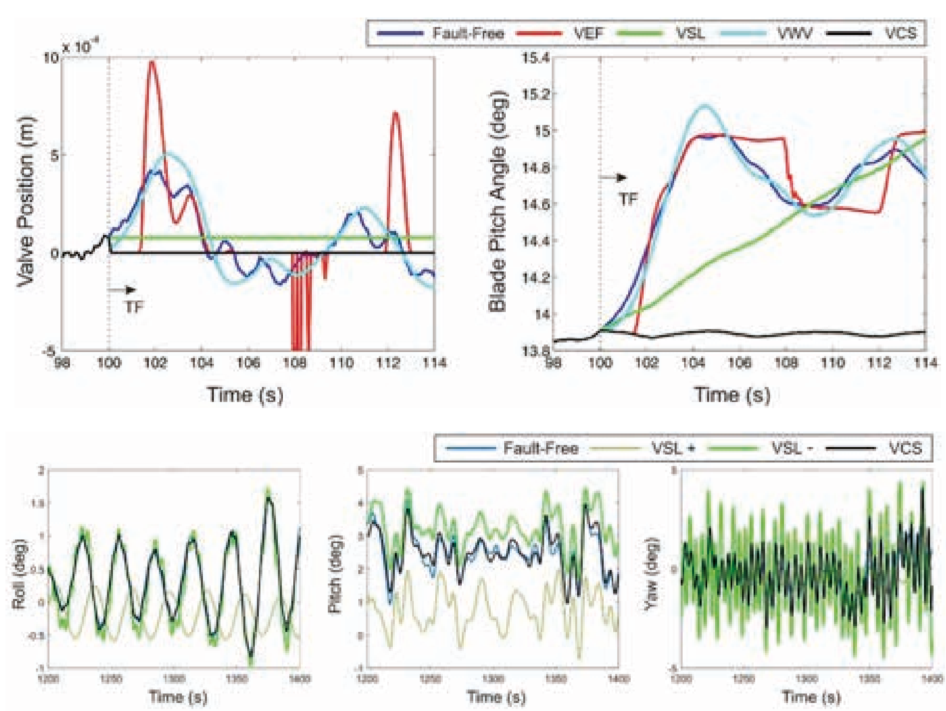

__Figure 19:__ Top: Simulated valve positions of hydraulic blade pitch actuator and resulting blade pitch angle for fault-free and fault cases; Bottom: Time series of spar wind turbine motion responses (roll, pitch and yaw) under stochastic wind and wave conditions (mean wind speed of 20m/s, significant wave height of 4.8m and spectral peak period of 10.8s).

They will also reduce the power absorption performance of the turbine. A comparative study was made considering the coupled analysis of the spar wind turbine under stochastic wind and wave loads, and the simulated faults in one of the blade pitch actuators. An example regarding the effect of these faults on the resulting pitch blade angle and the global responses (roll, pitch and yaw motions) of the spar is shown in Fig. 19. The observations indicate that both the faults of VCS and VSL, which cause blade pitch angle stuck and runaway, respectively, lead to increasing aerodynamic loads due to the difference of the blade pitch angle, as compared to the fault-free case. A significant imbalance of the rotor loads occurs and leads to larger tower torsional moments and floater yaw motions. However, the faults of VEF and VWV, which only lead to a time delay in blade pitch response, have minor effects on the aerodynamic loads and responses of the spar floating wind turbine:

The ability to model components such as the hydraulic pitch actuator and the drivetrain is an important input when moving towards a better operation of floating wind turbines, including fault detection and fault-tolerant control. For the lifetime system integrity management, it is important to develop numerical modelling tools that can accurately predict responses in both normal operation and conditions with faults [P3-R19].

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P3-R11 Lu W., Yu Z., Lubbad R., Amdahl J., Løset S., Kim E., 2020, Glacial Ice Actions: Executive summary of NORD ST20_2019/313 and NORD ST19, ArcISo_report 2019_ Ptil03

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P3-R14 Xu K., 2020, Design and Analysis of Mooring Systems for Semi-submersible Floating Wind Turbines in Shallow Water. PhD Thesis, Department of Marine Technology, NTNU.

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P3-R18 Cho S. P., 2019, Model-based Fault Detection and Diagnosis of a Blade Pitch System in Floating Wind Turbines. PhD Thesis, Department of Marine Technology, NTNU.

P3-R19 Moan T., Gao Z., Bachynski E. E. Nejad A. R., 2020, Recent Advances in Integrated Response Analysis of Floating Wind Turbines in a Reliability Perspective. *Journal of Offshore Mechanics and Arctic Engineering*. Vol. 142 (5).

NTNU AMOS PARTICIPATION IN ASSOCIATED PROJECTS

Awarded/Ongoing Completed Proposed

Awarded/Ongoing Projects

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Arctic ABCD	Geir Johnsen Asgeir J. Sørensen	13,5 MNOK	2016-2025	NFR INFRA	Infrastructure project of NFR funded ARCTIC ABC (ending in Dec 2019)	1-3 engineer + Lab Equipment, making ice-tethered buoy sensor system
Exposed Aquaculture Operations	Ingrid Schjølberg Marilena Greco Jørgen Amdahl Ingrid B. Utne	209 MNOK	2015-2022	SFI Centre	SINTEF Ocean NTNU SINTEF Digital Salmar, Grieg Mainstream Norway Biomar Egersund Net AkvaGroup ACE, KM	3 PhD Experiments
Center for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA)	Tor Arne Johansen	3 MNOK	2015-2022	SFI Centre	UiT NTNU	1 Postdoc
Intelligent monitoring of drilling operations in sensitive environments (project number 267793	Tor Arne Johansen	3 MNOK til NTNU	2017-2022	NFR PETROMAKS	Morten Alver, SINTEF Ocean	1 PhD
Nonlinear Autopilot Design for Extended Flight Envelopes and Operation of Fixed-Wing UAVs in Extreme Conditions (AUTOFLY)	Thor I. Fossen Tor Arne Johansen	10 MNOK	2017-2021	NFR Frinatek	NTNU	2 PhD 1 Postdoc
AILARON – Autonomous Imaging and Learning Ai Robot identifying ommunic taxa in-situ	Annette Stahl Kanna Rajan Martin Ludvigsen Nicole A-Malzahn Geir Johnsen	11.5 MNOK 9.5 MNOK til NTNU	2017-2021	NFR FRINATEK IKTPLUSS	NTNU, SINTEF Ocean, Uporto, UPTC, Sequoia Scientific Inc. US	1 PhD 1 Postdoc
Collision avoidance for autonomous ferry Associated to Autoferry	Edmund Brekke Tor Arne Johansen	4.1 MNOK	2017-2021	NTNU SO scholarship	NTNU	1 PhD

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Center for Marine Operations in Virtual Environments (MOVE)	Zhen Gao Roger Skjetne	3 MNOK	2015-2022	SFI Centre	NTNU SINTEF Ocean Equinor DNV-GL	2 PhD 1 Postdoc
Coordinate aerial-underwater operations with gliders for large scale remote ocean monitoring	Tor Arne Johansen	2 MNOK	2017-2020	MarTERA	Alex Alcocer, HIOA	1 Postdoc
Reducing risk of autonomous marine systems and operations (UNLOCK)	Ingrid B. Utne Asgeir J. Sørensen Tor Arne Johansen	12,5 MNOK	2018-2022	NFR FRINATEK	UCLA QUT	3 PhD
Online risk management and risk control for autonomous ships (ORCAS)	Ingrid B. Utne Asgeir J. Sørensen Tor Arne Johansen	15,4 MNOK	2018-2022	NFR MAROFF KPN	RRM, DNV GL	3 PhD 1 Postdoc
MarLander – Maritimt Landingssystem for UAS	Tor Arne Johansen	3 MNOK	2018-2021	MAROFF IPN	Maritime Robotics AS	2 yrs PhD
FlightSmart	Tor Arne Johansen	2 MNOK	2018-2021	BIA IPN	Equator Aircraft SA	1 Postdoc
ADRASSO – Autonomous Drone-based Surveys of Ships in Operation	Tor Arne Johansen Thor I. Fossen	2 MNOK	2018-2021	MAROFF IPN	DNV GL	1 Postdoc
MASSIVE – Mission-oriented autonomous systems with small satellites for maritime sensing, surveillance and communication	Tor Arne Johansen Kanna Rajan	16 MNOK	2018-2022	IKTPLUSS	NTNU	3 PhD 1 Postdoc
Legacy after Nansen – Arctic research project that provides integrated scientific knowledge base required for future sustainable management through the 21st century of the environment and marine resources of the Barents Sea and adjacent Arctic Basin	Martin Ludvigsen Ingrid B. Utne Geir Johnsen	20 MNOK (total budget 800 mNOK)	2017-2023	NFR, KUD and partners	NTNU, UiT, UiO, UiB, UNIS, IMR. NPI, MET, Akvaplan NIVA, Nansen Centre Env Remote sensing	5 PhD
Autoferry: Autonomous all-electric passenger ferries for urban water transport	Morten Breivik Edmund Brekke Egil Eide ++	25 MNOK	2018-2021	NTNU (IMT, ITK, IES, ID, IIK)	NTNU	8 PhD
Autonomous Operation of Snake-Like Robots in Challenging Environments	Kristin Y. Pettersen	0.1 MNOK	2018-2020	Imperial College	NTNU Imperial College	

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Real-time encryption of sensors in autonomous systems. NTNU Gjøvik/Trondheim.	Thor I Fossen	8 MNOK	2020-2023	NTNU ITK/Gjøvik	NTNU	2 PhD
Autonomous ships, intentions and situational awareness	Edmund Brekke	12 MNOK	2019-2022	RCN MAROFF	NTNU DNV GL KM MR	3 PhD
Efficient stochastic dynamic response analysis for design of offshore wind turbines	Torgeir Moan	3 MNOK	2014-2020	NFR	NTNU	1 PhD
Fault dertection and diagnosis in floating wind turbines	Torgeir Moan	6 MNOK	2014-2020	NFR Equinor	NTNU, DTU, MIT, Equinor	2 Phd
Dynamic response analysis of floating bridges	Torgeir Moan	6 MNOK	2016-2021	NPRA	NPRA	2 Postdoc
Safety Assesment of floating bridges	Torgeir Moan	3 MNOK	2019-2021	NPRA	NPRA	1 Postdoc
Dyn anal of floating surbmerged turibines	Torgeir Moan S. Fu	3 MNOK	2014-2020	CSC NTNU	Shanghai Jiao Tong University	1 PhD
Num modelling and analysis ofturbine blased	Torgeir Moan Z Ghao	3 MNOK	2014-2019	CSC NTNU	Fred Olsen Wind Carrier	1 PhD
Design and analyi of mooring system for floaters in shallow waters	Torgeir Moan	3 MNOK	2016-2020	CSC NTNU	Equinor	1 PhD
Real-time hybrid model testing for extreme marine environments	Roger Skjetne	3 MNOK		RCN	Sintef Ocean	1 PhD 1 Postdoc
SLADE KPN - Fundamental investigations of violent wave actions and impact response	J. Amdahl, O. M. Faltinsen, M. Greco	20, 5 MNOK Total NTNU-IMT 6,5 MNOK	2019-2021	RCN MAROFF	SINTEF Ocean, NTNU-SIMLab, NTNU-IMT	1 PhD 1 Postdoc
§ Rolls-Royce University Technology Center (UTC) on Ship Performance and Cyber-Physical Systems	T. A. Johansen					Extension with section on Cyber-Physical Systems
Cyber-Physical Security for Safety-Critical Aviation Operations	Nadia Sokolova, T. A. Johansen		2019-2022	NFR IKTPLUSS	Sintef Digital	1 PhD 1 Postdoc
D•ICEROTORS – Protecting the unmanned aircraft industry	T. A. Johansen	3 MNOK	2019-2022	NFR BIA IPN	UBIQ Aerospace	1 Postdoc

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Energioptimalisert konsept for hel-elektriske, utslippsfrie og autonome ferjer i integrerte transport og energisystemer	Morten Breivik Anastasios Lekkas	4 MNOK	2017-2020	PILOT-E (NFR Energix + Innovasjon Norge)	Kongsberg Maritime Fjellstrand Grenland Energy Grønn Kontakt NTNU	1 PhD
aFerry – An integrated autonomy system for on-demand, all-electric and autonomous passenger ferries	Egil Eide Morten Breivik Asgeir Sørensen T A Johansen	6 MNOK	2019-2020	NFR FORNY	TTO	
Realisering av en autonom byferge for passasjertransport til kommersielt bruk	T. A. Johansen	1 MNOK	2019-2021	NFR PILOT-T	Maritime Robotics mfl	
OceanEye – All-weather, high-precision intelligent payload for sea surface object detection	T. A. Johansen	1 MNOK	2019-2021	NFR MAROFF IPN	Maritime Robotics SINTEF Digital PGS NORUT	
OceanLab Trondheimsfjorden	AJ Sørensen M. Ludvigsen ++	100 MNOK	2019-2023	NFR Infrastructure	SINTEF Ocean, SINTEF Digital, NTNU	
SeeBee-Norwegian Infrastructure for drone-based research, mapping and monitoring in the coastal zone	TA Johansen A Sørensen G Johnsen	83 MNOK NTNU 18 MNOK	2019-2023	NFR Infrastructure	NIVA, NTNU, NR, NINA, IMR, GA	
Autonomous Robots for Ocean Sustainability (AROS)	Kristin Y. Pettersen M Greco JT Gravdahl A Stahl R Mester	21.5 MNOK	2019-2023	NFR IKTPLUSS	NTNU	5 PhD
Navigation System Integrity Assurance for Safety-Critical Autonomous Operations	Tor Arne Johansen	3.5 MNOK	2020-2023	NFR IKTPLUSS	SINTEF Digital NTNU	1 PhD
Autonomous Underwater Fleets: from AUVs to AUFs through adaptive communication and cooperation schemes	Kristin Y. Pettersen Damiano Varagnolo Hefeng Dong Claudio Paliotta Joao Sousa	14.6 MNOK	2020-2023	NFR FRIPRO	NTNU SINTEF Digital	3 PhD
SFI Harvest	Asgeir J. Sørensen Martin Ludvigsen M. Føre, ...	200 MNOK	2020-2028	SFI Centre	SINTEF Ocean, NTNU Aker Biomarine, PGS, Arnøytind, Scanbio, Kongsberg Maritimer Subsea, Optimar, ++	4 PhD 1 Postdoc campaigns

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
SFI Autonomous Ships	Mary Ann Lundteigen Tor Arne Johansen, Thor I . Fossen, Ingrid B. Utne, Edmund Brekke, Annette Stahl, Tasos Lekkas, Mortein Breivik Roger Skjetne	Not yet clear Ca 200 MNOK	2020-2028	SFI Centre	NTNU, SINTEF Ocean, Kongsberg, ..	5 PhD Postdoc
NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS)	Asgeir J. Sørensen, Kristin Y Pettersen, Martin Ludvigsen, Kjetil Skaugset	45 MNOK	2020-2025	VISTA	Equinor, NTNU, DNVA	6 PhD
Machine Piloted Unmanned Systems (MPUS)	Tor Arne Johansen	1MNOK	2020-2023	NFR MAROF	Radionor, MR, Seatex, NTNU	
Unmanned Aircrafts in All Future Airspace (UAAFA)	Tor Arne Johansen	3 MNOK	2020-2023	NFR BIA	Radionor, Andøya, NTNU	1 Postdoc
Icing effects, detection and mitigation on unmanned aerial vehicles (UAVs)	Tor Arne Johansen	12 MNOK	2021-2024	NFR IKTPLUSS	UBIQ MR Andøya VTT	2 PhD 1 Researcher
UAV Mission planning in adverse weather conditions	Tor Arne Johansen	7 MNOK	2020-2024	NFR IPN	UBIQ	2 PhD
Efficient Learning and Optimization Tools for Hyperspectral Imaging Systems (ELO-Hyp)	Tor Arne Johansen	5 MNOK	2020-2023	EEA Romania		Forskere
Assuring Trustworthy, Safe and Sustainable Transport for All -– TRUSST	Tor Arne Johansen Edmund Brekke	3.5 MNOK	2021-2023	NFR MAROFF	DNV GL Zeabuz MT	1 PhD
Deep Impact – biological surveys from lit ships in the dark – can we realistically use the results for stock assessments, ecosystem dynamics and biomass estimation of zooplankton and fish	G Johnsen	Total 10 MNOK 0,6 MNOK to AMOS	2019-2022	NFR Klimaforsk	UiT, NTNU, Uni Strathclyde, Memorial Uni St Johns Canada, Uni Delaware	
SFI BLUES Floating Structures for the Next Generation Ocean Industries	Erin Bachynski, Zhen Gao	Total 167 MNOK	2020-2028	SFI	SINTEF Ocean, NTNU, NGI, MET, Equinor, Mowi,NPRA, Dr. Techn Olav Olsen, Deep Sea Mooring, Ocean Sun, ++	3 PhD + 2 Postdoc

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
WAS-XL Wave Loads and Soil Support for Extra-Large Monopiles	Erin Bachynski	21 MNOK	2017-2020	KPN	SINTEF Ocean, NTNU, NGI, Equinor, RWE, EDF, Vattenfall, Multiconsult	1 PhD + 1 Postdoc
WINDMOOR Advanced wave and wind load models for floating wind turbine mooring system design	Erin Bachynski	16 MNOK	2019-2023	KPN	SINTEF Ocean, NTNU, Inocean, Equinor, APL NOV, MacGregor, RWE	1 PhD
FLOAWER (FLOAting Wind Energy network)	Erin Bachynski	3.5 MEUR	2019-2023	EU ITN	EC Nantes, NTNU, Polimi, DTU, USTUTT, UCC, UROS, ++	2 PhD at NTNU
Green energy at sea: offshore wind turbines and energy systems for shiops, ports, and offshore structures	Asgeir J. Sørensen Erin Bachynski	8 MNOK	2019-2023	INTPART	NTNU, U. Michigan	
Upscale – Building knowledge on the future generation of floating substructures for very large wind turbines	Erin Bachynski	14.5 MNOK	2020-2024	KPN	IFE, NTNU, U. Texas, Equinor, Aibel, GCE Node, Olav Olsen, Energy Valley	1 PhD
Marine archeology using marine robotics	Øyvind Ødegård Asgeir J. Sørensen	4 MNOK	2020-2023	NTNU VM		1 PhD
Perception & Fusion of Multidimensional Information & Cooperative Decision-making for Intelligent Diagnosis of Wind Turbine Critical Parts (InteDiag-WTCP)	Zhen Gao, Amir Nejad	8 MNOK	2020-2023	NFR IKTPLUSS (International Calls for Bilateral Project between Norway and China)	EDR & MEDESO AS, SAFETEC NORDIC AS	2 PhD
CONWIND: Research on smart operation control technologies for offshore wind farms	Amir Nejad, Trond Kvamsdal, Michael Muskulus, Zhen Gao	4 MNOK	2020-2023	NFR (International Calls for Bilateral Project between Norway and China on Energy)	NORCE, University of Bergen, SINTEF	1 Postdoc
Autonomous DP operation	Astrid Brodtkorb	4 MNOK	2020-2023	NFR	SINTEF Ocean Brunvoll	1 PhD
FME NORTHWIND – Norwegian Research Centre on Wind Energy	Zhen Gao, Erin Bachynski	Total 120 MNOK	2021-2028	FME	SINTEF, NTNU, UiO, NGI, NINA, Equinor, DNVGL, Kongsberg, Nexans, Aker	3 PhD
TechNOII – Technology for New Ocean Industries and Infrastructures – Offshore Wind, Aquaculture and Floating Bridges	Zhen Gao	4 MNOK	2019-2022	INTPART	Shanghai Jiao Tong University	

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Ship operational performance in following seas (ProfSea)	Tor Arne Johansen, Thor Fossen	4 MNOK	2021-2024	NFR KPN	Kongsberg Maritime, SINTEF Ocean	1 PhD
Science of resilient autonomy in perceptually-degraded environments (Sentient)	Kostas Alexis, Tor Arne Johansen	12 MNOK	2021-2024	NFR IKTPLUSS	DNV GL, Equinor, Altera, Scout	3 PhD
REmote Drone-based ship HUll Survey (REDHUS)	Kostas Alexis, Tor Arne Johansen	4 MNOK	2021-2024	NFR IPN	DNV GL, Klaveness, Scout, Altera	1 PhD

Completed Projects

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Design and verification of control systems for safe and energy-efficient vessels with hybrid power plants (D2V)	Asgeir J. Sørensen Tor Arne Johansen Roger Skjetne Ingrid B. Utne	18,7 MNOK	2011-2017	NFR MAROFF	NTNU Kongsberg Maritime DNV GL	6 PhD
Closed Flexible Cage (CFC)	Asgeir J. Sørensen	4 MNOK	2013-2017	NFR	SINTEF Ocean	1 PhD
Fault-Tolerant Inertial Sensor Fusion for Marine Vessels (MarineINS)	Thor I. Fossen Tor Arne Johansen	7 MNOK	2012-2016	NFR MAROFF	NTNU, RRM	2 PhD
Low-Cost Integrated Navigation Systems using Nonlinear Observer Theory (LowCostNav)	Thor I. Fossen Tor Arne Johansen	9 MNOK	2013-2016	NFR FRINATEK	NTNU FFI UNIK	3 PhD
Next Generation subsea inspection, maintenance and repair operations	Ingrid Schjølberg Ingrid B. Utne Thor I. Fossen	20 MNOK	2014-2017	NFR KPN Awarded	NTNU FMC Statoil SINTEF IKT	4 PhD
Autonomous Unmanned Aerial System as a Mobile Wireless Sensor Network for Environmental and Ice Monitoring in Arctic Marine Operations	Tor Arne Johansen	12 MNOK 0.9 MNOK for NTNU	2014-2016	NFR BIP Awarded	NTNU Radionor Maritime Robotics KM Seatex NTNU	Cover NTNU field trial cost, else company research
Power management on ships	Tor Arne Johansen	3 MNOK	2014-2017	NRC Industry PhD Espen Skjong	NTNU Ulstein Group	1 PhD
Arctic Ocean ecosystems - Applied technology, Biological interactions and Consequences in an era of abrupt climate change (Arctic ABC)	Asgeir J. Sørensen Geir Johnsen	51,5 MNOK	2016-2019	Forsker-prosjekt NFR	UiT NTNU SAMS APN UiD WHOI UMA	1 PhD 1 Postdoc for NTNU + Field experiments in the Arctic

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Networked Ocean – Networked ocean and air vehicles for communications and data collection in remote oceanic areas	Tor Arne Johansen	300 kEUR	2015-2016	EEA Grant (Portugal)	University Porto NTNU FFI	Support field experiments
UAV ice detection	Tor Arne Johansen	NTNU	2016-2017	ERCIM / NTNU		1 Postdoc
Forprosjekt design og konstruksjon av nyttelaster til NORSat	Tor Arne Johansen	250 kNOK	2017	Norsk Romsenter	Roger Birkeland, IET	
Snake Locomotion in Challenging Environments	Kristin Y. Pettersen	13.9 MNOK	2011-2015	NRC	SINTEF IKT	2 PhD 1 Postdoc
VISTA PhD-stipend Jørgen Sverdrup-Thygeson: Swimming Robot Manipulators for Subsea IMR.	Kristin Y. Pettersen	3 MNOK	2015-2018	VISTA	NTNU	1 PhD
VISTA Post doc –Eleni Kelasidi	Kristin Y. Pettersen	3 MNOK	2016-2018	VISTA	NTNU	1 Postdoc
Assessment of operational limits for installation of OWT monopile and transition piece and development of an alternative installation procedure	Torgeir Moan	6 MNOK	2013-2016	NFR		2 PhD
Experimental and numerical study of the combined wind/wave energy concept SFC in extreme and operational environmental conditions	Torgeir Moan Zhen Gao	3 MNOK	2014-2016	NFR	NTNU	1 Postdoc
Numerical analysis of the dynamic response of an offshore wind turbine under wind and ice loads	Torgeir Moan	3 MNOK	2014-2016	NFR	NTNU	1 Postdoc
Numerical modelling and dynamic analysis of floating vertical axis wind turbines	Torgeir Moan	3 MNOK	2013-2016	NFR	NTNU	1 PHD
Dynamical analysis of anchor handling and trawling operations	Torgeir Moan	3 MNOK	2013-2016	NFR	NTNU	1 PHD
TerraDrone	Tor Arne Johansen	15 MNOK	2016-2018	NFR BIA Innov prosjekt	Maritime Robotics IDLETech NTNU NGU	1 Postdoc
Multi-stage Global Sensor Fusion for Navigation using Nonlinear Observers and eXogenous Kalman Filter	Tor Arne Johansen Thor I. Fossen	10 MNOK	2016-2019	NFR FRINATEK		1 PHD 2 Postdoc
Integration of Manned, Autonomous and Remotely Controlled Systems for Coastal Operations	Tor Arne Johansen	1.2 MNOK til NTNU	2016-2018	NFR MAROFF	Radionor, Seatex, Maritime Robotics	
D-ICE	Tor Arne Johansen	6 MNOK	2017-2018	NFR FORNY	TTO	
SCOUT Inspection Drone	Tor Arne Johansen Thor I. Fossen	6 MNOK	2017-2018	NFR FORNY	TTO	

