NTNU AMOS
Centre for Autonomous Marine
Operations and Systems

NTNU AMOS
Centre for Autonomous Marine Operations and Systems

Annual Report 2018

Norwegian Centre of Excellence

The Research Council of Norway

OUR VISION

To establish a world-leading research centre for autonomous marine operations and systems:
To nourish a lively scientific heart in which fundamental knowledge is created through multidisciplinary theoretical, numerical, and experimental research within the knowledge fields of hydrodynamics marine biology, structural mechanics, guidance, navigation, and control. Cutting-edge inter-disciplinary research will provide the necessary bridge to realise high levels of autonomy for ships and ocean structures, unmanned vehicles, and marine operations and to address the challenges associated with greener and safer maritime transport, monitoring and surveillance of the coast and oceans, offshore renewable energy, and oil and gas exploration and production in deep waters and Arctic waters.

excellent – generous – courageous

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

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DIRECTOR'S REPORT

In this year's director´s report, I will emphasize the importance of knowledge and competence as a differentiator with a high impact for the society.

The main deliverables from NTNU AMOS are novel knowledge and competence in terms of published research results, graduated MSc, PhD and Postdoc, as well as innovations. After six years of operations we are sure that these deliverables will have a huge impact on the blue economy, which will be of considerable value for Norway.

At NTNU AMOS, we:

- foster the next generation of scientists, engineers and decision makers;
- create unique selling propositions, driving innovations in the ocean industry and public sector;
- provide sustainable solutions for an improved competitiveness of the ocean industry, and efficient methods and technology for a knowledge-based management of the oceans;
- develop technology and methods that create value and target global challenges related to a lack of energy, food and minerals, as well as contributing to a greener, smarter and safer future addressing environment and climate challenges.

From the mid-term evaluation we are in particular addressing two main recommendations in the research strategy:

- **Recommendation 1:** Stronger and more focused scientific strategy that balances and integrates the different research areas that NTNU AMOS covers.
- **Recommendation 2:** To publish an increased percentage of the AMOS papers in top-ranked journals and to co-publish more within the Centre.

NTNU AMOS is focusing on fundamental research within marine technology, control engineering and marine biology, leveraging ground-breaking results on autonomous marine operations and systems. An important aspect of this is also to enhance the impact and outcome by associated research projects and innovation activities. We are pleased to see the growing rate of delivery in terms of high-impact journals and completed theses.

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

In the ecosystem of knowledge generation, we are addressing fundamental knowledge fields and enabling technologies. The quality in research and research methodology, combining theoretical studies, numerical simulations and experimental field studies, enables us to address exciting research questions such as:

- How to achieve autonomous operation and vessel optimization in terms of fuel consumption, gas emissions, safety and operational efficiency?
- How to create intelligent Guidance, Navigation and Control (GNC) systems for fully autonomous vehicles and robotic systems supporting marine operations, mapping and monitoring in demanding environments?
- How to define and operate sustainable and autonomous systems for offshore renewable energy and aquaculture in shallow-to-deep waters?
- How to develop methods and fully autonomous systems for the characterization, prediction, control and monitoring of marine environmental and oceanographic parameters and ecosystems?
- How to ensure safe and successful marine structures and operations with increased autonomy during abnormal events or in hostile conditions, such as very deep water, a close vicinity of the sea floor, harsh weather and Arctic environments?
- How to develop intelligent marine operations to enable oil and gas field development and marine mining in deep water and harsh environment?

In a center such as NTNU AMOS, the importance of in-depth knowledge is clearly evident. Moreover, unique ground-breaking knowledge in particular is generated in areas where we succeed in approaching the research questions in a truly inter-disciplinary manner. It is inspiring to learn how NTNU AMOS has been able to influence the research, governance and industry agenda in Norway.

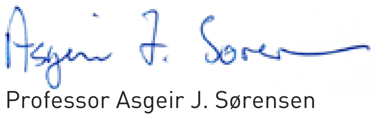
In order to leverage the next steps, we also recognize the importance to promote related knowledge fields not yet fully addressed by us. Examples of this are how to effectively involve humans-in-the loop, how to deal with cyber security and questions related to ethical dilemmas that will arise when higher level autonomy will be a reality for more and more systems. What should be the

decision criteria, and what if the systems fail? How well have we tested and verified these systems?
It is exciting to contribute here, as well with colleagues.

In the annual report, selected highlights are given. They give examples of in-depth technology development and projects exemplifying cooperation between technology and science for ground-breaking research. We are also proud to report that our key scientist Professor Tor Arne Johansen has received NTNU's award for innovation and business collaboration for 2018.

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

Sincerely,



Professor Asgeir J. Sørensen
Director NTNU AMOS

BOARD OF DIRECTORS

The Board met twice in 2018 to review progress, consider management issues, and offer advice on strategic directions for the Center.

The Board is very satisfied with the activities undertaken at NTNU AMOS during 2018. The Center and its staff have shown an impressive momentum. NTNU AMOS fulfills expectations as a Norwegian Center of Excellence, and in addition NTNU AMOS has a remarkable track record in creating associated research projects, innovations and spin-off companies. The inter-disciplinary nature of the Center, combining marine technology, cybernetics and marine biology, enables the creation of new knowledge to the global scientific community, as well as providing a significant added value to industry and society in general. The infrastructure that the Center has access to provides an excellent research environment.

A major activity in 2018 was the midpoint evaluation of the Norwegian Centers of Excellence. The evaluation concluded that the Center *"provides considerable excellent research, with a unique capacity in applications, making links across theory, numerical modelling, physical model building and experimentation."* Furthermore, the international evaluation panel recommended that NTNU AMOS focus the research into three projects:

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

Based on the evaluation process, The Research Council of Norway approved a continuation of the Center. After the midpoint evaluation NTNU AMOS ramped up its activities by employing a large number of highly qualified PhDs and Postdocs for the next five-year period. The expectations for the researchers are that they should publish their work in the finest journals in their respective fields. The Board is extremely satisfied with NTNU AMOS' publication and dissemination in 2018, in which more than 100 high-quality journal articles were published.

NTNU AMOS has graduated 77 PhDs within its first six years of operation, which is a much higher number than expected. This has been made possible thanks to increased funding from a large number of associated research projects. The Center has succeeded beyond expectations in attracting funding, in addition to that contributed by The Research Council of Norway and NTNU. The external projects now contribute with approximately two-thirds of the total funding. This has also resulted in an impressive interdisciplinary research portfolio. The researchers operate autonomous systems underwater, on the sea surface, in the air and now in space. The launching of the SmallSat Satellite Project in 2019 for data acquisition and the environmental monitoring of the oceans is a major step towards having a networked system for advanced multi-discipline operations. The Board looks forward to seeing future research results, in which autonomous systems in water, air and space operate in tandem.

The Board is also very satisfied with the innovation activity of the Center. The researchers have been instrumental in the start-up of five spin-off companies during the first five years. The Centre has also extended its inter-disciplinary research scope by appointing Professor Geir Johnsen from the NTNU Department of Biology as a key scientist. This will further increase the inter-disciplinary research between the departments of Marine Technology, Engineering Cybernetics and Biology.

The Board is very pleased with the HSE performance of AMOS, as there are few accidents and near accidents. The HSE awareness in the Centre's management is very good, and there is a good system for risk assessment and training for laboratory and field work.

The Board recommends a focus in 2019 on: 1) gender balance in the hiring of PhDs and Postdocs, and 2) increased interdisciplinary research work and publications between the departments involved in the Centre.

Lastly, the Board looks forward to an exciting and productive year in 2019, with an increasing number of high-quality publications, excellent PhD candidates and new spin-off companies.

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 available resources and within the research plan established by the Center. As part of their duties, the Board members have discussed and endorsed this Annual Report.

MAKING THE AUTONOMOUS FUTURE SAFE

One of the most exciting projects associated with AMOS right now is the UNLOCK project, which is headed by Professor Ingrid Utne of the Department of Marine Technology at NTNU. UNLOCK addresses research challenges related to risk acceptance and the supervisory risk control of autonomous systems and operations, and gets its funding from FRINATEK, a funding program provided by the Norwegian Research Council.

The aim of the project is to develop more powerful risk control solutions to achieve safe system performances, and to allow for the widespread use of autonomous systems.

"We have only worked on this project for a year now, but the avenue of approach is very promising", says Utne.

Utne is also managing a research project called ORCAS, which aims to make autonomous systems safer.
The KPN project is funded by the Research Council (MAROFF) in cooperation with the industry partners, Rolls Royce Marine and DNVGL. Whereas ORCAS focuses on autonomous ships, UNLOCK addresses UAVs (unmanned aerial vehicles) for industrial inspection and AUV (autonomous underwater vehicle) operations under ice.

Both of the projects connect the disciplines of cybernetics and risk management.

"This is a new way of doing things, but we think that we get better results if we connect these disciplines to each other from the very beginning of the development process of the control systems", says Utne.

The researchers at AMOS have discussed these issues for some time, but the funding of UNLOCK and ORCAS have allowed the researchers to focus on them in a way they were previously unable to do.

"We did not expect to get the funding for two such projects at the same time, so having ORCAS and UNLOCK side by side is great. We have now several PhDs, postdocs and master students, and I am happy to say that the teams are working great together, with an excellent cooperation with our industry partners", says Utne.

Autonomous systems for ships and other vehicles have the potential to reduce operating costs and improve safety, by, e.g., allow more departures for passenger ferries. Nevertheless, there are concerns about the risks related to these systems.

Utne expects better and safer control systems to make it easier to get autonomous systems approved for use, and more generally accepted in society. She also has high hopes for the potential of these systems.

"If we manage to use this opportunity and create excellent control systems, then the potential applications are far wider than just the marine area. Everything from drones to autonomous cars could make use of this", says Utne.

She also think that people who fear a lack of human control do not really need to worry, as the autonomous systems do not need to be completely unmanned and should be able to shift between different levels of autonomy.

"I think that advanced systems without any kind of human oversight is relatively farfetched. An important risk aspect is how the systems and the human operator or supervisor interact and work together. In the case of autonomous ships, for example, you may have people in land-based control centers that can intervene if necessary.

WITH A HEART FOR THE FISH

Fish farming is an increasingly important part of the Norwegian export economy, but the industry is plagued by several problems, from lice, to escaped fish, pollution and the health of the salmon.

Martin Føre is one of the scientists working on these problems.

Recently hired as an Associate Professor at the Department of Cybernetics at NTNU, Føre is working on models for the behavior and growth of salmon in fish cages. Cameras and other sensors will observe the fish, and in combination with mathematical models create a complete picture of the fish in the fish cage.

"Whereas a terrestrial farmer can easily see if something is wrong with the animals, it is far more difficult for a fish farmer to assess the health of the fish", says Føre.

Better models will allow fish farms to increase production effectiveness, and also improve the living conditions for salmon. Better living conditions and less stress for the fish will result in a better quality product.

"Right now, we see that there is much subjective assessment involved in the operation of fish farms, often based on experience and a 'gut-feeling', rather than science. Do not get me wrong, experience is very important, but I think there is a lot to gain by using science as a tool to achieve more objective decisions on how to run these farms", says Føre.

Working on fish farms can also be dangerous, and improving safety is a big goal for researchers.

"Fish farming is, in fact, the second most dangerous job in Norway, only beaten by working in the fisheries", says Føre.

He and his colleagues at NTNU and SINTEF hope that their research can improve safety and automate away a lot of the dangerous work. Their research strategy is toward "precision fish farming", Føre tells us.

By precision, the scientists mean that methods need to be consistent, and hit the target.

"You observe, interpret, decide and then act. These are the different phases of operations in fish farming, and are today executed mainly through manual work and subjective assessment. In Precision Fish Farming, we wish to improve human control and objectivity in these phases by introducing new technologies and automation principles. If we can improve the way fish farms operate, not only will the industry be more profitable, but the fish will have better lives as well, and that is an important bonus", smiles Føre.

Føre is adamant that working interdisciplinarily and connecting scientists with different expertise is key, and is very happy to be part of the Team at AMOS.

"I cannot see why anyone would not want be part of a team such as this. We are working across the fields of biology, cybernetics and marine technology, and this interdisciplinary research allows us to come up with novel solutions to problems", says Føre.

TEACHING THE ROBOTS TO SEE

Annette Stahl did her PhD in applied mathematics at the University of Heidelberg, Germany, and specialized in computer vision.

The field of computer vision seeks to automate tasks that the human vision system can do, and is therefore concerned with how computers can be made to gain a high-level understanding from digital images or videos. Stahl is developing the theory behind artificial systems that extract information from images in order to enable a robot to interpret what it sees and then perform the appropriate analysis, act and learn accordingly.

From autonomous cars and ships, to measuring wave flow, the applications for this field are many. For example, among other projects, Stahl has previously worked with St. Olavs Hospital on monitoring the newly born.

"Babies have distinct movement patterns when they are born, and if we use computers to perform a video analysis of the child for a certain time over a certain period, we would be able to tell if a baby might be at risk of developing cerebral palsy later on, and needs to be checked up on by a specialist to verify the results", says Stahl.

At AMOS, Stahl is working on the camera systems of AUVs, in cooperation with Sintef Ocean. More specifically, she is working on the first autonomous underwater vehicle (AILARON) created to do underwater imaging, machine learning and AI planning for plankton-taxa classification and mapping.

"Typically, the microscopic imaging of plankton is done on stationary platforms. If we are able to perform the entire imaging -classification -analysis and control chain on-board a moving platform such as an AUV, thereby increasing sampling rates, we would provide biological oceanography with a low-cost tool to determine temporal chances in community structure, abundance and dispersion of planktonic taxa."

Because plankton is the basis of the aquatic food web, it plays the role of an important indicator of the ecosystem condition, and is therefore of high value for the assessment of human activities and climate change.

"To be able to perform proper sampling is therefore key, and that is one of the things we are trying to achieve", says Stahl.

"We would like to combine data from the AUVs, UAVs and USVs with remote hyperspectral imaging of the small satellites that Tor Arne Johansen is working on in order to obtain measurements in fine scale from the tracking of the spatio-temporal distribution of phytoplankton to larger bulk scale phenomenon such as blooms, internal waves, fronts, anoxic zones and plumes."

The imaging technology that Stahl is working on could also have a huge impact on Norwegian aquaculture; it can identify harmful algae that would kill fish in large quantities.

One of the best in her field, Stahl is very happy at AMOS and in Trondheim.

"Trondheim is a great place for me to be. The people, the nature, the size of the town, all of it is perfect for raising a family. In addition, for a researcher, especially in technology, it is the perfect place to be. The entire scientific environment in Trondheim is moving in the right direction. I think we have a great chance to be at the top of research, within some of the new trends. AI, robotics, small satellites; all the topics that are getting important now and in the future, we will be at the forefront of", smiles Stahl.

RECONCILING THE MODELS AND PHYSICAL OBSERVATION

One of the newest scientists in the AMOS family, Morten Omholt Alver, has specialized in aquaculture and ocean models. Alver has been associated with NTNU and AMOS for several years, but started working full time at the Department for Cybernetics in December 2018.

For his master's project, he worked on ways to model the number of salmon in any given fish cage, while on his PhD he looked at the production of cod.

"I also worked closely with SINTEF during my PhD, and after I finished my project, I was recruited to work on Ocean modelling on SINTEF's SINMOD model. SINMOD was developed by Dag Slagstad, and is a model that connects and simulates physical and biological processes in the ocean. When used in conjunction with SINTEF's OSCAR and DREAM models, SINMOD can be used to predict from the results of, for instance, oil spills and waste dispersal from aquaculture. It can also be used for estimating conditions for marine structures and get better data on climate change, and how this affects the polar ice caps and biological growth in the Polar Regions", explains Alver.

At AMOS, Alver will use his experience and expertise to reconcile the predictions of the ocean model, with the physical observations that are made by AUVs and other observation platforms.

"One of the problems that follows with the use of AUVs is that it needs to be able to predict conditions in order to move to a position where it can get the most useful observations possible. Ocean models allow the AUV to make these predictions. I will work on ways to make sure that the models that we have created will allow the AUVs to get the best possible observations. We then combine these observations with the predictions of the model, in order to get the best possible overview of any given situation."

There are several real-world applications for this technology.

"We can use it to more efficiently investigate physical and biological processes in the ocean, thereby providing better tools for marine science. The methods can also be used in the handling of both planned and accidental releases of pollution, such as mining waste or oil spills. The combination of model and AUV observations can help us efficiently monitor these situations", Alver explains.

When Alver started up, few people within cybernetics chose to work within the ocean field, but as time has passed this field become increasingly popular, as the possibilities have grown steadily these over the last few years.

"I choose to work with the oceans because the possibilities excited me, and as the field has evolved, the potential for new research has just grown", says Alver.

INCREASING VISIBILITY

In order for science and research to have the desired effect, the results need to be properly communicated. Private industry, politicians and the general public should all be kept informed of research results, as well as the potential of these results.

At NTNU AMOS, we have recently hired a new communications advisor, Sigmund Bolme, to help increase the visibility of the research projects and the impact of the SFF.

"The research conducted here at NTNU AMOS is incredibly exciting, and has the potential to change society. That is inspiring for a communications advisor, and I am very happy to be part of this team", says Bolme.

Bolme is a former journalist and political communications advisor, and he will work to make AMOS more visible. Bolme shares his time between AMOS, the Department of Marine Technology at NTNU and NTNU Oceans, all of which are areas connected to ocean-based technology.

"I believe that the Oceans hold the answer to several of the great challenges that face the world. Nevertheless, we need knowledge and new technological solutions if we are to make use of these opportunities. The scientists at AMOS are giving us that knowledge, and are creating the foundation for new technology, methods and standards that will open up the oceans in new and exciting ways. This research needs to be communicated to a wider audience if it is to have the necessary impact, and I hope to contribute to that", says Bolme.

ORGANIZATION, INTERNATIONAL COLLABORATORS, AND FACTS AND FIGURES

Organization

NTNU AMOS Board Members:
- Dean Olav Bolland, Chair, NTNU
- Dean Geir E. Øien, NTNU
- Dean Øyvind Weiby Gregersen, NTNU
- Vegar Johansen, SINTEF Ocean
- Kjetil Skaugset, Equinor
- Liv A. Hovem, DNV GL

NTNU AMOS Management:
- Asgeir J. Sørensen, Director
- Thor I. Fossen, Co-director
- Sigrid B. Wold, Senior Executive Officer
- 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
- Technical University of Denmark
- 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, Singapore
- University of California, Berkeley, USA
- University of California, Santa Barbara, USA
- University of Delaware, USA
- University of Linköping, Sweden
- University of Michigan, USA
- University of Porto, Portugal
- University of Rijeka, Croatia
- Woods Hole Oceanographic Institution, USA
- University of Zagreb, Croatia
- University of Cassino and Southern Lazio, Italy

Facts and figures

Personnel 2018

- 7 keypersons
- 17 adjunct prof/assoc.prof
- 22 affiliated scientists
- 2 Scientific Advisers
- 8 post docs/researchers
- 20 affiliated post docs/researchers
- 119 PhD candidates (incl. Affiliated)
- 15 Visiting prof/researchers
- 4 administrative staff
- 2 Management
- 3 technical staff

- 10 graduated PhD candidates financed by NTNU AMOS
- 14 graduated PhD candidates associated to NTNU AMOS (1 of those financed by CeSOS)

Revenues (NOK)

Income	59 300 000
Costs	58 414 000
Year end allocation	886 000

Publications

- 115 refereed journal articles
- 94 refereed conference papers
- 1 book
- 3 book chapters
- 10 international keynote lectures
- 44 news media articles and other coverage

MAIN RESEARCH AREAS AND PROJECTS

The NTNU AMOS has two research areas:

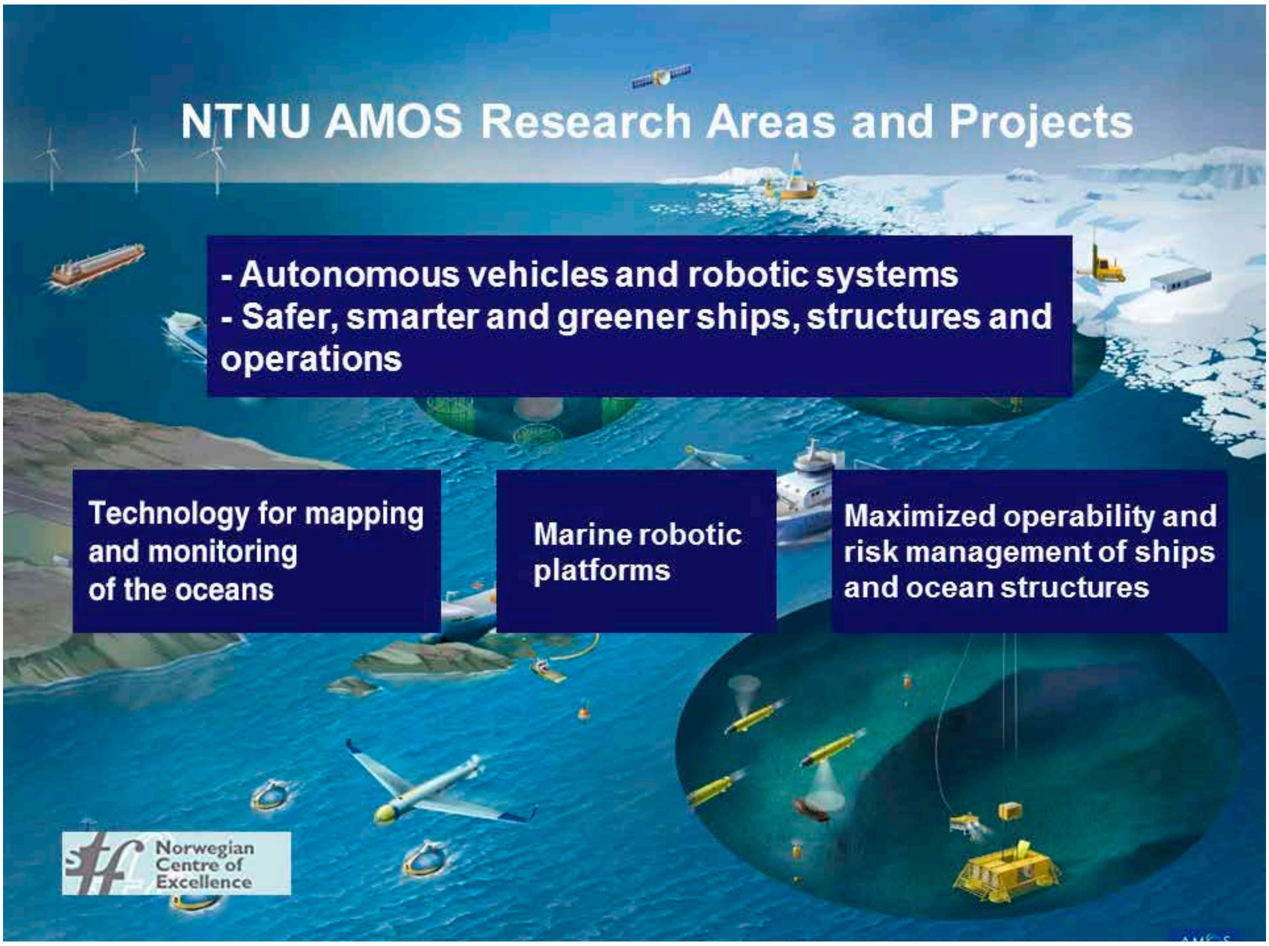
- Autonomous vehicles and robotic systems
- Safer, smarter and greener ships, structures and operations

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 ships 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, Kanna Rajan, 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), Jeff Delaune (Jet Propulsion Lab, USA)

Research activities:
This project considers the modeling, 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

Underwater Hyperspectral Imaging
The evaluation using Underwater Hyperspectral Imager (UHI) on Remotely Operated Vehicles (ROV) and landers for the identification and mapping of minerals and macrofauna at the Peru Basin at a depth of 4,200 meters was finalized in 2018, and comprises three papers P1-R1, P1-R2 and P1-R3. The identification of benthic megafauna is commonly based on an analysis of physical samples or imagery acquired by cameras mounted on underwater platforms. The physical collection of samples is difficult, particularly from the deep sea, and the identification of taxonomic morphotypes from imagery depends on resolution and investigator experience. Here, we show how an UHI can be used as an alternative in situ taxonomic tool for benthic megafauna. An UHI provides a much higher spectral resolution than standard RGB imagery, thus allowing marine organisms to be identified based on specific optical fingerprints. A set of reference spectra from identified organisms is established, and a supervised classification performed to identify benthic megafauna semi-autonomously. The UHI data provide an increased detection rate for small megafauna that are difficult to resolve in standard RGB imagery. In addition, sea-floor anomalies with distinct spectral signatures are also detectable. In the region investigated, sediment anomalies (spectral reflectance minimum at ~675 nm) unclear in RGB imagery were indicative of chlorophyll-a on the seafloor. Underwater hyperspectral imaging has been shown to have a great potential in seafloor habitat mapping and monitoring, with areas of application ranging from shallow coastal areas to the deep sea.