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
European Training Network funded by H2020 for 2015-2018 Marie Curie Marine UAS	Tor Arne Johansen Thor I. Fossen	4 MEUR	2015-2018	EU	NTNU IST UiP LiU NORUT Maritime Robotics Honeywell Catec iTUBS	15 PhD whereof 5 PhD at NTNU + project managem.
Drone air traffic control	Tor Arne Johansen	0.9 MNOK til NTNU	2017-2018	JU SESAR	Internasjonalt konsortium ledet av Airbus	
Safe operation of CLOSED aquaculture CAGES in WAVES	Odd Faltinsen Claudio Lugni	2,2 MNOK til NTNU	Q4 2017-Q3 2019	NFR MAROFF	SINTEF Ocean (P. Lader)	1 Postdoc
Sensor Fusion and Collision Avoidance for Autonomous Surface Vehicles (Autosea)	Edmund Brekke Morten Breivik Tor Arne Johansen	11,2 MNOK	2017-2018	RCN MAROFF	NTNU DNV GL Kongsberg Maritime Maritime Robotics	3 PHD 1 Postdoc
Enabling Technology providing knowledge of structure, function and production in a complex Coastal Ecosystem (ENTiCE)	Martin Ludvigsen Geir Johnsen Asgeir J. Sørensen	6 MNOK	2016-2019	NFR, Marinforsk	SINTEF Ocean, NTNU IBI and IMT, SAMS	1 PHD 1 Postdoc
Ice-algal and under-ice phytoplankton bloom dynamics in a changing Arctic icescape –"Boom or bust Boom or bust"	Geir Johnsen	3 MNOK	2016-2018	NFR – Polprog	NP, NTNU, AWI	1 PhD

PHOTO GALLERY

Key scientists

Prof.
Asgeir J. Sørensen

Prof.
Thor I. Fossen

Prof.
Jørgen Amdahl

Prof.
Marilena Greco

Prof.
Tor Arne Johansen

Prof.
Geir Johnsen

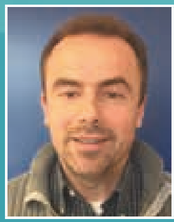
Prof.
Kristin Y. Pettersen

Adjunct professors and adjuct associate professors

Adj. Prof.
Jørgen Berge

Adj. Prof.
Arne Fredheim

Adj. Prof.
Maarja Kruusmaa



Adj. Prof.
Claudio Lugni

Adj. Ass. Prof.
Ulrik D. Nielsen

Adj. Prof.
Kjetil Skaugseth

Adj. Prof.
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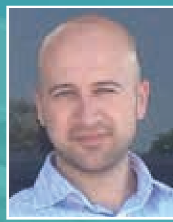
Nguyen Trong Dong



Adj. Ass. Prof.
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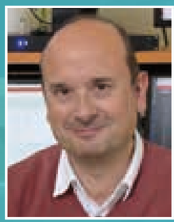
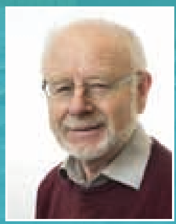
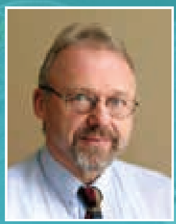


Adj. Prof.
Fernando Aguado Ageleet

Senior Scientific advisers

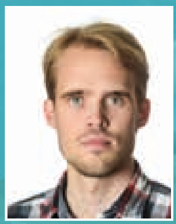


Prof.
Odd M. Faltinsen



Prof.
Torgeir Moan

Management and administration



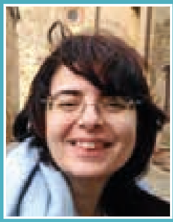
Sigmund Bolme

Renate Karoliussen

Knut Reklev

Postdocs/researchers


Dr. Roger Birkeland


Dr. Giuseppina Colicchio

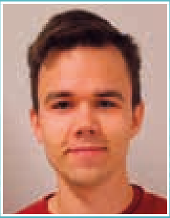

Dr. Bjørn-Olav Holtung Eriksen

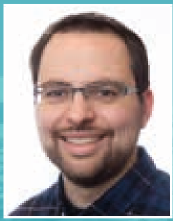

Dr. Trygve Fossum

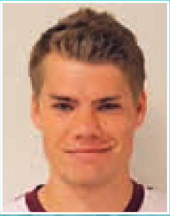

Dr. Glaucia Moreira Fragoso


Dr. Joseph Garrett

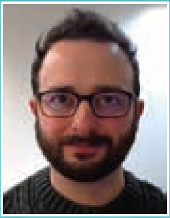

Dr. Stephen Grant


Kristoffer Gryte

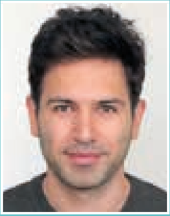

Dr. Richard Hann


Dr. Håkon Hagen Helgesen


Dr. Ravinder Praveen Kumar Jain

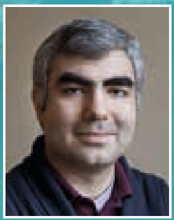

Dr. Alun Jones

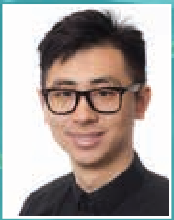

Dr. Fredrik Stendahl Leira


Dr. Mojatba Mokhtari


Dr. Petter Norgren


Dr. Stein Melvær Nornes


Dr. Babak Ommani

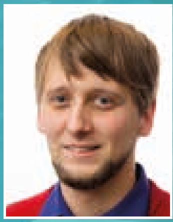

Dr. Zhengru Ren


Dr. Børge Rokseth


Dr. Yugao Shen


Dr. Christoph Alexander Thieme


Dr. Kadir Atilla Toker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Dr. Erik F. Wilthil


Dr. Yu Zhaolong


Dr. Artur Piotr Zolich


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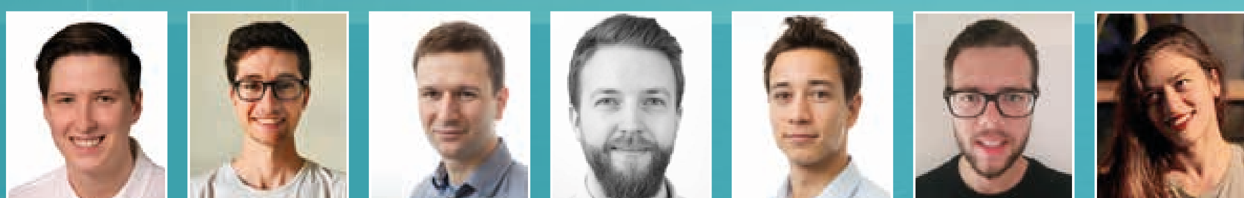
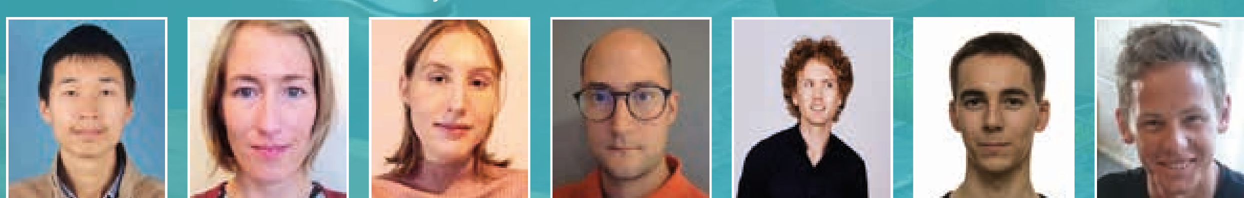
Tore Mo-Bjørklund | Jon Bjørnø | Simon Blindheim | Pål Tokle Bore | Ida-Louise Garmann Borlaug | Vasileios Bosdelekidis | Jens Einar Bremnes

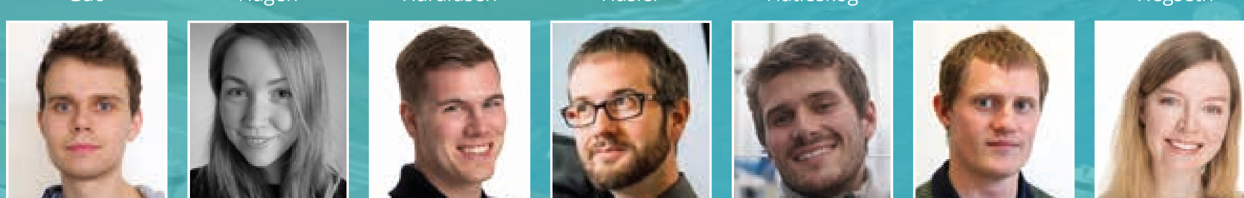


Eivind E. Bøhn | Alexandre Cardaillac | Krzysztof Cisek | Erlend Magnus Lervik Coats | Andreas Reason Dahl | Albert Dallolio | Eleni Diamanti

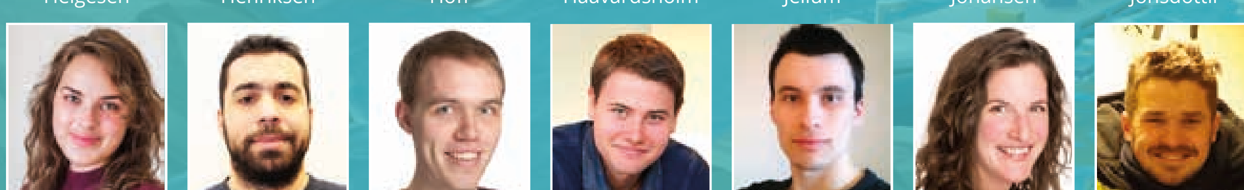
Gara Quintana Diaz | Johan Alexander Dirdal | Andrea Faltynkova | Andreas L. Flåten | Joao Fortuna | Fan Gao | Mariusz Eivind Santora Grøtte



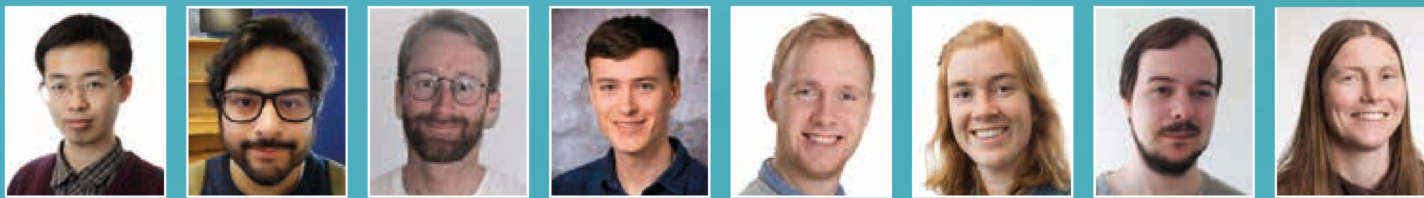
Chuanqui Guo | Inger Berge Hagen | Aurora Haraldsen | Oliver Kevin Hasler | Johan Hatleskog | Simen Haugo | John Marius Hegseth



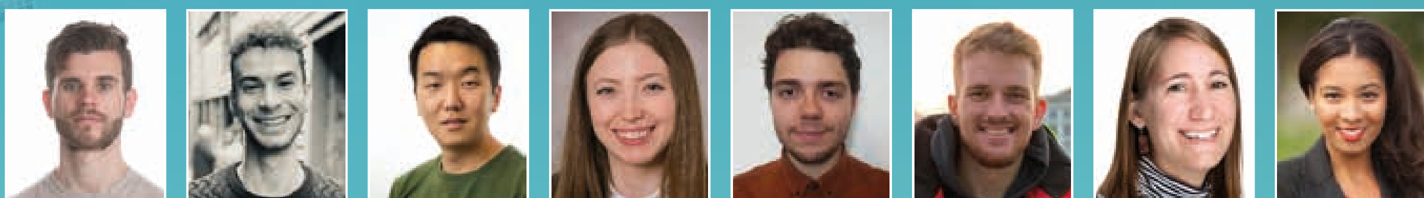
Øystein Kaarstad Helgesen | Marie Bøe Henriksen | Simon A. Hoff | Trym Vegard Haavardsholm | Erling Rennemo Jellum | Thomas Johansen | Kristbjörg Edda Jónsdóttir



Marianna Kaminska-Wrzos | George Katsikogiannis | Bjørn Andreas Kristiansen | Tord Hansen Kaasa | Dennis D. Langer | Evelyn Livermor-Honoé | Håvard Snefjellå Løvås

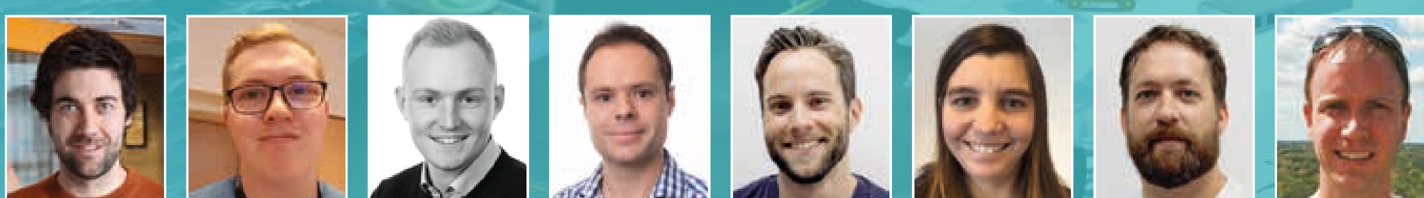


Shaojun Ma | Renan Maidana | Mathias Marley | Andreas Bell Martinsen | Pål Holthe Mathisen | Siri Holthe Mathisen | Josef Matous | Mariann Merz



Aksel Alstad Mogstad | Raphael Mounet | Woongshik Nam | Carina Norvik | Amer Orucevic | Casper Potter | Elizabeth Frances Prentice | Nathalie Ramos

Namireddy Praveen Reddy | Dirk Peter Reinhardt | Sverre Velten Rothmund | Dag Rutledal | Henrik Schmidt-Didlaukies | Mohd Atif Siddiqui | Tale Skrove | Robert Skulstad



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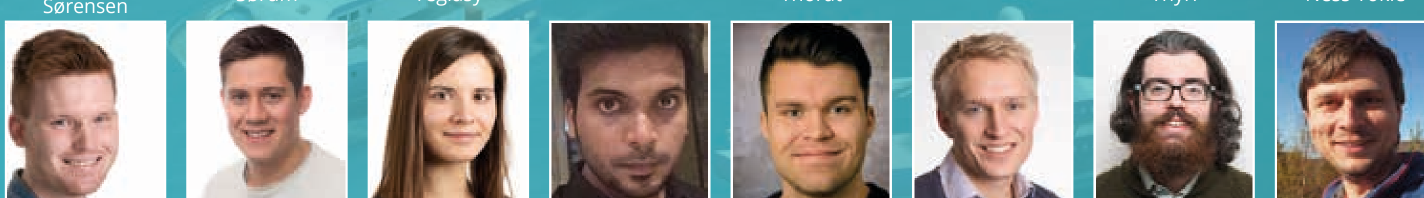
Mikkel Eske Nørgaard Sørensen | Stian Høegh Sørum | Bálint Zoltán Téglasy | Trym Tengesdal | Laxminarayan Thorat | Marius Thoresen | Emil Hjelseth Thyri | Lars-Christian Ness Tokle



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Menging Wu | Hui-Li Xu | Kun Xu | Libo Xue | Henning Øvreaas

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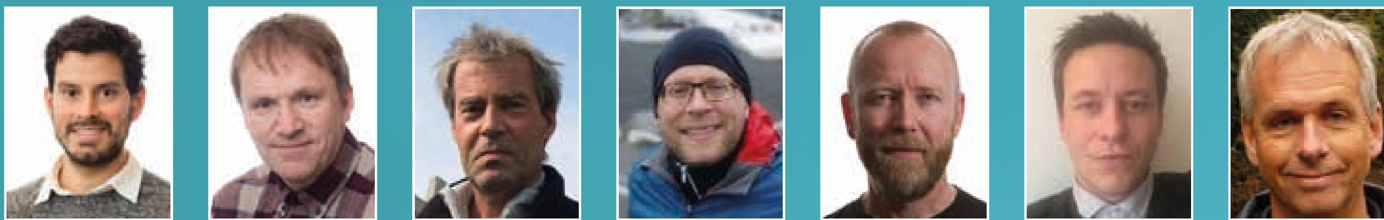
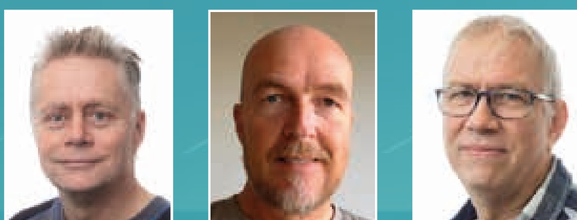


Pedro De La Torre | Trond Innset | Pål Kvaløy | Christian Malmquist | Terje Rosten | Kay Arne Skarpnes | Henricus Van Rijt



Ole Erik Vinje | Frode Volden | Torgeir Wahl

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Ass. Prof. Martin Føre | Prof. Zhen Gao | Prof. Jan Tommy Gravdahl | Prof. Lars S. Imsland | Ass. Prof. Ekaterina Kim | Prof. Trygve Kristiansen | Prof. Alexis Konstantinos

Prof. Pål Lader | Ass. Prof. Anastasios Lekkas | Prof. Martin Ludvigsen | Prof. Mary Ann Lundteigen | Prof. Marta Molinas | Ass. Prof. Eilif Pedersen | Prof. Slobodan Petrovic

Prof. Yngvar Olsen | Prof. Ingrid Schjølberg | Prof. Roger Skjetne | Ass. Prof. Annette Stahl | Prof. Oleksandr Tymokha | Prof. Ingrid Utne | Prof. Houxiang Zhang

HIGHLIGHTS OF THE APPLIED UNDERWATER VEHICLE LABORATORY (AURLAB)

The lab's webpage: https://www.ntnu.edu/aur-lab

To address challenges in the ocean space, AUR-Lab runs and maintains a park of AUVs, ROVs, instruments, samplers and navigation equipment with support systems on behalf of partners from five different faculties. The lab represents an interdisciplinary scientific community in which scientific questions are addressed by teams with specialists from many specialties. Opportunities for faculty, researchers, PhD- and MSc students to test and experiment are provided with enhancing hypotheses and theoretical work. Some of the scientific questions for 2020 have been related to Arctic operations, archaeology and maritime heritage, pollution and oceanography. The Department of Marine Technology hosts the lab, and the University Museum, the Department of Engineering Cybernetics and Department of Biology are partners.

In early January, we participated in a Polar Night cruise onboard the research vessel Helmer Hansen organized by UiT. The research theme for the operations was a light climate in the Arctic, including the effects of anthropogenic light in the Polar night. The AUV Thor was deployed in Kongsfjorden with a SilCAM particle imager. Our Northernmost ROV deployment was also completed using a ROV SF 30k to recover a lost instrument rig from a depth of 230 meters.

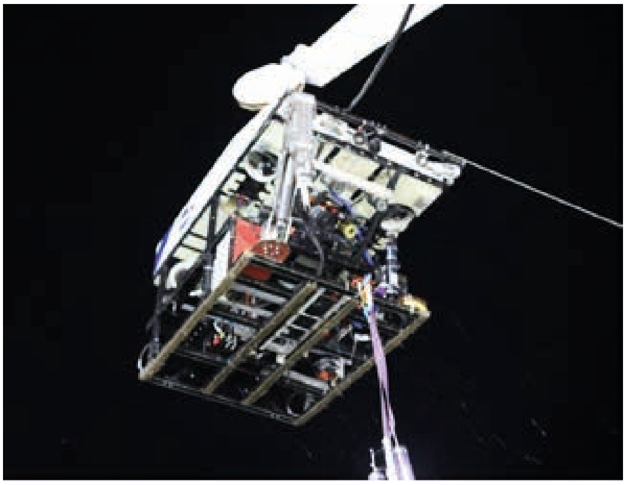


Figure 7: *ROV SF 30k launch to recover an instrument rig in Kongsfjorden*

In late summer, the AUR-Lab took the snake robot Eely for commissioning from the start-up company Eelume. The vehicle is an articulated intervention AUV with four joints and three hull sections. The vehicle is remotely controlled to change shape and orientation for intervention and observation operations. Experiments for AMOS' PhD students were performed in MC-Lab, developing control algorithms to optimize the behaviour of the vehicle. Several deployments from Gunnerus showed the

Figure 6: *Deploying AUV Thor in Kongsfjorden in the Polar night.*

Figure 8: *The Eelume underwater vehicle doing a seabed inspection*

performance of the system in the Ocean, providing valuable insight for further research using this flexible platform. In the next stage, the vehicle will advance ROV to AUV, increasing its capacities for autonomous operations.

Together with SINTEF Ocean, the Department for Marine Technology has been awarded funding to realize the OceanLab project (https://www.ntnu.edu/oceanlab), with the AUR-Lab working hard to realize infrastructure components related to subsea technology. Both the Subsea Docking Plate (SDP) and the mock-up Pig Loop Module (PLM) will be used and complemented with more instruments to facilitate full-scale field experiments for inspection, intervention and docking. Control room facilities are a central part of the concept, and operational concepts have been developed together with NTNU Samfunnsforskning, inspired by their experience from satellite and space operations. Adapted to marine scenarios, remote operations from a control room have been tested for AUV deployments. The work with OceanLab will continue through 2021, developing the control room, instruments and vehicles.

Figure 9: *Testing the operational concept for control room operations using a mock-up remote controlling an AUV deployment*

HIGHLIGHTS SMALLSAT LAB

The HYPSO-1 (The HYPer-Spectral smallsat for Ocean observation) spacecraft is part of a larger effort towards "... a concerted and unified cross-disciplinary focus on designing, building and operating small satellites as parts of an autonomous system for maritime sensing, surveillance and communication" - https://www.hypso.space/.

HYPSO will observe oceanographic phenomena via a small satellite with a hyperspectral camera, intelligent on-board processing and in collaboration with marine robots. Why? The ocean is of great interest to understand the effects of climate change and human impact on the world. Traditional earth-observation satellites are very expensive, and take several years to develop and launch. Dedicated small satellites can be used to provide images of selected areas of interest with shorter revisit times and better spectral resolution through hyperspectral imaging, see Figure 1. The information can be downloaded to the ground and used by both end-users and marine robots, which can further investigate the areas of interest.