AUV - Information-driven robotic sampling in the coastal ocean
The efficient sampling of coastal ocean processes, especially mechanisms such as upwelling and internal waves and their influence on marine primary production, is critical for understanding our changing oceans. Coupling robotic sampling with ocean models provides an effective approach to the adaptive sampling of such features. We present methods that capitalize on information from ocean models and in situ measurements, using Gaussian process modeling and objective functions, thereby allowing sampling efforts to be concentrated to regions with a high scientific interest. We demonstrate how to combine and correlate marine data from autonomous underwater vehicles, model forecasts, remote sensing satellite, buoy and ship-based measurements, as a means to cross-validate and improve ocean model accuracy, in addition to resolving upper water-column interactions. Our work is focused on the west coast of mid-Norway, where a significant influx of Atlantic water produces a rich and complex physical–biological coupling, which is hard to measure and characterize due to the harsh environmental conditions. Results from both simulation and full-scale sea trials are presented.

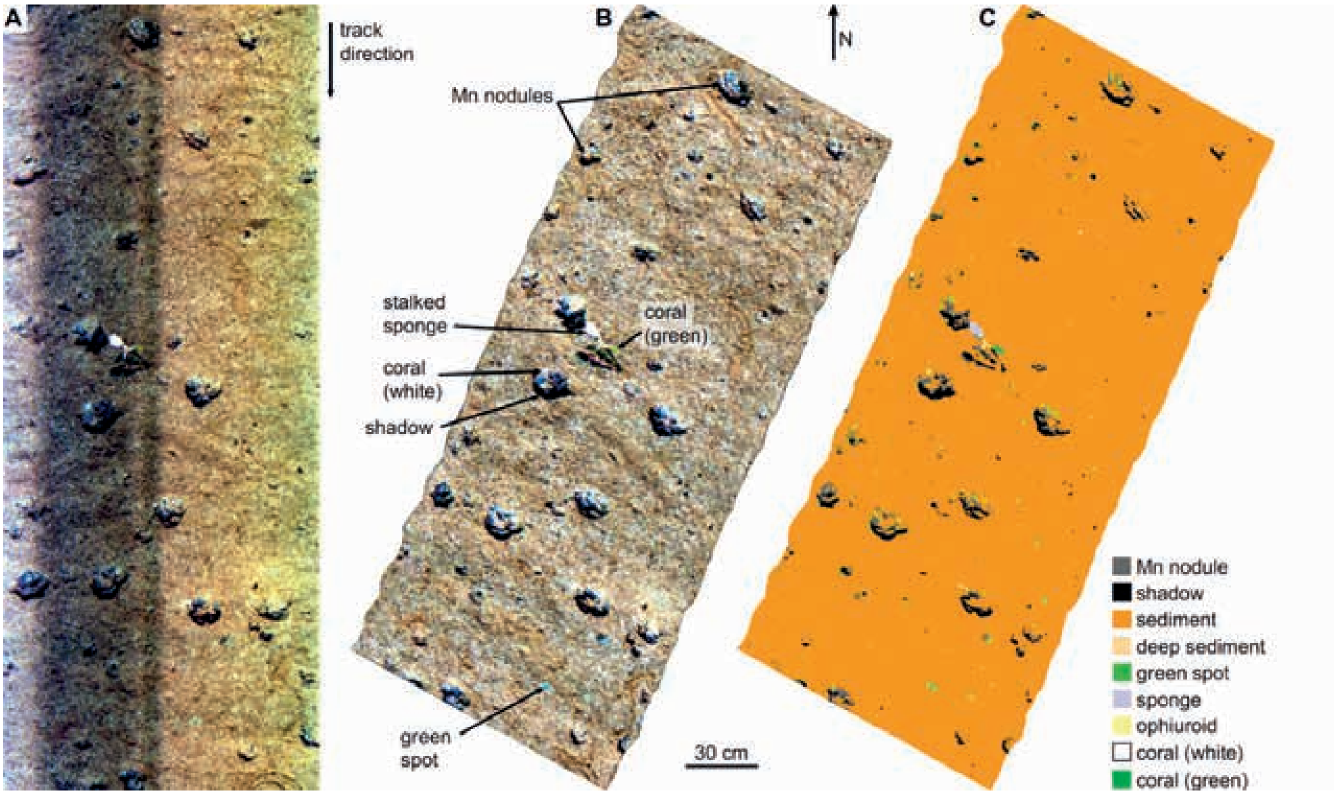


Figure 1: *(a) UHI radiance data in pseudo-RGB (R: 645 nm, G: 571 nm, B: 473 nm), showing manganese nodules and a stalked sponge with a brittle star wrapped around the stalk. Note the dark shading caused by the ROV's manipulator arm blocking the light. (b) Geocorrected pseudo-reflectance data in pseudo-RGB. The division of each pixel spectrum by its corresponding along-track median spectrum is completely removed the dark shadow. (c) SVM classification image based on the data in (b) and user-defined region of interest. From reference P1-R1.*

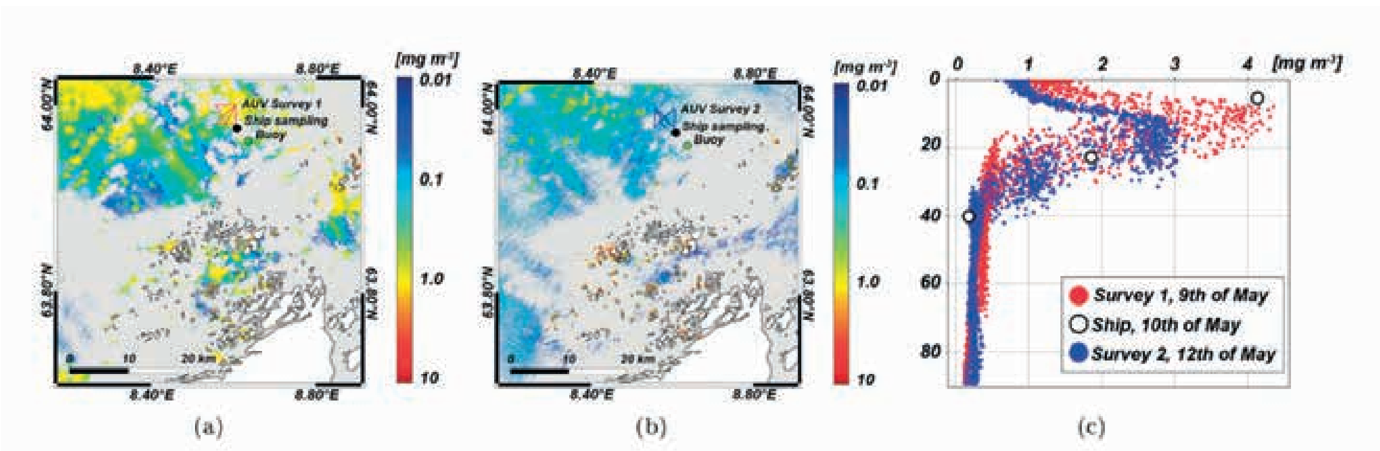


Figure 2: *Chlorophyll-a concentration as an estimate of phytoplankton biomass for May 9 and 12, 2017, processed from Copernicus Sentinel Data (OC2 algorithms compared with in situ measurements from AUV and the research vessel Gunnerus. (a) Sentinel-2A , CHL OC2, May 9, 2017, 10:56 a.m. (b) Sentinel-2A , CHLOC2, May 12, 2017, 11:13 a.m. (c) AUV and vessel R/V Gunnerus, May 9, 2017. From reference P1-R4.*

Underwater Hyperspectral Imaging (UHI) in Marine Archaeology
This study explored the suitability of UHI as a tool for classifying Underwater Cultural Heritage (UCH), and proposed a method for UHI-based detection and identification in marine archaeology, reference P1-R6. One of the scientific contributions of the project was the development of a spectral library of signatures from a selection of materials likely present on many UCH sites. Spectral signatures were obtained by measuring different materials in a laboratory with a controlled light environment. Characteristics of the different materials were compared using a Principal Component Analysis, and based on the results several spectral signatures were selected for the supervised Spectral Angle Mapper (SAM) classification of a subset of the same objects imaged in an uncontrolled environment at sea. Glass, ceramics and other materials were successfully classified. The signatures were further used in a supervised classification of UHI images acquired at a wreck site where glass bottles and rust identified by HD video were successfully classified. The study proposes that UHI imaging will be a valuable new method for the detection and mapping of underwater cultural heritage. To the best of the authors' knowledge, this study is the first application of this technology to Marine Archaeology, and should be regarded as an initial study on the field, and therefore the main scientific contribution of the study. The results suggest that the classification of underwater cultural heritage using spectral libraries obtained in laboratory could be done autonomously, e.g., with AUVs on mapping surveys of long duration.

Do-it-yourself Hyperspectral Imager
In cooperation with the Kjell Henriksen Observatory (KHO) at the University Center of Svalbard, Prof. Sigernes and co-workers, we have successfully applied their knowledge of spectroscopy to construct a small lightweight push broom Hyper Spectral Imager (HSI) for drone operations. The instrument is low-cost, and prototyped by using commercially available optical parts and 3D printing.

The work was awarded a **press release** by the Optical Society of America (OSA) in May of 2018, and the paper P1-R7 published in Optics Express was ranked by the journal to be among the 10 most read papers for six months. Ten HSI units have been serially produced by Moon Labs in collaboration with NTNU in order to support various research projects.

Figure 3 (top): *A selection of objects scanned in the laboratory*

Figure 4 (above): *UHI images of a metal frame with objects deposited on the seabed. Image to the right shows classifications based on a spectral library created in the laboratory.*

Figure 5 (left): *Supervised SAM classifications of a UHI-based photomosaic of a wreck transect. From left: glass bottle, rust and ceramic.*

Figure 6: *Second prototype of Hyper Spectral Imager (HSI) for drone operations*

The next step has been to design, develop and test a new prototype HSI for CubeSat satellites aimed at detecting various oceanic targets.

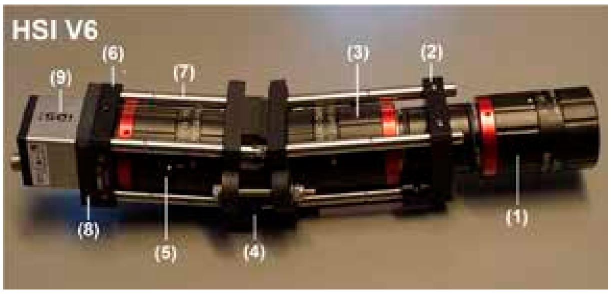


Figure 7: *Assembled HSI V6 instrument using a standard USB 3.0 iDS camera head. (1) front lens, (2) CP12 cage plate, (3) collimator lens, (4) 3D printed grating holder, (5) camera lens, (6) CP03/M cage plate, (7) steel rods, (8) 3D printed camera mount insert and (9) iDS CMOS camera head.*

The design named HSI V6 is based on a 300 grooves/mm blazed transmission grating. It is blazed at 17.5 degrees, and the efficiency is above 50% for the wavelength range 400-800 nm. The only part that needs to be constructed (3D printed) is the grating holder. All other components are mainly off-the-shelf from Thorlabs and Edmund Optics. The detector is an industrial camera using a CMOS image sensor (Sony IMX147/IMX252). The effective aperture is 18.14 *mm*, with an input F/value of 2.8. The input slit width is fixed, with no magnification of the slit height (h = 7.0 mm). A slit width of w = 50 micrometer will result in a spectral bandpass (*FWHM*) of approximately 3.3 nm.

Shallow water habitat mapping using hyperspectral imaging from UAV and USV

Just before the spring phytoplankton bloom in Hopavågen, a landlocked bay near the Sletvik Field Station, two robotic platforms were used to collect data for biological studies. The timing was important to make sure that the water was clear enough, without too much plankton. It was also crucial that we had enough daylight.

The goal was to classify spectrally relevant seafloor classes such as coralline algae, brown macroalgae (seaweeds), green algal films and invertebrates (e.g. sea anemones). This is made easier by the wealth of data provided by hyperspectral measurements. Different classes of bio/geological elements have different spectral signatures, which can be more easily distinguished when using hyperspectral sensors, as opposed to RGB cameras.

By using multiple platforms, we can overcome individual limitations: too shallow water does not allow a USV to sail through safely and acquire a sufficient swath width, whereas too deep water does not let the airborne

Figure 8: *Field experiment in Hopavågen*

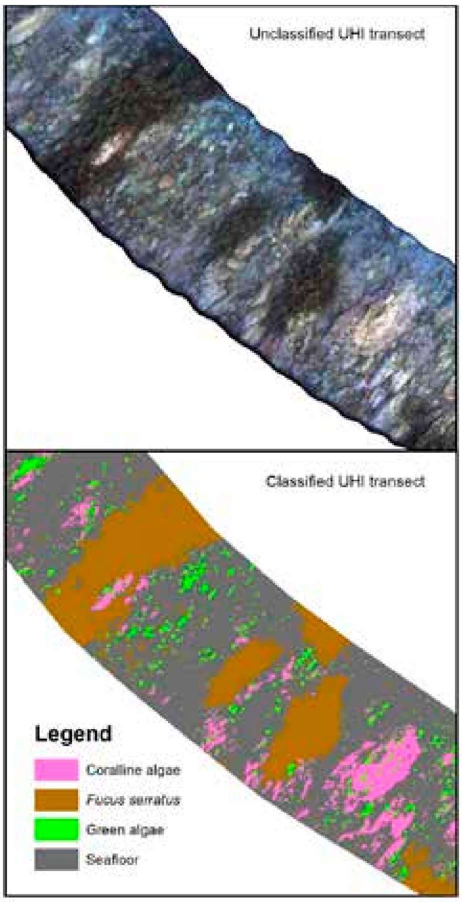


Figure 9 (above): *Flying over, a hexacopter carrying a prototype hyper-spectral instrument developed in partnership between UNIS and NTNU, references P1-R7 and P1-R9. On the water surface is a Maritime Robotics Otter USV equipped with an underwater hyperspectral imager (UHI) made by Ecotone. Both assets were operated by Maritime Robotics.*

Figure 10 (right): *The top panel shows an RGB representation of underwater hyperspectral imagery recorded at a shallow-water habitat in Hopavågen, Agdenes, using an OTTER USV (Maritime Robotics AS, Trondheim, Norway) equipped with the hyperspectral imager UHI4 (Ecotone AS, Trondheim, Norway). Underwater hyperspectral imagers record imagery, in which each image pixel contains a contiguous light spectrum that permits mapping through, e.g., supervised classification. The bottom panel shows an attempt to map the distribution and abundance of characteristic organism groups found at the survey location. A manuscript entitled: "Shallow-water habitat mapping using underwater hyperspectral imaging from an unmanned surface vehicle: A pilot study" (reference P1-R8), has been submitted for publication (November 2018), and is currently under peer review. The manuscript features an overview of the UHI results from Hopavågen, while the presented findings suggest that an USV-based UHI may serve as a powerful technique for detailed mapping of highly heterogeneous seafloor areas of interest.*

camera see the bottom. When both systems are able to collect data from the same location, we can use that to compare and calibrate between them.

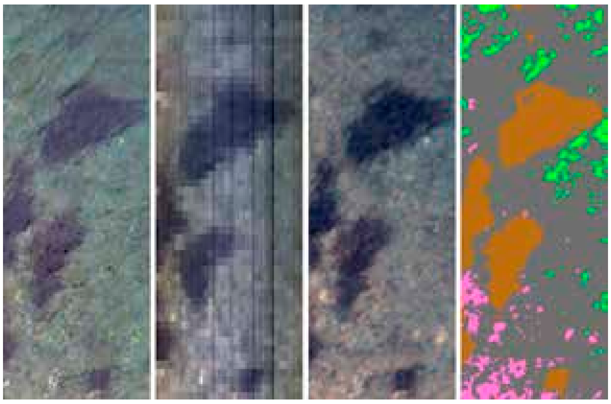


Figure 11: *Airborne payload data. From left to right, first an image captured by the high resolution RGB camera, then an RGB representation of the hyperspectral data of the same region. On the third panel, an RGB representation of the same hyperspectral data after enhancement through fusion with the high resolution RGB image. Finally, classification using the same classes as in the UHI images.*

The UAV- and USV-acquired hyperspectral datasets were found to complement each other. Because an unmanned aerial vehicle (UAV) is flown at relatively high altitudes, it is capable of covering larger areas (km scale) at a medium spatial resolution (cm-dm scale). On the other hand, USVs are situated much closer to the survey area, which results in a reduced areal coverage (m-km scale), but with a notably higher spatial resolution (mm-cm scale). For future surveys of shallow-water areas, an interesting approach would thus be to first map and investigate the area of interest using a UAV, and subsequently revisit the locations thought to be of particular interest using a USV for smaller-scale, higher-resolution mapping. By using an approach like this, a larger total area can be covered while keeping the size of the generated data to a minimum.

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Marine Robotic Platforms

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Other involved scientists: Prof. Jørgen Berge (UiT The Arctic University of Norway/UNIS), Prof. Roy E. Hansen (University of Oslo), Kjetil Bergh Ånonsen (Norwegian Defence Research Establishment (FFI), Prof. Mogens Blanke and Assoc. Prof. David Johan Christensen (Technical University of Denmark), Prof. Thijs J. Maarleveld (University of Southern Denmark), Prof. Gianluca Antonelli (University of Cassino, Italy), Prof. Sauro Longhi (UNIVPM, Italy), Prof. Tim W. Nattkemper (Bielefeld University, Germany), Dr. Francesco Scibilia and Dr. Vidar Hepsø (Equinor), Dr. Ståle Johnsen (SINTEF), Prof. Mark Moline, Prof. Jon Cohen, Dr Ian Robbins (University of Delaware, USA), Dr. Cecilie von Quillfeldt (Norwegian Polar Institute), Dr. Finlo Cottier (Scottish Association for Marine Science, Scotland), Dr. Kai Sørensen and Marit Norli (Norwegian Institute of Water Research, NIVA), Dr. Maxime Geoffroy (Memorial University of Newfoundland, Canada), Prof. Hanumanth Singh (Northeastern University, USA), Dr. Malin Daase (University of Tromsø)

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 of unmanned ships, underwater vehicles, aerial vehicles, and small satellite 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 from open waters advected under the sea ice in the Arctic

Main results

Articulated intervention-AUVs
The articulated intervention-AUV originates from our research on underwater snake robots, motivated by nature and the excellent mobility properties of biological snakes. A natural next question was then, "What if we combine the best from biology with the best from technology, and equip the snake robot with additional effectors?" In particular, for underwater snake robots, a natural next step was to investigate what can be achieved by equipping the robot with thrusters along its body. By combining the slender, multi-articulated, and thus flexible body of snakes with the efficient propulsion provided by thrusters, we created a new type of robot. This robot combines several beneficial features of survey AUVs, work-class ROVs and observation ROVs and AUVs into one tool. The robot shares the same advantageous hydrodynamic properties as the survey AUV, thereby making it suitable for long range transportation. The flexible and slender body can access and operate in restricted areas of subsea structures, hence achieving excellent access capabilities compared to small observation ROVs/AUVs. Furthermore, the vehicle itself is a dexterous robotic arm that can operate tools and carry out intervention tasks, operating as a floating base robotic manipulator. These combined features make it an excellent choice for a subsea resident robot that can be permanently installed on the seabed, where it is ready 24/7 for planned and on-demand inspection and intervention operations. This new robotic platform will reduce the use of the expensive surface vessels currently needed to support such operations. As a result, this new platform will provide safer, greener and more cost-effective subsea operations.

We have derived mathematical models of the USMs, and have developed a control framework that includes inverse kinematic control, dynamic controllers, thruster allocation and collision avoidance. The theoretical results have been validated both by simulations and experiments. More specifically, since the AIAUV is subject to hydrodynamic and hydrostatic parameter uncertainties, uncertain thruster characteristics, unknown disturbances and unmodeled dynamics, and since the coupling forces caused by joint motion are even larger for the AIAUV than for ROVs because it has no separate vehicle base and a low mass compared to an ROV, it is essential for the control approach to be robust. Several robust control approaches have been developed and validated by both simulations and experiments, e.g., in [P2-R1] where we have proposed the super-twisting algorithm (STA) with adaptive gains. This is a powerful second-order continuous sliding mode control algorithm which attenuates chattering; therefore, no conservative upper bound on the disturbance gradient has to be considered to maintain sliding because of the adaptive gains.

The bio-cyber-hydrodynamics research also includes preparations for experiments on real fish to study the locomotion, swimming and fast starting of fish. The experiments will be carried out in February 2019 at the CNR in Sardinia (Italy). The results of these experiments will move to further increase the locomotion efficiency, first of fish robots and subsequently of articulated AUVs.

Figure 1: *The Eelume articulated intervention-AUV inspecting a subsea installation (Courtesy: Eelume)*

Following curved paths in the presence of unknown ocean current disturbances

While the literature for the straight-line path following of underactuated marine vessels is by now well established, even in the presence of unknown disturbances, the problem of path following for curved paths is sparser and has some gaps. For the case of general curved paths, the existing literature did not provide any approach with a complete analysis of the resulting closed-loop dynamics. Specifically, the sway dynamics was not analyzed, and the existence and boundedness of the control input was not guaranteed. To accommodate this, in [P2-R1] we propose a guidance-based controller, which is line-of-sight-like in the sense that it adopts a time-varying look-ahead distance depending on the path-following error.
The time-varying look-ahead distance is modified compared to previous approaches, and it is shown that the resultant new dependency of the look-ahead distance on the path-following error is crucial to prove the boundedness of the sway velocity, which is seen to be the best behavior that can be achieved for the zero dynamics in the case of general curved paths.
An alternative approach is proposed in [P2-R2], in which a control strategy for the trajectory tracking and path following of generic paths is proposed for underactuated marine vehicles. While [P2-R1] controls the position of the pivot point, [P2-R2] extends the definition of the hand position point, introduced for ground vehicles, to autonomous surface vehicles and autonomous underwater vehicles, and then use the hand position point as output. The presented strategy is able to deal with external disturbances affecting the vehicle, including constant and irrotational ocean currents. Through a Lyapunov analysis, we are able to prove that the closed-loop system has an external dynamics that is globally exponentially stable, and an internal dynamics that has ultimately bounded states, both for the trajectory tracking and the path following control problems. The theoretical results are validated, both through a simulation case study and through experimental results.

Unmanned surface vehicles to estimate the effect of ambient light on zooplankton vertical migration during the polar night (Figure 2), [P2-R4]

After several years with the development of the USV "Jetyak", with respect to the movement control of the vehicle, and using new sensors measuring ambient light during the polar night simultaneously with the vertical and horizontal distribution of zooplankton, we were able to be the first to report on the effect of ambient and artificial light on zooplankton behavior. This study shows that the ship-based stock assessment of zooplankton and fish needs to consider that artificial light from ships may affect the distribution of organisms at night and during polar night surveys. The ship-based stock

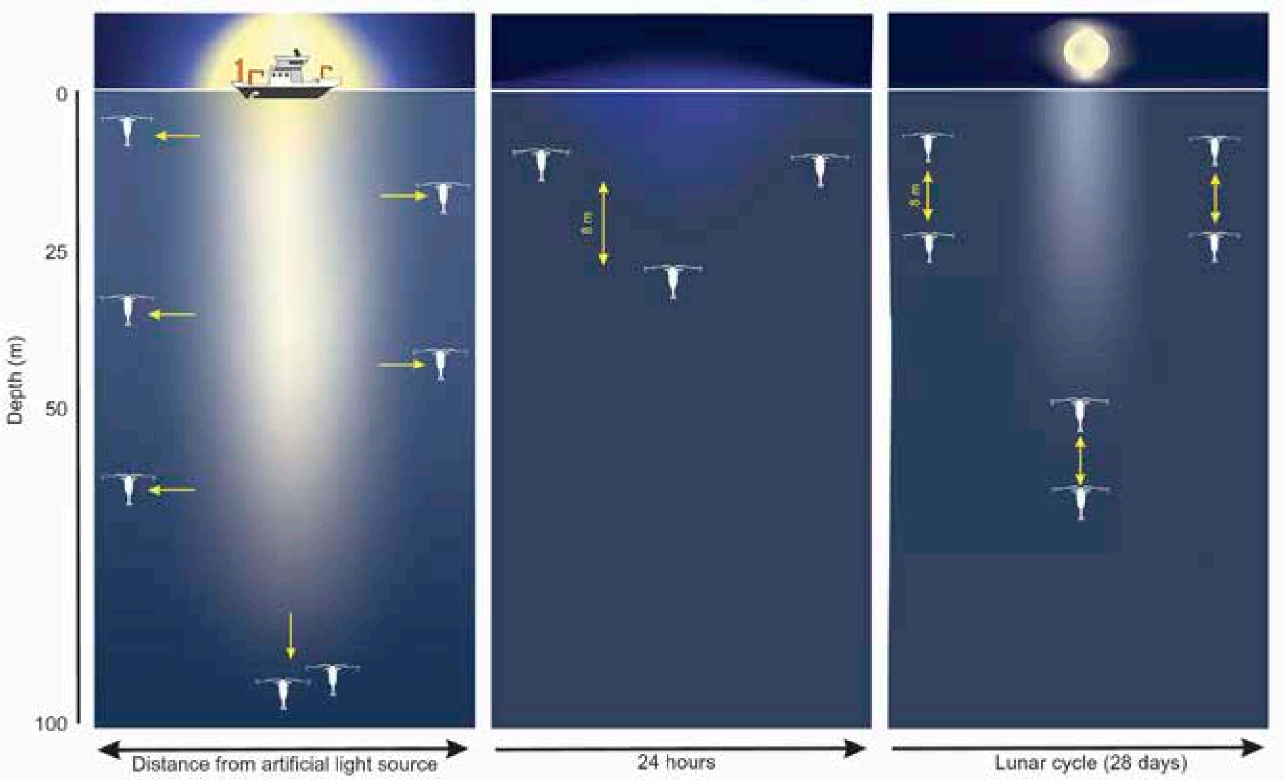

Figure 2: *Conceptual model of the behavioral response of zooplankton to natural solar light, light pollution and lunar light. (A) Light escape response (vertical and horizontal arrows) from light pollution from a ship detected down to 100 m and up to 180 m on each side of the ship. (B) DVM of zooplankton in response to natural ambient light during the polar night. Centered around noon, organisms perform a DVM with an amplitude of 8 m within the upper 20 m of the water column. (C) In response to lunar light, zooplankton and fish perform DVM, but at different depths depending on the moon phase. From Ludvigsen et al. (2018) Science Advances. Reprinted with permission from AAAS under license distributed under a Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC).*

assessment occurs both day and night globally, and this study elucidates the effect of light pollution (artificial light) on stock estimates.

Light is a major cue for nearly all life on Earth, with most of our knowledge concerning the importance of light based on organisms' response to light during daytime, including the dusk and dawn phase. When it is dark, light is most often considered as pollution, with an increasing appreciation of its negative ecological effects. Using an Autonomous Surface Vehicle fitted with a hyper-spectral irradiance sensor and an acoustic profiler, we detected and quantified the behavior of zooplankton in an unpolluted light environment during the high Arctic polar night, and compared the results with that from a light-polluted environment close to our research vessels. First, in environments free of light pollution, the zooplankton community is intimately connected to the ambient light regime, and performs synchronized diel vertical migrations in the upper 30m, despite the sun never rising above the horizon. Second, the vast majority of the pelagic community exhibits a strong light-escape response in the presence of artificial light, observed down to 100 m. We therefore conclude that artificial light from traditional sampling platforms affects the zoo-plankton community to a degree where it is impossible to examine its abundance and natural rhythms within the upper 100 m. This study underscores the need to adjust sampling platforms, particularly in dim-light conditions, to help capture relevant physical and biological data for ecological studies. It also highlights a previously unchartered susceptibility to light pollution in a region destined to see significant changes in light climate due to a reduced ice cover and an increased anthropogenic activity.

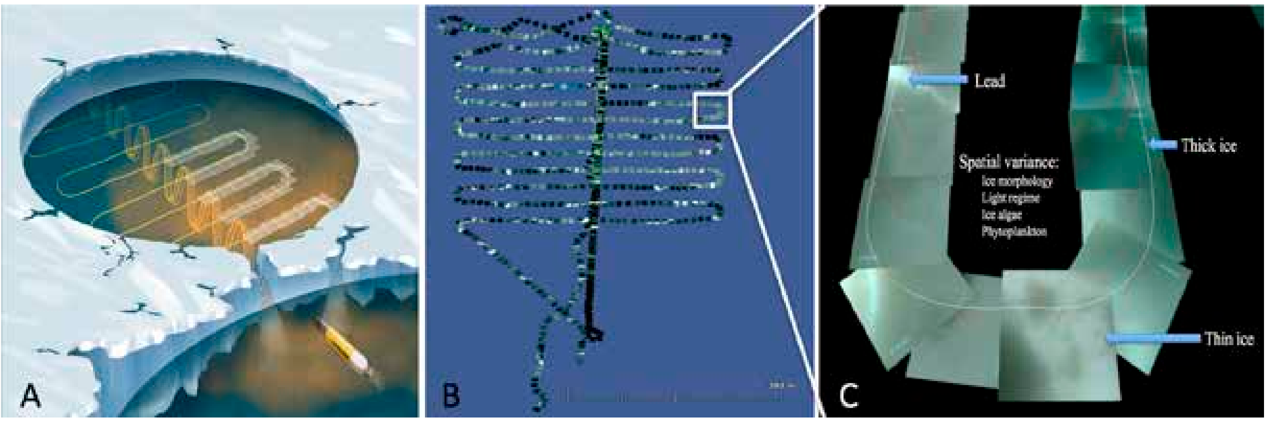

Figure 3: *AUV-based under sea-ice photomosaic images at 10 m depth (horizontal survey, covering 80,000 m2) under the sea ice on the 16th of May at the ice station. AUV deployment at 80°640′ N, 5°024′ E at an average speed of 1.5 m s^{-1}. At noon, under-ice irradiance was between 1.2 and 2.1 µmol photons m^{-2} s^{-1} at 10 m depth. At 22:00, irradiance was typically about 30% of noon values. A. Schematic image of underwater AUV photomosaic images of underside of sea ice with camera facing upwards at a 10 m depth during the horizontal transect grid line. Indications on photomosaic images along track line shown on right side. B. Complete photomosaics along the grid line at a 10 m depth. C. Details (from B, white frame) of geo-tagged photomosaic images of under-ice light climate and ice morphology as a function of thick sea ice (dark picture frames), leads and thin ice (bright frames), with blue areas indicating melt ponds (blue frames) and areas with high [Chl a] (green frames, indicating ice algae and phytoplankton). From Johnsen et al. 2018, Polar Biology, with permission.*

The advective origin of an under-ice spring bloom in the Arctic Ocean using multiple observational platforms [P2-R5]

Using a combination of satellite remote sensing of phytoplankton biomass, in situ observations under sea ice from an autonomous underwater vehicle (AUV), and in vivo photophysiology, we examined the composition, magnitude and origin of a bloom detected beneath the sea ice Northwest of Svalbard (Southern Yermak Plateau) in May. An in situ concentration of up to 20 mg chlorophyll a [Chl a] m^{-3} were dominated by the northern planktonic spring species of diatoms, *Thalassiosira nordenskioeldii*, *T. antarctica* var. *borealis, Chaetoceros socialis* species complex and *Fragilariopsis oceanica*. These species were also found south of the marginal ice zone (MIZ). Cells in the water column under the sea ice were typically high-light acclimated, with a mean light saturation index (E_k) of 138 µmol photons m^{-2} s^{-1}, and a ratio between photoprotective carotenoids (PPC) and Chl a (w:w) of 0.2. Remotely sensed data of [Chl a] showed a 32,000 km^2 bloom developing south of the MIZ. In effect, our data suggest that the observed under-ice bloom was in fact a bloom developed in open waters south of the ice edge, and that a combination of northward-flowing water masses and southward drifting sea ice effectively positioned the bloom under the sea ice. This has implications for our general understanding of under-ice blooms, suggesting that their origin and connection with open water may be different in different regions of the Arctic.

Finding the safest path to mitigating the risks in the event of a critical engine or generator failure in hybrid-electric UAS

Hybrid-electric powertrains used by long-range fixed-wing unmanned aerial vehicles often employ an internal combustion engine as the main source of power. It has been witnessed that the internal combustion engine is often a critical point of failure. In such an event, a functioning electric motor may still be able to propel the aircraft for a short period by utilizing the remaining battery capacity.

Therefore, it is desirable to ensure that the aircraft is able to reach a safe landing spot in the event of a critical engine or generator failure. This is done by taking into consideration the presence of expected local winds and their effect on the range of the aircraft, based on the aircraft performance model and the mission parameters. The resulting optimum path is found by applying the technique of Particle Swarm Optimization (PSO), in which the algorithm discretizes the path into N points, and then calculates the range from each point to the closest landing zones. The optimum path is the one with an optimum balance between the length of the path and the path's safety. The constant that specifies how the algorithm will balance length and safety is chosen by the mission manager.

The scenario chosen for the simulation comprises the area located to the north of the Norwegian city of Trondheim. For this study, the Norwegian Defence Research Establishment (FFI) made regional wind models available for calculating wind speeds and directions for different altitudes with a resolution of 2.5 km. The straight-line path distance between origin and destination is 210 kilometers, and has a path safety of 72.6%. The safe landing spot locations were manually selected through studying satellite imagery. The initial cruise altitude is chosen to be 1,500 meters, meaning it can pass any mountain the aircraft may encounter within the specified region. The case study utilized the P31015 concept UAV, which is a fixed-wing aircraft in a conventional pusher configuration. In this theoretical study, the model shall employ a hybrid propulsion system with a sufficient capacity to allow continuous in-flight recharging of the batteries.

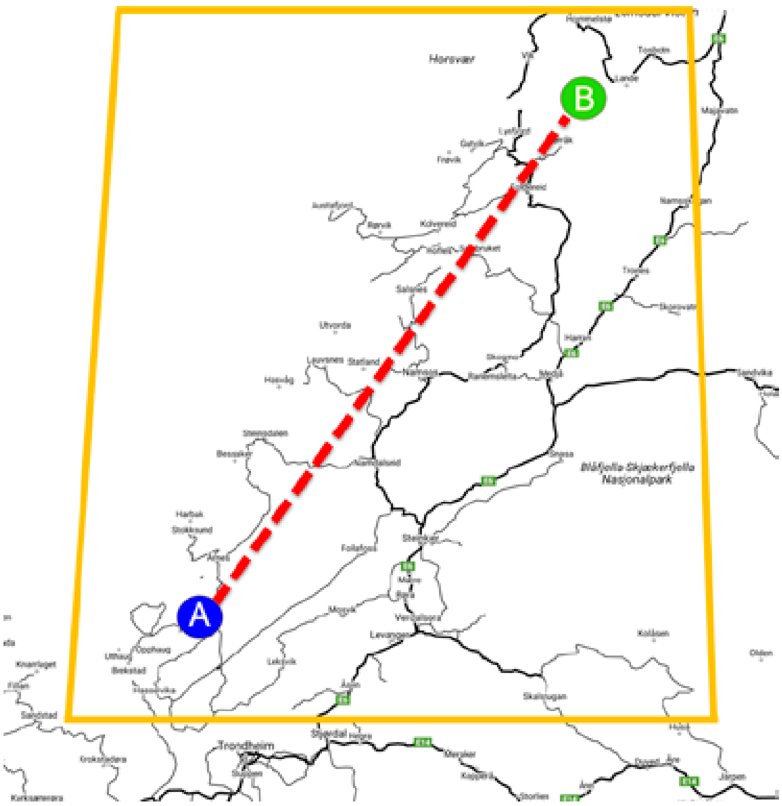

Figure 4: *Scenario for case study*

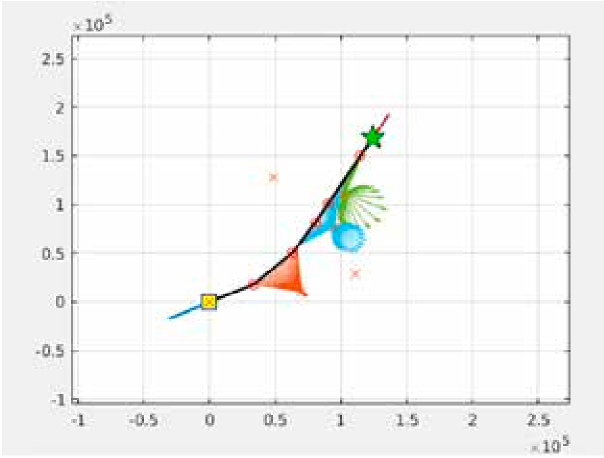

Figure 5: *The optimal path from the starting location (yellow) to the final location (green). The red crosses mark possible emergency landing sites. It is indicated which emergency landing site should be chosen at each point along the optimal path.*

The resulted optimum path obtained by the optimization algorithm achieved 100% safety, with a total length of 215.4 kilometers. This route is only 5.4 kilometers longer than the straight path distance between origin and destination, with the advantage of ensuring that the aircraft is able to reach a safe landing zone in case of an engine or generator failure during the entire period of the mission execution.

The research was conducted by A. Hovenburg, F. Andrade and C. Dahlin Rodin under the supervision of T. A. Johansen and R. Storvold.

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- 01.02.18: Lysforurensning – enda en kilde til bekymring. Svalbardposten. J. Berge & G Johnsen. https://svalbardposten.no/leserinnlegg/lysforurensning-enda-en-kilde-til-bekymring/19.9360
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- **Vox videos** (5 min educational YouTube videos). Overview of UiT and NTNU AMOS "polar night biology"). Support from Pulitzer Center of Crisis Reporting. These three videos are a sketch for the documentary film "Into the dark" to be published in 2019.
- 09.04.18: "Thaw" episode 1 of 3 – What melting sea ice means for life in the Arctic. By Eli Kintisch, approx. 360,000 views. https://www.youtube.com/watch?v=msD4agiRTxM&feature=youtu.be
- 17.04.18: "Thaw", episode 2 of 3 - How a warmer Arctic could intensify extreme weather. By Eli Kintisch. https://www.youtube.com/watch?v=yQliow4ghtU
- 23.04.18: "Thaw", episode 3 of 3, Why Atlantic fish are invading the Arctic. By Eli Kintisch, approx. 425,000 views. https://www.youtube.com/watch?v=-3h4Xt-9No9o
- 23.07.18: Slik finner ny teknologi skipsvrak på havets bunn. Gemini.no. NTNU AMOS, with focus on marine archaeology. By Idun Haugan. https://gemini.no/2018/07/slik-finner-ny-teknologi-skipsvrak-pa-havets-bunn/

Plenary lectures at international conferences

- **Pettersen, Kristin Ytterstad.** Underwater swimming manipulators. Keynote lecture at the 5th Workshop on EU-funded Marine Robotics and Applications (EMRA'18), 12-13 June 2018, Limerick, Ireland.

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: Erin Bachynsky, Roger Skjetne, Ingrid .B Utne, Zhen Gao, Trygve Kristiansen, Eilif Pedersen, Josef Kindl, Torgeir Moan, Odd M. Faltinsen, Ekaterina Kim, Kjetil Skaugset, Kjell Larsen, Ulrich D. Nielsen, Arne Fredheim, Claudio Lugini, Oleksandr Tymokha, Edmund Brekke, Morten Breivik, Anastasios Lekkas, Marta Molinas, Martin Føre, Vahid Hassani, Leif E. Andersson, Torleiv Bryne, Astrid Brodtkorp, Børge Rokseth, Ida Strand, Babak Ommani, Giuseppina Colicchio, Zhengshun Cheng, Yanyan Sha, Zhaolon Yu, Chenyu Luan, Zhiyu Jiand, Stian Sørum, Emil Smilden, Woongshik Nam, Stefan Vilsen, Thomas Sauder, Tobias Torben
Other involved scientists: Murat Arcak, Michael Triantafyllou, Andy Teel, Jørgen Juncher Jensen

Research activities
For ships and ocean structures, the focus will be on the development of methods to maximize operability with an improved risk management. This will be achieved by combining advanced numerical hydrodynamic and structural mechanical models for analysis, monitoring and control. The research will integrate the AMOS team's competence on control theory, risk, safety, hydrodynamics and marine structures for multi-body autonomous marine operations in normal operation, as well as with extreme conditions and abnormal events due to extreme weather and faults. Methods from machine learning, model reduction and adaption, system simulation, optimization, response estimation and prediction will be combined into new operational philosophies, structural design, algorithms and system architecture for real-time decision support and autonomous control systems. Application areas include offshore wind, offshore oil and gas installations, aquaculture, coastal infrastructures, coupled multi-body marine structures, marine operations, autonomous ships, inspection and installations. Associated scientific research challenges will also provide input to projects 1 and 2. In return, this project will integrate results from projects 1 and 2, thus enabling technology towards autonomous marine operations and systems.