The spacecraft is being developed in collaboration between the Department of Electronic Systems and the Department of Engineering Cybernetics, with support from the Department of Mechanical and Industrial Engineering. The HYPSO-1 project team in 2020 consisted of nine PhD fellows (Evelyn Honoré-Livermore,

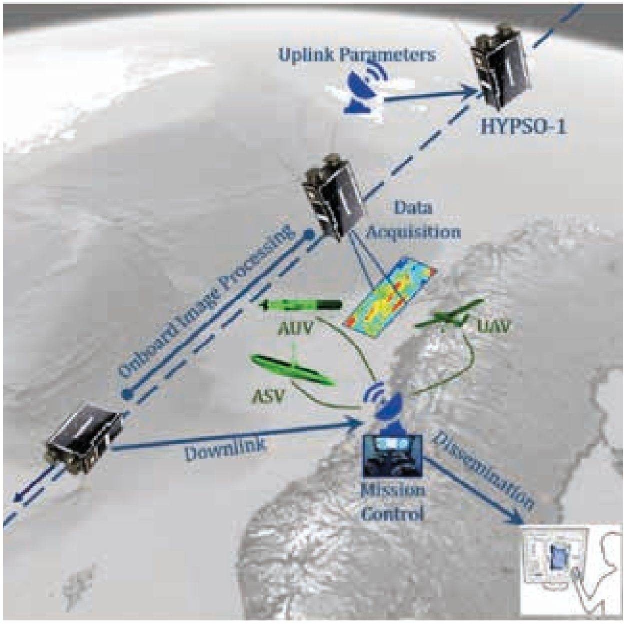


Figure 10. *Through slewing the spacecraft when above the targeted oceanographic area, the satellite will achieve a higher ground sampling distance, which in turn will be used to increase the spatial resolution of the images.*

Figure 11. *One of the highlights from 2020 was the agreement to collaborate between NTNU and the European Space Agency (ESA), with a focus on small satellites. The agreement was facilitated by Dean Ingrid Schjølberg, and signed in 2020 by NTNU Rector Anne Borg and director of ESA Johann-Dietrich Wörner.*

Figure 12: *Drawing of custom designed hyper-spectral imager for ocean colour.*

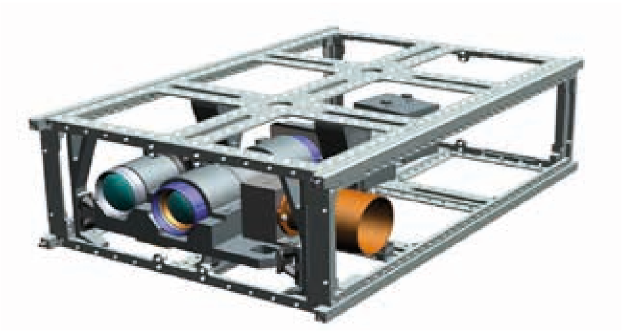


Figure 13: *Illustration of the integration of HSI, RGB camera and star tracker in the 6U HYPSO-1 cubesat.*

Gara Quintana Diaz, Elizabeth Prentice, Dennis Langer, Mariusz Grøtte, Bjørn Kristiansen, Marie Henriksen, Mariusz Grøtte and Sivert Bakken), two Postdocs (Roger Birkeland and Joseph Garrett), approximately 20 MSc and BSc students, technical staff (Terje Mathisen, Amund Gjersvik and others), and Professors Milica Orlandic, Fernando Aguado Agelet, Jan Tommy Gravdahl, Egil Eide, Fred Sigernes, Geir Johnsen, Asgeir Sørensen, Cecilia Haskins, Nils Torbjörn Ekman and Tor Arne Johansen all working together in the NTNU SmallSatLab.

Payload development

This year, the hardware team has focused on these primary tasks in preparation for launch by finalizing the hyper-spectral imager (HSI), custom designed by Fred Sigernes and the RGB camera, to survive the space environment and fit a 6U CubeSat; this included environmental testing and instrument validation. The images it takes will enable us to observe ocean colour from space, for example, monitoring algae blooms. Therefore, image quality is a key part of our mission.

We have developed a new version of the electronics, see Figure 9, done the thermal design with thermal straps, developed Ground Support Equipment for all the testing we want to perform, and established a cleaning procedure for all parts so that it can be assembled for space. We have done some optical modifications to ease assembly and reduce the number of parts. The hardware and software team have also worked closely on developing the software needed for testing the functionality of the payload during environmental tests.

We have been conducting environmental testing to understand how both our COTS and custom-made components will handle launch and a 5-year lifetime in space. With optics, these conditions can be particularly harsh. During this past year, we have conducted thermal, vacuum, shock, vibration and radiation tests using facilities on campus and elsewhere, which will continue throughout the final phases of development.

In December, we got a chance to perform a low-pressure vacuum test at Norbit in Trondheim, see Figure 10. We wanted to

Figure 14. *Glenn Angell at the mechanics workshop is producing the fine mechanics of the HSI in aluminum.*

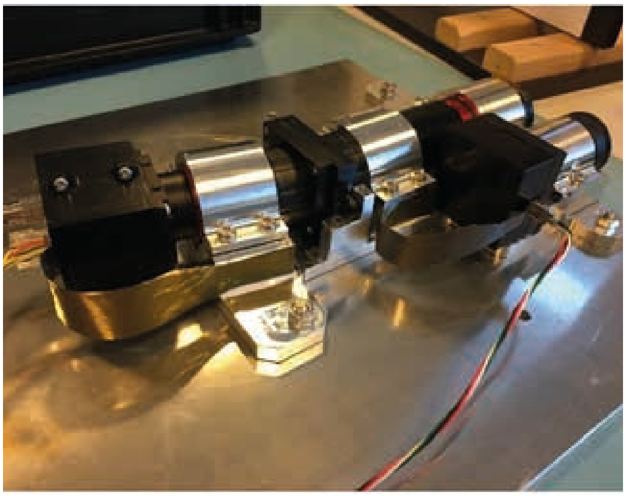


Figure 15: *Test assembly of custom built HSI and RGB cameras.*

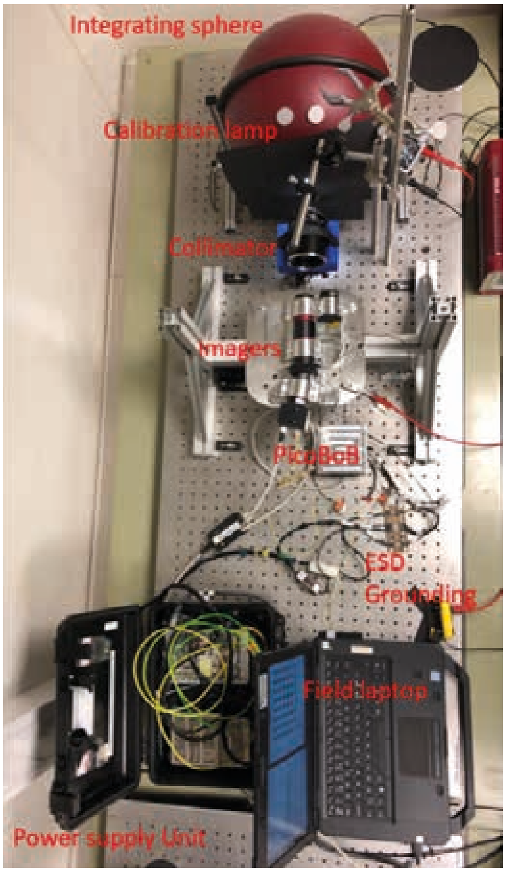


__Figure 16:__ Optical lab test setup used to calibrate and verify performance of HSI before and after environmental tests, software upgrades, etc.

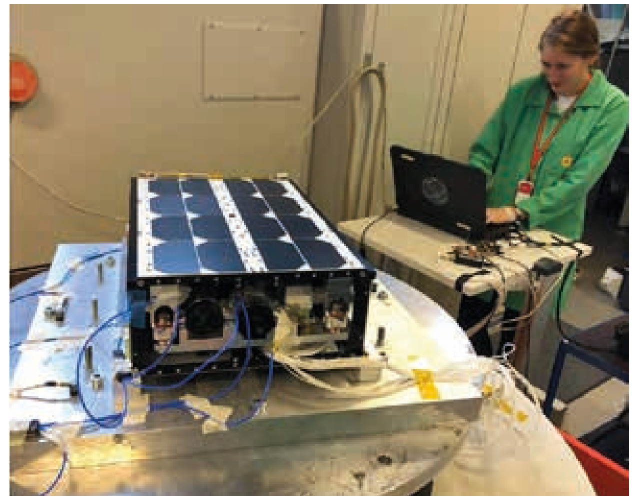


__Figure 17:__ Vibration table test of satellite at FFI's lab at Kjeller.

characterize the performance of our electronic parts to see how they would perform at high temperature in a low vacuum, which is typically the harshest environment for the electronics. We are planning to perform a full thermal vacuum test in January, but this preliminary test provided strong confidence in the design because the system performed well, and we do not expect any problems in January.

After the thermal vacuum test in January, we will ship the flight model to our partner NanoAvionics in Vilnius, and the integration will continue there so that the spacecraft can be launched as soon as possible after that.

Finally, we have worked on simplified methods for evaluating image quality and imager performance, both prior to and after environmental testing, see Figure 7. In this way, we are able

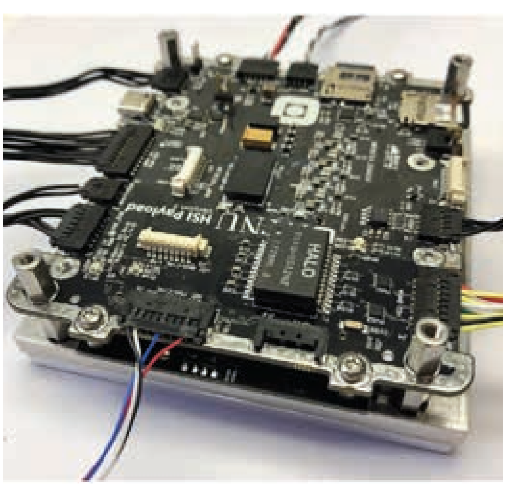


__Figure 18:__ Custom designed electronics board (PicoBOB) that interfaces the payload instruments to the satellite bus and data processing system

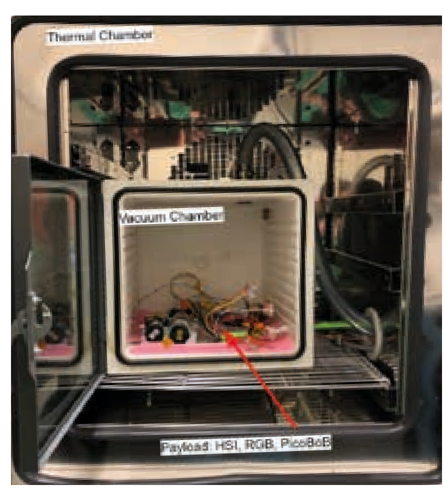


__Figure 19:__ Testing of components in a vacuum chamber inside a thermal chamber

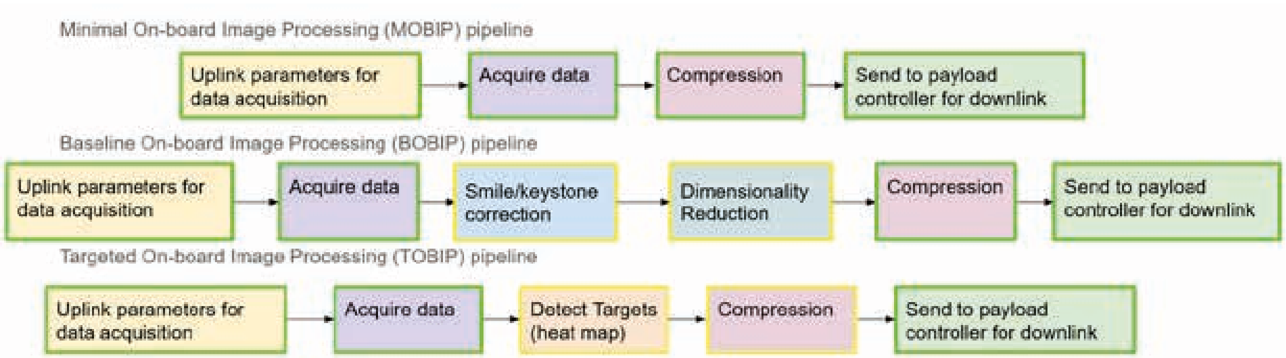


Figure 20: *Alternative processing pipelines that can be executed onboard the satellite.*

to understand whether our "images" are good enough to fulfil mission requirements, and what kinds of calibration and image corrections will be necessary to implement in software on the satellite and the ground.

HYPSO-1 Software and firmware development

The software and firmware team has been focusing on developing the necessary reliable camera control and integration with the NanoAvionics spacecraft. Because of the short schedule until the launch of the spacecraft, the focus has been on reliable firmware and software for camera control, and for implementing the support of in-orbit upgrades of firmware and software. During the commissioning of the payload, it is expected that the software and firmware must be updated, and that new on-board processing algorithms can be uploaded. The future on-board processing pipeline will include synchronized image acquisition, data calibration and correction (radiometric, spectral, keystone, smile and atmosphere), image registration, geo-referencing, super-resolution processing, dimensionality reduction, compression, target detection and classification using AI/machine learning, data storage and communication, see Figure 11.

We have introduced a stricter workflow using GitHub and continuous integration, and we run our software development using the agile practice Sprint.

The COVID-19 pandemic affected the SmallSatLab, as well as many other lab activities at NTNU. However, students and researchers were able to use the infrastructure because many of the hardware-in-the-loop systems were set up to be remotely accessible. The lab is prepared to function as a safe working area for sensitive equipment and electronics, such as the payload in development and hardware-in-the-loop setup, which includes in-house developed electronics and systems connected to payload interfaces. These setups allowed the software development to continue while the campus was locked down, in addition to their intended objectives of providing a more streamlined verification and validation approach, and integration to the spacecraft bus.

Development of mission control center at NTNU and rehearsal of operations of HYPSO-1

The NTNU Small Satellite operations team performed two rehearsals in the fall of 2020. In each rehearsal, operators controlled a FlatSat, a functional mock-up of the satellite, through the nominal satellite imaging operations while being subject to a limited and variable connectivity. A rehearsal is a simulated operations sequence of the satellite, in which the operators send messages to the spacecraft and downlink data. These rehearsals have uncovered critical functional gaps in software and have enabled us to better develop the system before flight.

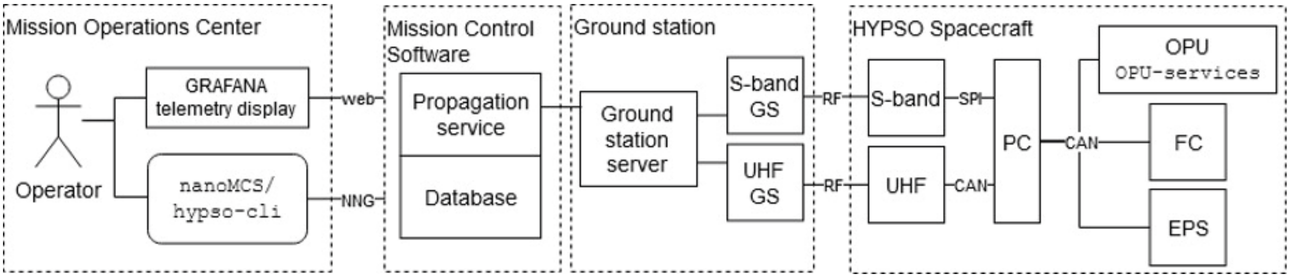


Figure 21: *System architecture illustrating the main data processing and communication components. PC: Payload controller. FC: Flight controller. OPU: Onboard processing unit. EPS: Electrical power system. GS: Ground station.*

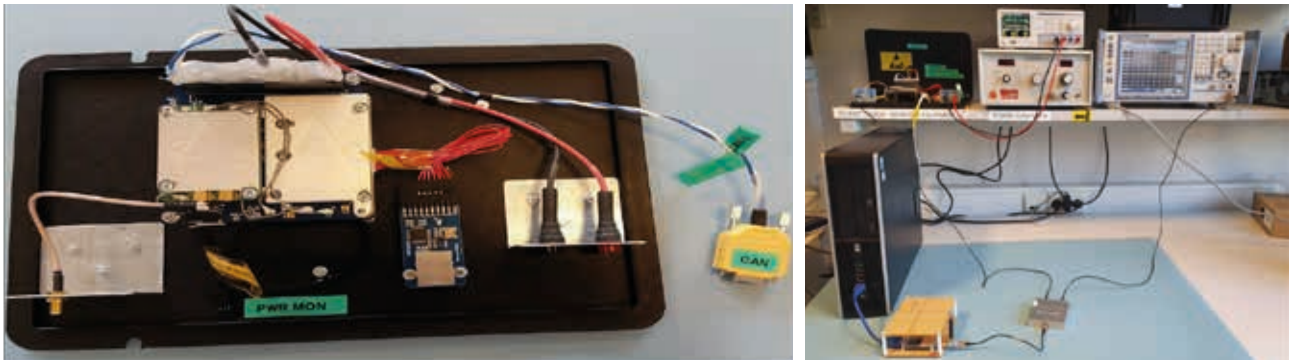


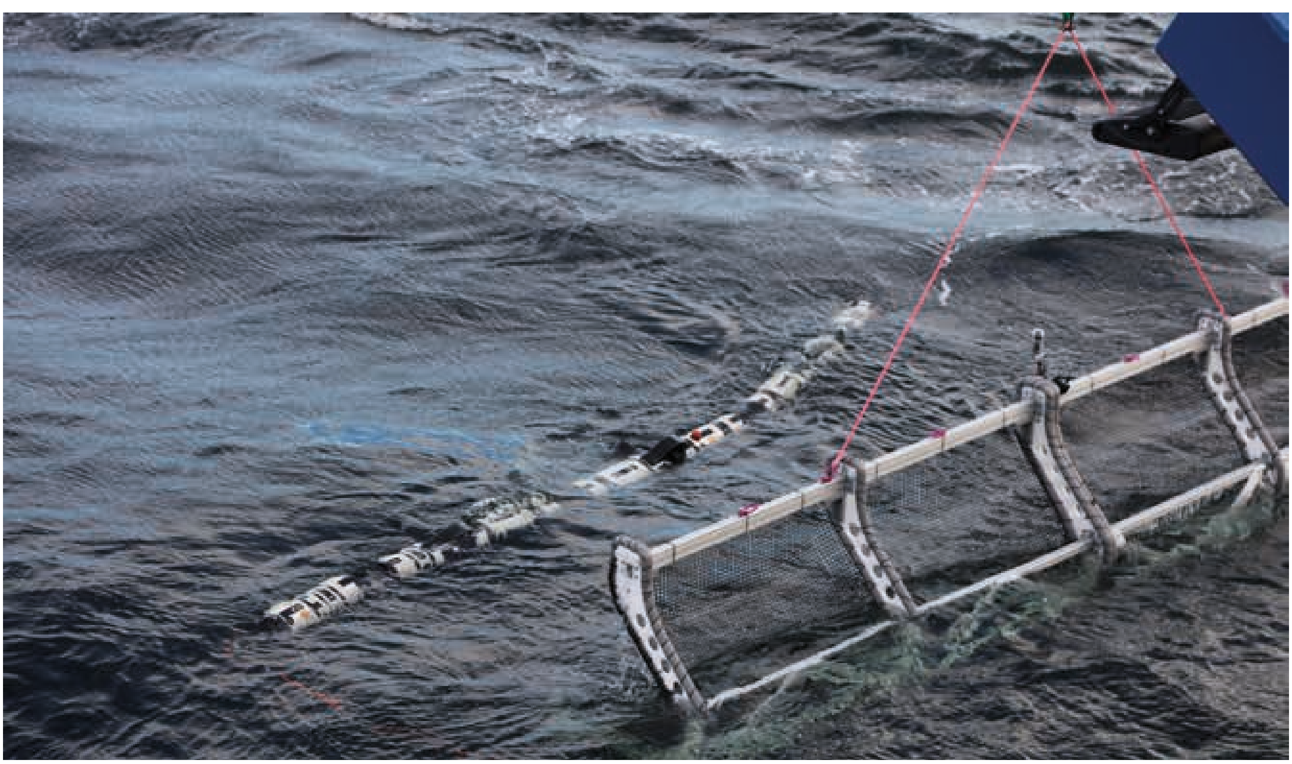
Figure 22: *SDR test setup.*

Simulation and HIL-testing of SDR

In addition to the hyperspectral payload development, the SmallSatLab is host to the development of a Software Defined Radio (SDR) payload. The payload is planned to be a part of the HYPSO-2 mission, and the software developed is already flying on a different mission, LUME-1, provided by Universidade de Vigo. The first version of the measurement software has been developed. It will measure the time-frequency characteristics of radio interference using very little data due to the limited data throughput available in LUME-1. It has been tested on a FlatSat setup in the lab using Totem SDR, which is the same as in LUME-1.

Theoretical and simulation results have been compared to test results in the lab. The software passed lab tests, and was sent to Universidade de Vigo and Alén Space (spin-off from the university) for further tests before uploading the software. The software has been uploaded to LUME-1, and will be installed shortly. Measurement campaigns have been planned for the next month.

The second version of the software measures the cumulative distribution function of the radio interference and the windows of opportunities that can be used for communication. This software has also been developed and tested using the FlatSat setup.



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HIGHLIGHTS OF THE UNMANNED AERIAL VEHICLE LABORATORY

Marlander project – recovery of fixed-wing UAVs on ships

One of the focus areas of AMOS is operations in maritime environments, for which there are many solutions. Unmanned aerial vehicles (UAVs) are particularly suited for many mapping and monitoring missions, and they are capable of scanning considerably larger areas than surface or underwater vehicles. Fixed-wing UAVs have a considerably longer range and endurance, and fly at a higher speed and altitude, when compared to the typical multirotor UAVs that have become common in the last years. However, a challenge with fixed-wing UAVs is landing,

Figure 23: *Testing of automatic recovery of fixed-wing UAV in a moving net in Åsenfjorden.*

especially in space-restricted and moving locations, such as a ship. In such locations, landing in an arrest system, i.e., a mechanical system that seeks to remove the kinetic energy from the UAV and bring it to a standstill, exemplified by a net in Figure 23, is desirable as the space requirements are reduced. Today, landing in a moving arrest system is a challenging, manual operation, requiring a highly skilled pilot and large margins of error, which limit the operations to good weather conditions in calm seas.

The automatic landing of fixed-wing UAVs in moving arrest systems has been a focus of AMOS since the beginning, and a number of concepts and systems have been tried and tested. The Marlander project builds on this knowledge, and aims to provide a mature and robust foundation for industrial development. As a result, the solution is based as much as possible on existing, well-established commercial off-the-shelf software and hardware. The project is funded by the Research Council of Norway in a collaboration between Maritime Robotics, PGS, Equinor, NOFO and AMOS UAVlab. The work at the UAVlab has been performed by Martin Sollie and Kristoffer Gryte, under the guidance of Tor Arne Johansen.

A standard landing flight plan is illustrated in Figure 24: Landing plan geometry, in which an automatically generated path is used to align the UAV's course and altitude with the start of the automatic landing approach. In the "Final alignment" stage, the UAV attempts to align itself with a virtual runway that is constantly moving with the net, using line-of-sight path-following guidance. The motion of the net is automatically registered using two GNSS receivers, one on each side of the net, in which one acts as an RTK moving base and the other as a rover. This provides the UAV with precise knowledge of the position, as well as the heading angle and roll angle of the net. The UAV itself is also equipped with an RTK GNSS receiver, in order to obtain precise knowledge of its position relative to the net.

To test the method, it is implemented using the open-source autopilot software ArduPlane, which receives commands from an embedded computer running the open-source Unified Navigation Environment (DUNE). In addition to running the guidance controllers, the embedded computer also monitors the landing to automatically abort in case communication links or the net positioning system fails, to help relieve the burden of the operator. It also ensures that the motor is turned off before impact with the net, to avoid damage and entanglement. The entire operation is fully autonomous, starting with the UAV in an arbitrary position relative to the arrest system.