Highlights

There is significant potential for increasing marine food production by **moving marine fish farms to more exposed areas**. However, the systems would be subject to more energetic waves and stronger currents. New designs have been proposed, but it is worth investigating the operational limits for standard net-based fish farms. To this scope, the dynamic response of a realistic floating circular collar-type fish farm (with single cage) has been numerically analyzed (left side of Fig. 1). The floating collar, the elastic sinker tube, the flexible-closed net cage and the complex mooring system are all modeled with state-of-the-art theoretical and numerical formulations within a time-domain solver. The mooring

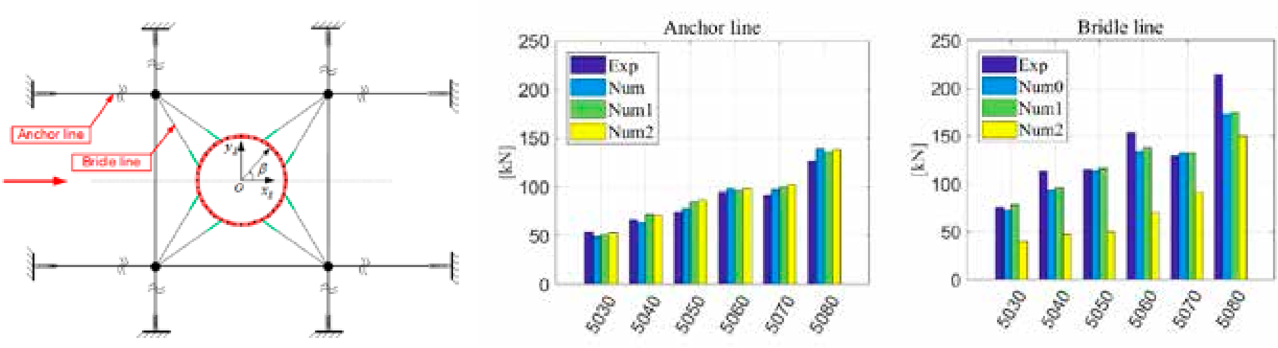


Figure 1: *Fish farm with inflow in* x_E *direction (left: top view). Comparison of the maximum values of the anchor loads (middle) and bridle loads (right) from model tests and numerical simulations in irregular waves. Increasing test numbers correspond to increasingly significant wave height and peak wave period. Num0, Num1 and Num2 denote basic numerical results, results using zero-frequency added mass for different modes of the floating collar and results considering a rigid floating collar, respectively.*

loads obtained from the simulations compare successfully against available experimental data [P3.R1], as shown in Fig. 1 in terms of maximum anchor (middle) and bridle (right) loads in irregular waves. From the analysis, the floater flexibility does not matter for the anchor loads, while it is responsible for substantially higher bridle loads.

The hydrodynamic forces on the floater play a limited role in the mooring loads and can be approximated using zero-frequency values. The floating collar tends to follow long waves, both with and without a current presence. The latter can significantly increase the net-volume reduction (left side of Fig. 2), which represents the main constraint for the studied fish farm to operate in more exposed regions. Just one realization is examined in Fig. 1. In reality, the maximum value is realization-dependent in a stochastic sea. For the isolated fish farm, equivalent regular waves can be used to estimate the mooring loads. The latter are of similar magnitude, but generally more conservative than those in irregular waves (right side of Fig. 2).

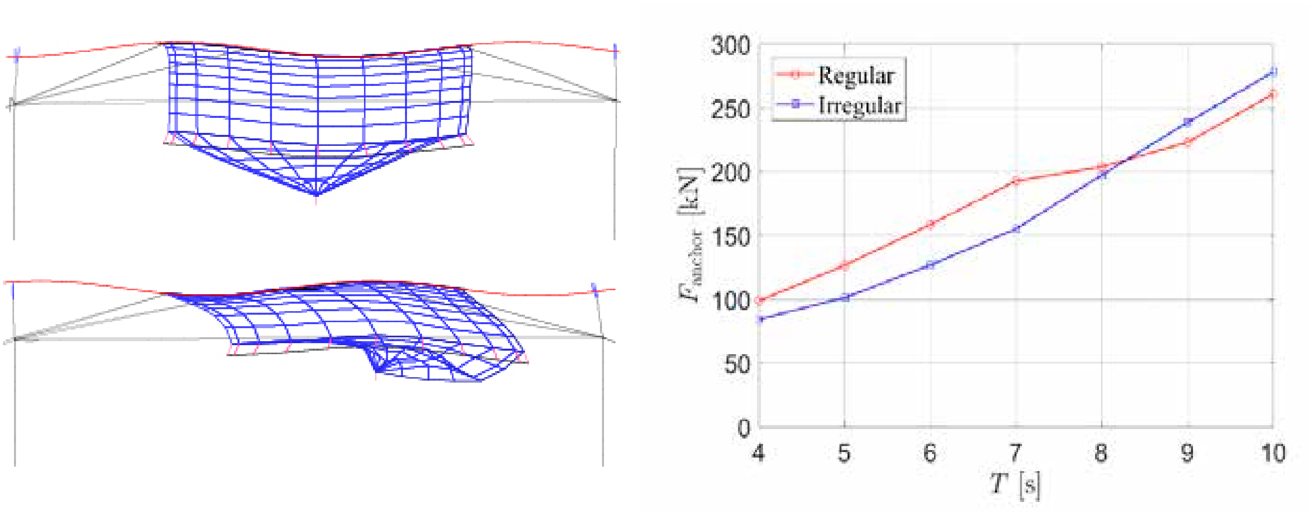


Figure 2: *Left: Numerical net-based fish farm in regular waves (period T = 6, height H = 2.5 m), without current (top) and with current speed U∞ = 0.5 m/s (bottom). Right: Comparison of the maximum anchor loads by numerical calculations in irregular waves and equivalent regular waves. The considered regular wave steepness is Hλ= 1/15, the current velocity is U∞ = 0.7 m/s. The significant wave heights for irregular waves are given as Hs= H/1.9.*

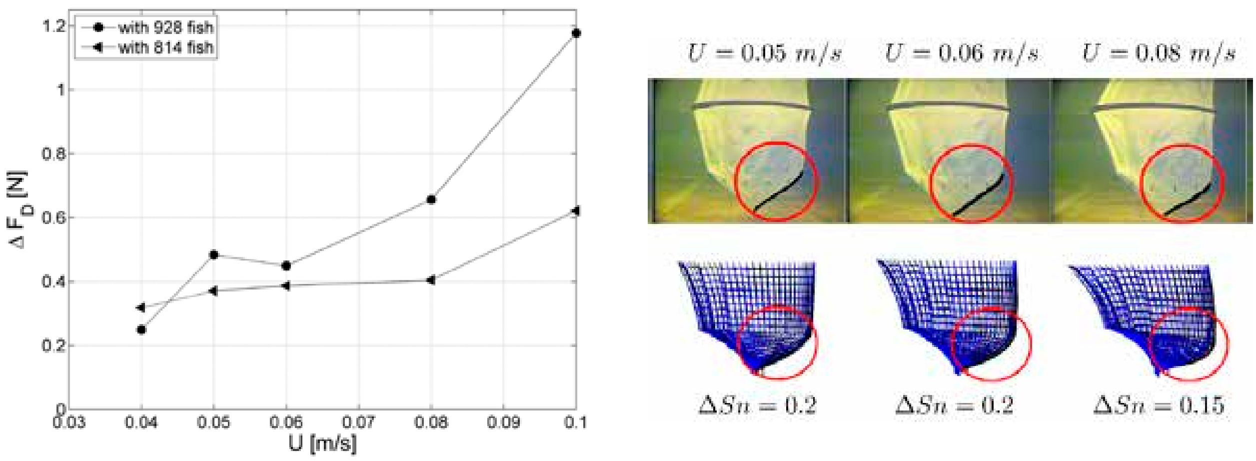


Figure 3: *Fish farm in current. Left: Experimental relative drag change $\Delta F_D/F_D$ caused by live fish. Right: Experimental (top) and numerical (bottom) net deformation in the experiment with 814 live fish. The area inside the red circle indicates the touching area. ΔS_n represents the increase of solidity ratio at the back-cone part of the cage modeled in the calculations.*

The study of **fish influence on mooring-line loads and net deformations** has continued. Artificial fish and live fish experiments (previously performed at MC Lab with a scale 1:25) were further analyzed and complemented by numerical investigations [P3.R2]. For the artificial fish case, potential-flow slender-body theory was applied to model the displacement flow caused by the fish and combined with empirical viscous-wake flow. The displacement flow was clearly more important than the wake flow. Both numerical results and experiments documented an insignificant influence of the artificial fish on the mooring loads, with a change within 3%. The experiments highlighted a much greater influence of live fish (left side of Fig. 3). Based on a synergic experimental-numerical analysis, this is connected with a larger solidity ratio (closed net area relative to the total net area) caused by live fish (right side of Fig. 3).

Closed fish farms are alternative concepts for off-shore aquaculture insofar as providing environmental advantages, but they can experience challenges connected with the specific design. Strand [P3.R3] studied, both numerically and theoretically, the wave-induced behavior of a closed membrane-type fish farm by a 2D model. From her studies, the normal and tangential membrane deformations have a significant influence, as resonant water motions inside the fish farm (sloshing) matter. Snap loads in the membrane can be of concern in non-small sea states. The difficulties in properly modeling the elasticity effect of the membrane in model tests are therefore emphasized.

Sloshing is also relevant as a mechanism to reduce roll ship motions. Free-surface anti-rolling tanks typically work with **shallow-filling depths**, and the sloshing scenarios can lead to non-linear and complex features of the internal water. A simplified model has been proposed to reproduce the flow field and evaluate the loads induced on the tank [P3.R4]. This can be used within a non-linear seakeeping potential-flow model of the vessel in waves. Through the modal representation introduced in previous papers authored by the same research team, the expressions for the global force and moment acting on a rectangular 2D sloshing tank have been derived. To overcome the limits of the modal scheme when the water depth is very shallow, a diffusive term is introduced in the continuity equation of the depth-averaged system. The numerical solver has been extensively validated through comparison with experimental data for forced harmonic roll motions at different excitation amplitudes, namely θ_0 = 2°,4°,6°. Fig. 4 confirms the model capability near resonant conditions of the internal liquid. The agreement with the measurements is good, especially for the roll moment. The horizontal force presents pronounced non-linear features.

The failure of offshore crane operations, leading to objects being dropped into the sea represents a major hazard for subsea structures, pipelines and risers, and is therefore given attention in offshore engineering. Important factors are: (1) the excursion of dropped objects, and (2) the energy involved in their impact with subsea modules and/or the sea bottom. The risk analysis must involve many scenarios; this prevents the use of complex numerical solvers. The 3D response of falling submerged pipes with end caps has been analyzed using slender-body theory to estimate the potential-flow hydrodynamic loads, in addition to a 2D+t method handling the varying cross-flow separation along

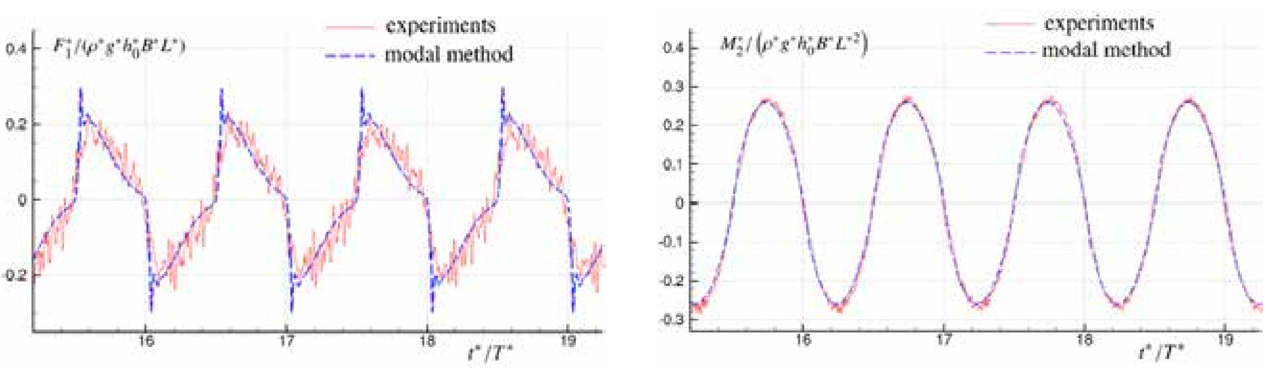


Figure 4: *Evolution of global force (left) and moment (right) for ϑ_0 = 4°, σ/σ_r = 1.0027. ϑ^0 and $\sigma=2\pi/T$ are roll excitation amplitude and frequency, respectively. σ_r is the first linear resonant frequency. L_0, B and h_0 are the tank length, the tank width and the filling depth, respectively. Variables with symbol * are made non-dimensional.*

the pipe [P3.R5]. The numerical results for submerged drops are consistent with experimental envelopes at the same drop angles (Fig. 5).

The analysis highlighted the typical scenarios of the drops. A slender pipe can drop in water like a leaf falling through the air from a tree. Other scenarios involve important 3D motions of the body, caused by large asymmetric vortex shedding; pipe turning, due to directional instability; longitudinal stopping of the pipe, caused by the weight in water, so that the front and end of the pipe alternate.

Within the framework of developing advanced numerical methods, a detailed and systematic analysis was performed on the local and global properties of the **harmonic polynomial cell (HPC) method** [P3.R6]. This was proposed by Shao and Faltinsen (2012, 2014) as an accurate and efficient field solver for problems governed by the Laplace equation for the velocity potential φ. It means, for instance, wave propagation and wave-body interaction problems dominated by potential-flow effects. At the local level, a simple rule was identified for the proper representation of φ in cells with symmetry properties. The local solution error, its convergence

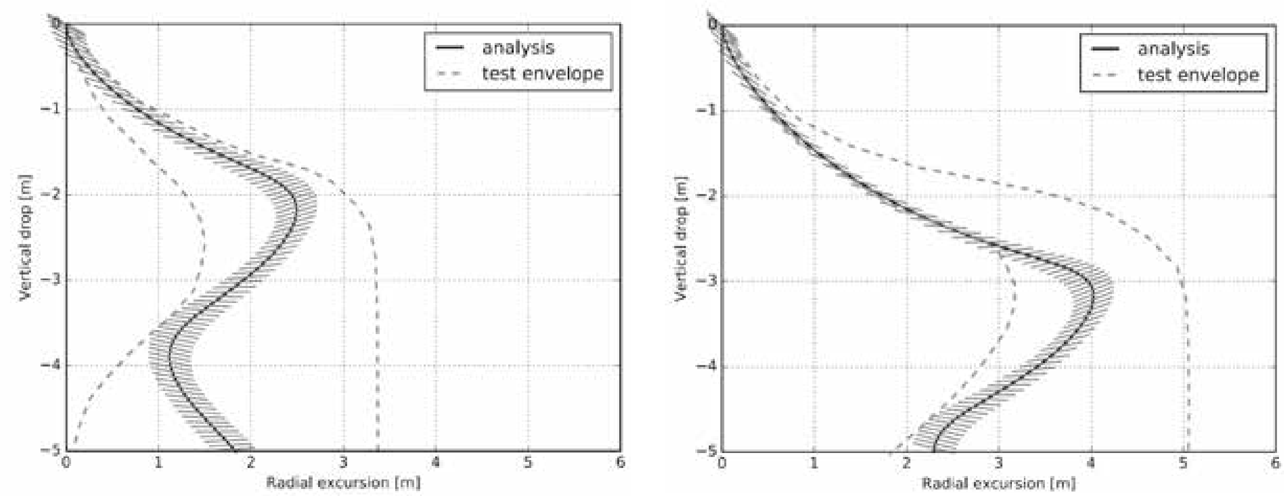


Figure 5: *Numerical drop trajectory for a submerged drop and corresponding envelope from Aanesland's tests. Left: drop angle = 30°. Right: drop angle = 45° (right).*

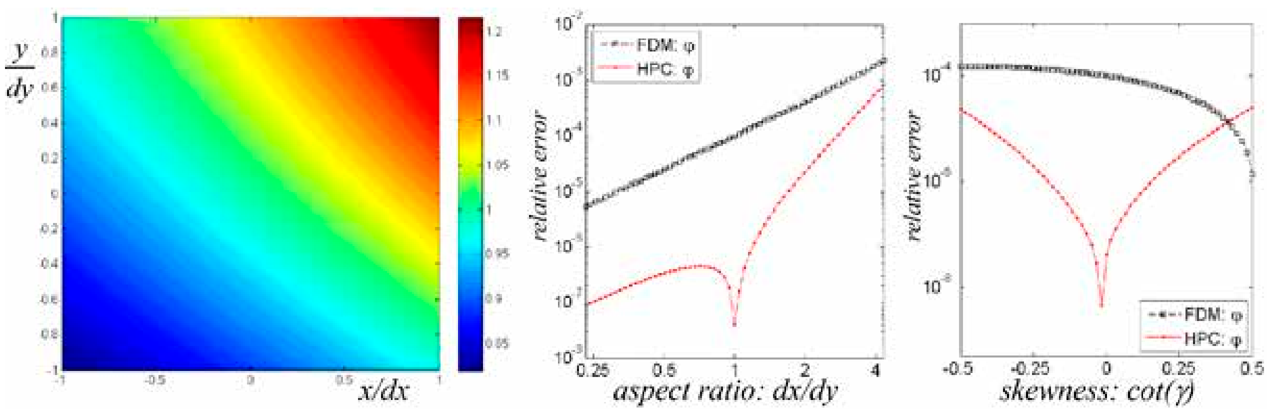


Figure 6: *Local analysis for a cell with dimensions dx, dy, assuming a true velocity potential φ with contour plot in the left. Relative error as a function of cell aspect ratio dx/dy (middle) and of cell skewness cot γ (right) for a standard finite-difference method (FDM) with local 4th-order accuracy and for HPC. The latter allows local 8th-order accuracy.*

rate, its dependence on the cell topology, its distribution inside the cell and its features across cells with different dimensions have been carefully examined with relevant findings for HPC numerical implementations. The accuracy of the HPC method generally benefits from squared/symmetric cells, while severe stretching or distortion of the grid should be avoided (Fig. 6). For overlapping grids or immersed boundary methods, the interpolated nodes or markers should be located close to the cell center. At the global level, the error convergence rate has been analytically estimated in terms of error contributions from the boundary conditions, and from inside the liquid domain. In most cases, the error associated with boundary conditions dominates the global error.

Using the HPC method, a 2D numerical wave tank was developed to study wave-propagation problems with different sources of non-linearity in deep and shallow water. Overlapping grids and immersed-boundary modeling, which are novel concepts in relation to the HPC method, were combined. This allowed for the implementation of recommendations from the above study through using Cartesian grids with solely squared cells. In a systematic investigation of regular waves, the method was able to study steep waves close to breaking over a long time with good accuracy [P3.R7]. Fig. 7 compares the time history of simulated wave elevation for a focused wave in shallow water with experiments. The examined wave probe is close to the zone where a plunging breaker occurred in the experiments. By implementing a wave-breaking suppression scheme in the numerical analysis, the simulation was able to continue beyond the experimental wave breaking. This shows that the method is powerful, hence allowing for simulated waves that are close to the limiting capability of potential-flow theory. CPU optimization has not been a primary focus in the current research. For a simulation of 60 s, and with a time step of 0.05 s, the total simulation time on a single-core standard laptop was approximately 25 minutes. This can be reduced to less than 10 minutes on a more powerful workstation. Moreover, the HPC equation matrix is well suited for code parallelization, which can lead to a substantial CPU-cost reduction.

The modeling of the **turbulent flow behind a breaking wave** in the open sea is a challenge of interest in several marine problems (e.g. the wake of a ship, fluid-structure interaction and air-wave energy exchange). A dedicated 2D Particle Image Velocimetry (PIV) experimental study has been carried out in order to investigate the single-phase turbulent flow during the evolution of an unsteady spilling breaker [P3.R8]. The main emphasis was given to the curvature of the mixing layer (white region in the plots of Fig. 8), which induces some extra rates of strain at the local free surface. They should be accounted for in algebraic-type turbulence closures. The data enabled for the validation of a simplified turbulence closure model, as well as the evaluation of the extra strain rates. Three different stages have been identified in the kinematic evolution of the breaker: (i) generation of the turbulent layer after the breaking onset; (ii) transient evolution dominated by the geometric flow unsteadiness; and (iii) a quasi-steady regime of the spilling breaker, with kinematic features resembling the hydraulic jump evolution. Fig. 8 refers to regime (iii) and compares the Reynold stress (top-left panel), the mean simple shear (top-right panel) and the two main extra rates of strain, i.e., the streamline curvature (bottom-left panel) and the geometric curvature (bottom-right panel). The Reynolds stress and the mean simple shear appear to

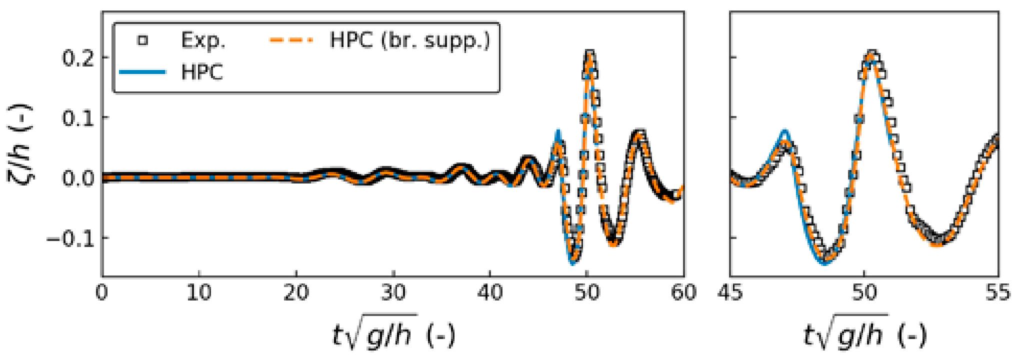


Figure 7: *Non-dimensional wave-elevation time series for a focused wave in shallow water. ζ, h, t and g are wave elevation, water depth, and time and acceleration of gravity, respectively. Exp.= experiments by Dommermuth et al. (1988); HPC and HPC (br. supp.) = HPC results without and with wave-breaking suppression, respectively.*

be important contributions. However, in the region just downstream of the breaker toe and down to the wake region, the streamline curvature tends to increase and resembles their behavior (see reddish zone in the bottom-left panel). This also highlights the important role of this term, usually neglected in simplified turbulence closure models. Conversely, the geometric curvature term is negligible everywhere if compared with the other contributions. This is related with the advection of the cross-flow mean velocity associated with the vorticity injected at the breaker toe.

Cyber-physical empirical methods applied to ultra-deep water floating systems and their fidelity have been investigated [P3.R9], as empirical methods constitute the cornerstone of most scientific fields. They enable us to generate knowledge about a system *through observation*, to verify hypotheses and build models of the reality that surrounds us. In marine technology, however, some floating structures installed in ultra-deep water, are not easily modeled in hydrodynamic laboratories. Indeed, testing a typical production platform anchored in 3,000 m at a reasonable scaling ratio (typically 1/60) would require a laboratory with a diameter of at least 100 m and a water depth of 50 m. In other words, it is unfeasible in any of the existing ocean basins.

We have investigated a solution called ReaTHM® testing (a trademark of SINTEF Ocean), in which such dynamical systems could be partitioned into physical and numerical substructures that interact in real-time through a control system (see Fig 9). The physical substructure consists of the floater and the mooring in the free-surface region (where complex hydrodynamic phenomena take place). The numerical substructure consists of the "truncated" part of the mooring line, and is described by validated, but in general non-analytic, computational models. See Figure 10..The control system at the heart of ReaTHM testing plays a crucial role for its validity as an empirical method. Indeed, the dynamical properties of this "cyber–physical empirical setup" (Figure 9b) **must** reflect those of the real system under study (Figure 9a) in spite of heterogeneous and uncertain *artifacts* such as time delay or sensor noise, which are inevitably introduced by the components of the control system in Figure 9b.

We defined a performance criterion, which was denoted *fidelity*, to quantify the resemblance between 1a and 1b, and developed a new method to verify the *probabilistic robust* fidelity of a setup and to derive fidelity bounds. These can be used as specifications to the control system. The devised method is: (1) non-intrusive, and thus not limited to analytic models, which allows its application to a wide class of dynamical systems well beyond marine technology. (2) It allows handling an arbitrary number and type of artifacts that exhibit parametric uncertainty. (3) It is based on surrogate modeling and active learning techniques (Adaptive Kriging, see Figure 11) to achieve unprecedented computational efficiency, even for high-dimensional and high-reliability problems.

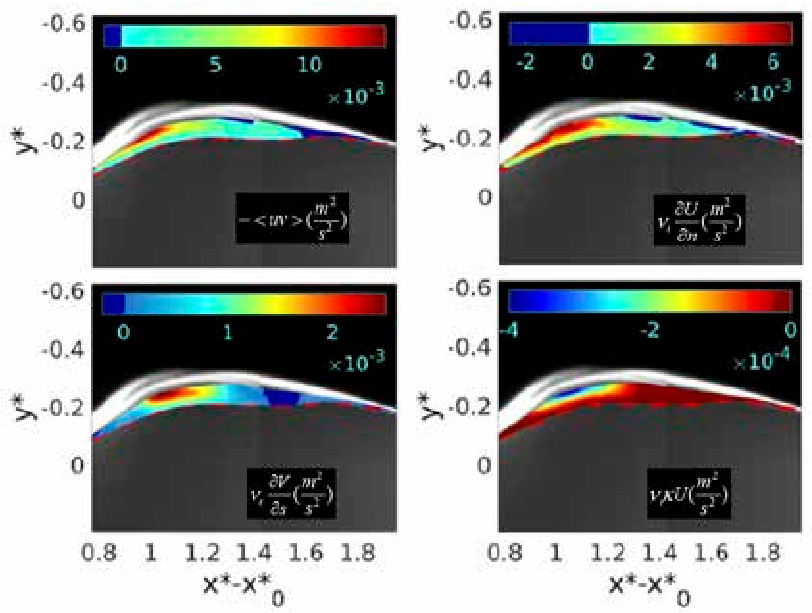


Figure 8: *From left to right and from top to bottom: spatial maps at the stage (iii), of the Reynolds stress (top left), mean simple shear (top right), streamline curvature (bottom left) and geometric curvature (bottom right), respectively. The dashed red line gives the lower boundary of the turbulent region. Variables with the symbol * are made non-dimensional.* x^*_0 *indicates the origin of the image.*

Among others, this study enabled us to gain insight into the complex interaction between the two substructures and the control system. It put in evidence the importance of calibration errors and signal loss in the force

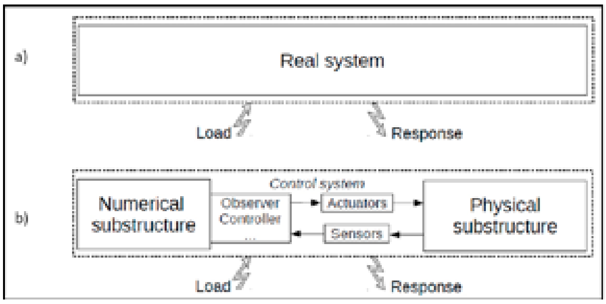


Figure 9: *Partition of the system under study into a physical and a numerical substructure, connected through a control system. The fidelity of the cyber-physical empirical setup represented in b) quantifies how close its responses of interest are from those of a).*

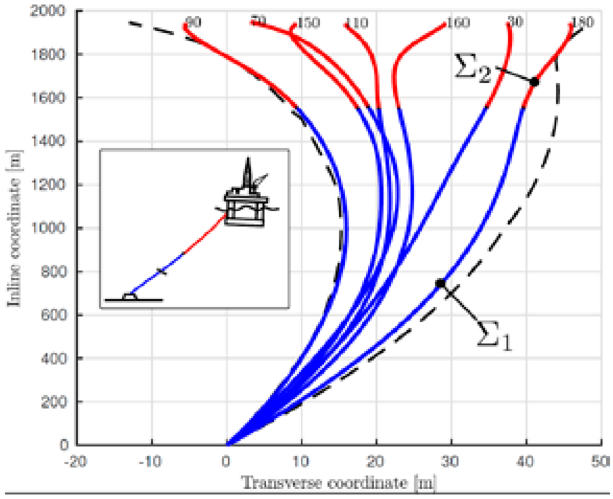


Figure 10: *Snapshots at given times of a substructured mooring line, when subjected to an exogenous load. The numerical substructure is represented in blue and the physical substructure in red.*

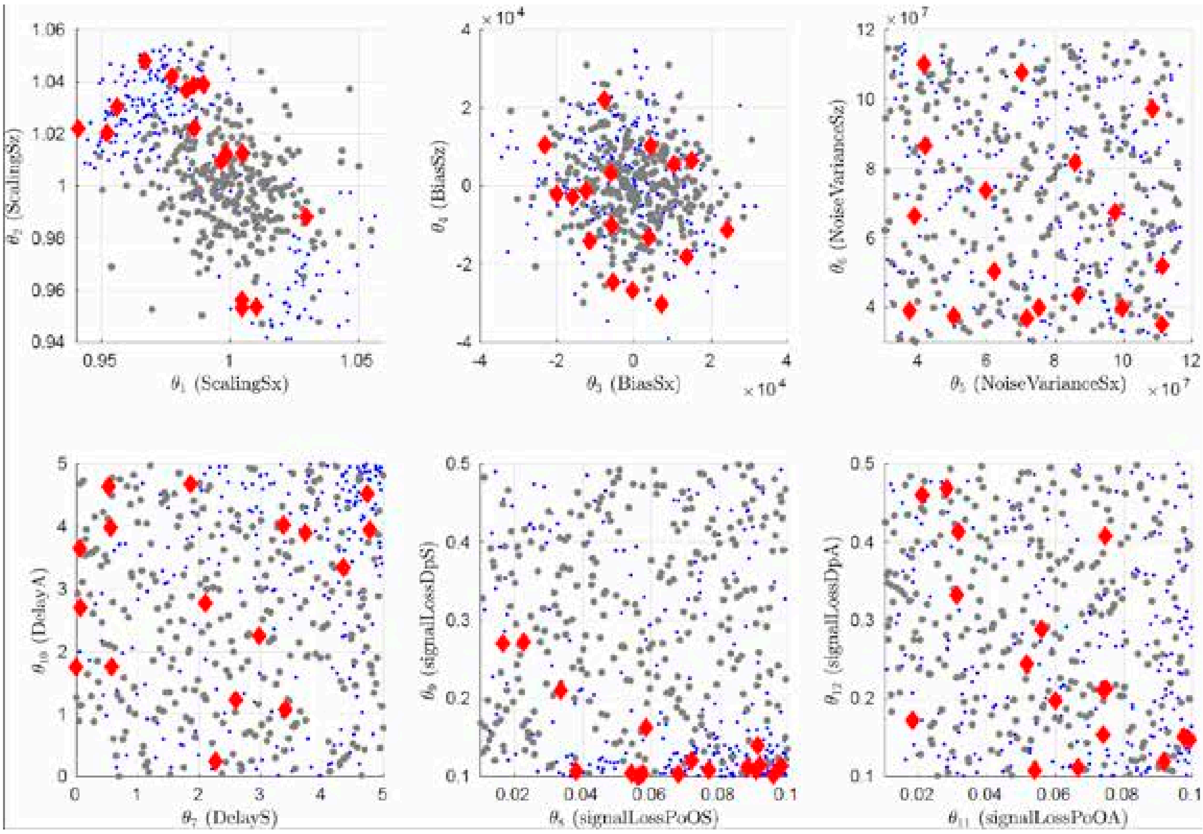


Figure 11: *One step of Adaptive Kriging. New samples (in red) are generated in the artifact space, to identify the low fidelity domain.*

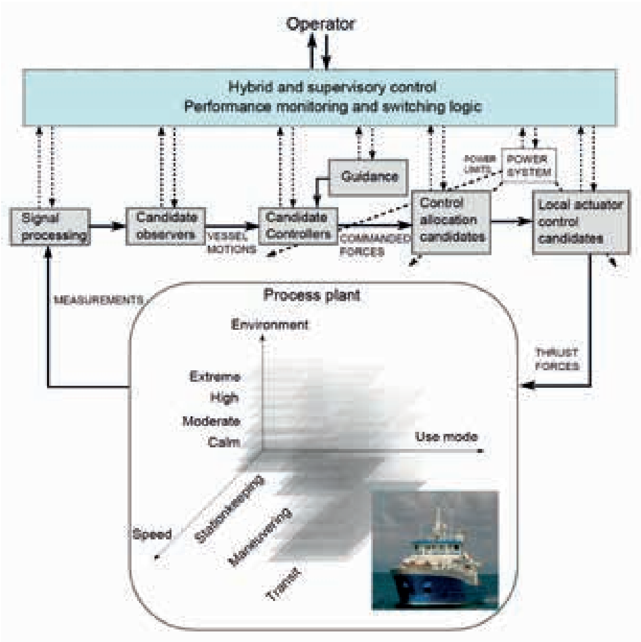


Figure 12: *Block diagram of a hybrid control system for a marine vessel in an unknown environment.*

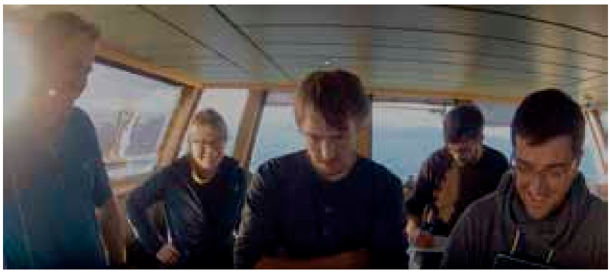


Figure 13: *Prof. Roger Skjetne, Postdoc Astrid H. Brodtkorb, PhD candidate Mikkel E. N. Sørensen, Msc student Alexander Mykland, PhD. Vincenzo Calabrò testing algorithms onboard R/V Gunnerus during the AMOS DP research cruise 2016. Photo: Mikkel E. N. Sørensen (2016).*

measurement. The effect of noise on the fidelity was found to be insignificant. The analysis also indicated that artifacts of a different nature were interacting, and it was quantified how they jointly influenced the fidelity. We finally showed quantitatively that, for a given control system, it was beneficial to lower the truncation point to achieve higher fidelity.

The demand for **increased levels of autonomy and system integration for marine vessels** has forced control engineers to deal with increasingly larger and more complex systems. Higher levels of autonomy may lead to performance improvement in terms of increased precision, larger operational windows, lower fuel consumption and increased safety for passengers, crew and equipment.

During marine operations, both variations in stationary dynamics and transient behavior are important to account for in an all-year operation philosophy subject to changing weather, sea loads and modes of operation. Hybrid systems theory provides a formalism for the integration of multi-functional controllers combining discrete events and continuous control, see Figure 12.

A **hybrid control concept** for the proper switching of candidate observers and controllers is proposed for marine vessels [P3.R10]. For particular observer candidates, this work combines a model-based observer, a signal-based observer, a controller, and switching logic into a hybrid system with the goal of improving the transient response. Performance of the proposed concept is demonstrated experimentally through model-scale experiments, with the hybrid observer estimates used in closed-loop output feedback control and through estimation on full-scale field data collected on the AMOS DP research cruise, see Figure 13 [P3.R11].

Ships and offshore structures may be subjected to extreme actions where the **steel material is exposed to very low temperatures**, e.g., due to ship or ice impacts in the Arctic, or temperature stresses induced by cryogenic spills. During these actions, the structure may undergo ductile or brittle fracture. The occurrence of the latter event may be particularly critical. Realistic analysis for large structural subsystems by means of the non-linear finite element method, in which the **ductile-brittle fracture transition in steel** is taken into account, is therefore essential. Numerical simulations require large shell elements, typically in the range of 3-5 times the plate thickness, where detailed modeling of crack initiation and propagation is not feasible. To help overcome this obstacle, the strain energy density (SED) criterion was proposed to predict ductile-brittle fracture transition in non-linear finite element analyses using large shell elements [P3.R12]. Critical values of the SED were determined based on local simulations of fracture for a range of temperatures and plane-stress states based on the combined use of the Gurson model for ductile damage and fracture and the Richie-Knott-Rice criterion for brittle fracture. In order to evaluate the proposed model, six drop tests on stiffened and unstiffened steel plates carried out at room temperature

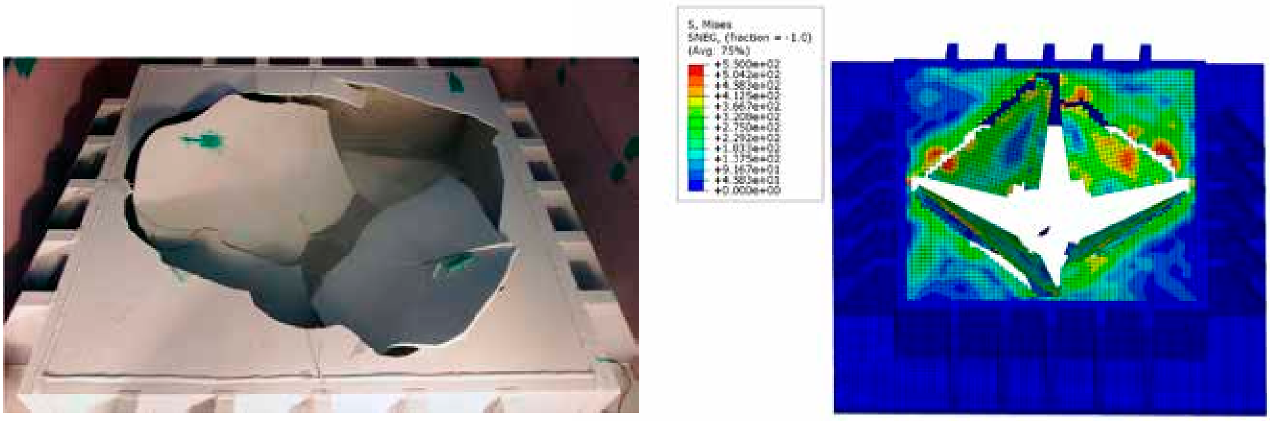


Figure 14: *Left: Drop test carried at a temperature of -100°C. (Kim KJ, Lee JH, Park DK, Jung BG, Han X, Paik JK. An experimental and numerical study on non-linear impact responses of steel-plated structures in an Arctic environment. I.J of Impact Engineering. 2016;93:99-115). Right Numerical prediction of the deformation mode. The fringe plot shows the von Mises stress field (in MPa) at the end of the simulation.*

and sub-zero temperatures were analyzed with shell finite elements and the SED criterion. In some of the drop tests, the steel plate exhibited ductile behaviour while in others the behaviour was more brittle, see Figure 14. The simulations of the drop tests illustrated the feasibility of the SED. The plate response to the impact was predicted quite well for the unstiffened plates, whereas failure in the heat affected zone (HAZ) occurring at sub-zero temperatures was not captured. Two effects push the failure mode towards more brittle fracture than it was possible to simulate at the present stage: i) The stiffener and the welds caused a significant stress and strain concentration that was not taken into account in the shell finite element modelling, and ii) The residual stresses in the HAZ will generally attain the yield stress level. The HAZ material will be heavily stressed, and may thus more easily attain the critical SED by low temperature exposure.

The need to carry out dedicated low temperature tests of stiffened and unstiffened plates with better controlled conditions was acknowledged. The verification study was also made difficult because the number of temperature levels is small. The critical SED changes rapidly from -60°C to -100°C. Hence, the occurrence of brittle failure or ductile failure is somewhat "binary"; as a result, it is difficult to know how close the numerical simulations are to the correct temperature level.

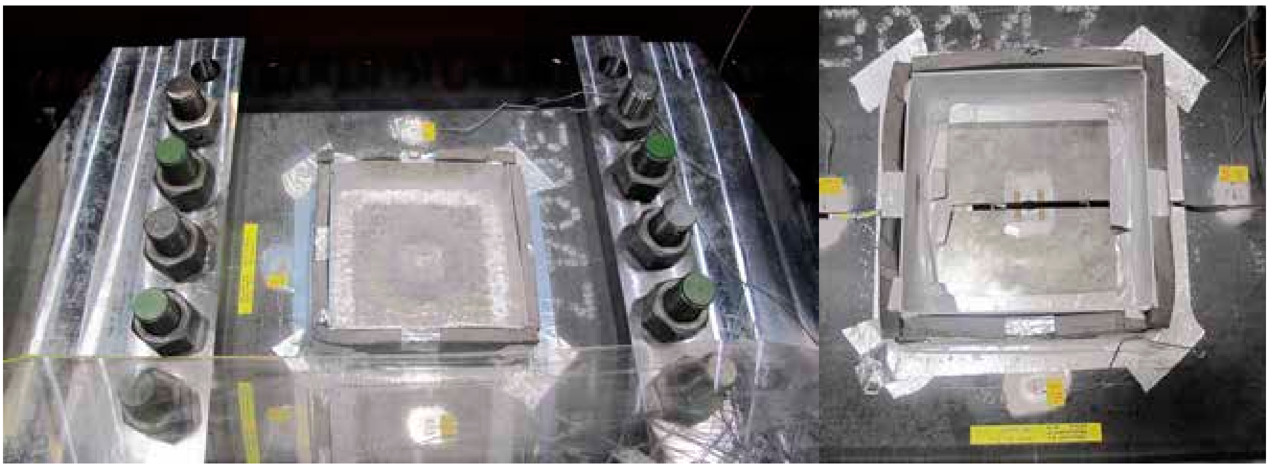


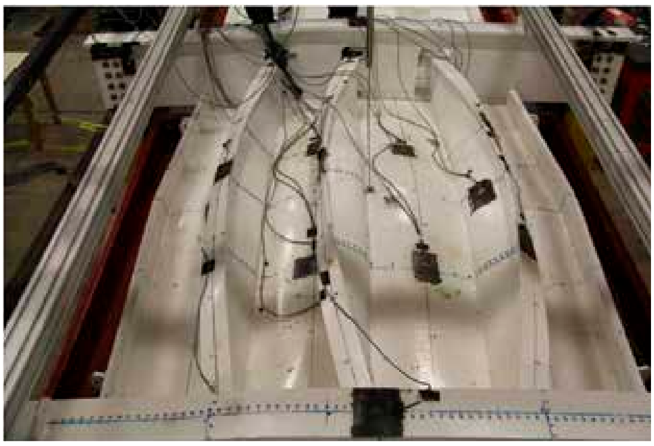
Figure 15: *Left: Plate with initial crack in the middle subjected to cooling from liquid Nitrogen. Right: Brittle crack propagated from the middle crack and stopped closed to plate edges with higher temperatures.*

In order to increase the test basis for verification of the brittle fracture model, 8 mm plates with an initial crack were attached to a hydraulic jack and subjected to cooling from liquid nitrogen, which evaporates at -196 °C at atmospheric pressure. The pool was confined to the middle part of the plate. Thermal contraction induced increasing tensile stresses. To initiate crack propagation, the tension was increased by the hydraulic jack when the middle part of the plate reached a steady state temperature. The initial crack was formed by water cutting to 16 mm, and extended 5-6 mm on each side by cyclic fatigue loading. The crack was oriented transverse or parallel to the rolling direction for un-welded specimens, and along the crack in HAZ for plates joined by welding in the center line. Figure 15 demonstrates a brittle fracture that occurred in an un-welded specimen.

Stiffened panels are widely used in marine structures, and are often exposed to the risk of explosions, ship collisions, violent water slamming, ice pressure and impacts from dropped objects. Potential consequences may vary from minor local deformations to major structural damage and plate rupture, thus causing compartment flooding or oil leakage. Consequently, it is crucial to estimate the resistance and damage with good efficiency and accuracy, notably when the panels are loaded to their extreme performance limits during accidental events. Plastic methods were used to derive a simplified formulation for the **large deformation resistance of stiffened panels under concentrated-, uniform- or patch loading** [P3.R13]. Comparison with experiments, see Figure 16, and a non-linear finite element analysis with LS-DYNA showed that the developed formulations had a good prediction capability, provided that the stiffener profile was compact and not subjected to tripping at the early stage of deformation, or to very high utilization of the web in shear.

Due to the relative motions between the water and the structure – enhanced by high speed or breaking waves – damage due to **water impacts or slamming** may occur for marine structures, e.g., ships, high-speed vessels, free-falling life boats and offshore platforms. The COSL Innovator accident in the North Sea in 2015 is a recent example of this. Significant interaction exists between the hydrodynamic pressure and the structural response, which may be in the elastic or elasto-plastic regime. Analysis methods for hydro-elastic slamming have been known for several years, but a large deflection plastic response or hydro-plastic slamming has not been considered so far. In a two-part companion paper [P3.R14], an analytical solution for the hydro-plastic response of beams and stiffened panels subjected to extreme water slamming was formulated. Based on drop tests modeling, a two stage approach was adopted: 1) In the acoustic stage, the structure was given a deformation velocity equal to the initial impact velocity; 2) In the free deflection phase, in which interaction with the hydrodynamic pressure is important, the structure decelerates to zero velocity. A key element of the

Kim H. An experimental study of the design and overload capacity of structural grillages subjected to ice loads MSc thesis, Memorial Univ. of Newfoundland; 2014.



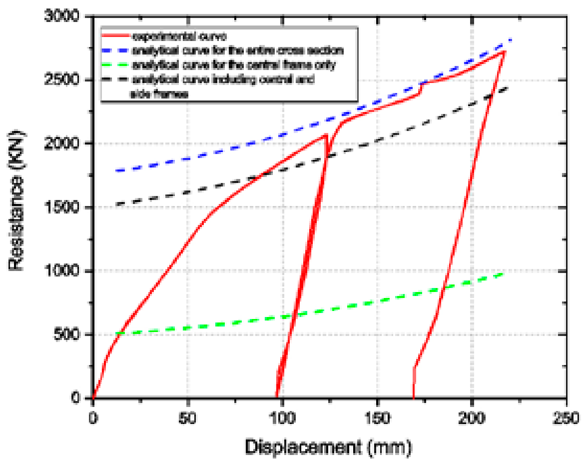


Figure 16 Left: *Deformed full-scale ship grillage after loading with a cone shaped ice indenter. Right: Force –displacement curve form the experiments and prediction by the theoretical model.*

theoretical model is the traveling hinge concept used to describe the plastic deformation for beams and stiffened panels. The validity of the concept was confirmed from the snapshots of plate displacement profiles from hydro-elastoplastic slamming simulations with LS-DYNA using the Arbitrary Lagrangian Eulerian (ALE) method, refer to Figures 17 and 18.