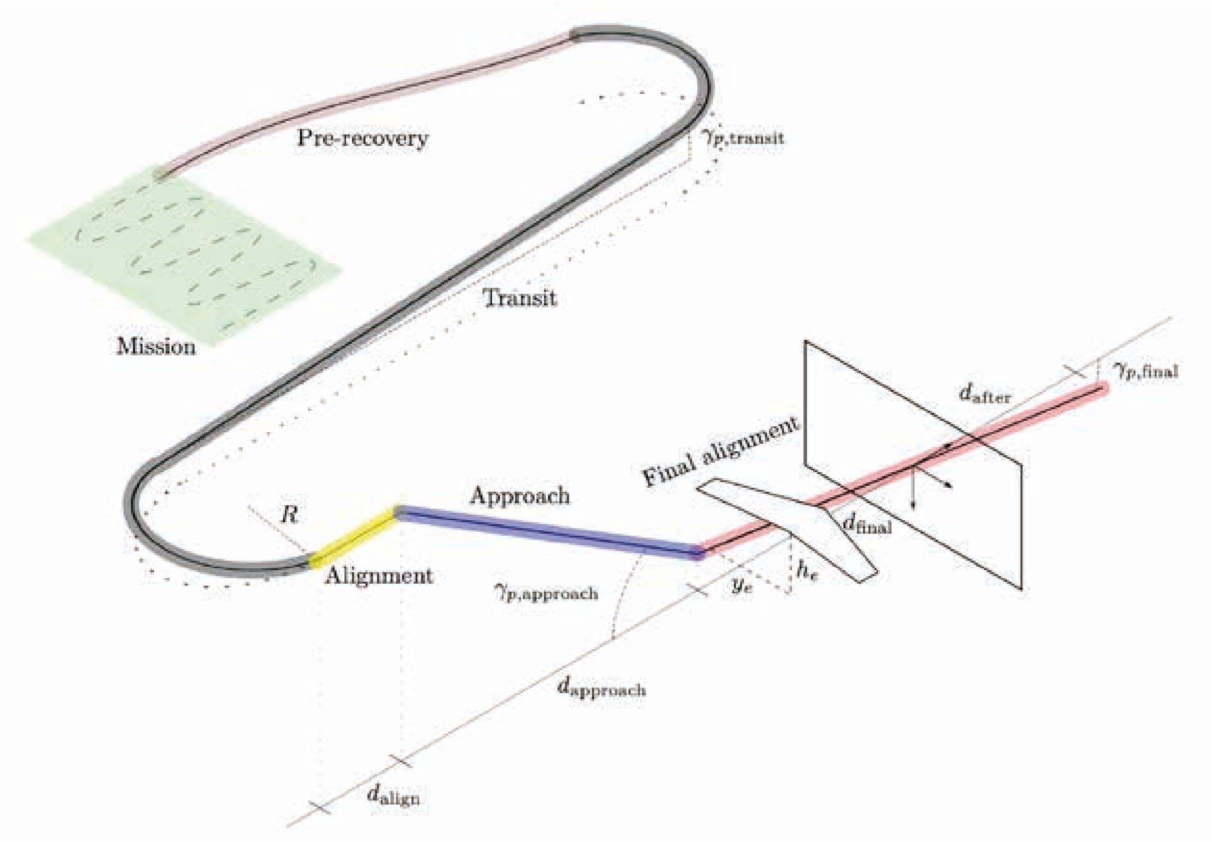


Figure 24: *Landing plan geometry.*

Figure 3: *On-board view from the Dolphine UAV flying towards the barge-mounted net in Åsefjorden.*

An extensive testing was performed, using two different fixed-wing UAV platforms and two different scenarios, with 15 successful landings in a barge-mounted net towed by a ship, as seen in Figure 23 and Figure , with results in Figure . The latter test campaign was also filmed, which can be viewed at https://youtu.be/n4XhzcKLgm8. The success was secured by a preliminary test with 43 fly-throughs of a virtual stationary net, with results given in Figure 5.

The results show random errors of less than a 0.5 metre vertically and horizontally for the stationary scenario, and less than a 0.5 metre vertically and 1.0 metre horizontally for the moving scenario. In addition, there are some systematic-, dominated by communication delays, that can be compensated for.

Media

https://www.youtube.com/watch?v=milq2_nf04s

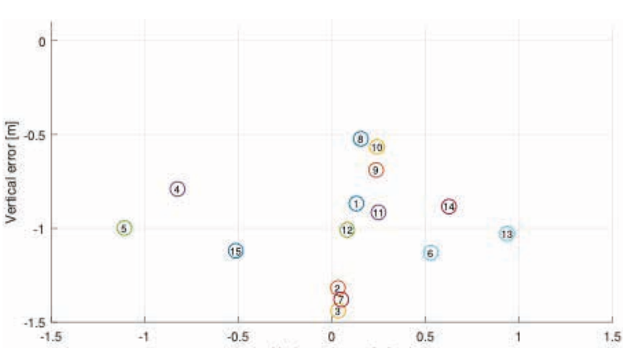


Figure 4: *Moving net impact points.*

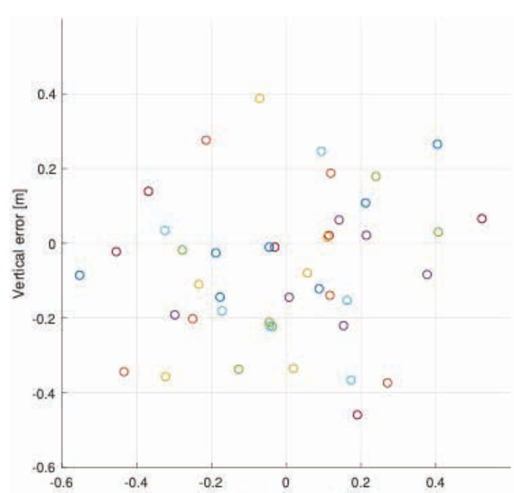


Figure 5: *Stationary net impact points.*

AWARDS AND HONOURS 2020

The IEEE OES Autonomous Maritime Systems Rising Star Award for 2020 has been awarded to Martin Ludvigsen at the Department of Marine Technology and NTNU AMOS

The Institute of Electrical and Electronics Engineers Ocean Engineering Society (IEEE OES) instituted the Maritime Systems Rising Star Award as a mid-career award meant to recognize faculty and researchers who have done exceptionally good work. The IEEE OES also want the award to celebrate the future potential of these individuals.

Martin Ludvigsen is the manager of the Autonomous Underwater Robotics Lab at NTNU, and teaches the course: Underwater Engineering at the Department of Marine Technology. Under Ludvigsen's leadership, the AUR lab has become a key player in most of NTNUs underwater research. The lab has been, and is currently, involved in several multidisciplinary research projects spanning such diverse fields as underwater engineering, biology, conservation and archaeology.

Kristin Y. Pettersen has been named "Digit-kvinne" of 2020.

The award honours women who have delivered strong contributions to the IT- and media technology field within the last year. The jury states that Pettersen "inspires her colleagues, her students and people from academia and industry with her work. She fills up to two cardboard boxes with mathematical calculations every day. Many also consider her research field to be one of the fields of technology that will determine how we live and work in the future."

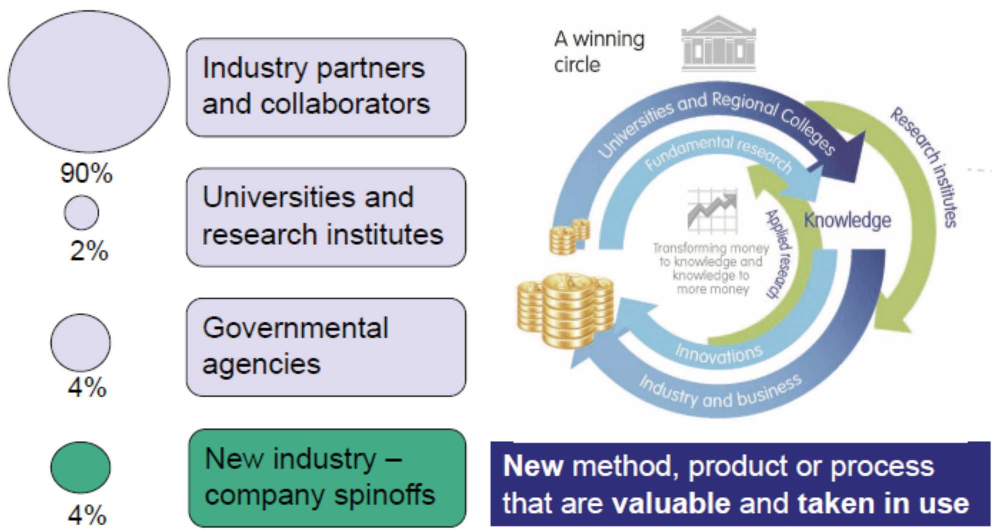
RESEARCHER-DRIVEN INNOVATION AT NTNU AMOS

At AMOS, the main research direction developed in 2011/2012 was defined towards increased digitalization, robotics and autonomous systems, including artificial intelligence operating in a marine domain. Research accomplishments from AMOS have been true to this strategy. Major achievements were accomplished in this context, and NTNU AMOS is preparing to become a leading international player in heterogeneous robotic systems for marine mapping and monitoring. These efforts are strongly supported by industry and governmental agencies.

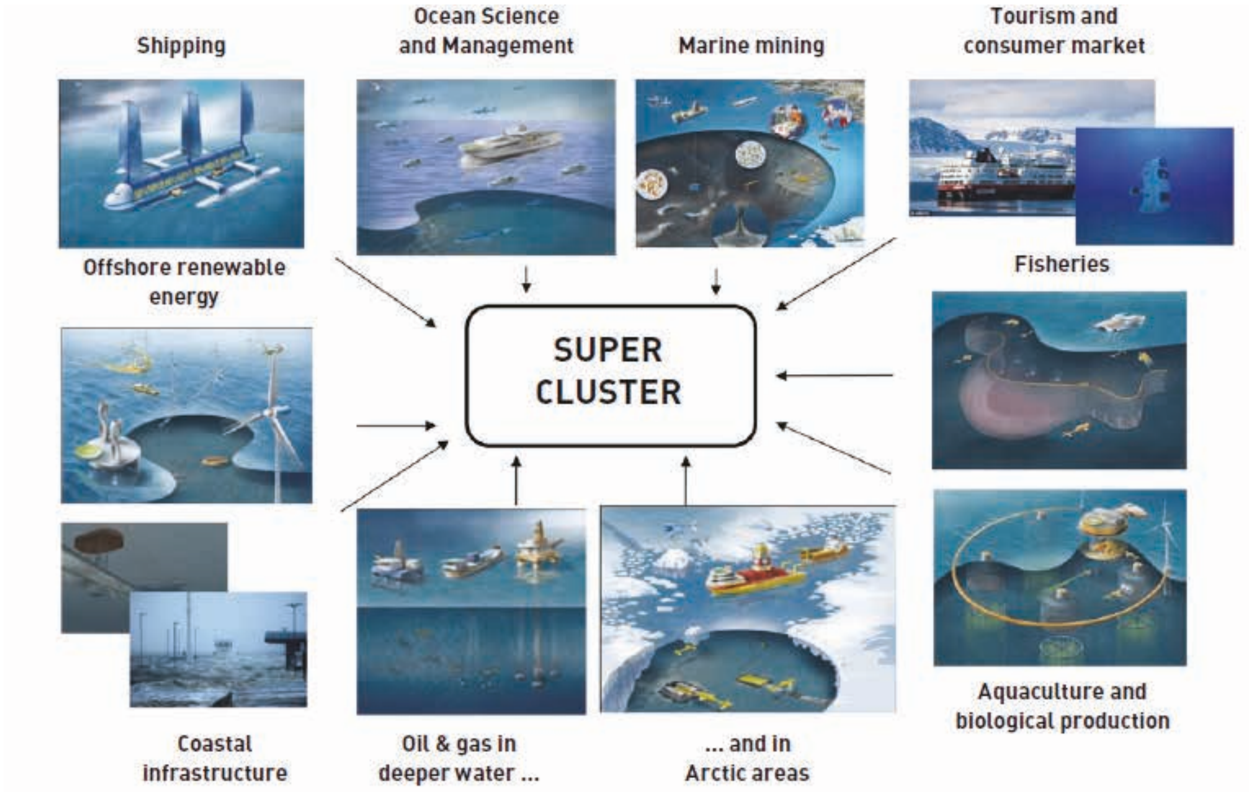
Key scientists hypothesized the importance of these topics 3-5 years before they become "hot¨ in Norway and elsewhere. This is also one reason for the great interest and rapid growth of AMOS in terms of funded PhDs and affiliated scientists. AMOS research topics have become an important part in the Norwegian transition towards a more digitized future directed by a blue economy, which would create new possibilities and reduce the cost of operations.

Because AMOS was clearly affected by this wave and rapid transition both socially and industrially, it became a huge responsibility to secure new industry positions that were about to be created. That is why the AMOS School of Innovation, later known as the Ocean School of Innovation, was established. Research-driven innovations and entrepreneurships were then systematically explored, and PhD and postdoc candidates were offered training on innovation processes. To date, five spin-offs organizations represent a direct measurable outcome of this in addition to several filed patents.

In the immediate future, we foresee the need to develop autonomous instrumental carrying platforms due to human impacts for improved knowledge-based mapping and monitoring of the marine environment; this will lead to better natural resource management and decision making and help to integrate AMOS disciplines at all levels and departments.



Innovation arenas at the NTNU AMOS

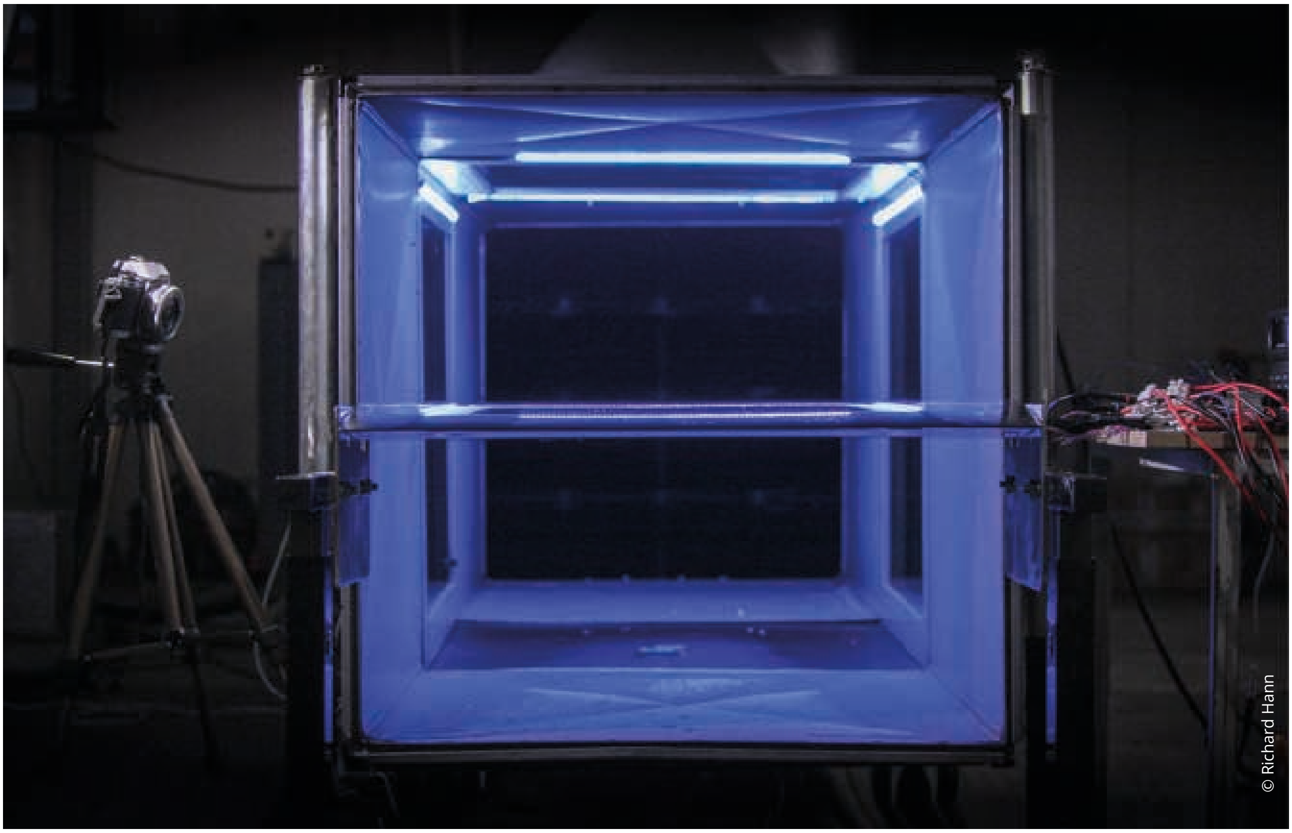


The blue economy that comprises a super cluster over Norway.

NTNU AMOS has several innovation areas. The most important area is established industry. However, we see an increasing trend in innovation that we directly contribute to the public sector. For instance, we strongly believe that strategic cooperation between different private and public players can pave the way for a new era of management regimes, robotic platforms and advanced sensing systems ranging from oceans to space. These efforts will create new workplaces based on a holistic and sustainable approach within the blue economy, which are clustered over Norway.

DE-ICING THE DRONES

In recent years, NTNU AMOS has moved to the forefront of drone technology and operations. A key focus area has been on how to protect drones from crashing due to icing on the wings.



De-icing experiment in a wind-tunnel

One of the great challenges of early commercial aviation was how to avoid the buildup of dangerous amounts of ice on the wings and fuselage, as certain cloud conditions lead to the hazard of icing. The resulting ice can accumulate quickly on the wings of an aircraft, and is potentially very dangerous. Icing on manned aircraft is a mature topic; however, the new technology of drones brings new challenges that need to be researched in detail.

– When drones and aircraft fly through clouds, they risk running into conditions which contain super-cool water, liquid that has a temperature below 0oC that is still not frozen. When this water hits the wings the ice can grow into quite big shapes, which affect airflow and add weight. There are stories about airplanes crashing because of this, says Dr. Richard Hann.

At the forefront

Hann finished his PhD this summer, and is now working on these challenges as a postdoc researcher at AMOS. The methods for avoiding icing have been well known in aviation since at least the 1950s, but the icing problem has not been properly investigated for UAVs. NTNU is one of the first universities in the world to look into this, and is currently at the forefront of developing good solutions.

– We have worked on solving this issue since 2012. It is a niche that very few people have yet investigated, but nonetheless is a very important niche. As of today, there are no mature systems that protect UAVs against ice. The consequence is that if there is a chance that you may run into icing conditions, you simply do not fly that day. This is a big limitation on drone technology, says Hann.

Big potential

The ability to operate at all times is crucial to many drone users. Militaries across the globe are increasingly making use of drones for surveillance and reconnaissance, with the ability to always have drones airborne being a great aid in that work. The same is true for search and rescue, ocean surveillance and research work.

– Even purely commercial operators would be interested in these solutions, from Amazon delivery services to offshore resupply. What we find is that many people have thought about the end applications, but not necessarily about secondary issues like icing, says Hann.

While drones are mostly unmanned these days, that may change soon, and while losing an expensive drone is a costly problem, losing a drone that carries passengers is a disaster.

– NASA has a project called Advanced Air Mobility, in which the plan is to come up with drones that can function as a passenger taxi. Naturally, icing is a big issue here.

Ice forming on a drone wing.

– At NTNU we are looking more closely at the physics involved. Why is icing happening, and why does the effect differ from a large manned airplane to a smaller drone? Consequently, we have developed methods to mitigate the negative effects of icing, Hann tells us.

The research work is done by numerical simulation and practical experiments in wind tunnels, in which the researchers can spray the drone with super cooled water, thus recreating conditions you find in the real world.

Spinoff

Hann and his colleagues created a new spin-off company a few years ago as a result of the research done at NTNU. And UBIQ Aerospace has already gotten international funding and is growing fast.

– I think it is a textbook example of how research activities lead to innovations. The researchers at NTNU are now working very closely with UBIQ, and the company is even paying for some of the research, as the NTNU research is such a good fit for UBIQ.
– We have seen a lot of interest for the company, as everybody are building their systems and then suddenly realize that they need to take icing into account. The Norwegian Ministry of Defence is the first big client. They have a large project that we are working on, but we are also talking to most other UAV manufacturers, says Hann.

The system that UBIQ and NTNU have come up with is based on electro thermal zones. What this means is that the drone is equipped with heating zones made up of carbon fibres that melt the ice when electricity is applied to the zone.

– By placing these strategically around the drone, we are able to protect it by using as little energy as possibly, says Hann.

The project has recently gotten two new research grants from the Norwegian Research Council, and is planning to start with five new PhD candidates in 2021.

– We are working with research institutions in Finland, Germany, Canada and the US, and are positioning ourselves to be a cluster of excellence on UAV icing, says Hann.

NEW NORWEGIAN ALTERNATIVE TO GPS NAVIGATION

AUTHOR: KJERSTI LUNDEN NILSEN

Kristoffer Gryte has had an interest in drone technology since he was a child, and this summer he received his PhD degree in engineering cybernetics from NTNU. As a NTNU AMOS PhD candidate, Gryte's research has focused on alternatives to GPS drone navigation.

"Before we can use drones and other unmanned vehicles in safety critical functions, like operations in urban areas and inspecting oil rigs and power lines, we must have a viable alternative to GPS navigation," says Gryte.

Vulnerable drones

In recent years, the vulnerabilities inherent in GPS have become very apparent, as nation-states and other actors use jammers to disrupt and shut down GPS signals.

A cheap jammer only costs 10 US dollars, and some states have the technical ability to scramble the signal over large areas. The result can be a lost drone or even worse, an uncontrolled crash into infrastructure or crowds.

GPS is also vulnerable to naturally occurring phenomena such as solar storms. No matter the origin of the disturbance, the results are the same, with potential lost drones and a threat to people and property.

Photo: Kai T. Dragland

NTNU drone pilot Pål Kvaløy with Kristoffer Gryte.

Photo: Kai T. Dragland

Gryte's solution uses phased-array radio to supplement the GPS signals. If the signal is lost for some reason, the radio signal takes over, thereby ensuring that the drone can complete its mission or land safely.

Important industry partners

During the years as a PhD candidate, Gryte has conducted several experiments in close cooperation with local industry. The Trondheim-based firm Radionor Communications A/S has been key.

Radionor has developed and delivered phased array technology to NTNU. A phased array antenna allows the operator to electronically control the beams without using any movable parts.

"The researchers at the Department for Engineering Cybernetics and NTNU AMOS have, in cooperation with Radionor, developed a solution for navigation and positioning of UAVs. This solution is based on Radionor's radios for long distance communication with high band-width," Gryte explains.

"Radionor's technology is unique because it has built-in positioning possibilities by calculating angle and distance with great accuracy, that is then used as sensor data in a positioning system. Thanks to the knowledge of Kristoffer and the cybernetics team at NTNU, we have seen very exciting advances in this field," says CEO of Radionor Communications A/S, Atle Sægrov.

He is full of praise for the yearlong collaboration between NTNU and Radionor.

"We have worked with dedicated experts and researchers, who have excited us with their enthusiasm for developing new technology. Besides conducting world-class research into advanced navigational systems, they also have impressive practical skills," says Sægrov.

New opportunities

Gryte thinks the new technology will open new doors for the drone industry.

"With this technology, we will gain better security against the vulnerabilities present in GPS systems. We can even operate completely without GPS, and this allows us to start operating the drones completely autonomously. We won't be dependent on a drone operator who keeps watch on the drone."

The system has already been tested in the field. In late 2019, Gryte and his team flew a drone 20 kilometres, with a maximum distance of five kilometres from the take-off area, without the use of GPS. This flight would have been unaffected by any jamming attacks or solar storms.

"The drone flew autonomously, based on the plan we had given it. And managed to figure out it's location thanks to our new system. As far as we know, no one has ever managed a flight like this without GPS before us," Gryte smiles.

NEW VISTA CENTRE SPIN-OFF FROM NTNU AMOS' AUTONOMOUS UNDERWATER ROBOTICS RESEARCH

The Norwegian Science Academy (DNVA) and Equinor are providing 25 million NOK to a new research centre at NTNU

The centre will function as a spin-off from NTNU AMOS, and will be connected to the Department for Marine Technology and the Department of Engineering Cybernetics Director at AMOS. Professor Asgeir Sørensen will head the new centre, which has been named the "NTNU-VISTA Centre for Autonomous Operations Subsea" or "CAROS" for short.

The goal is to become a world-leading research centre on autonomous underwater robotic operations with a focus on resident and collaborating autonomous underwater vehicles (AUVs) supported by subsea docking systems for energy charging and communication.

The director at AMOS, Professor Asgeir Sørensen, will head the new centre, which has been named the "NTNU-VISTA Centre for Autonomous Operations Subsea" or "CAROS" for short.