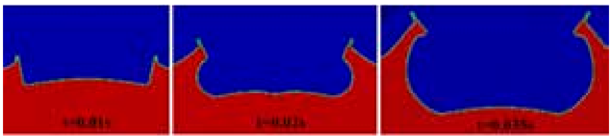


Figure 17: *Snapshots of the plate deformation and flow field during water entry; initial impact velocity is 10 m/s*

The probability of fatigue failure is governing the design of **offshore wind turbines** (OWTs). Significant uncertainties are associated with both the engineering models adopted and the established design basis for a wind farm. To ensure sufficient structural reliability, design calculations are typically carried out using safety factors to account for the uncertainties. As the engineering models are improved, the safety factors should be re-calibrated to avoid overly conservative designs. It was shown that improved modeling of environmental parameters has a large effect on the required safety factors [P3.R15]. The same was observed for improved wave load modeling.

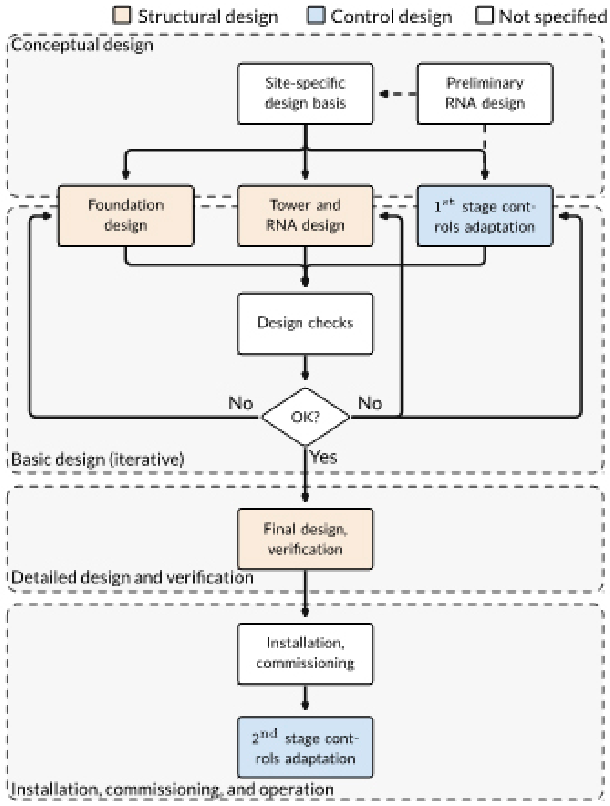


Figure 19: *Outline of the design process for an offshore wind turbine with a two-stage adaptation of load reducing controls (Based on information from Seidel et al., Fischer et al. and IEC 61400-3)*

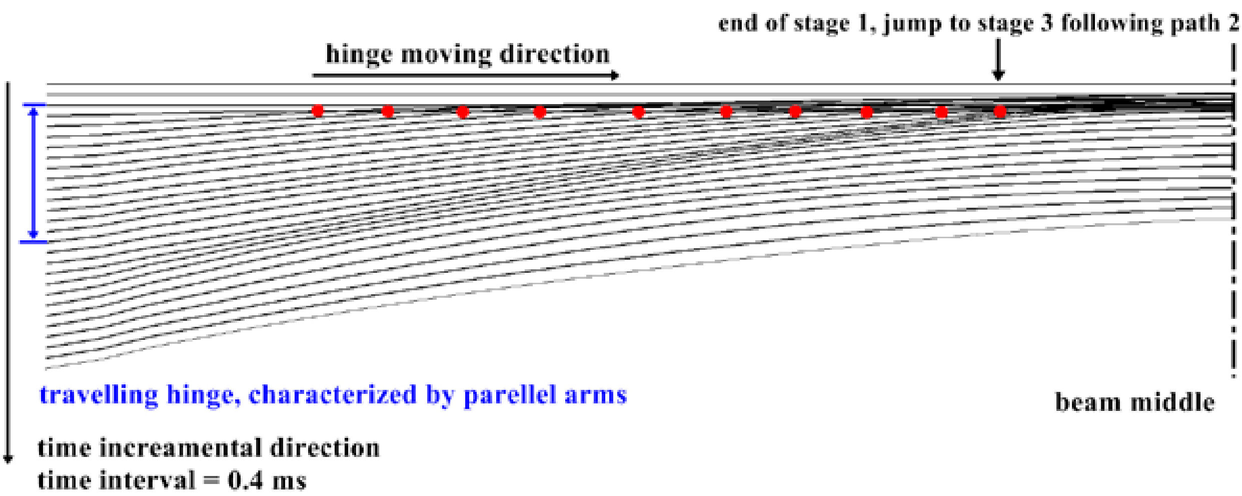


Figure 18. *Snapshots of displacement profiles for a half plate strip during water entry; the plate thickness is 6 mm and the initial impact velocity is 10 m/s. The time interval is 0.4 ms. The red points denote positions of the traveling hinge at each time instant.*

The design basis includes uncertainties that can be reduced once the OWT has been installed. A novel design methodology based on a two-stage controller adaption was proposed, which allows for more economical designs [P3.R16]. In the first stage, the design is carried out assuming the use of load mitigation strategies. After commissioning, the structural properties are reassessed. The control strategy can then be adapted to the true structural properties, which are likely to be less conservative than those assumed during the design stage. This strategy is illustrated in Figure 19. The feasibility of this design approach was demonstrated in a case study, in which the uncertainty in soil stiffness was evaluated. On the farm level, a significant reduction of the adverse side effects of load mitigation was achieved by means of the second stage controller adaption. At the same time, the benefit of load mitigation from the first stage controller adaption, in terms of reduced design loads, was obtained for all turbines.

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P3.R2 He Z., Faltinsen O. M., Fredheim A., and Kristiansen T., 2018. The influence of fish on the mooring loads of a floating net cage, *Journal of Fluids and Structures*, 76.

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Awarded/Ongoing Projects

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 project	NTNU IST UiP LiU NORUT Maritime Robotics Honeywell Catec iTUBS	15 PhD whereof 5 PhD or NTNU + project management
Arctic ABCD	Geir Johnsen Asgeir J. Sørensen	13,5 MNOK	2016-2025	NFR INFRA	Same as ARCTIC ABC	1 Postdoc + Lab Equipment
Exposed Aquaculture Operations – Autonomous Systems and Offshore Structures	Ingrid Schjølberg	209 MNOK	2015-2022	SFI proposal	SINTEF Ocean NTNU SINTEF Digital Salmar, Grieg Mainstream Norway Biomar Egersund Net AkvaGroup ACE, KM	PhD Postdoc Experiments IS, MG, JA
VISTA PhD-stipend Jørgen Sverdrup-Thygeson: Swimming Robot Manipulators for Subsea IMR.	Kristin Y. Pettersen	3 MNOK	2015-2018	VISTA	NTNU	1 Post doc/PhD
Center for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA)	Tor Arne Johansen	3 MNOK	2015-2022	SFI proposal	UiT NTNU ..	1 Post Doc/PhD for AMOS
Sensor Fusion and Collision Avoidance for Autonomous Surface Vehicles (Autosea)	Edmund Brekke Morten Breivik Tor Arne Johansen	11,2 MNOK	2015-2018	RCN MAROFF	NTNU DNV GL Kongsberg Maritime Maritime Robotics	2 PhD + 1 postdoc
VISTA Post doc – Eleni Kelasidi	Kristin Y. Pettersen	3 MNOK	2016-2018	VISTA	NTNU	1 Postdoc
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	2017-2019	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
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
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
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	2017-2020	NFR Frinatek IKTPLUSS	NTNU	2 PhD + 1 Postdoc
AILARON – Autonomous Imaging and Learning Ai Robot identifying ommunic taxa in-situ	Annette Stahl Kanna Rajan 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	2 PhD
Collision avoidance for autonomous ferry	Edmund Brekke Tor Arne Johansen	4.1 MNOK	2017-2021	NTNU SO scholarship	NTNU	1 PhD
Drone air traffic control	Tor Arne Johansen	0.9 MNOK til NTNU	2017-2018	JU SESAR	Internasjonalt konsortium ledet av Airbus	
Center for Marine Operations in Virtual Environments (MOVE)	Zhen Gao	9 MNOK	2015-2022	SFI proposal	NTNU SINTEF Ocean Statoil DNV-GL ...	
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	2018-2020	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	2018-2021	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 årsverk PhD
FlightSmart	Tor Arne Johansen	2 MNOK	2018-2021	BIA IPN	Equator Aircraft SA	2 årsverk postdoc
ADRASSO – Autonomous Drone-based Surveys of Ships in Operation	Tor Arne Johansen Thor I. Fossen	2 MNOK	2018-2021	MAROFF IPN	DNV GL	2 årsverk 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	2 PhD, 1 postdoc. 1 ekstra PhD gitt av IE.

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
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 Asgeir J. Sørensen 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	2 post doc 5 PhD
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 post doc 1 PhD
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 – Pol-prog	NP, NTNU, AWI	1 PhD
Autoferry: Autonomous all-electric passenger ferries for urban water transport	Morten Breivik Edmund Brekke Egil Eide ++	25 MNOK	2018-2021	NTNU (IMT, ITK, IET)	NTNU	8 PhD
Real-time encryption of sensors in autonomous systems. NTNU Gjøvik/ Trondheim.	Thor I Fossen	4 MNOK	2019-2022	NTNU ITK/ Gjøvik	NTNU	1 PhD
Autonomous ships, intentions and situational awareness	Edmund Brekke	12.5 MNOK	2019-2022	NFR MAROFF	NTNU, DNV GL, Kongsberg Maritime, Maritime Robotics	3 PhD
Characteristic Environmental Loads and Load effects on Floating Bridges	Torgeir Moan	MNOK 4.86	2017-2020	NPRA	NTNU	2 postdoc.
Fault detection and diagnosis in floating wind turbines	Torgeir Moan	MNOK 6 (NTNU)	2015-2019	Equinor, NTNU	NTNU, MIT, Equinor	2 PhD
Real-time hybrid model testing for extreme marine environments	Roger Skjetne	MNOK 16	2016-2020	NFR MAROFF	Sintef Ocean, NTNU, Equinor, Salmar, ABB	1 PhD, 1 post-doc
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 post-doc

PHOTO GALLERY

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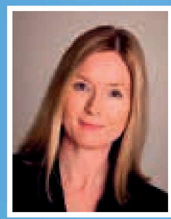

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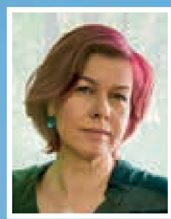

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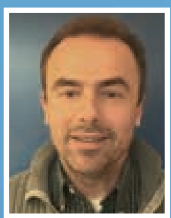

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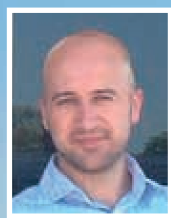

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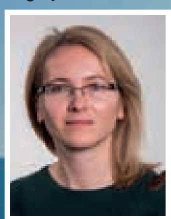

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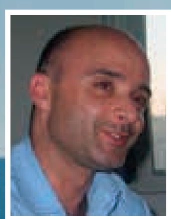

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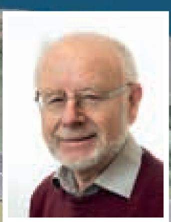

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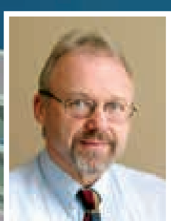

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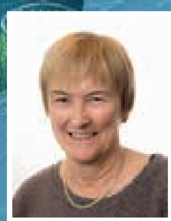

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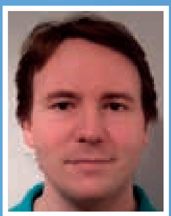
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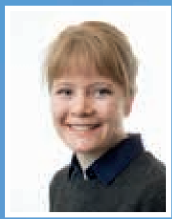
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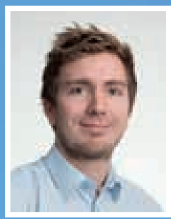
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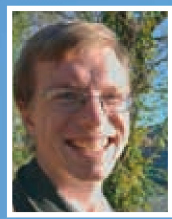
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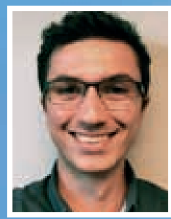
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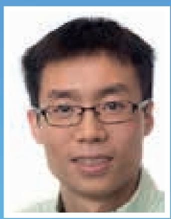
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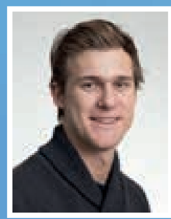
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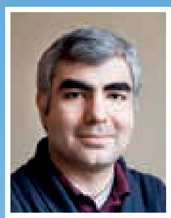
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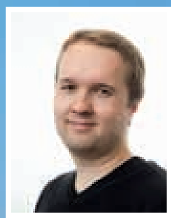
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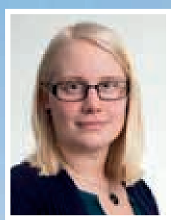
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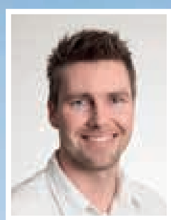
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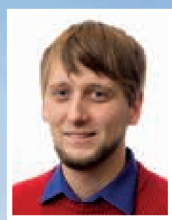
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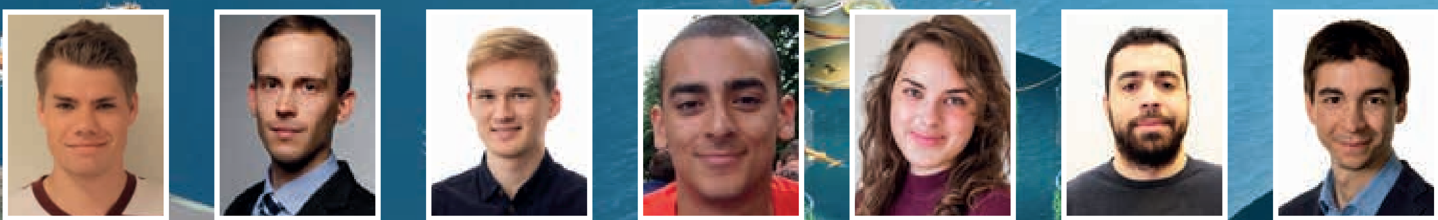

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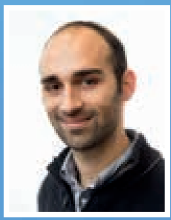
Evelyn Honoré-Livermore | Chenyu Luan | Shaojun Ma | Andreas B. Martinsen | Pål Holthe Mathisen | Siri H. Mathisen | Marianne Merz


Aksel Alstad Mogstad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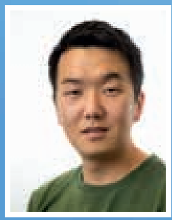
Woongshik Nam


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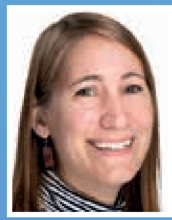
Harald Lennart Jonatan Olofsson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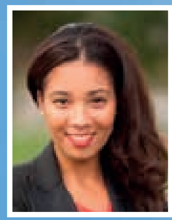
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Zhengru Ren

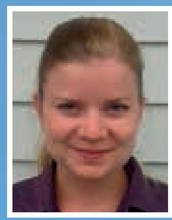

Christopher D. Rodin


Sverre Velten Rothmund


Thomas Sauder


Deng Shi


Mohd A. Siddiqui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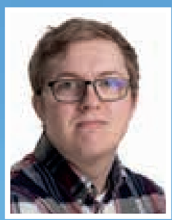
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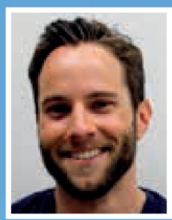
Carlos Souza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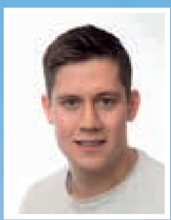
Stian Sørum


Christoph A. Thieme


Jørgen Sverdrup-Thygeson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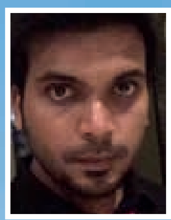
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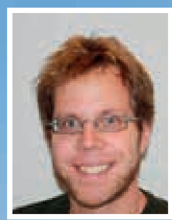
Stefan Vilsen


Andreas Wenz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Erik F. Wilthil


Mengning Wu


Hui-li Xu


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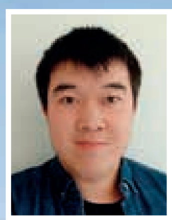
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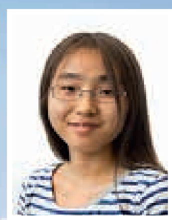
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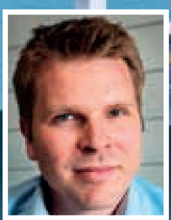
Artur Zolich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Ass. Prof. Ekaterina Kim

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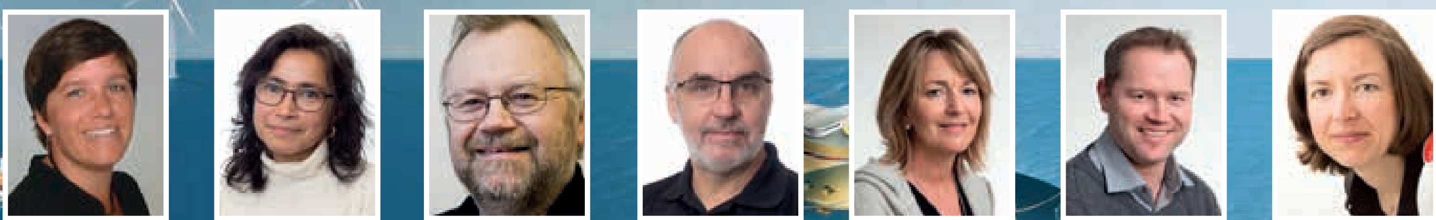


Ass. Prof. Nicole Aberle-Malzahn

Prof. Marta Molinas

Prof. Yngvar Olsen

Ass. Prof. Eilif Pedersen

Prof. Ingrid Schjølberg

Prof. Roger Skjetne

Ass. Prof. Annette Stahl

Prof. Oleksandr Tymokha

Prof. Ingrid Utne

Prof. Houxiang Zhang

LABORATORY HIGHLIGHTS AND RESEARCH CAMPAIGNS

Highlights of the Applied Underwater Vehicle laboratory (AUR lab)

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

Figure 1: *ASV Jetyak in Krossfjorden on Svalbard during a field campaign in April 2018*

To address challenges in the ocean space, the 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, where scientific questions are addressed by teams with specialists from many specialties. Opportunities for faculty, researchers, PhD- and MSc students to test and experiment is provided by enhancing hypotheses and theoretical work. Some of the scientific questions for 2018 have been related to coordinated vehicle networks, Arctic oceanography, and system autonomy. The Department of Marine Technology hosts the lab, and the University Museum, the Department of Engineering Cybernetics and the Department of Biology are partners.

Through the H2020 project SWARMS (http://swarms.eu), the AUR lab prepared our AUV Fridtjof to participate in the final project demo in Trondheim. The general approach of the project was to design and develop an integrated platform for a new generation of autonomous maritime and underwater operations, as a set of software/hardware components, adopted and incorporated into the current generation of maritime and underwater vehicles in order to improve the autonomy, robustness, cost-effectiveness and reliability of offshore operations, namely through a vehicles cooperation.
The NTNU vehicle was interfaced with the middleware developed in the project, which allowed coordinated operations of multiple vehicles to address applications such as plume detection. The demo was successfully conducted in June with more than 30 partners visiting.

Figure 2: *The AUVs used for the demo in the SWARMS project in the Trondheimfjord*

Figure 3

Figure 4

Figure 5

At the same time, the lab was part of a cruise in the Pacific in collaboration with the LSTS lab from the University of Porto and the Schmidt Ocean Institute (https://schmidtocean.org). The goal of this cruise was to demonstrate a novel approach to observe the ocean with multiple underwater, surface, and aerial vehicles, as well with the R/V Falkor, which was also used as the base and control center for all assets. The approach combined a set of new technologies that enabled scientists and engineers to obtain a synoptic view of the study area, with an adjustable spatial and temporal resolution, and to compare data collected in near real-time to the outputs of computational models. This approach was applied to map the Pacific Ocean's Subtropical front with unprecedented spatial and temporal resolutions.

In the fall, the lab took delivery of our new ROV which will be a main asset in the lab in the years to come. The vehicle has an open software development interface, and can run using our own control system. The planned underwater infrastructure in the Ocean Space Center – Fjord lab will take advantage of the system for operation, maintenance and research. In 2019, the vehicle will be equipped with a hydraulic seven-function manipulator arm, thus also enabling research for intervention tasks.

As part of the Nansen Legacy project (https://arvenetternansen.com), the AUR lab participated in a oceanographic process study north of Svalbard onboard the new Norwegian ice-going research vessel Kronprins Haakon in September. The AUV Harald equipped with CTD was programmed to find the front, and track the front through an adaptive mission plan. At 82°N, the vehicle was deployed close to the marginal ice zone and locked on to a front zone.

In combination, the Equinor AUR lab and AMOS will deploy a Subsea Docking Plate (SDP) at a depth of 360 meters. The unit will be connected to shore with an umbilical providing power and communication, which will provide a test facility for resident underwater vehicles. By connecting to the station, systems can be remotely monitored and controlled from anywhere. To help provide a stable foundation for the installation, a suction anchor will be installed on the seabed using the ROV Gunnerus and ROV SF 30k. The docking plate and the umbilical to shore will be installed in 2019.