– We will develop technology, which in the short term can reduce the environmental impact of the ocean industry and also reduce risk, and in the long run will be part of a subsea infrastructure of great importance for the surveillance and understanding of biology, chemistry, physics and dynamics in the sea and on the ocean floor, says Sørensen.

The AUVs developed at the centre shall be able to operate between different locations on an offshore subsea field being launched from a docking station, navigate to a targeted asset, inspect and if needed conduct manipulation (intervention) tasks, before moving to another asset and finally returning to the docking station for reporting, the charging of batteries, changing any needed tools, and subsequently departing for the next mission.

The centre will also make use of already existing infrastructure in the Trondheim harbour, and will be a part of the coming Ocean Space Centre. Professor Sørensen thinks the new centre will be important to Norway's role as an ocean nation.

– If we are successful in building the necessary infrastructure for the digitalization of the oceans, while at the same time acquiring different robots and systems to work together under water, on the surface and in the air, we will increase our operative capabilities and "move the comma" with regard to data capture and surveillance of the oceans, Sørensen tells us.

CAROS will be headed by Asgeir Sørensen, and include key scientists Kristin Y. Pettersen, Martin Ludvigsen and Kjetil Skaugset. Besides the key scientists, the plan is that in the coming years, six PhDs and more than 20 master students will be involved with the centre. Hopefully, these new young experts will further cement Norway's position as a leading nation on AUR research.

COULD NTNU AMOS HELP IDENTIFY VIKING SHIPS AT THE BOTTOM OF LAKE MJØSA?

We know that many ships, trucks, and even ammunition have been dumped or sunk in Norway's largest lake. This year saw the start of a large research project to discover what is hidden in the deep

AUTHOR: IDUN HAUGAN

Today, Lake Mjøsa is dominated by leisure boats and the "White Swan", Skibladner, the world's oldest paddlewheel steamer still in use. But since before the time of the Vikings, Mjøsa has been an important waterway for both goods and people. Before the car and the modern roads, boats were the most efficient way to travel if you lived close to the lake.

There is a lot of history connected to the area around Mjøsa, and many clues to the past lie at the bottom of the lake. That is what researchers from NTNU in Gjøvik and Trondheim will attempt to uncover.

Ambitious goals

NTNU AMOS is heading the project, which involves 16 researchers and students. Senior researcher Øyvind Ødegård from NTNU AMOS, and the NTNU University Museum, is the project leader. In addition to several NTNU departments, the project also includes local museums, municipalities and the Mjøsa Diving Club. The Norwegian Armed Forces has also expressed interest in participating.

"We have wanted to increase the cooperation between researchers in Trondheim and Gjøvik for a long time. When Pro-rector Jørn Wroldsen at Gjøvik suggested this project, we got very excited," says Ødegård.

The project includes archaeologists, engineers, biologists and many other experts.

"I think the project is very promising. Our team consists of many different people who will examine a number of different things at the same time. When you work with people from other research fields you often get very exciting results," Ødegård said, adding that he is looking forward to getting back into the field after the coronavirus pandemic stopped all field work for several months.

"Our ambitions are pretty high, and we plan to collect a lot of data. Up until now, our knowledge of Mjøsa has been limited, but this project will fix that," Ødegård said.

Drones, sensors and cameras

The researchers have already begun to map the lake bottom to look for historic shipwrecks, cars, dumped ammunition and other environmental hazards in select areas of Mjøsa.

They are using an AUV (autonomous underwater vehicle), which will be programmed to operate within a set area, and five ROV (remote operated vehicles) drones from the NTNU AMOS spin-off company Blue Eye.

The drones can reach a depth of 150 metres, and are equipped with a hyperspectral camera among other sensors. This camera allows the researchers to use colours as optical fingerprints to identify and classify both biological organisms and archaeological material.

Espen Saastad is also involved in the project, and will bring a larger ROV for use at greater depths, and a multi-beam sonar from Kongsberg Maritime capable of creating high-definition 3D-models of the lake floor.

Cars, ammunition and a whole military convoy

Much as how people once dumped garbage in the ocean, Lake Mjøsa has been used to dispose of unwanted cars, and even large quantities of ammunition from the local ammunition factory at Raufoss. The area where these materials were dumped is close to where 100,000 people get their drinking water, and the project will help provide information as to whether the ammunition could pose a health risk.

"This is an issue where it is quite critical for us to find answers. There are also other areas where we know ammunition has been dumped, and we will also examine those locations," says Ødegård.

During WWII, an entire Norwegian military convoy was lost in the lake. Arne Julsrud Berg, managing director at Mjøsmuseet (the Lake Mjøsa Museum), says that during the German invasion of Norway a Norwegian military convoy was on its way to resupply Norwegian forces further north. Since the bridge had been blown up earlier in the campaign, the Norwegians decided to try crossing the frozen lake by driving on the ice.

"The convoy got stuck in the ice between Eidsvoll and Toten. All the drivers got out safely, but all the vehicles, including several lorries, passenger cars and a bus, eventually sank," Berg said.

The area where the convoy disappeared is one of the places the researchers will examine in detail.

Viking ships

Even more exciting is the possibility of discovering far older wrecks. We know that Mjøsa was teeming with activity during the Viking Age and medieval period. It is not farfetched to suspect that one or several ships from this period lie hidden beneath the waves.

"If we found a medieval ship, we would really be hitting the bullseye, it would be fantastic, but we don't dare to hope yet," says Ødegård.

However, the researchers have some clues to guide them. In the early 1980s, when the Mjøsa bridge was being built, a diver reported that he had seen a large rowboat approximately 20 metres long. Few rowboats of that size have been built in Norway since the medieval period.

"This is an oral, undocumented story, so it is all very uncertain, but it's only 80 metres deep in this area, so we can examine it in detail," Ødegård said, adding that it's likely they won't find anything. Nevertheless, the possibility is exciting.

Digital twin

The data collected will be used to develop a digital twin for the lake. This will be created using information from historical maps, lake bottom data, 3D-models, seismic data, aerial photographs, biological observations and satellite data.

The combination of so many different sources will allow the researchers to visualize patterns, and see connections that cannot be seen any other way.

Gjøvik municipality is an important partner in the project, and is planning to use the digital twin in their management of the lake.

Further research

The project will continue into 2021, with the researchers planning an expedition in March when the northern part of the lake is hopefully covered in ice. At this time, biology will be the focus, and NTNU AMOS scientist Geir Johnsen will lead this part of the project. In addition to providing biological data, the expedition will provide a great opportunity to gain valuable experience in underwater robotics operations, a key area for NTNU AMOS. The researchers also hope to return in the summer when the lake is more active from a biological standpoint. No matter what the researchers uncover, their efforts will greatly expand our understanding of Norway's largest lake.

Mapping Mjøsa. Photo: NTNU

CREATING TRUST

As autonomous systems improve, and new methods for control are developed, the potential of these new technologies is steadily increasing. The possibilities derived from autonomous ships, drones and other ocean vessels could revolutionize transport, sea travel, surveillance and how we conduct maritime and offshore operations.

Programme Director at DNV, Asun Lera St. Clair, argues that autonomous solutions can create new solutions for transport, infrastructure and sustainable development for cities and communities. Along the way they will "unlock economic growth and employment for multiple actors, and can increase the competitiveness of several Norwegian industrial sectors".

Nevertheless, challenges remain. Reducing the human presence to a monitoring role, and leaving the control of ships and other ocean vessels to computer systems, can be a daunting prospect. NTNU AMOS has now joined with DNV, Zeabuz and Marine Technology LLC to create the TRUSST project, sponsored by the Research Council of Norway through grant no. 313921.

The primary goal of TRUSST is to "innovate an integrated assurance framework that transforms a complex and interdependent system of people, technology, organizations and the natural environment into a trust ecosystem, that in turn unlocks the potential for testing, deploying and scaling up autonomous passenger vehicles in society".

"What we lack is the trust that these autonomous and zero emissions ferries can operate safely, reliably and with enough societal acceptance, as well as recognition of their contributions to the Sustainable Development Goals (SDGs). In order to unlock the potential for sustainable value creation, this ecosystem of technology, people and their social and natural environment needs to become a trust ecosystem", says St. Clair.

"Video game"

Among other initiatives, the project will incorporate work done by Kjetil Vasstein at NTNU. He will start working on his PhD thesis in connection with TRUSST, and brings with him his experience with video games. Taking inspiration from something as care-free as video games when working on a project like TRUSST may seem odd at first, but Vasstein plans to use that experience to find new solutions for testing and verification.

"You could say that my PhD project is about using (among others) video game technologies for doing the verification and testing of autonomous marine vessels, by creating a so-called digital twin of the vessel and its surroundings. Serious people call it a simulator, but I like to call it a video game, since that's where it all started," says Vasstein.

Vasstein and his friend Thomas Skarshaug – now employed at Zeabuz – have been working on their Gemini system for some time, building it into what Skarshaug calls "the maritime sector's answer to visual simulators like Carla, AirSim and LGSVL". It is now sparking interest from several organizations and companies operating in the maritime sector.

"How Gemini fits into TRUSST is perhaps easiest seen when looking at the Open Simulation Platform (OSP) developed in cooperation between DNV, Kongsberg, SINTEF and NTNU. OSP is an open-source initiative to create a co-simulation of maritime equipment, systems and ships, which is not that far from what we wanted Gemini to be in the beginning."

"Gemini is 'just' a game in this perspective, visualizing and simulating data heavy models such as the EMR sensors (radar, lidar, cameras, infrared), while OSP will be the connector to the established product models from the maritime industry, including dynamics and actual control systems. Using this ecosystem to study the safety, reliability and sustainability of autonomous ships in a realistic operating environment is a core part of what the TRUSST project is all about," says Vasstein.

Looking at the whole picture

"The TRUSST project is maturing into an assurance framework, the Assurance of Digital Assets Framework (ADA Framework), which takes a holistic view. This enables us to frame and analyse this ecosystem of organizations, technology, people and their social and natural environment from a systems perspective", says St. Clair.

From small ferries for use in urban waterways to larger ships built for bulk transport, autonomous systems must account for a wide variety of scenarios and conditions. A verification system meant to ensure the public that these systems are safe must account for that variety.

"The ADA Framework takes as a fundamental point of departure the identification of the stakeholders involved and their diverse interests, goals and concerns. From this point of departure, the TRUSST project will be able to identify a wide set of opportunities, hazards and risks, as well as non-technical requirements to inform the creation of an assurance case to substantiate trust. The project will build a digital twin to simulate important

The TRUSST project will ensure that autonomous systems can be trusted to operate safely in a complex urban environment. *Graphic: Zeabuz/NTNU*

evidence required for the assurance case. The project also has a dedicated focus to ensure that AI technologies are treated with the necessary care. Lastly, the TRUSST project will engage with citizens to ensure that their concerns and views are integrated, and identify the risks and opportunities to promote environmental sustainability", says St. Clair.

"As easy as stepping on to a bridge"

Øyvind Smogeli, COO and co-founder at Zeabuz, and recently appointed adjunct professor at NTNU, has been heavily involved in designing the project. He explains that the public's trust is vital for companies like Zeabuz.

"The whole business model of Zeabuz is based upon the trustworthiness of our mobility system, comprised of electric, autonomous passenger ferries and the surrounding infrastructure. Our vision it that it should be as easy and mindless to step on board one of our ferries as it is to walk across a bridge. To achieve this, it is not sufficient to make the system safe only from a technical point of view; the perceived safety – which is what builds societal trust – is just as important and might be just as hard to achieve."

The TRUSST project caters to both of these dimensions, Smogeli tells us. But building trust is also dependent on robust rules and regulations, which in recent years have been left behind by the speed with which technology has advanced.

"Existing rules, regulations and standards were never designed for assurance of the kind of complex, software-driven systems with embedded AI algorithms that we are developing in Zeabuz. This means we also need to innovate the assurance processes and tools needed to build trust, and then deploy these in a close cooperation between technology and system providers, assurance providers and regulators. One of the key elements is the establishment of a sophisticated digital twin incorporating high-fidelity simulation models, autonomation and autonomy software, and a visual simulator that generates input to the perception sensors of the ferry. Building on the OSP and Gemini platforms enables an end-to-end testing of the complete autonomous ferry in a virtual operating environment. At Zeabuz we believe that the trust-building process we are piloting in TRUSST will be just as challenging – and require a similar amount of resources – as building the autonomy solutions for the ferry", says Smogeli.

WAVE MOTION COMPENSATION IN DYNAMIC POSITIONING OF SMALL AUTONOMOUS VESSELS

As smaller autonomous vessels become capable of conducting increasingly difficult operations, the opportunity presented by them increases, but so does the challenges of operating them. The "ROV Revolution" project seeks to meet some of those challenges.

The first phase of the "ROV Revolution" project is led by Kongsberg Maritime in collaboration with NTNU, SINTEF Ocean and DOF Subsea. The main idea is that ROV operations can be supported by a relatively small autonomous surface vessel, which may lead to significant cost reductions compared to the conventional approach that uses relatively large offshore support vessels.

However, smaller autonomous vessels are more affected by the environment, especially oscillatory first-order wave motions. This motion causes challenges, especially during the launch and recovery of ROVs. Extensions of conventional dynamic positioning (DP) control algorithms that compensate for oscillatory wave motions have been analysed in the master theses of Håkon Halvorsen, Olav Landstad and Henning Øveraas, and continued by students Kristoffer Nordvik and Aleksander Elvebakk, under the supervision of Professor Tor Arne Johansen.

A multi-body simulator of the surface vessel, the launch and recovery system, and the ROV is built with MATLAB and Simulink, by utilizing the toolboxes Marine Systems Simulator (MSS), Marine Power Plant Simulator (MarPowSim) and WAMIT for hydrodynamic modelling.

Figure 25: ROV launched and recovered from a relatively small USV. Courtesy Kongsberg Maritime.

Successful DP algorithms for dynamic first-order wave motion reduction include acceleration feedback, optimal control, roll damping and feed-forward using short-term wave prediction in order to partially compensate for thruster dynamics. The use of short-term wave prediction provided good results in regard to absolute oscillatory motion reduction, with a significant reduction of horizontal motion peak amplitudes across the most relevant sea states and a better synchronization of the surface vessel and ROV motions. Increased variations in thruster use seem to be an unavoidable consequence of the dynamic wave compensation. However, the total energy consumption is not much affected since a wave compensation mode is not needed outside the very short critical phase of launch and recovery. Rapid thrust response is therefore necessary for these algorithms to have a good performance, and batteries are generally needed in a hybrid diesel-electric power system in order to avoid electric power frequency variations that could otherwise lead to blackout. A short-term wave prediction can be done using various sensors, with the use of inertial sensors and analytic prediction methods found to give statistically accurate predictions one half wave period into the future.

Active control of the ROV using thrusters to track the surface vessel during launch and recovery was also studied. This was found to increase the workability even more, and as an effective control system to avoid collisions between the ROV and USV during launch and recovery.

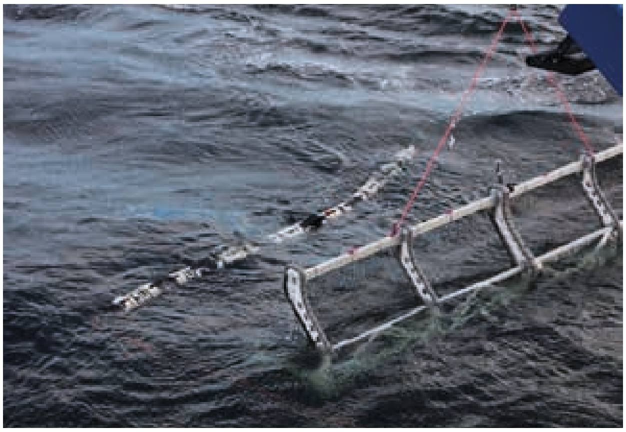
GREATER THAN THE SUM OF THE PARTS

One of the greatest strengths of NTNU AMOS is extensive interdisciplinary collaboration between researchers, collaboration that has proven crucial to achieving our visons.

As technology advances, it is becoming increasingly difficult for one type of expert to do "everything", and new solutions are often dependent on input from several different research disciplines.

Two of many AMOS PhD candidates working closely together across different fields are Erlend Andreas Basso and Henrik Schmidt-Didlaukies. Erlend has a background in Cybernetics and Henrik in Marine Technology.

Here, they tell us about their project, and how they managed to combine two different fields to achieve a result greater than the sum of the parts.



The Eelume snake-robot in action

Tell us a little bit about what you two are working on right now?

"We are researching and developing autonomous underwater robotic systems for inspection and light intervention tasks for the aquaculture and oil and gas industries. Our goal is to refine and replace the state of the art of today's industry using advanced mathematical concepts, resulting in simpler system architectures with better capabilities. As we all know, it is generally more difficult to devise a simple and effective solution than a complex and effective solution."

That sounds ambitious, what use do you envision you research will have?

"We aim to accelerate the industry's transition toward robotized and autonomous underwater operations. Underwater robots are well-suited for inspection, ocean sampling and light intervention operations. Consequently, resident underwater robots can eliminate the need for divers in aquaculture operations, or the use of ROVs in combination with surface ships for subsea oil and gas operations, reducing costs and saving time."

Erlend Andreas Basso and Henrik Schmidt-Didlaukies on a research cruise.

Have you gotten any interesting results so far?

"Erlend started looking at model-based task-prioritized control applied to the Eelume robot. This allows for the resolution of multiple conflicting robot control objectives. Henrik started out working on the modeling of underwater robots, generalizing and unifying several existing modeling approaches."

"We then collaborated on globally stabilizing switching control methods, focusing on the application of this paradigm to underwater robot control. This methodology has subsequently also been applied to path following for surface vessels. It is great to see that our methods can solve control problems other than those they were initially developed for."

How has your experience working together across disciplines been?

"Our cross-disciplinary approach has enabled us to look at problems in entirely new ways. We are convinced that interdisciplinary collaboration is a key ingredient for state-of-the-art engineering research benefiting society. Even though this form of collaboration may be hard to combine with a PhD education, we have found that our academic backgrounds, research interests and personalities complement each other nicely."

And what is your plan going forward?

"We aim to establish a new initiative called TUR-Lab, the theoretical underwater robotics laboratory, and have just acquired our first ROV, "Lars Vegard". He will be used as a testbed for advanced underwater robot control algorithms. In particular, we will formulate an integrated and robust solution to motion planning and motion control."

CONTROLLING THE SHIPS OF THE FUTURE

When Anete Vagale finished her master's degree in Latvia, the maritime industry was very far from her mind, but after an exchange year at NTNU Ålesund, she suddenly found herself working on developing control systems for autonomous ships.

"It wasn't planned that I should move to Norway. In my 2nd semester of master's studies in the spring of 2016, I went on an Erasmus+ exchange in a Simulation and visualization study programme at NTNU in Ålesund. During this exchange, I got a chance to participate in a MarKom project, "Automatic Identification System (AIS) and Maritime Transport", which let me stay in touch with Ottar L. Osen who is my current supervisor."

"After receiving a M.Sc. degree, I was looking for options to pursue a doctoral degree so that I could fully devote myself to research. I got my chance when Ottar notified me that the Cyber-Physical Systems (CPS) Lab at NTNU in Ålesund had a vacant position for a PhD candidate in autonomous ships. An application and an interview later, and here I am," says Vagale.

Improved autonomous navigation

After a small period in which she considered a wide variety of research topics, Vagale managed to narrow down the focus of her research to "evaluating path planning algorithms and assessing risks of an autonomous surface vessel (ASV) when navigating in congested waters based on collision risk assessment". Autonomous ships have the potential to vastly improve the efficiency and safety of the shipping industry, but much work remains if their potential is to be fully realized. Vagale is working on how these future ships can operate safely.

"My idea is to develop a method that could evaluate different paths generated by path planning algorithms from the safety aspect. In the best-case scenario, this method would allow comparing different algorithms between themselves and find the 'best' choice for each situation considering ASVs efficiency and safety when navigating in changing weather conditions and different environments," Vagale explains.

One of the key challenges of autonomous ship technology is to make it so safe that it can supplant the human control element. With the human reduced to a monitoring role, the ships can be made more efficient and one can eliminate human error from the equation. More efficient ships will also help create a shipping industry that is more environmentally sustainable. Vagale hopes that her research can contribute to achieving this goal.

"In an ideal case, my developed method could be implemented on autonomous ships that are being developed. That would lead to an improvement of the vessel's guidance and navigation system. The higher goal here is improving safety on waters in general, avoiding human error and the potential accidents that follow when navigating, and striving for good seamanship skill in autonomous ships."


Anete Vagale

Difficult year but great city

The last year has been challenging for many researchers, and, as with many of her colleagues, Anete Vagale found that the pandemic would hamper her work.

"This was the year when I was supposed to participate in my first international events and presenting my research, but due to the coronavirus all the deadlines got postponed, and most events got postponed or were put on hold until further notice. Having to change my plans, as well as other delays that also slowed down the progress of my research, has also been affecting my motivation."

"It has been a difficult period mentally with constant home office, not being able to meet colleagues and friends, fear of the situation in general, and lower motivation at work. However, I did my best to keep my research going, and luckily my motivation is back. I feel like I am successfully back on track and moving steadily forward."

One inspiration to Vagale during her time in Norway has been the city of Ålesund itself and the nature surrounding it.

"I really enjoy working from Ålesund. The nature is fascinating, and it was one of the reasons why I decided to move here. I have been using my weekends and evenings after work for various activities, such as, hiking, bouldering, cycling, running, kayaking, simply walking and enjoying the view, and many more. The old town itself looks a bit like a fairytale town, especially around Christmas. The city looks magical with all the lights."

"The research environment is also excellent. My colleagues here are experts in different topics, so whenever I need advice, I know whom to talk to. I am also very lucky with my supervisors, who have provided me with great advice throughout my time here. Finally, I really like the close connection between the researchers in Ålesund and those in Trondheim. This has allowed me to meet and make use of a larger research community; it has also given me a taste of life in a larger university town."

NORWEGIAN HIGH SCHOOL STUDENTS TO GATHER OCEAN DATA FOR NTNU AND PARTNERS

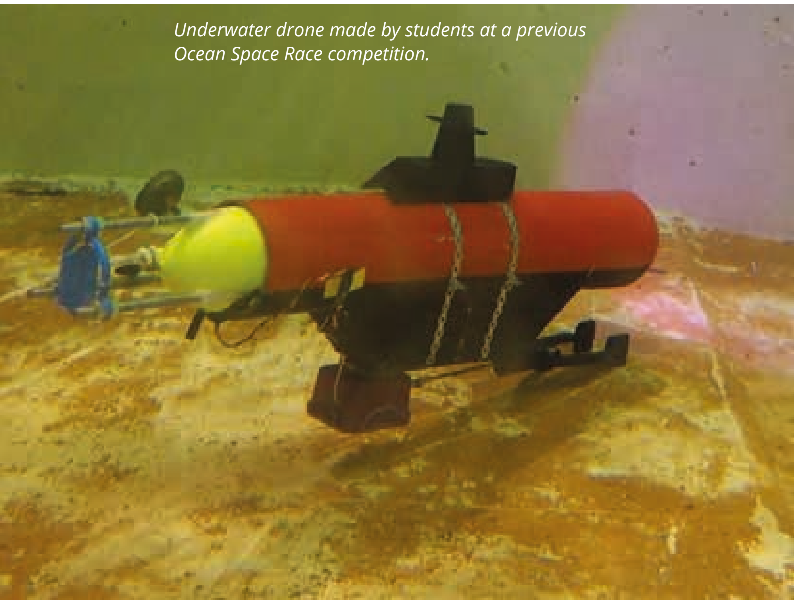
NTNU, SINTEF, Equinor and several other partners will spend more than 2.2 million NOK over the next four years on a new teaching programme for Norwegian high school students. The students will develop platforms that can measure and gather ocean data, such as temperature, information about waves and salinity. The collected data will be used by researchers at SINTEF and NTNU, and fits perfectly into NTNU AMOS' goal to help map and monitor the oceans.