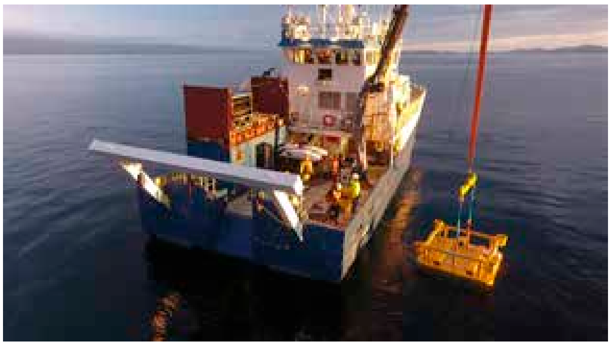


Figure 6

Highlights from small wave flume lab, IMT NTNU

Technical specifications
This small wave flume is 15 m long and 0.58 m wide, and its water depth can range between 0.8 m and 1.2 m. The large length-to-breadth ratio allows reproducing two-dimensional (2D) flow conditions in the flume, when studying wave-body interactions or forced body motions. The wave flume consists of a hinged wave maker at one end and a parabolic beach at the other end. The wave maker can generate waves for periods ranging from 0.6 to 2.2 seconds. Waves with a length less than 3 m can be handled inside the flume without any significant reflections from the beach. The flume also has a linear oscillator, which can be used to generate forced body motions. When forced motions are performed, beaches are used at both ends of the flume.

Experiments
A set of experiments were performed in 2018 in the wave flume on a thin-walled prismatic model (Figure 1), with damage along the side of the model. They represent repetitions and complementary tests of an extensive experimental campaign carried out in 2017 within the PhD studies of Mohd Atif Siddiqui, with Prof. Marilena Greco as the main supervisor. This PhD research focuses on the behavior of a damaged ship section in waves. The test was designed to obtain 2D behavior for the model, so therefore the model used was slightly smaller than the tank breadth. Forced heave motions and freely floating tests in beam sea waves were performed to study hydrodynamic forces and motions of a damaged model section. The tests help to identify the resonance behavior of floodwater inside the damaged compartment (example shown in Figure 2).

Forced heave motions are used to study the change in hydrodynamic forces on the damaged section compared to an intact section. Three forcing amplitudes (3mm, 5mm, 7 mm) were used, with forcing periods varying from 0.6 to 2.5 seconds. For forced heave tests, three filling depths in the damaged compartment were examined. These depths are associated with a different floodwater mass, and demonstrate flooding behavior associated with different submergence depths of the damaged opening. In addition, the influence of the size of the damage opening and of air compressibility in the damaged compartment was studied.

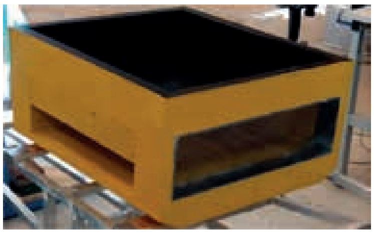


Figure 1: *Damaged model section*

Freely floating tests in beam sea waves were also performed to understand the effect of floodwater on the motions of the ship section. Wave periods ranged between 0.6 and 2.2 seconds, and were combined with two values of the wave steepness. The effect of asymmetric compartment damage, air compressibility and the size of the damage opening were studied. Finally, an initially dry freely floating model with a damage opening located above the draft waterline was tested in beam sea waves to study the transient flooding phase. The wave steepness, wave period and initial stability (KG) of the model were varied to identify cases when flooding occurred, in addition to the time duration of flooding. In this case, asymmetric compartment damage is used since it causes larger motions.

Forces and motions were measured in the forced and freely floating tests, respectively. Video recordings, measurements of wave elevation both inside and outside the damage compartment (using wave probes) were performed in all experiments. Accelerometers were placed to check the frequency and motions, and test repeatability and main error sources in the tests were established.

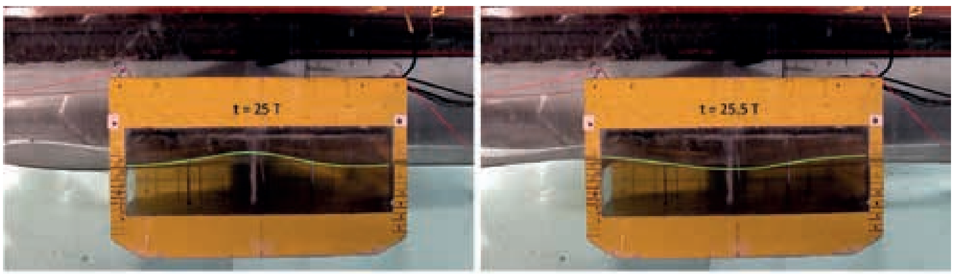


Figure 2: *Second sloshing mode inside the damaged compartment in beam sea waves with period T*

Highlights of the SmallSat Laboratory

AMOS and the Department of Engineering Cybernetics, together with the Department of Electronic Systems at NTNU, established a SmallSatellite (SmallSat) program in 2017. The SmallSat team is led by Professor Tor Arne Johansen, and consists of a multidisciplinary group of a few professors and approximately 30 students, consisting of bachelor's, master's and PhD students from a multitude of fields of study. The team's background spans electronics, cybernetics, mechanics, material science and more. The purpose is to design and operate a range of nano-satellite missions for maritime remote sensing and Arctic communications.

HYPer-spectral SmallSat for Ocean Observation (HYPSO)

The first mission, "HYPer-spectral SmallSat for Ocean Observation (HYPSO)", is a 6U CubeSat dedicated to detecting and monitoring harmful and non-harmful algal blooms, phytoplankton and river plumes, as well as sediments and pollution in the ocean. In Q2 2020, it is scheduled to be launched from India with the Polar Satellite Launch Vehicle (PSLV) into a Sun-Synchronous Orbit (SSO) at an altitude of 500 km.

HYPSO's payload is an in-house hyperspectral imager (HSI) designed with spectral range of 400-800 nm, a spectral resolution of 5 nm and a Swath Width of 70 km. The NTNU SmallSat team is working extensively on the calibration, characterization and mechanical design of the camera in order to work optimally in an unforgivingly harsh space environment. Additionally, intelligent on-board image processing will leverage customized and compressed image products that contain readily calibrated data, high resolution, geo-referenced coordinates, target detection and a high signal-to-noise ratio.

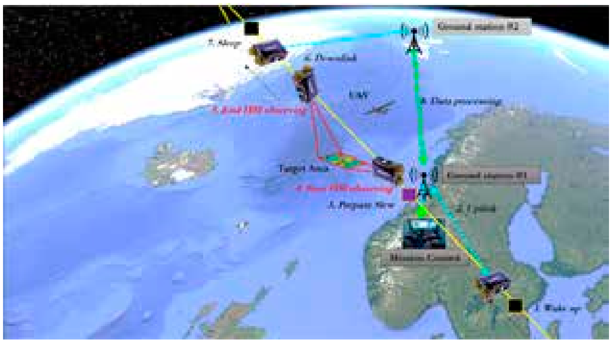


__Figure 1:__ HYPSO Concept of Operations (CONOPS). The goal is to enable quick communication among agents, imaging small target areas, automated on-board processing and the rapid downlink of images and other data products with relevant features for post-analysis and dissemination at NTNU mission control.

Upon an observable event, for example an algal bloom, appearing in the coast or in the ocean, the spacecraft will point in the direction of the target and perform a slew of maneuvers to effectively improve the ground sampling distance while scanning with the HSI. An on-board super-resolution algorithm will utilize these overlapping pixels to help enhance the effective spatial resolution to less than 40 meters.

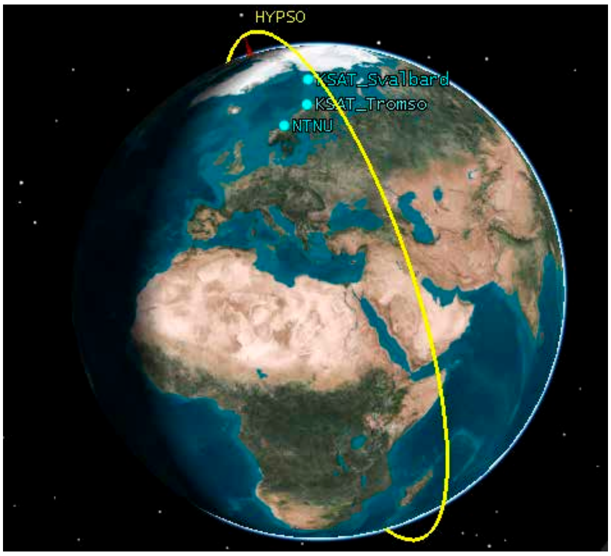


__Figure 2:__ HYPSO orbit configuration in SSO

Mission operations and data will be downloaded through a ground station and mission control center at NTNU, as well as through the Kongsberg Satellite Services (KSAT) ground station network.

Contrary to traditional multi-purpose Earth Observation (EO) satellites operated by agencies such as NASA and ESA, a constellation of CubeSats may considerably decrease costs, development time and risk while meeting several scientific objectives. Such a constellation gives rapid revisit times and may deliver important information about highly transient events that are difficult to otherwise monitor with ground assets only. With this in mind, CubeSat will directly augment and constitute a coordinated robotic platform consisting of UAVs, ASVs and AUVs for rapid synoptic ocean observations.

The spacecraft is based on the M6P 6U nano-satellite bus provided by NanoAvionics. The bus platform will provide a high power and battery capacity, a suite of navigational and attitude sensors, robust mechanical interfaces, UHF radio for communication and S-band radio for downlinking large amounts of data. Additionally, it has advanced attitude determination and control software to ensure high precision in the maneuvering and pointing procedures required during operations with the hyperspectral camera. Furthermore, the bus is planned to host secondary payloads: a software-defined radio (SDR) used for cross-link measurements from ground to the satellite, and a RGB camera to support the hyperspectral data characterization and calibration.

Hyperspectral imaging payload development and testing

The primary payload of the HYPSO mission is a hyper-spectral imager designed by Prof. Fred Sigernes with Commercial Off The Shelf (COTS) components, see Figure 5. This relatively low-cost imager fits into the 6U CubeSat design (the payload dimensions are within

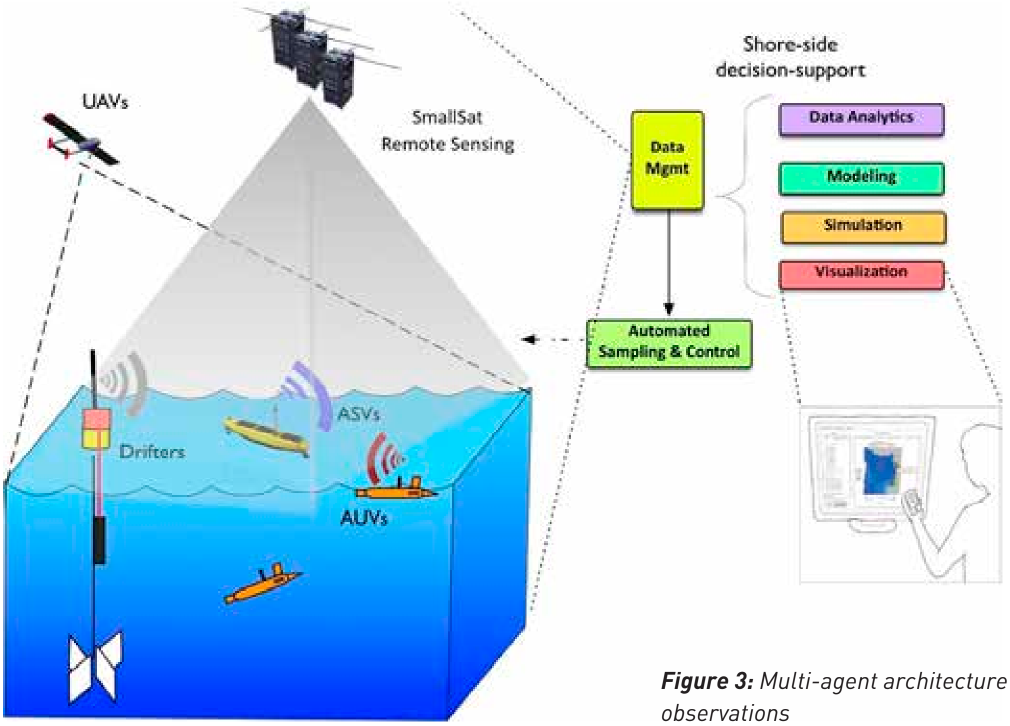


Figure 3: *Multi-agent architecture for synoptic ocean observations*

Figure 4: *M6P 6U nano-satellite bus, NanoAvionics*

Figure 5: *Prototype of HYPSO's primary payload, the hyperspectral imager (HSIv6) with satellite mounts [credit: Henrik Galtung, Tord Kaasa and Tuan Tran]*

30x10x10 cm), while still achieving a high spectral resolution. The improved spectral resolution will help researchers identify targets through comparing unique spectral signatures, and push the boundaries of more commonly used multi-spectral satellite data for ocean color applications. These advances will be made with a combination of innovative optical/mechanical assembly, maneuver planning, image processing software and cooperation with robotic agents closer to the target.

Testing this year commenced with the delivery of the first prototype of the imager. The initial step towards operation was an optical characterization. Since the imager has custom designed optics and interfaces with a commercial camera, it is imperative to understand its unique optical properties and how those properties translate to the hyperspectral imagery that the satellite will gather throughout the HYPSO space mission. Several calibration tests were run in NTNU's Optical Laboratory, as well as at the University Center at Svalbard and in the lab of Norsk Elektrooptikk. For radiometric (Figure 6) and spectral calibration, we used known light sources and an integrating sphere to convert raw sensor readings to readable units. Image distortions were characterized and corrected through a series of geometric light tests and software implementations.

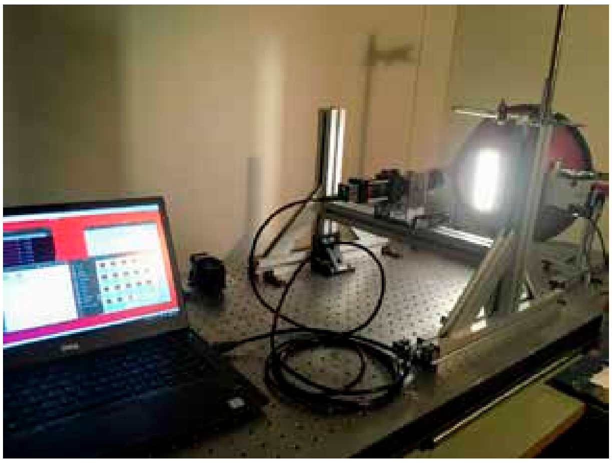


Figure 6:*. Radiometric calibration of the HSIv6 with an integrating sphere*

The HSIv6 took its maiden flight in November 2018 at the Udduvoll Remote-Controlled (RC) aircraft field just south of Trondheim. The UAVlab assisted in integrating the imager payload on their DJI S1000 octocopter, see Figure 7. This flight test was proof of the concept as it involved coordinating the new imager, DUNE software environment developed at the LSTS lab in Porto, Portugal (an AMOS International collaborator), the SenTiBoard or sensor timing board developed at the UAVlab and various other electronic components. Despite the low lighting conditions of Trondheim in November, the researchers were able to obtain hyperspectral images of differing ground targets, thereby signaling a green light for further testing.

Figure 7: *The HSIv6 mounted on the DJI S1000 octocopter UAV, from NTNU UAVlab*

At the end of November, the team shipped the HSIv6 imager and octocopter to Porto for a first look at ocean color from above. Porto was selected for its proximity to the outlet of the Douro River, where yellow/brown (or "gilded" as douro translates from Portuguese) river waters mix with the ocean - a visibly distinct color gradient. Additionally, the river outlet is located a few minutes from the LSTS lab at the University of Porto, with the south promising more sunshine (necessary for the imager, of course). The LSTS crew helped the team establish a ground station for UAV operations at the river outlet, and the UAV flew several flights despite challenging weather conditions.

Selected media coverage:

- https://www.tu.no/artikler/smallsat-lab-sender-kamera-i-bane-rundt-jorda-for-a-hjelpe-laks-a-unnga-alger/449407
- https://fiskeribladet.no/tekfisk/nyheter/?artikkel=63368

Highlights of the Unmanned Aerial Vehicle Laboratory

Autonomous recovery system for fixed-wing UAVs

An autonomous recovery system for fixed-wing UAVs, which is using a line suspended between two multi-rotor UAVs to catch a line with a hook hanging from a fixed-wing UAV. This method of recovery is particularly suitable for recovery in space-constrained areas, such as on small ships. The concept is presented in reference UAV-R1, and is developed based on the net recovery concept previously presented in reference UAV-R2. The research was primarily funded by the EU's H2020 program through the MarineUAS innovative training network.

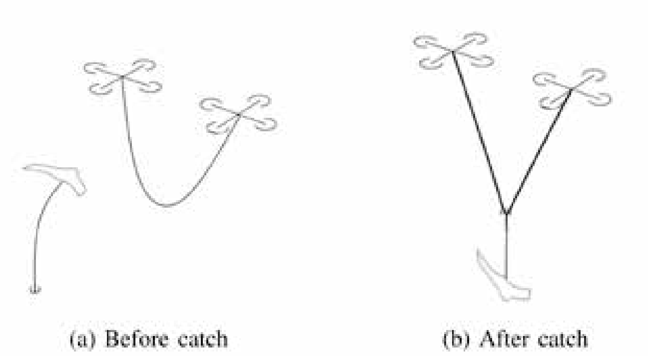


Figure 1: *A sketch of this system is shown in part (a). In order for the catch to happen, the fixed-wing UAV passes under and in-between the multirotors, such that the catch line crosses the multirotor line. When the fixed-wing UAV passes the multirotors, the hook at the end of the catch line will catch the multirotor line, and the fixed-wing is thereby caught. After the catch, the fixed-wing hangs below the multirotors as seen in part (b), and can be lowered to the ground for a successful recovery.*

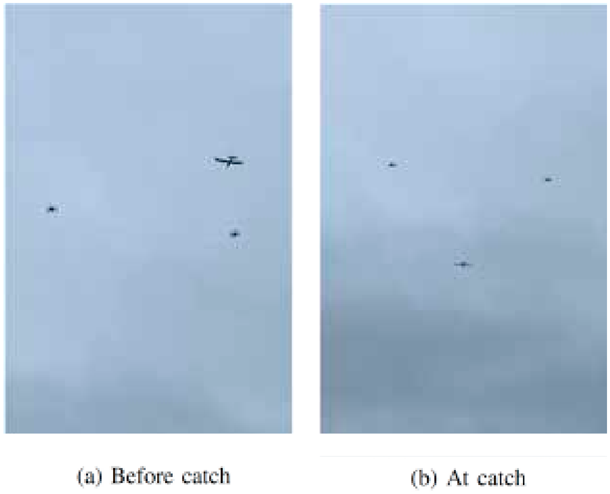


Figure 2: *Pictures from the experiments at Eggemoen jointly with Maritime Robotics AS. Part (a) shows the moment just before the catch. Part (b) shows the moment of the catch. Notice that the hook from the catch line is attached to the multirotor line, but the fixed-wing UAV is still flying.*

A control system has been developed for the proposed recovery concept, and the concept is validated through experiments. The results include 17 test runs and three successful recoveries. The multirotors were able to track the fixed-wing UAV, with a mean error of 0.8 m at the moment the catch would have taken place in the 17 test runs. The margins for missing for the three recoveries were 1.0-2.1 m, demonstrating that this recovery method is relatively robust.

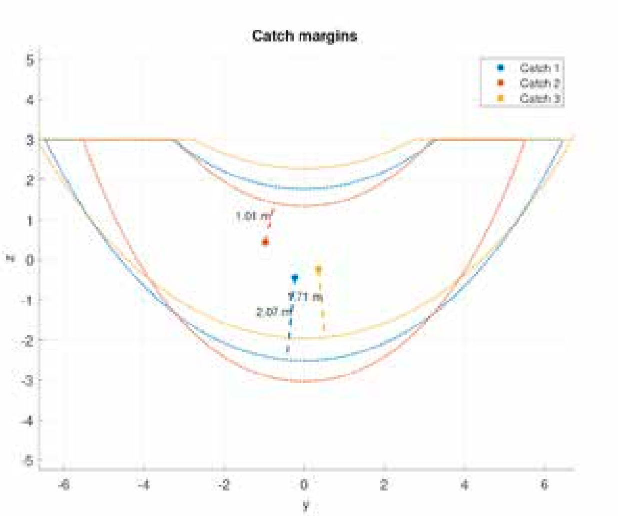


Figure 3: *Margins for missing the catch for each of the three catches. The smallest margin and direction are marked.*

Icing wind tunnel testing on UAVs

Unmanned aerial vehicles (UAVs) can be used for a multitude of autonomous applications, e.g., remote sensing, search and rescue, oil spill detection or ship-based iceberg tracking. One of today's significant limitation on the operational envelope of such UAVs is atmospheric icing. This phenomenon is also called in-cloud icing, and occurs when aircrafts traverse clouds consisting of super-cooled liquid droplets. In such an environment, ice accumulates on the wings, sensors and propellers of the UAVs, which often causes the vehicles to crash due to a degradation of the aerodynamic performance.

Figure 4: *Examples of icing that was built up on the leading edge of wing during tests*

Within AMOS, we are working on understanding the underlying physical processes, and aim to develop suitable mitigation technologies. Within this workgroup, we have been visiting the icing wind tunnel facilities at the University of Cranfield (UK) in the autumn of 2018. There, we have performed a series of experiments under controlled conditions. The main objectives were to generate validation data for numerical simulation models and to test an icing mitigation prototype developed in collaboration with UBIQ Aerospace, which is a technology spin-off originated from AMOS aimed to develop and commercialize icing protection systems for UAVs. The system is based on a nano-carbon coating that can be electrically heated.

The test campaign was conducted successfully, and we obtained valuable data for our future research. We have collected the ice geometries that result on wings in different icing conditions, and will compare them to predictions from our numeric tools. The icing protection system has proven that it is capable to automatically identify icing conditions and active mitigation measures.