The project will be organized as a new participation class under the Ocean Space Race umbrella which came about thanks to the Norwegian Research Council's innovation prize for 2019 awarded to the Director at NTNU AMOS, Professor Asgeir Sørensen. Sørensen used the 500,000 NOK prize to support the new participation class. The project received further financial support from SINTEF Ocean (500,000 NOK) and Equinor (1.2 million NOK). The Norwegian Meteorological Institute and REV Ocean/Ocean DATA/ Foundation/C4IR will also participate and support the project.

Wants to motivate students for a research career

The rector at NTNU, Anne Borg, believes the new participation class will help motivate Norwegian students to choose an education in science, as well as mobilize teenagers to participate in the UN Ocean Decade, in which knowledge and innovation will help solve the great challenges the world is facing.

– This is a project that bridges the gap between schools and research. It will contribute to both new and better data for our researchers, but also help motivate young people by involving them in discovering new knowledge and finding new solutions. The Ocean is vital for Norway and the international community. Helping to increase our knowledge and create a greater engagement about the Ocean is very much in line with NTNU's motto, "Knowledge for a better world".



Underwater drone made by students at a previous Ocean Space Race competition.

The director for SINTEF Ocean, Vegar Johansen, shares Borg's ambitions for the new programme.

– Many of the solutions to the challenges of today's society and ecosystems are found in the oceans. It is important that both Norway and the World understand this, and it is vital that high school students get the knowledge and motivation to participate through actively choosing their own studies and carriers. We in SINTEF are very happy to be a part of this initiative, and we support it wholeheartedly, Johansen says.

Pilot project

– We will start with a pilot project with 10 schools, and expand from there. The plan is to include schools from all over the country in order to cover as much of the coast as possible. We will also cooperate with similar initiatives, says Asgeir Sørensen.

The data the students will collect is "essential" ocean data, such as temperature, information about waves, wind and salinity. As long as they use the right type of equipment and methods, this is data that the students can do on their own, despite not being trained researchers. The students are free to choose what kind of platform they wish to develop for gathering the data, with anything from drones to simple buoys being acceptable.

NTNU, SINTEF, the Ocean Data Foundation and others will develop a system that registers the collected data. These will then be connected to SINTEF and NTNU's own systems, ocean models and data in order to create a more complete picture of the Norwegian coast and ocean. This is knowledge which can help in the fight against climate change and loss of biodiversity.

– I am convinced that this project will give us some fantastic results. It is a win-win situation for everybody. Researchers get a broader data foundation, the students get to participate in exciting projects that draws on almost all elements of science, NTNU gets more and even better applicants for our study programmes and Norway gets more excellent engineers and researchers, says Sørensen.

WARMING WATERS THREATENS THE HISTORY OF THE ARCTIC

Painting of Dutch 17th century whaling ships. By Bonaventura Peeters. Source: Wikimedia

In 1693, near Smeerenburg at the northwestern tip of Spitsbergen, more than 17 Dutch whaling ships were sunk by a French fleet following direct orders from King Louis XIV. The nine-year war was raging in Europe between France and a coalition that included the Dutch Republic, and the "Sun King" wanted to hurt the Dutch economy.

Now an interdisciplinary research team from NTNU and UIT, using AMOS technology, have gone looking for the lost fleet. What they found was surprising and worrying.

Warming waters

The ships that the researchers expected to find were simply gone. No trace could be found of the Dutch whaling fleet.

A marine archeologist at NTNU AMOS, Øyvind Ødegård, fears that shipworms may be the culprit.

"It is plausible that the wrecks have all 'disappeared' due to wood devouring creatures. We know that shipworms are able to destroy a wreck in just a manner of decades in more temperate waters, and the notion that this could also be happening in the Arctic is alarming from an archaeological standpoint. This possible scenario raises many questions, not least if it is related to climate change in the Arctic."

As climate change accelerates, changes are also picking up pace in the Arctic Ocean. Warmer water and less ice are now affecting marine eco-systems at an unprecedented rate. An efficient mapping and monitoring of the Arctic regions is a crucial goal for NTNU AMOS, the importance of which has just increased as worry grows over the future of the Arctic eco-system. Recent research at NTNU and UiT now indicates that it is not only the future of the Arctic Ocean that is at risk, but also its past.

"While the cold waters in this region have perfectly preserved the now famous wrecks of the HMS Terror and HMS Erebus in Canadian waters, the story seems to be different in Svalbard," says Ødegård.

Lost history

Despite the location of the battle being well documented, and meticulous surveying with high-resolution sonar and cameras using AUVs and ROVs, the research team was unable to locate any wrecks.

"We cannot rule out that the positions we investigated were wrong, or that the historical sources were misleading. Unfortunately, other evidence suggests another, perhaps more likely explanation for the missing wrecks."

Ødegård fears that growing temperatures have created a suitable environment for organisms that eat and destroy shipwrecks like those the team expected to find at Smeerenburg.

"In 2016, a log of Siberian driftwood was recovered from a 300 metre depth by scientists on the annual Polar Night cruise on board the RV Helmer Hanssen. After lying more than 100 years in -2º C water in the Rijp Fjord at 80º north, the log was heavily infested by shipworms – a type of organism that previously was not believed to exist in such low temperatures."

Ødegård tells us that this unsettling discovery led to an increased awareness among scientists of this potential threat to underwater cultural heritage. Since then, more observations on an underwater wreck site and on driftwood found on the beaches indicate that the presence of shipworms in the Rijp fjord was not a unique incidence.

"This possible scenario raises many questions, not least if it is related to climate change in the Arctic. These questions can only be answered through interdisciplinary research and pan-Arctic collaboration," says Ødegård.

Tore Mo-Bjørklund, Øystein Sture and Martin Ludvigsen operates an AUV.

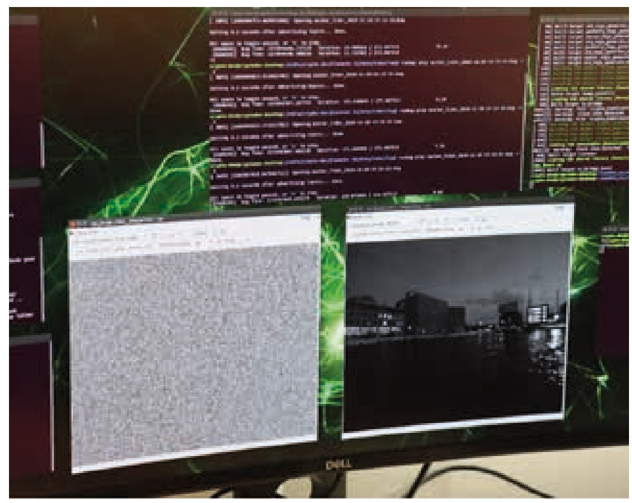
Martin Ludvigsen and Anne Husebekk operating a Blueye drone.

Driftwood in the Smeerenburg fjord

NTNU AMOS
HAS ENTERED THE FIELD OF CYBER SECURITY

From subsea to outer space, NTNU AMOS is working at the cutting edge of autonomous systems and mapping and surveillance. Yet, the new interconnectivity provides fresh challenges and new demands to safety and security. In the digital world of 2020, it does not take a tech expert to imagine the risks associated with increasing connectivity.

Øystein Volden and Petter Solnør.



The image on the right is a live feed from an autonomous vessel in the Trondheim Fjord, whereas the image on the left is the same data, but encrypted in order to protect the data.

From hackers listening in to information on its way from sensors to receiver, to full-blown hijacking of autonomous systems, the danger posed by criminals and other illegitimate actors is real.

To face these challenges, PhD candidates Petter Solnør and Øystein Volden are hard at work mapping weaknesses and creating and testing efficient encryption methods.

Solnør started on an integrated PhD while he was still working on his master's degree. This allowed him to get a "flying start to his PhD project by taking cyber security classes at NTNU Gjøvik early on."

– I think there are advantages to an integrated PhD. It allowed me to start working on this project straight away, as I had already completed the necessary classes, says Solnør

Volden's supervisor on the master's degree was Professor Thor Inge Fossen, and it was Fossen who suggested a PhD to him.

– I needed some time to decide, but after a few meetings with Thor Inge I got more and more excited about the project and decided to go for it. It is safe to say that I don't regret that decision, says Volden.

The two candidates are also aided by their co-supervisor Slobodan Petrovic from the Department of Information Security and Communication at NTNU Gjøvik. The cooperation between NTNU AMOS and the formidable cyber security research community at Gjøvik is an important component for success in this field.

Benevolent hacking

They are currently exploring two different sides of cyber security. In one of these projects, the researchers themselves are working on how to hack systems and break down security encryptions in order to uncover weaknesses, so-called benevolent hacking.

– In short, we want to show different ways a system can be attacked. Right now, we are focusing on "Man in the middle" attacks. These are attacks where a "hostile" computer spoofs the data traffic that goes from one computer to another. In other words, a situation where all the traffic from one computer to another goes through a third computer, without the sender or receiver being aware of this, says Volden

– These kinds of attacks give the attacker several possibilities. Passive attacks can simply listen to and steal sensitive information, and active attacks can change the data that is sent to the legitimate receiver. Changing the data can do a lot of damage to autonomous systems like drones or autonomous ships, potentially hijacking the system. It is therefore not enough to encrypt the data, the origin point of the data must also be properly authenticated, says Solnør.

The potential gains for an attacker are varied and can be considerable, from industrial espionage to hijacking a system for blackmail purposes or even terrorism.

Eventually Volden and Solnør hope to do experiments where they conduct attacks against systems in the field. The primary goal is to show how encryption and authentication already developed can protect systems against these types of attacks.

Demands for efficiency

The second project they are working on focuses on using state-of-the-art encryption algorithms for efficient encryption while also maintaining sufficient safety margins. While encryption and authentication are key, it is also vital that the methods used do not markedly slow down the signal.

Autonomous systems must be able to receive new input in real time, and advanced sensors that send large amount of data will become close to useless if the signal is slowed to a crawl.

– Efficient algorithms give you minimal delays, which can be critical to autonomous systems. It is particularly relevant to sensor data that demands a high bandwidth. To put it this way, it would be completely meaningless to encrypt large amounts of data for autonomous systems if they didn't reach the intended target in time, says Volden.

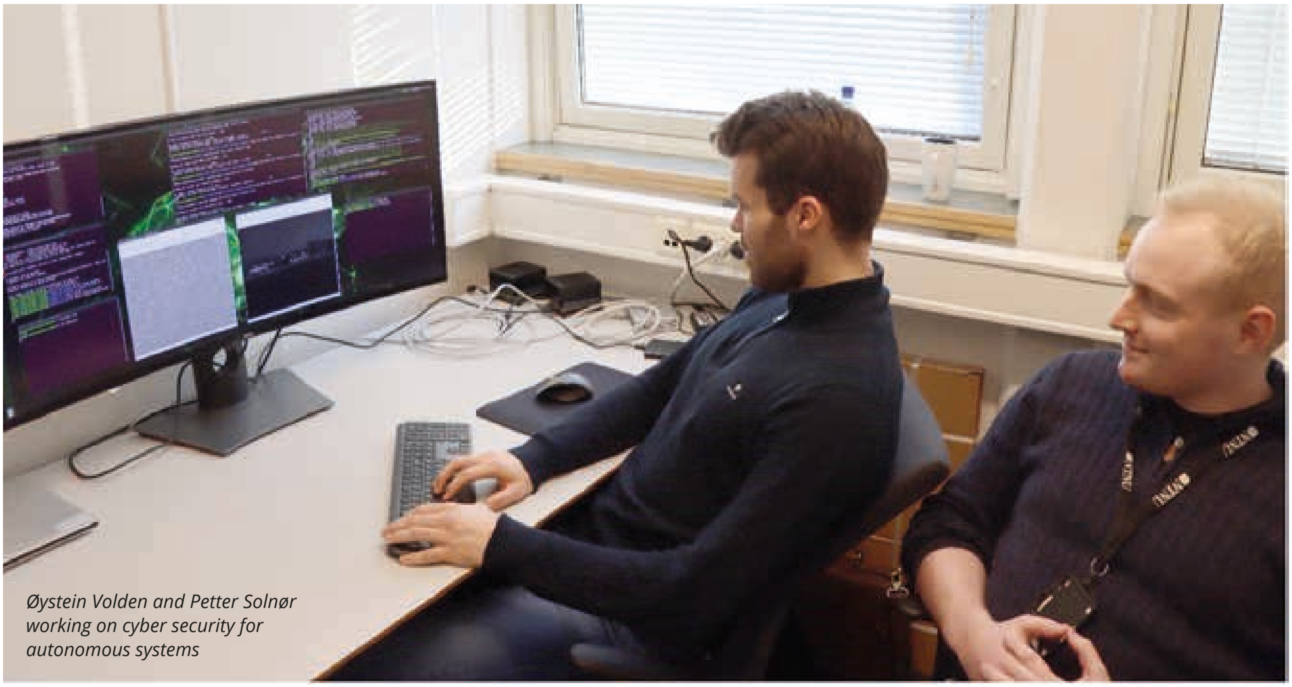
– Real-time encryption is very important, so it is not always the heaviest encryptions that are the best. You must encrypt efficiently. Data from LIDAR is the biggest challenge, but we have managed to get that to work efficiently as well, Solnør tells us.

Protecting future industry

The stakes are high. As Norway and the world become increasingly interconnected, and as autonomous systems come into widespread use, the importance of cyber security increases.

No autonomous technology can survive if it is not also safe to use, and many of the smaller companies may not have the resources or know how to properly implement sufficient security measures. To Volden and Solnør, making cyber security available to everybody is a key motivation.

– Many big companies already have good security measures in place, so an important goal now is to make this technology available to medium sized and smaller businesses that may not have the resources to protect themselves to the same extent as major international ones. That is part of what drives us, that and the fact that this work is all very good fun, says Volden and Solnør.

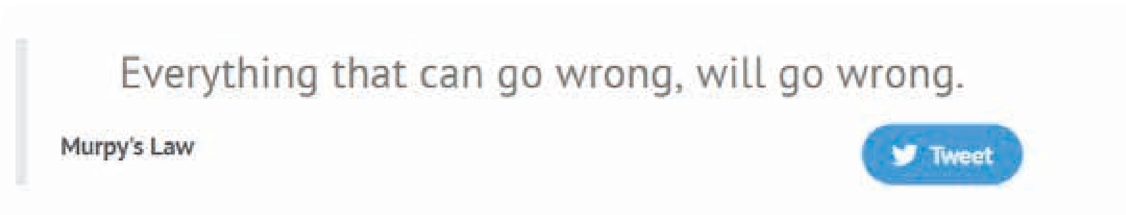


Øystein Volden and Petter Solnør working on cyber security for autonomous systems

WHEN MURPHY WINS

BY TORE MO-BJØRKELUND, PHD CANDIDATE, NTNU AMOS

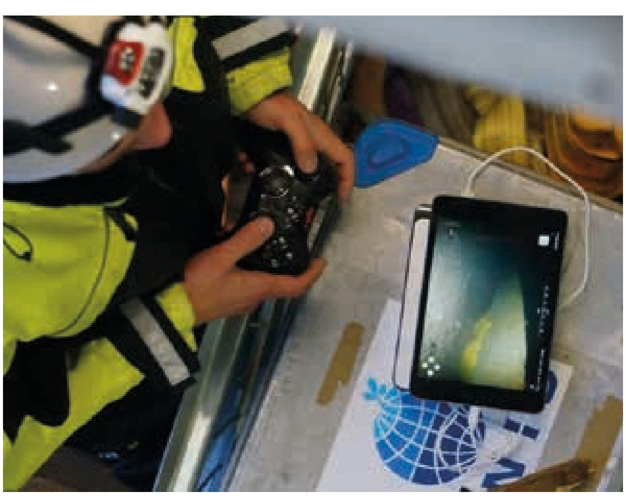
Scientists in movies and on television are often presented as brilliant people, knowing exactly what they do and what they want to achieve; furthermore, their experiments always succeed. That is, if they fail, they fail spectacularly, becoming mutants, blowing up the world or some such. This post is about real scientists and failing unspectacularly.



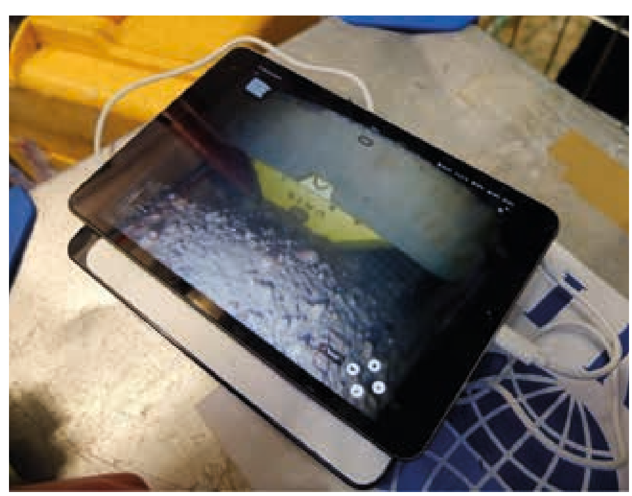
This is mainly because real scientists are also real people, and thus prone to all the real-life challenges, such as seasickness and tiredness, on top of trying to measure the temperature in the Barents Sea to the fifth decimal point. Sometimes, scientists fail, not because we are bad at science, but because failure is a part of trying. An unintended galvanic reaction alone has probably claimed its share of moorings, in which shackles and chains have rusted away in the deep. In October 2020, The Nansen Legacy conducted a cruise to the Barents Sea, with planned activities in turbulence measurements, Autonomous Underwater Vehicle (AUV) operations and the retrieval of moorings. Some part of all these activities failed, things broke and Murphy won.

Failure no. 1: The mooring

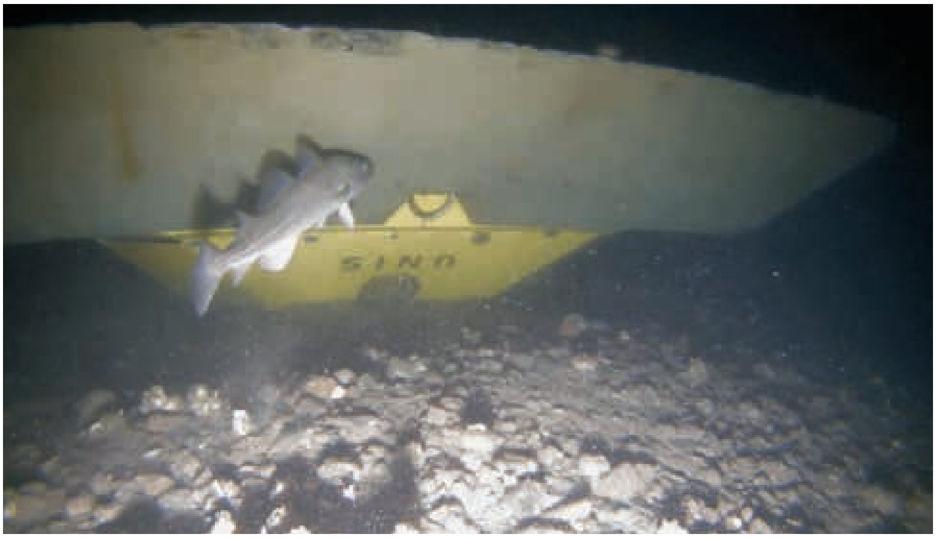
A trawl-proof mooring looks like a concrete pyramid with the top cut off, which is made such that fishing trawls will pass over it. It sits calmly on the seabed, measuring current, temperature and salinity, waiting for a research vessel to retrieve it. On the morning of the retrieval, the ship steamed to the location of the mooring, and the scientists on board activated the acoustic release, and the mooring replied that it was released. Hopeful scientists and able seamen gathered on deck and scouted for the mooring, presumably rising to the surface by Archimedes' might. It is yellow, so it should not be so hard to spot. Some time passed,



Inspecting the upside-down mooring. Photo: Christine Gawinski



Inspecting the upside-down mooring. Photo: Ragnheid Skogseth



The upside-down mooring, with a cod silently mocking the scientists *Photo: Tore Mo-Bjørkelund*

and the mooring did not surface, the scientists performed range measurements and saw that its position did not move. They accurately triangulated the position of the mooring and sent down a small robot to look for it, and after a while they found it still sitting there on the seabed. However, there was only one small problem: It was upside down. The trawl proof mooring had been flipped, presumably by a trawl. The general consensus was: Oh well, nothing we can do now, let's come back for it later. Goodbye mooring, goodbye science, goodbye publications and goodbye completing the PhD. Oh well, at least it was not the scientists' fault, at least this time.

Failure no. 2: The AUV

An AUV is a torpedo-shaped robot, with a propeller, some fins for control and a lot of sensors for tasting, smelling and touching the ocean. In this case, the AUV is called Harald, and it has one extra sensor on board, a microstructure sensor. This sensor can measure tiny changes in temperature and flow, what is known as turbulence. Some claim to know what turbulence is, but there is a nonzero chance that they are lying; honestly, it is more complicated than quantum mechanics. I will not claim to understand it either. To the point: To measure these tiny oceanic vibrations, the sensor needs some expensive and sensitive sensor probes. For our small test mission, we of course outfitted the sensor with a full range of probes, since it was only a test run and no real data was planned to be collected (direct example on how stupid scientists can be). The test mission was as follows: Dive to a depth of five metres, go 100 meters south and come back to the surface. This should take approximately five minutes or less. The scientists were out with the small boat of the research vessel, the mission was underway and life was good. Some 45 minutes

LAUV Harald, carrying the microstructure sensor (AKA the shock absorber). *Photo: Ragnheid Skogseth*

The broken antenna of LAUV Harald, the connector to the antenna is visible in gold. *Photo: Ragnheid Skogseth*

later, after no contact with the AUV, the mood was quite different. *Where are you Harald? I do not want to tell my boss I lost equipment worth several years of my salary*. There was no contact with Harald, and it was believed to be lost. Suddenly, it was spotted from the bridge: *It's underneath the ship!* Then it was gone again. Again, with a sudden movement, the boat driver sped the small boat around the research vessel and there it was, the AUV, Harald. A sight for sore eyes. Despair turned into elation: *Whew! I thought I had lost 2 million NOK worth of equipment, before lunch even*. After that, the rescue mission was quick and effective.

With everyone back on board, the damage was assessed, as the other scientists on board had not seen probes more smashed than this. Harald's brain was opened, and the code running in the vehicle was inspected. The failure stemmed from a single true/false statement in the code, a single bit, flipped, a 1 that should have been a 0. In this case, it made all the difference between success and failure. The AUV Harald had broken its antenna, and was out of service for the rest of the cruise.

The microstructure probes, broken by the impact with the research vessel.
Photo: Ragnheid Skogseth

Failure no. 3: The VMP

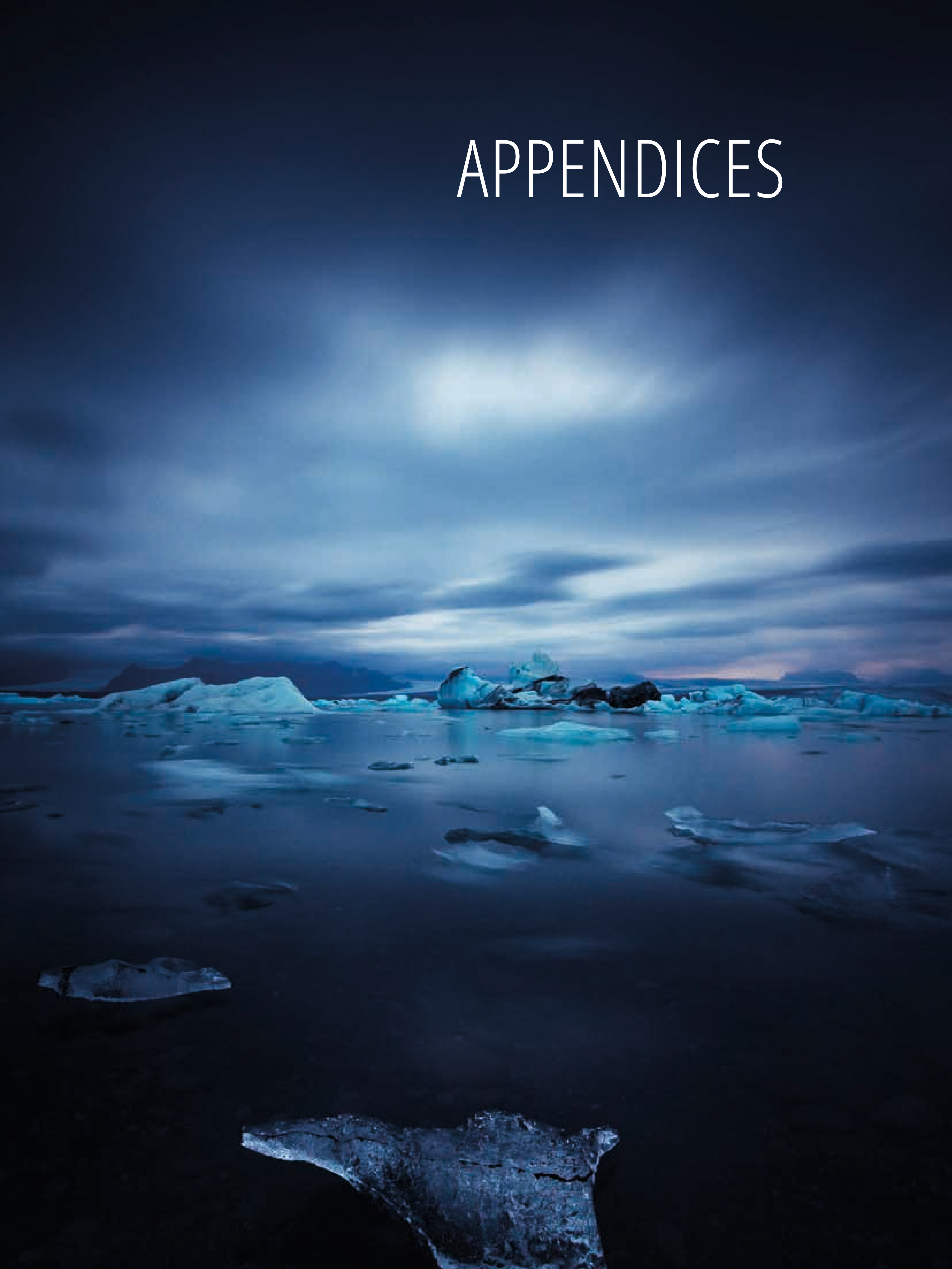
A Vertical Microstructure Profiler (VMP) looks like a large, black and yellow toilet brush. It is made to fall gracefully towards the seabed, measuring microstructure along its way into the abyss. It is connected to the ship via a cable that transmits data one way and power the other. This instrument was broken when the scientist got on board, somewhere during the transit from Bergen; something in the electronics failed, and made the sensor output gibberish as data. The precise reason is still unknown, and the VMP was out of service for the rest of the cruise.

All that can go wrong will go wrong, but not all the time. It is not the aim of this post to paint a gloomy picture of ocean science, but rather to say that it is not always that we succeed. All in all, the cruise was a success, a lot of data was gathered and moorings were retrieved and deployed, as were several glider vehicles, and the VMP had a backup: the MSS (Microstructure Sonde). The mooring retrieval was attempted one week later, but without success. The current plan is to come back with a work class ROV, an underwater robot, to retrieve the mooring.

We work with sensors and instruments that often are one of a kind, and all of them have their strengths, weaknesses and quirks. As ocean scientists, we not only need to know the ocean, we need to know our instruments. We need to know how they work, and all the million little things around their operation, the things we have yet to learn and the knowledge that is not written down. We do our best, and sometimes we fail.

We learn from our mistakes so that the next time we may succeed, and Murphy may lose.

APPENDICES



ANNUAL ACCOUNTS AND MAN-YEAR EFFORTS

Annual accounts and man-year efforts

REVENUES IN 2020 (amount in NOK 1000)	
Actual:	
Income	52,678
Costs	51,305
Year end allocation	1,373
In Kind	
Income	8,762
Costs	8,762
Total	
Income	61,440
Costs	60,067
Year end allocation	1,373
AMOS 1 end allocation	5,497

PERSONNEL 2020	
Keypersons	7
Adjunct prof/associated prof	15
Affiliated scientists	31
Scientific advisers	2
postdoc/researchers	8
Affiliated postdocs/resarchers	19
PhD Candidates	31
Affiliated PhD candidates	74
Administrative staff	3
Management	2
Technical staff	2
Graduated PhD candidates financed by NTNU AMOS	3
Graduated PhD candidates associated to NTNU AMOS	9

Annual accounts and man-year efforts

ANNUAL ACCOUNTS	
Operating income	**Accountes income and costs**
The research council of Norway	14,730
NTNU	33,772
Others	4,226
in kind	8,762
Sum operating income	**61,490**
Operating income	**Accountes income and costs and costs**
Salary and social costs	45,899
Equipment investments	2,819
Procurement of R&D servises	441
Other operating costs	2,145
in kind	8,762
Sum operating costs	**60,067**
Year end allocation	1,373
Opening balance 20180101	5,497
Closing balance 20181231	6,382

Total man-years efforts	
Man-years	2020
Centre director	0.30
Co-director	0.20
Adm.personnel	1.20
Technical staff	1.00
Summary	**2.70**

Key professor	3.50
Adjunct prof/ass.prof	2.72
Affiliated prof/scientists	6.50
Scientific advisor	0.50
Postdocs	5.20
Postdoc (affiliated)	12.82
Visiting researchers	-
PhD candidates	18.08
PhD candidates (affiliated)	47.33
Total research man-years	**99.35**

Number of researchers and personnel man-years according to category and nationality

NATIONALITY	KEY PROFESSOR	ADJUNCT PROF/ ASS PROF	AFFILIATED SCIENTIST	SCIENTIFIC ADVISOR	POSTDOC/ AFFILIATED POSTDOC	VISITING PROFESSOR/ RESEARCHER	PhD	Assc PhD	ADMINISTRA-TIVE STAFF*)	SUM
Norwegian	6	7	20	2	13	-	19	44	5	
Other nationalities	1	8	11	-	14	-	12	30	-	
Sum	**7**	**15**	**31**	**2**	**27**	**-**	**31**	**74**	**5**	**-**
Man-years	3.50	2.72	6.50	0.50	17.28	-	18.08	47.33	2.20	98.11

Summen over viser ikke centre director og co-director

AMOS PERSONNEL 2020

Management and administration

NAME	TITLE	ACRONYM
Bolme, Sigmund	Higher executive officer - communications	SB
Prof. Fossen, Thor I	Co-director	TIF
Karoliussen, Renate	Senior executive officer	RK
Reklev, Knut	Senior engineer	KR
Prof. Sørensen, Asgeir J	Director	AJS

Key scientists

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Prof. Amdahl, Jørgen	NTNU, Dept.Marine Technology	Structural load effects, resistance, accidental actions	JA
Prof. Fossen, Thor I.	NTNU, Dept.Engineering Cybernetics	Guidance, navigation and control	TIF
Prof. Greco, Marilena	NTNU, Dept.Marine Technology	Marine Hydrodynamics	MG
Prof. Johnsen, Geir	NTNU, Dept.Biology	Marine biology	GJ
Prof. Johansen, Tor Arne	NTNU, Dept.Engineering Cybernetics	Optimization and estimation in control	TAJ
Prof. Petterse, Kristin Y.	NTNU, Dept.Engineering Cybernetics	Automatic control	KYP
Prof. Sørensen, Asgeir J.	NTNU, Dept.Marine Technology	Marine control systems	AJS

Senior Scientific advisers

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Prof. Faltinsen, Odd M.	NTNU, Dept.Marine Technology		OF
Prof. Moan, Torgeir	NTNU, Dept.Marine Technology		TM

Adjunct professors and adjuct associate professors

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Adj. Prof. Berge, Jørgen	UiT, The Artic University of Norway	Marine biology	JB
Adj. Prof. Fredheim, Arne	SINTEF Ocean	Fisheries and aquaculture	AF
Adj. Prof. Kruusmaa, Maarja	Talin University of Technology	Marine robotics	MK
Adj. Prof. Lugni, Claudio	CNR - INM	Marine hydrodynamics	CL
Adj. Ass. Prof Nielsen, Ulrik Dam	DTU	Wave-ship interactions	UDN
Adj. Prof. Skaugset, Kjetil	Equinor	Marine operations and structures	KS
Adj. Prof. Sigernes, Fred	UNIS	Remote sensing	FS
Adj. Ass. Prof. Sokolova, Nadezda	SINTEF Digital	Integrated navigation systems	NS
Adj. Ass. Prof. Storvold, Rune	NORUT	Aircraft and remote sensing	RS
Adj. Prof. Sousa, Joao	Porto University	Autonomous systems	JS
Adj. Prof. Johansson, Karl Henrik	KTH	Automation and control	KHJ
Adj. Prof. Larsen, Kjell	Equinor	Marine operations and structures	KL

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Adj. Ass. Prof. Nguyen, Trong Dong	DNV GL	Marine control systems	TDN
Adj. Ass. Prof. Scibilia, Francesco	NTNU, Dept. Engineering Cybernetics	Remote sensing and autonomy	FS
Adj.Prof Ageleet, Fernando Aguado	UiVIGO - University of Vigo	Systems engineering for small satellite systems	FAA

Affiliated scientists

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Ass. Prof. Aberle-Malzahn, Nicole	NTNU, Dept. of Biology	Marine biology	NAM
Ass. Prof. Alfredsen, Jo Arve	NTNU, Dept.Engineering Cybernetics	Automation in fisheries and aquaculture	JAA
Ass. Prof. Alver, Morten Omholt	NTNU, Dept. Engineering Cybernetics	Automation in fisheries and aquaculture	MOA
Ass. Prof. Brekke, Edmund F.	NTNU, Dept.Engineering Cybernetics	Sensor fusion	EB
Prof. Bachynski, Erin E.	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	EEB
Ass.Prof. Brodtkorb, Astrid Helene	NTNU, Dept.Marine Technology	Marine Cybernetics	AB
Adj.Prof. Bryne, Torleiv Håland	NTNU, Dept. Engineering Cybernetics	Navigation systems	THB
Dr. Breivik, Morten	NTNU, Dept.Engineering Cybernetics	Nonlinear and adaptive motion control	MB
Ass. Prof. Bye, Robin T.	NTNU, Dept.Of ICT and Natural Sciences	Cyber-physical systems and AI	RTB
Ass. Prof. Eide, Egil	NTNU, Department of Electronic Systems	Nagvigation of autonomnous ships	EE
Ass. Prof. Føre, Martin	NTNU, Dept.Engineering Cybernetics	Fisheries and aquaculture	MF
Prof. Gao, Zhen	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	ZG
Prof. Imsland, Lars S.	NTNU, Dept.Engineering Cybernetics	Automatic control, optimization	LI
Prof. Kristiansen, Trygve	NTNU, Dept.Marine Technology	Marine hydrodynamics	TK
Ass. Prof. Kim, Ekaterina	NTNU, Dept.Marine Technology	Marine structures	EK
Prof. Lader, Pål	NTNU, Dept.Marine Technology	Aquaculture structures and Experimental hydrodynamics	PL
Ass. Prof. Lekkas, Anastasios	NTNU, Dept.Engineering Cybernetics	Fusing artificial intelligence with control engineering to develop cyber-physical systems of increased autonomy	AL
Prof. Ludvigsen, Martin	NTNU, Dept.Marine Technology	Underwater technology and operations	ML
Prof. Lundteigen, Mary Ann	NTNU, Dept.Engineering Cybernetics		MAL
Prof. Molinas, Marta	NTNU, Dept.Engineering Cybernetics	Marine power systems	MM
Prof. Pedersen, Eilif	NTNU, Dept.Marine Technology	Mathematical modeling of marine physical systems and operations.	EP
Prof. Olsen, Yngvar	NTNU, Dept. of Biology	Marine biology	YO
Prof. Schjølberg, Ingrid	NTNU, Dept.Marine Technology	Underwater robotics	IS
Prof. Skjetne, Roger	NTNU, Dept.Marine Technology	Marine control systems	RS
Ass. Prof. Stahl, Annette	NTNU, Dept.Engineering Cybernetics	Robotic vision	AS
Researcher Tymokha, Oleksandr	NTNU, Dept.Marine Technology	Marine hydrodynamics	OT
Prof. Utne, Ingrid B.	NTNU, Dept.Marine Technology	Safety critical systems and systems engineering	IBU
Prof. Zhang, Houxiang	NTNU, Dept. of Ocean Operations and Civil Engineering	Robotics and Cybernetics	HZ

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Prof. Petrovic, Slobodan	NTNU, Dept. of Information Security and Com.Techonolgy	Information Security	SP
Prof. Gravdahl, Jan Tommy	NTNU, Dept.Engineering Cybernetics	Control Engineering	JTG
Prof. Konstantinos Alexis	NTNU, Dept.Engineering Cybernetics	Autonomous systems	KA

Technical staff, directly funded by NTNU AMOS

NAME	INSTITUTION, DEPARTMENT	ACRONYM
Kvaløy, Pål	NTNU, Dept.Engineering Cybernetics	PK
Volden, Frode	NTNU, Dept.Marine Technology	FV

Postdocs/researchers

NAME	INSTITUTION	MAIN FIELD OF RESEARCH	ACRONYM
Dr Ommani, Babak	SINTEF Ocean	Numerical modelling for nonlinear stochastic processes	BO
Dr Zhaolong, Yu	NTNU, Dept. of Marine Technology	Marine Structures	UZ
Dr. Grant, Stephen	NTNU, Dept. of Biology	Light climate measurements in the Arctic	SG
Dr. Mokhtari, Mojatba	NTNU, Dept. of Marine Technology	Assessment of marine structures in Arctic and Cryogenic conditions	MM
Dr Shen, Yugao	NTNU, Dept. of Marine Technology	Limits for fish-farm operations	YS
Dr.Fragoso, Glaucia Moreira	NTNU, Dept. of Biology	Marine primary production: Bio-diversity, bio-geography, enabling technology for marine ecology	GMF
Dr.Ødegård, Øyvind	NTNU, Dept. of Marine Technology	Use of underwater robots and sensors in marine archaeology, including the integration of autonomy in scientific knowledge production	ØØ
Dr. Colicchio, Giuseppina	CNR - INM	Mesh generation and analysis for acomputational fluid mechanics	GC
Dr. Toker, Kadir Atilla	NTNU, Dept. Engineering Cybernetics	Airborne GNSS/GBAS receiver experimental platform for UAVs	TA
Dr. Garrett, Joseph	NTNU, Dept. Engineering Cybernetics	Superresolution techniques for hyperspectral remote sensing	JG
Gryte, Kristoffer	NTNU, Dept. Engineering Cybernetics	autonomous systems software	KG
Dr. Helgesen, Håkon Hagen	NTNU, Dept. Engineering Cybernetics	Autonomous ships	HHH
Dr. Jones, Alun	NTNU, Dept. of Marine Technology	Ecosystem indicators for the Barents Sea	IU
Dr Leira, Fredrik Stendahl	NTNU, Dept. Engineering Cybernetics	autonomous systems software	FSL
Dr Nornes, Stein Melvær	NTNU, Dept. of Marine Technology	Simultaneous mapping, navigation and monitoring with unmanned underwater vehicle using sensor fusion	SMN
Dr Norgren, Petter	NTNU, Dept. of Marine Technology	Under ice technology development	PN
Dr. Rokseth, Børge	NTNU, Dept. of Marine Technology	Online risk control of automatic sailing and power and propulsion systems.	BR
Dr Wenz, Andreas Wolfgang	NTNU, Dept. Engineering Cybernetics	Flight performance, optimization and fault tolerance with hybrid power and propulsion	AW
Dr. Thieme, Christoph Alexander	NTNU, Dept. of Marine Technology	Online risk modelling for autonomous systems	CAT
Dr. Birkeland, Roger	NTNU, Dept. of Electronic Systems	Mission-oriented autonomous systems – with small satellites for maritime sensing, surveillance and communication	RB

NAME	INSTITUTION	MAIN FIELD OF RESEARCH	ACRONYM
Dr. Fossum, Trygve	NTNU, Dept. of Marine Technology	Intelligent autonomy, data-driven sampling, and planning for marine robotics	TF
Dr. Eriksen, Bjørn-Olav Holtung	NTNU, Dept. Engineering Cybernetics	Robustifying control and collision avoidance systems for autonomous ferries	TOF
Dr. Jain, Ravinder Praveen Kumar	NTNU, Dept. Engineering Cybernetics	Machine learning methods for adaptive sampling and control	EB
Dr.Wilthil, Erik F.	NTNU, Dept. Engineering Cybernetics	Situational awareness for autonomous urban ferries	EW
Dr. Ren, Zhengru	NTNU, Dept. of Marine Technology	Control methods for more efficient offshore wind installation	ZR
Dr. Zolich, Artur Piotr	NTNU, Dept. Engineering Cybernetics	Coordination of unmanned vehicles in marine environment	APZ
Dr. Hann, Richard	NTNU, Dept. of Cybernetics	Icing and icing mitigation in UAV rotors and propellers	RH

Photo: Geir Johnsen

ArcLight: *Light collection dome for Arctic Light observatory near Ny Ålesund, Svalbard. This ArcLight observatory provides high resolution light regime data for biology, modelling and potential use for remote sensing.*

PhD cadidates associated with NTNU AMOS with other financial support

NAVN	SUPERVISOR	TOPIC
Aminian, Behdad	DV	Channel-aware adaptive numerical optimization algorithms for distributed underwater systems'
Amro, Ahmed W.	SK	Communication and cybersecurity for autonomous passenger ferry
Ahani, Alireza	MG	Local structural response due to wave slamming
Bitar, Glenn Ivan	MB	Energy-optimal and autonomous control for car ferries
Berget, Gunhild	TAJ	Intelligent monitoring of drilling operations in sensitive environments
Bjørkelund, Tore-Mo	ML	Adaptive and collaborative vehicle behaviour for mission management for autonomous underwater vehicles
Bjørnø, Jon	RS	Icebreaker guidance and coordination for effective ice management tactics
Blindheim, Simon	TAJ	Risk-based optimization of control system behavior
Bosdelekidis, Vasileios	TAJ	Navigation System Integrity Assurance for Safety-Critical Autonomous Operations,
Bremnes, Jens Einar	AJS	Risk-based planning and control of AUVs
Bøhn, Eivind	TAJ	Machine learning in control and estimation
Guo, Chuanqui	SH	Risk analysis and management for autonomous passenger ferry
Cardaillac, Alexandre	ML	Autonomous Robotic Inspection and Maintenance on Ship Hulls and Storage Tanks
Coates, Erlend Magnus Lervik	TIF	Nonlinear Autopilot Design for Operation of UAVs in Extreme Conditions
Dahl, Andreas reason	RS	Nonlinear and fault-tolerant control of electric power production in Artic DP vessels
Dallolio, Albert	TAJ	Autonomous wave powered surface vessel for oceanography
Diaz, Gara Quintana	TE	Small satellite system communication
Diamanti, Eleni	ØØ	underwater robotics and sensors in marine archaeology
Faltynkova, Andrea	GJ	Detection of microplast using new optical tools
Flåten, Andreas L.	EB	Multisensor tracking for collision avoidance
Foseid, Eirik Lothe	KYP	Robust motion planning and control of AIAUVs
Gao, Fan	AB	Hybrid combinator curves for autonomous ships
Grøtte, Mariusz Eivind Santora	TG	Attitude Determination and Control for Hyperspectral Imaging Small Satelite in Multi-Agent Observation System
Hann, Richard	TAJ	Icing and anti-icing of UAVs
Haavardsholm, Trym Vegard	AST	Collaborative visual mapping and exploration for teams of unmanned systems
Hagen, Inger Berge	EB	Collision Avoidance for Autonomous Ferry
Haraldsen, Aurora	KYP	Autonomous Collision Avoidance
Hasler, Oliver Kevin	THB	Multi-sensor fusion for increased UAV resilience and safety,
Hatleskog, Johan	TAJ	Autonomous Industrial Inspection in a Contextualized Environment
Haugo, Simen	AST	Computer vision methods for assisted teleoperation of unmanned air vehicles
Helgesen, Øystein Kaarstad	EB	Sensor fusion for autonomous ferry
Hegseth, John Marius	EB	Efficient Modelling and Design Optimization of Large Floating Wind Turbines
Hoff, Simon A.	KYP	Distributed communication-aware path planning for autonomous underwater fleets
Jellum, Erling Rennemo	THB	Next generation hardware for multi-sensor timing, data processing and fusion
Johansen, Thomas	IU	Risk Modeling for Supervisory Risk Control
Jónsdóttir, Kristbjõrg Edda	JAA	Dynamics of waterflow and turbulence in large-scale aquaculture sea cages
Kaasa, Tord Hansen	JAM	Aluminium Ship Design with Extruded Panels
Katsikogiannis, George	EB	Loads and Responses of Large-Diameter Monopile Wind Turbines
Livermor-Honoé, Evelyn	EE	Rapid systems engineering
Martinsen, Andreas Bell	AL	Reinforcement learning methods for guidance, navigation and control

NAVN	SUPERVISOR	TOPIC
Matous, Josef	KYP	Distributed cooperative control of marine multi-vehicle systems
Mathisen, Siri Holthe	TAJ	Embedded Optimization for Autonomous Unmanned Aerial Vehicle Mission Planning and Guidance
Orucevic, Amer	JTG	Energy harvesting for underwater snake robots
Potter, Casper	MG	Bio-inspired flow sensing for articulated intervention autonomous underwater vehicles
Reddy, Namireddy Praveen	MZ	Intelligent power & energy management system for autonomous ferry
Reinhardt, Dirk	TAJ	Nonlinear Autopilot Design for Extended Flight Envelopes and Operation of Fixed-Wing UAVs in Extreme Conditions
Rothmund, Sverre	TAJ	Decision making under uncertainty in risk-based autonomous control
Rutledal, Dag	TP	Human factors, remote monitoring and control for autonomous passenger ferry
Prentice, Elizabeth	TAJ	Onboard data processing for planning and operation of SmallSat mission
Skrove, Tale	YO	Environmental assessment of coastal surface waters
Skulstad, Robert	HZ	Data-based Ship Motion Prediction in Offshore Operations
Sollie, Martin	TAJ	Autonomous ship-landing of UAVs
Solnør, Petter	TIF	Real-Time Encryption of Sensor and Communication Signals in Feedback Control Systems for Safe Operation of Autonomous Vehicles
Souza, Carlos Eduardo Silva de	ERB	Structural modeling and optimization of floating wind turbines
Sture, Øystein	ML	Autonomous exploration of Marine Minerals
Summers, Natalie	GJ	Primary production in the Arctic using new enabling technology
Sverdrup-Thygeson, Jørgen	KYP	Motion control and redundancy resolution for hybrid underwater operations
Svendsen, Eirik	MF	Technological solutions for online observation of physiological and behavioural dynamics in farmed fish
Sørensen, Mikkel Eske Nørgaard	MBR	Nonlinear and adaptive control of unmannes vehicles for maritime applications
Téglasy, Bálint Zoltán	MAL	safety and security of next generation industrial control systems
Thorat, Laxminarayan	RS	Control Methods for Highly Redundant and Energy Efficient Shipboard Electric Power Production Systems
Thoresen, Marius	KYP	Motion planning in rough terrain for unmanned ground vehicles
Thyri, Emil Hjelseth	MB	Mission planning and collision avoidance for autonomous passenger ferry
Tokle, Lars-Christian Ness	EB	Sensor fusion for autonomous ferry
Torben, Tobias Rye	AJS	Verification and Control Design for Safe Autonomous Ships
Ueland, Einar S.	RS	Study of Fundamental Constraints in the Hybrid Test Loop, and Optimal Control and Estimation Strategies for Actuation of Effort on the Physical System
Vagale, Anete	RB	Intelligent Collision Avoidance and Path Planning for Autonomou Surface Vessels in Opertaing in Confined Waters
Verma, Amrit Shankar	ZG	Development of explicit response-based criteria for operability assessment for insatallation of offshore wind turbines using floating vessels
Volden, Øystein	TIF	Real-Time Encryption of Computer Vision Feedback Control Systems for Autonomous Ships
Winter, Adrian	TAJ	Multi-sensor fusion for increased resilience of UAVs with respect to satellite navigation cyber-security
Wu, Menging	TM/ZG	Sea state forecasting using data driven models for decision making for marine operations
Xue, Libo	AL	AI Planning and control for underwater intervention drones
Xu, Kun	TM/ZG	Mooring systems for floating wind turbines in shallow water
Øvreaas, Henning	THB	Autonomous navigation and mission planning of wave propelled unmanned surface vehicle (USV

PhD candidates with financial support from NTNU AMOS

NAME	SUPERVISOR	TOPIC
Bakken, Sivert	TAJ	Coordinated oceanographic observation system with autonomous aerial/surface robots and hyper-spectral imaging in SmallSat
Basso, Erlend, Andreas	KYP	Motion Planning and Control of Articulated Intervention-AUVs
Borlaug, Ida-Louise	KYP	Robust control of articulated intervention AUV
Bore, Pål Tokle	JAM	Structural design of reliable offshore aquaculture structures
Cisek ,Krzysztof	TAJ	Multi-body unmannes aerial systems
Didlaukies- Schmidt Henrik	AJS	Modeling and Control of Hyper-Redundant Underwater Manipulators
Dirdal, Johan	TIF	Sea-State and Ship Response Estimation
Fortuna, Joao	TIF	Processing and analysis of Hyperspectral Images from unmanned systems
Gryte, Kristoffer	TIF	Fixed-wing UAV operations from autonomous floating docking station
Henriksen, Marie Bøe	TAJ	Hyperspectral imaging in drones and small satellites
Kaminska-Wrzos, Marianna	KYP	Free-floating intervention operations using AIAUVs
Kristiansen, Bjørn Andreas	JTG	Energy optimality for spacecraft attitude manoeuvres
Langer, D.Langer	AJS	Hierarchical Control of Heterogenous Robotic Systems from Satellites.
Løvås, Håvard Snefjellå	AJS	Classification and Detection of Microorganism Including Plastics in the Oceans Using Optical Methods
Marley, Mathias	RS	Resilient hybrid motion control of autonomous vessels
Mathisen, Pål	TIF	Sea-State and Ship Response Estimation
Ma, Shaojun	MG	Manoeuvring of a ship in waves
Merz, Mariann	TAJ	Deplyment, search and recovery of marine sensors using a fixed- wing UAV
Mounet, Raphael	AB	Sea state estimation based on measurements from multiple observation platforms
Nam, Woongshik	JAM	Structural resistance of ships and offshore structures sunjected to cryogenic spills
Maidana, Renan	IU	Risk Assessment for Decision-support in Automated Planning and Resource Management in Autonomous Marine Vehicles
Mogstad, Aksel Alstad	GJ	Marine biological applications for underwater hyperspectral imaging (UHI)
Norvik, Carina	MG	Bio-inspired fins for highly performant articulated autonomous underwater vehicles
Ramos, Nathalie	KJ	4D printing of intelligent marine structures
Siddiqui, Mohd Atif	MG	Behaviour of a damged ship in waves
Slagstad, Martin	JAM	Advanced and rational analysis of steel fish farms in exposed waters
Sørum, Stian Hoegh	JAM	Offshore Wind Turbines
Tengesdal, Trym	TAJ	Risk-based COLREGS compliant collision avoidance for autonomous ships
Værnø, Sven Are Tutturen	RS	Topics in motion control of offshore vessels
Williamson, David	ML	Autonomous approaches to in-situ monitoring of early fish life stages
Xu, Hui-Li	MG	Fish-hydrodynamic study finalized to the bio-cyber-hydrodynamics
Johansen, Thomas	IU	Risk Modeling for Supervisory Risk Control
Jónsdóttir, Kristbjõrg Edda	JAA	Dynamics of waterflow and turbulence in large-scale aquaculture sea cages
Kaasa, Tord Hansen	JAM	Aluminium Ship Design with Extruded Panels
Katsikogiannis, George	EB	Loads and Responses of Large-Diameter Monopile Wind Turbines
Leonardi, Marco	AS	Visual odometry and servoing for 3D reconstruction
Li, Qinyuan	TM	Long-term extreme response prediction for offshore wind turbines
Livermor-Honoé, Evelyn	EE	Rapid systems engineering
Martinsen, Andreas Bell	AL	Reinforcement learning methods for guidance, navigation and control
Mathisen, Siri Holthe	TAJ	Embedded Optimization for Autonomous Unmanned Aerial Vehicle Mission Planning and Guidance

NAME	SUPERVISOR	TOPIC
Olofsson, Harald Lennart Jonatan	TIF	Bayesian iceberg risk management
Reddy, Namireddy Praveen	MZ	Intelligent power & energy management system for autonomous ferry
Ren, Zhengru	RS	Control and Online Decision Support of Crane Operations for Fixed and Floating Offshore Wind Turbines
Rothmund, Sverre	TAJ	Decision making under uncertainty in risk-based autonomous control
Rutledal, Dag	TP	Human factors, remote monitoring and control for autonomous passenger ferry
Prentice, Elizabeth	TAJ	Onboard data processing for planning and operation of SmallSat mission
Shi, Deng	TM/ZG	Vortex induced vibrations of a submerged floating tunnel
Skrove, Tale	YO	Environmental assessment of coastal surface waters
Skulstad, Robert	HZ	Data-based Ship Motion Prediction in Offshore Operations
Sollie, Martin	TAJ	Autonomous ship-landing of UAVs
Solnør, Petter	TIF	Real-Time Encryption of Sensor and Communication Signals in Feedback Control Systems for Safe Operation of Autonomous Vehicles
Souza, Carlos Eduardo Silva de	ERB	Structural modeling and optimization of floating wind turbines
Sture, Øystein	ML	Autonomous exploration of Marine Minerals
Summers, Natalie	GJ	Primary production in the Arctic using new enabling technology
Sverdrup-Thygeson, Jørgen	KYP	Motion control and redundancy resolution for hybrid underwater operations
Svendsen, Eirik	MF	Technological solutions for online observation of physiological and behavioural dynamics in farmed fish
Sørensen, Mikkel Eske Nørgaard	MBR	Nonlinear and adaptive control of unmannes vehicles for maritime applications
Thoresen, Marius	KYP	Motion planning in rough terrain for unmanned ground vehicles
Thyri, Emil Hjelseth	MB	Mission planning and collision avoidance for autonomous passenger ferry
Tokle, Lars-Christian Ness	EB	Sensor fusion for autonomous ferry
Torben, Tobias Rye	AJS	Risk Handling and Control for Autonomous Ships
Ueland, Einar S.	RS	Study of Fundamental Constraints in the Hybrid Test Loop, and Optimal Control and Estimation Strategies for Actuation of Effort on the Physical System
Vagale, Anete	RB	Intelligent Collision Avoidance and Path Planning for Autonomou Surface Vessels in Opertaing in Confined Waters
Verma, Amrit Shankar	ZG	Development of explicit response-based criteria for operability assessment for insatallation of offshore wind turbines using floating vessels
Wilthil, Erik F.	EB	target tracking under navigation uncertainty
Winter, Adrian	TAJ	Multi-sensor fusion for increased resilience of UAVs with respect to satellite navigation cyber-security
Wang, Chun-Deng	YO	Marine monitoring
Wan, Ling	TM	Experimental and numerical study of a combined offshore wind and wave energy converter concept
Wu, Menging	TM/ZG	Sea state forecasting using data driven models for decision making for marine operations
Xue, Libo	AL	AI Planning and control for underwater intervention drones
Xu, Kun	TM/ZG	Mooring systems for floating wind turbines in shallow water

PhD degrees 2020

Supervised by Key Scientists at AMOS

NAME	DATE	TOPIC	SUPERVISOR
Siddiqui, Mohd Atif	November 27	Behaviour of a damged ship in waves	MG
Borlaug, Ida-Louise	November 26.	Robust Control of Articulated Intervention-AUVs using Sliding Mode Control	KYP
Nam, Wongshik	November 11	Structural resistance of ships and offshore structures sunjected to cryogenic spills	JAM
Hann, Richard	July	Atmospheric Ice Accretions, Aerodynamic Icing Penalties, and Icing Protection Systems on Unmanned Aerial Vehicles	TAJ
Gryte, Kristoffer	June 29	Precision Control of Fixed-Wing UAV and Robust Navigation in GNSS-Denied Environments	TIF
Mathisen, Siri H.	February	Autonomous Aerial Recovery: Fixed-Wing UAV Ballistic Airdrop and Deep-Stall Landing	TAJ

Supervised by AMOS Senior Advisors Odd M. Faltinsen and Torgeir Moan - scholarship at CeSOS/IMT

NAME	DATE	TOPIC	SUPERVISOR
Shi, Deng	September 9	Vortex induced vibrations of a submerged floating tunnel	TM
Xu, Kun	March 3	Mooring systems for floating wind turbines in shallow water	TM
Cho, Seongpil	January 22	Model-Based Fault Detection and Diagnosis of a Blade Pitch System in Floating Wind Turbines	TM

Supervised by Affiliated Scientists at AMOS

NAME	DATE	TOPIC	SUPERVISOR
Hegseth, John Marius	November 30	Efficient Modelling and Design Optimization of Large Floating Wind Turbines	EB
Tutturen, Svenn Are	November 18	Topics in motion control of offshore vessels	RS
Verma, Armit S.	September 9	Development of explicit response-based criteria for operability assessment for insatallation of offshore wind turbines using floating vessels	ZG

PUBLICATIONS

Journal articles

Abrahamsen, Bjørn Christian; Alsos, Hagbart Skage; Aune, Vegard; Fagerholt, Egil; Faltinsen, Odd Magnus; Hellan, Øyvind. Hydroplastic response of a square plate due to impact on calm water. Physics of Fluids 2020; 32 (8).

Alexander, Andreas; Kruusmaa, Maarja; Tuhtan, Jeffrey; Hodson, Andrew; Schuler, Thomas; Kääb, Andreas. Pressure and inertia sensing drifters for glacial hydrology flow path measurements. The Cryosphere.

Berge, Jørgen; Geoffroy, Maxime; Daase, Malin; Cottier, Finlo Robert; Priou, Pierre; Cohen, Jonathan H.. Artificial light during the polar night disrupts Arctic fish and zooplankton behavior down to 200 m depth. Communications Biology 2020; 3 1-8

Berget, Gunhild Elisabeth; Eidsvik, Jo; Alver, Morten; Py, Frédéric; Grøtli, Esten Ingar; Johansen, Tor Arne. Adaptive Underwater Robotic Sampling of Dispersal Dynamics in the Coastal Ocean. Springer Tracts in Advanced Robotics 2020;

Bitar, Glenn Ivan; Martinsen, Andreas Bell; Lekkas, Anastasios; Breivik, Morten. Two-Stage Optimized Trajectory Planning for ASVs Under Polygonal Obstacle Constraints: Theory and Experiments. IEEE Access 2020; 8 199953-199969

Bjørne, Elias; Brekke, Edmund Førland; Bryne, Torleiv Håland; Delaune, Jeff; Johansen, Tor Arne. Globally Stable Velocity Estimation Using Normalized Velocity Measurement. The international journal of robotics research 2020; 39 143-157

Bjørne, Elias; Brekke, Edmund Førland; Bryne, Torleiv Håland; Johansen, Tor Arne. Semiglobally Asymptotically Stable Nonlinear Observer for Camera Aided Navigation. IEEE Transactions on Control Systems Technology 2020;

Borisov, O. I.; Dahl, Andreas Reason; Pyrkin, A. A.; Gromova, F. B.; Skjetne, Roger. Consecutive Compensator in Station-Keeping of a Surface Vessel. Mehatronika, Avtomatizaciâ, Upravlenie 2020; 21 566-574

Borlaug, Ida-Louise Garmann; Pettersen, Kristin Ytterstad; Gravdahl, Jan Tommy. Combined Kinematic and Dynamic Control of Vehicle-Manipulator Systems. Mechatronics (Oxford) 2020; Vol. 69, Aug. 2020, pp. 102380.

Borlaug, Ida-Louise Garmann; Pettersen, Kristin Ytterstad; Gravdahl, Jan Tommy. Tracking control of an articulated intervention autonomous underwater vehicle in 6DOF using generalized super-twisting: Theory and experiments. IEEE Transactions on Control Systems Technology, Vol. 29, No. 1, 2021, pp. 353-369.

Bornebusch, Mads Friis; Johansen, Tor Arne. Autonomous recovery of a Fixed-wing UAV Using a Line Suspended Between Two Multirotor UAVs. IEEE Transactions on Aerospace and Electronic Systems 2020;

Boskovic, Dordije; Orlandic, Milica; Johansen, Tor Arne. A reconfigurable multi-mode implementation of hyperspectral target detection algorithms. Microprocessors and microsystems 2020; 78 –

Bremnes, Jens Einar; Brodtkorb, Astrid Helene; Sørensen, Asgeir Johan. Hybrid observer concept for sensor fusion of sporadic measurements for underwater navigation. International Journal of Control, Automation and Systems 2020; 18 1-8

Bremnes, Jens Einar; Thieme, Christoph A.; Sørensen, Asgeir Johan; Utne, Ingrid B.; Norgren, Petter. A Bayesian Approach to Supervisory Risk Control of AUVs Applied to Under-Ice Operations. Marine Technology Society Journal, Volume 54, Number 4, July/August 2020, pp. 16-39. ISSN 0025-3324

Cheng, Zhengshun; Gao, Zhen; Moan, Torgeir. Extreme responses and associated uncertainties for a long end-anchored floating bridge. Engineering structures 2020; 219

Cho, Seongpil; Bachynski, Erin Elizabeth; Rasekhi Nejad, Amir; Gao, Zhen; Moan, Torgeir. Numerical modeling of the hydraulic blade pitch actuator in a spar-type floating wind turbine considering fault conditions and their effects on global dynamic responses. Wind Energy 2020; 23 370-390

Dai, Jian; Leira, Bernt Johan; Moan, Torgeir; Kvittem, Marit Irene. Inhomogeneous wave load effects on a long, straight and side-anchored floating pontoon bridge. *Marine Structures* 2020 ;Volum 72.

Deng, Shi; Ren, Haojie; Xu, Yuwang; Fu, Shixiao; Moan, Torgeir; Gao, Zhen. Experimental Study on the Drag Forces on a Twin-tube Submerged Floating Tunnel Segment Model in Current. Applied Ocean Research 2020; 104

Deng, Shi; Ren, Haojie; Xui, Yuwang; Fu, Shixiao; Moan, Torgeir. Experimental study of vortex-induced vibration of a twin-tube submerged floating tunnel segment model. *Journal of Fluids and Structures* 2020 ;Volum 94. s. –

Dong, Wenbin; Rasekhi Nejad, Amir; Moan, Torgeir; Gao, Zhen. Structural reliability analysis of contact fatigue design of gears in wind turbine drivetrains. Journal of Loss Prevention in the Process Industries 2020; 65

Dunlop, Katherine Mary; Renaud, Paul Eric; Berge, Jørgen; Jones, Daniel O.B.; Harbour, Rob P.; Tandberg, Anne Helene S.; Sweetman, Andrew K.. Benthic scavenger community composition and carrion removal in Arctic and Subarctic fjords. Polar Biology 2020; Vol. 44. ISSN 0722-4060.s 31 - 43.s

Eriksen, Bjørn-Olav Holtung; Bitar, Glenn Ivan; Breivik, Morten; Lekkas, Anastasios M.. Hybrid Collision Avoidance for ASVs Compliant with COLREGs Rules 8 and 13-17. Frontiers in Robotics and AI 2020; 7

Faltinsen, Odd Magnus; Lagodzinskyi, Oleksandr E.; Timokha, Alexander. Resonant three-dimensional nonlinear sloshing in a square base basin. Part 5. Three-dimensional non-parametric tank forcing. Journal of Fluid Mechanics 2020; 894

Ferrandis, José del Águila; Bonfiglio, Luca; Rodríguez, Ricardo Zamora; Chryssostomidis, Chryssostomos; Faltinsen, Odd Magnus; Triantafyllou, Michael. Influence of Viscosity and Non-Linearities in Predicting Motions of a Wind Energy Offshore Platform in Regular Waves. Journal of Offshore Mechanics and Arctic Engineering 2020 ; 142.

Fiskin, R; Atik, O; Kisi, H; Nasibov, E; Johansen, Tor Arne. Fuzzy domain and meta-heuristic algorithm-based collision avoidance control for ships: Experimental validation in virtual and real environment. Ocean Engineering 2020;

Fortuna, João; Martens, Harald; Johansen, Tor Arne. Multivariate Image Fusion: A Pipeline For Hyperspectral Data Enhancement. Chemometrics and Intelligent Laboratory Systems 2020; 205

Ghamari, Isar; Greco, Marilena; Faltinsen, Odd Magnus; Lugni, Claudio. Numerical and Experimental Study on the Parametric Roll Resonance for a Fishing Vessel with and without forward speed. Applied Ocean Research 2020; 101

Gryte, Kristoffer; Bryne, Torleiv Håland; Johansen, Tor Arne. Unmanned Aircraft Flight Control Aided by Phased-Array Radio Navigation. Journal of Field Robotics (JFR) 2020; 38

Guidi, Giuseppe; Lekkas, Anastasios M.; Stranden, Jon Eivind; Suul, Jon Are Wold. Dynamic Wireless Charging of Autonomous Vehicles: Small-scale demonstration of inductive power transfer as an enabling technology for self-sufficient energy supply. IEEE Electrification Magazine 2020; 8 37-48

Halvorsen, Håkon Skogland; Øveraas, Henning; Landstad, Olav; Smines, Vidar; Fossen, Thor I.; Johansen, Tor Arne. Wave motion compensation in dynamic positioning of small autonomous vessels. Journal of Marine Science and Technology 2020;

Hann, Richard; Hearst, R. Jason; Sætran, Lars Roar; Bracchi, Tania. Experimental and numerical icing penalties of an S826 airfoil at low Reynolds numbers. Aerospace 2020; 7 –

Haring, Mark; Johansen, Tor Arne. On the stability bounds of Kalman filters for linear deterministic discrete-time systems. IEEE Transactions on Automatic Control 2020; 65 4434-4439

Heyn, Hans-Martin; Mogens Blanke; Roger Skjetne. Ice condition assessment using onboard accelerometers and statistical change detection. IEEE J. Oceanic Engineering, Vol. 45, No. 3, pp. 898-914, 2020 (online from 2019).

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Hovenburg, Anthony Reinier; Andrade, Fabio; Hann, Richard; Rodin, Christopher D; Johansen, Tor Arne. Long range path planning using an aircraft performance model for battery powered sUAS equipped with icing protection system. IEEE Journal on Miniaturization for Air and Space Systems 2020;

Hung, Nguyen T; Crasta, Naveena; Salinas, D M; Pascoal, António M.; Johansen, Tor Arne. Range-based Target Localization and Pursuit with Autonomous Vehicles: An Approach using Posterior CRLB and Model Predictive Control. Robotics and Autonomous Systems 2020; -

Hung, Nguyen T; Pascoal, António M.; Johansen, Tor Arne. Cooperative path following of constrained autonomous vehicles with model predictive control and event-triggered communications. International Journal of Robust and Nonlinear Control 2020; 30 2644-2670

Haavardsholm, Trym Vegard; Skauli, Torbjørn; Stahl, Annette. Multimodal Multispectral Imaging System for Small UAVs. IEEE Robotics and Automation Letters 2020; 5 1039-1046

Iglikowska, Anna; Krzemińska, Małgorzata; Renaud, Paul Eric; Berge, Jørgen; Hop, Haakon; Kuklinski, Piotr. Summer and winter MgCO3 levels in the skeletons of Arctic bryozoans. Marine Environmental Research 2020; Volum 162. ISSN 0141-1136.s

Jiang, Zhiyu; Yttervik, Rune; Gao, Zhen; Sandvik, Peter Christian. Design, Modelling and Analysis of a Large Floating Dock for Spar Floating Wind Turbine Installation. Marine Structures 2020; 72

Klausen, Kristian; Meissen, Chris; Fossen, Thor I.; Arcak, Murat; Johansen, Tor Arne. Cooperative Control for Multirotors Transporting an Unknown Suspended Load under Environmental Disturbances. IEEE Transactions on Control Systems Technology 2020; 28 653-660

Kostakis, I.; Röttgers, R.; Orkney, A.; Bouman, H.A.; Porter, M.; Cottier, Finlo Robert; Berge, Jørgen; Mckee, David. Development of a bio-optical model for the Barents Sea to quantitatively link glider and satellite observations. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 2020; Volum 378. ISSN 1364-503X.s

Kruusmaa, Marja; Gkliva, R.; Tuhtan, J. A.; Tuvikene, A; Alfredsen, Jo Arve. Salmon behavioral response to robots in an aquaculture sea cage. The Royal Society Open Science.

Kunisch, Erin; Bluhm, Bodil; Daase, Malin; Gradinger, Rolf; Hop, Haakon; Melnikov, Igor A.; Varpe, Øystein; Berge, Jørgen. Pelagic occurrences of the ice amphipod Apherusa glacialis throughout the Arctic. Journal of Plankton Research 2020; Volum 42 (1). ISSN 0142-7873.s 73 - 86.s doi: 10.1093/plankt/fbz072.

Leira, Frederik Stendahl; Helgesen, Håkon Hagen; Johansen, Tor Arne; Fossen, Thor I.. Object Detection, Recognition and Tracking from UAVs using a Thermal Camera. Journal of Field Robotics (JFR) 2020;

Maidana, Renan Guedes; Utne, Ingrid Bouwer; Sørensen, Asgeir Johan. State-of-the-Art on Artificial Intelligence for Risk-based Decision-making in Autonomous Marine Vehicles. I: *e-proceedings of the 30th European Safety and Reliability Conference and 15th Probabilistic Safety Assessment and Management Conference (ESREL2020 PSAM15)*. Research Publishing Services 2020 ISBN 9789811485930. s. -

Marley, Mathias; Skjetne, Roger; Breivik, Morten; Fleischer, Caroline. A hybrid kinematic controller for resilient obstacle avoidance of autonomous ships. IOP Conference Series: Materials Science and Engineering 2020; 929

Martinsen, Andreas Bell; Bitar, Glenn Ivan; Lekkas, Anastasios M.; Gros, Sebastien. Optimization-Based Automatic Docking and Berthing of ASVs Using Exteroceptive Sensors: Theory and Experiments. IEEE Access 2020; 8 204974-204986

Martinsen, Andreas Bell; Lekkas, Anastasios M.; Gros, Sebastien. Reinforcement Learning-Based Tracking Control of USVs in Varying Operational Conditions. Frontiers in Robotics and AI 2020;

Martinsen, Andreas Bell; Lekkas, Anastasios; Gros, Sebastien. Combining system identification with reinforcement learning-based MPC. IFAC-PapersOnLine 2020;

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Mathisen, Siri Gulaker; Leira, Frederik Stendahl; Helgesen, Håkon Hagen; Gryte, Kristoffer; Johansen, Tor Arne. Autonomous ballistic airdrop of objects from a small fixed-wing unmanned aerial vehicle. Autonomous Robots 2020;

Meurer, Christian; Fuentes-Pérez, Juan Francisco; Schwarzwälder, Kordula Valerie Anne; Ludvigsen, Martin; Sørensen, Asgeir Johan; Kruusmaa, Maarja. 2D Estimation of Velocity Relative to Water and Tidal Currents Based on Differential Pressure for Autonomous Underwater Vehicles. IEEE Robotics and Automation Letters 2020; 5 3444-3451

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Pekkoeva, Svetlana N.; Murzina, Svetlana A.; Nefedova, Zinaida A.; Falk-Pedersen, Stig; Berge, Jørgen; Lønne, Ole Jørgen; Nemova, Nina N.. Fatty acid composition of the postlarval daubed shanny (Leptoclinus maculatus) during the polar night. Polar Biology 2020; Volum 43 (6). ISSN 0722-4060.s 657 - 664.s

Prpić-Oršić, Jasna; Sasa, Kenji; Valčić, Marko; Faltinsen, Odd Magnus. Uncertainties of ship speed loss evaluation under real weather conditions. Journal of Offshore Mechanics and Arctic Engineering 2020; 142

Pustina, Luca; Lugni, Claudio; Bernardini, Giovanni; Serafini, Jacopo; Gennaretti, Massimo. Control of power generated by a floating offshore wind turbine perturbed by sea waves. Renewable & Sustainable Energy Reviews 2020; 132

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