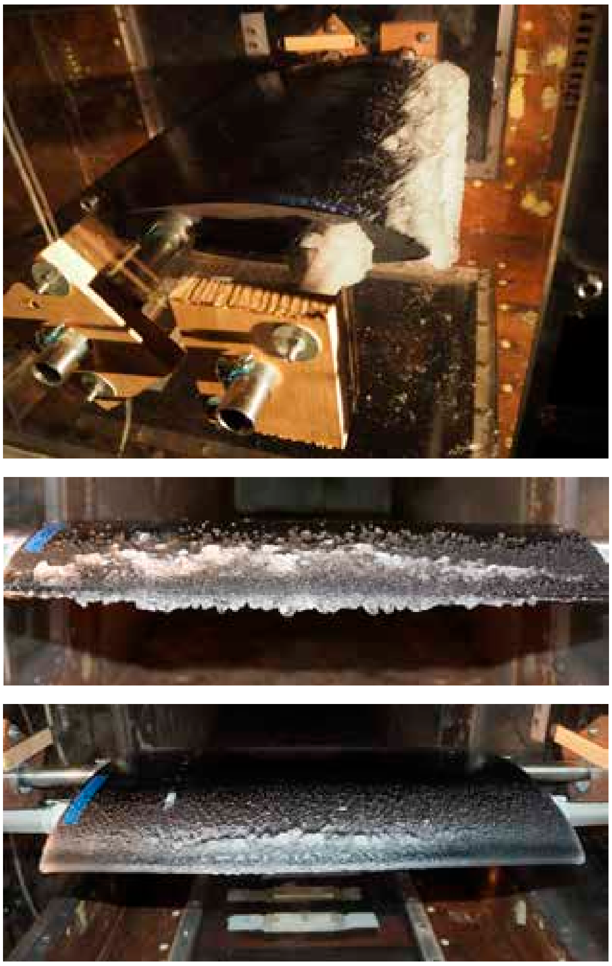


Figure 5: *The upper and lower part show different kinds of icing accretion test during severe icing conditions.*

Selected references:

- UAV-R1. M. F. Bornebusch, and T. A. Johansen, Autonomous recovery of a Fixed-wing UAV Using a Line Suspended between Two Multirotor UAVs, submitted for publication, 2019.
- UAV-R2. K. Klausen, T. A. Johansen, and T. I. Fossen, Autonomous Recovery of a Fixed-Wing UAV Using a Net Suspended by Two Multirotor UAVs, J. Field wRobotics, Vol. 35, pp. 717-731, 2018; DOI: https://doi.org/10.1002/rob.21772

HONOURS AND AWARDS

Kristin Y. Pettersen was appointed a Distinguished Lecturer of the IEEE Control Systems Society, in 2018.

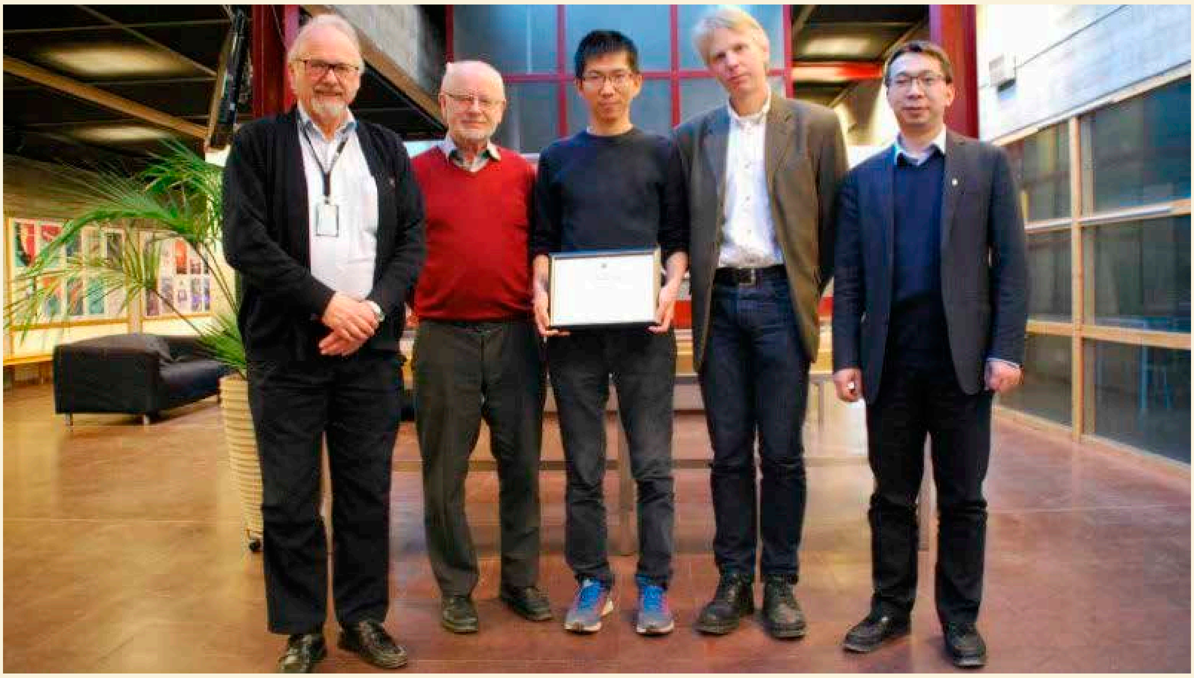
Walter Caharija received SINTEF's 2018 award for outstanding research. The researcher received the award for a much quoted scientific article. There, Walter Caharija describes research he has done - through his PhD study at NTNU AMOS - on a control system for autonomous ships. The system is designed to keep a predetermined course under the influence of waves, currents and wind.

During AMOS day 2018, Professor Mogens Blanke of DTU was honored with not one, but two honorable knight appointments. Professor Blanke was inducted into the Order of the Golden Anchor, and the Order of the Golden Feedback Loop for his outstanding contribution to the research and education in cooperation between NTNU and DTU.

Odd Magnus Faltinsen receives the CEMT Award for Outstanding Contribution to the European Maritime Industry 2017. Odd Magnus Faltinsen receives the 2017 CEMT Award, in recognition of distinguished career in naval architecture and ocean engineering for nearly 50 years, and of exceptional contribution in the field of hydrodynamics.

The CEMT Award is presented annually by the Council of the Confederation of European Maritime Technology Societies (CEMT) in recognition of the outstanding contribution made to the success of the global maritime industry by an individual, company or organization based in Europe. Such a contribution may be technological, political or economic, and may have been achieved by a personal contribution over a period of time, or by the recent introduction of a product or service.

2018 marked the fourth year for the Moan-Faltinsen Best Paper Award. Zhaolong Yu, from NTNU, won the Moan-Faltinsen Best Paper Award on Marine Structural Mechanics/Dynamics 2018, and Guoqiang Tang, from Dalian University of Technology, won the Moan-Faltinsen Best Paper Award on Marine Hydrodynamics 2018.



Professor Tor Arne Johansen has received NTNU's award for innovation and business collaboration for 2018. Tor Arne Johansen has had an excellent academic career as one of NTNU's most published professors, especially known as NTNU's serial entrepreneur. He currently works with autonomous systems, such as drone aircraft, small satellites and autonomous ships.

RESEARCHER-DRIVEN INNOVATION AT NTNU AMOS

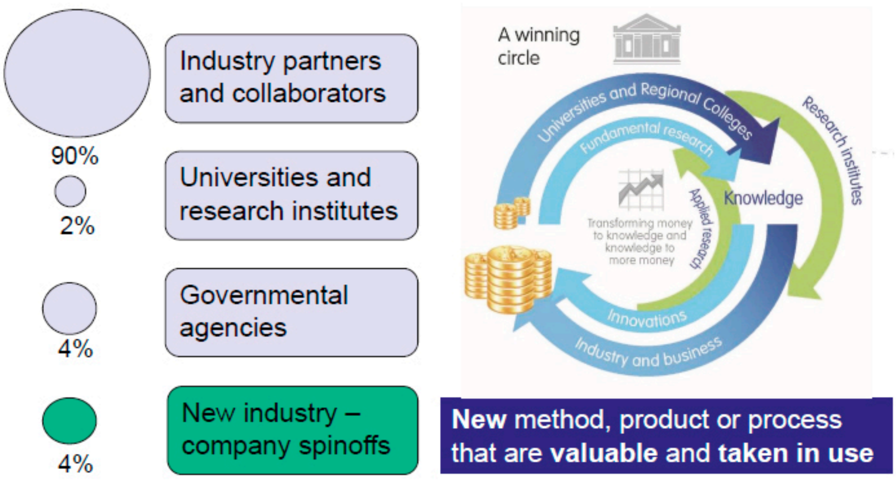
At AMOS, the main research direction developed in 2011/2012 was defined towards increased digitalization, robotics and autonomous systems, including artificial intelligence operating in a marine domain. Research accomplishments from AMOS have been true to this strategy. Major achievements were accomplished 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.

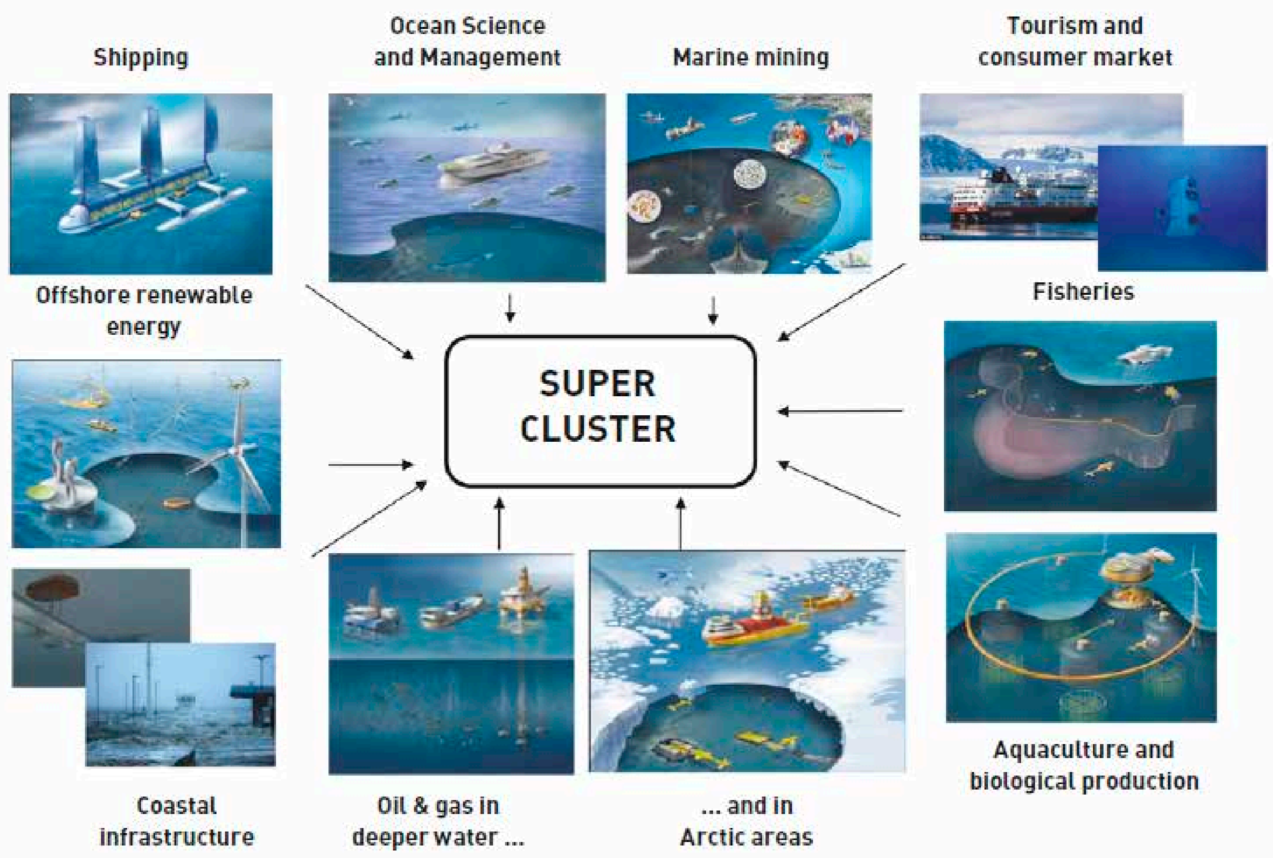
Because AMOS was clearly affected by this wave and rapid transition both socially and industrially, it became a huge responsibility to secure new industry positions that were about to be created. That is why the AMOS School of Innovation, later known as the Ocean School of Innovation, was established. 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.

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.



Innovation arenas at the NTNU AMOS



The blue economy that comprises a super cluster over Norway.

Interview with Tor Arne Johansen

One of the two recipients of NTNU's 2018 Prize for Innovation and Cooperation with Private Industry was Tor Arne Johansen. Johansen is Professor at the Department for Engineering Cybernetics at NTNU, and one of the key scientists at AMOS.

The prize is awarded to an employee or research group who have contributed to NTNU's goal to promote research-based innovation and cooperation with private industry and business.

Johansen is one of NTNU's top publishing researchers, and is currently working on autonomous systems for ships, drones and small satellites. He says that it is an honor to be recognized in this way.

"It is a great honor, and a recognition of the work that not only I have been doing, but perhaps even more the innovative organizations and smart people that I work with. This includes colleagues in AMOS, the department, industrial partners, NTNU's Technology Transfer Office and students and co-founders. In particular, the award is certainly a recognition of the innovation strategy and outcomes of AMOS, where center leader Asgeir Sørensen and co-leader Thor Fossen need to be mentioned", says Johansen.

NTNU encourages its employees to look for areas where research results can be used for innovation. What is your approach to this kind of work?

"I think that it is useful to combine fundamental research with an eye for applications and commercial opportunities in collaboration with end users. This combination can create unique ideas and opportunities that gives a competitive edge. Innovation is not only about making something that is new and useful, but actually taking it into the market so it is being used."

Over the years you have worked on many different projects. Are there any of these of which you are particularly proud of?

"There are many industrial collaboration projects across industries such as automotive, maritime and aerospace that should be mentioned. Much of this has happened within joint research and innovation projects where the results have been used directly or indirectly by established companies. I was also heavily involved for many years in the company Marine Cybernetics, which we established to introduce hardware-in-the-loop simulation testing, in order to increase safety and efficiency in software-based control systems in the maritime and offshore industries. The company was acquired by DNV GL, and has had an impact through improved international standards, classification rules and services. The recent spin-off companies Scout Drone Inspection AS and UBIQ Aerospace AS are direct outcomes of AMOS technology and doctoral candidates. They have great potential to conquer international markets, but are of course still in their very early stages.

Innovation has traditionally been an area where private business and industry have dominated. What role can academia play in these processes?

"Academia needs to provide fundamental and applied research and education as a basis for innovation. In my opinion, supplying the industry with competent candidates and participating in joint research and innovation projects is our primary role. In exceptional cases, when the established industry is not able or willing to take the opportunities that are created through new research results, the university should establish spin-off companies to put results into use. It is not the university's role to compete with the private sector."

The value for the private sector is obvious, but what can scientists and students gain by looking for the business potential in their research?

"Innovation processes are focused on the usefulness and use of the research outcomes, and provide highly valuable insight into the relevance of our research and education."

What is your best advice for other scientists and researchers that want to collaborate more closely with private business and industry?

"Be curious, listen to the industry, learn about its business, understand its products and services, work with them and identify what are the opportunities and needs. This is not easy, it will take a lot of time, and you need to be committed. Then use your toolbox with methods and knowledge, and figure out how it can be used, both to make disruptive and incremental differences that create value."

A fresh look at research-based innovation

Innovation is a core area in NTNU's strategy for 2018-2025, and the university recently hired fifteen innovation managers to help realize more of the innovation potential in research and research collaboration.

AMOS will be served in this capacity by the innovation manager at NTNU Oceans, Kjell Olav Skjølsvik. Skjølsvik has his engineering degree from the Department of Marine Technology at NTNU, and has extensive experience working on innovation processes in the private sector.

He will be working to improve the University's innovation activity, and to increase the knowledge about innovation processes among researchers and students, and even challenge the way many scientists thinks about innovation.

"An important task will be to use the excellent research done at NTNTU, to bring forward new ideas, ideas that can be developed into new business opportunities in collaboration with the industry and the public sector", says Skjølsvik.

Connecting scientific research and innovation has not always been a priority in academia, but this is set to change as more and more academic institutions are focusing on the innovation potential inherent in their research.

"The foundation for knowledge-based innovation is established by the research being done at universities like NTNU. Looking past the knowledge that our students bring with them when they graduate, the research done here is generating large amounts of new knowledge that can be put to use in the development of new products, services and processes", says Skjølsvik.

He thinks one of the roles of academia is to identify the potential in the research being conducted, and to inform the industry about prospective new technologies or methods, or even to develop these ourselves when required.

"NTNU's vision is 'knowledge for a better world', and I interpret that to mean that we have to take responsibility and ensure that new knowledge is taken into use to create positive effects for the society, and we achieve this through innovation", says Skjølsvik.

What kind of innovation potential do you see in the work being done at AMOS?

"So far, I have only been able to look at a fraction of the research being done here, but my impression is that the potential must be huge. We are already seeing some results already, for example" the development of new underwater robotics technology and new design tools based on research results", says Skjølsvik.

He says that the experience of going from industry to working with innovation in academia has been exciting.

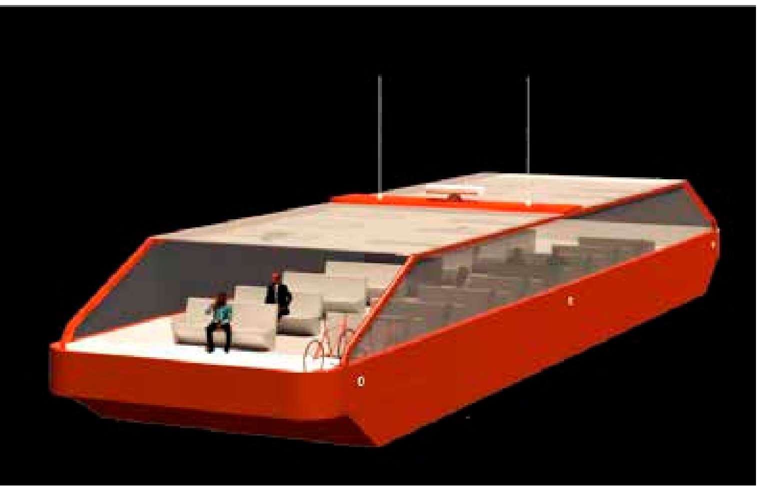
"I am learning a lot, and am working with experts in several very exciting fields. The biggest change is probably that research processes are more long-term than what I am used to from working as a consultant in the marine and offshore industry. For me the most important thing now at the beginning is to get to know the people and all the different research activities going on here; that is key for a position like mine."

Reusing the old waterways of modern cities

New technology from NTNU is about to bring back an old mode of transportation. In many Norwegian cities there used to be several small boats, often rowed by a single man, ferrying people back and forth across the canals and rivers. Today, these mini-ferries are long gone, but new technology for autonomous vessels may help bring them back in a new form.

"We are creating the world's first autonomous bicycle and passenger ferry here at NTNU. Back in the day, there used to be 'fløtmenn', who would row people over the rivers or city canals for a fee. Autonomous ferries can bring this system back to life. It would be a very cost-efficient alternative to building expensive bridges", says Morten Breivik.

Figur 1: *milliAmpére on a test run*



Figur 2: *Concept for a larger passenger ferry*

Breivik, head of the Department of Engineering Cybernetics and an associate scientist at AMOS, is one of the key researchers working on the Autoferry project.

The project's hypothesis is that these small ferries will be able to operate safely together with several other vessels in confined areas such as rivers, harbors and canals. In order to do this, the ferry must have a set of advanced sensors, such as radar, LIDAR, infrared and optical cameras to sense their surroundings, as well as GPS for navigation. The vessel will also need advanced autonomy software to enable it to make decisions on its own.

In order to achieve this, researchers must work across research disciplines, with Autoferry involving students and scientists from several different disciplines, from Marine Technology and Cybernetics to Design and Architecture.

"It is an interdisciplinary project, which is the only way to succeed with this kind of technology. We will install new sensors on milliAmpére, our test vessel, soon. In the time ahead, we will focus on developing advanced autonomy for controlling the ferry", says Breivik.

NTNU recently received Forny funds from the Norwegian Research Council, which will go towards further developing and verifying the autonomy systems of the ferry in in realistic operational conditions and getting the technology closer to commercialization.

The next step for the project is to create a full-scale ferry, and several Norwegian cities have already shown interest in such a solution. Cities such as Stavanger, Tønsberg and Kristiansund all see great potential in an autonomous passenger ferry.

The ferries will be very cost-efficient to operate, since a single person can monitor several ferries at the same time, and they will generate new jobs for a market that does not currently exist.- The old "fløtmann" profession disappeared a long time ago, so this technology will not replace humans with autonomous systems. Instead, the construction, maintenance and monitoring of these ferries will create new jobs that do not exist today. You really get the best of both worlds. The cities will save money, as these ferries are far cheaper than building expensive bridges, and the ferries will create new jobs and give more flexible transportation opportunities.

Adaptive sampling of fronts with AUVs in the Arctic Ocean

Figure 1: *Adaptive sampling of fronts with AUVs in the Arctic Ocean*

On September 12, 2018, the R/V Kronprins Haakon left Longyearbyen on the second cruise for the research project named "the Nansen Legacy". Its goal was to study oceanographic processes north of Svalbard, in order to understand the effects of changes in the water masses due to the inflow of Atlantic water masses.

The climate is changing fast, especially in the Arctic Ocean, where extant sea ice continues to decease. Understanding the effects of the changing climate on the fragile Arctic ecosystem is of utmost importance, as changes in the sea ice cover will have direct consequences on the ecosystem.

The team that left Longyearbyen was a diverse group, consisting of scientists from the fields of oceanography, marine technology and meteorology, as well as an outreach group. Among them were members of AMOS's AUR lab.

To better understand ocean processes, it is necessary to collect measurements of the water column. The standard method for acquiring the measurements is to use moorings and point samples of conductivity and temperature at different depths (CTD). The point samples provide a sparse set of spatially distributed measurements, while the moorings provide excellent temporal coverage and resolution, but are very limited in their spatial distribution.

Gliders are a type of unmanned underwater vehicles (UUVs) that utilize changes in buoyancy to produce forward thrust, and these vehicles have been used extensively to understand large-scale ocean processes. During the Legacy cruise, two such gliders were deployed. One would collect measurements for several months; the other glider was recovered after nine days out in the ocean.

Glider measurements have a limited resolution, since gliders often move slower than the water masses they are sampling. Autonomous underwater vehicles (AUVs) are a class of UUVs that are propeller driven, which have the potential to deliver high-resolution, spatially

Figure 2: Launch of the Light AUV (LAUV) Harald used for water-column sampling during the Legacy cruise.

distributed samples of the water masses. However, the ocean is vast, and care must be taken to utilize the resource in an optimal manner.

The goal of the group from the Applied Underwater Robotics laboratory (AUR lab) at NTNU (Norwegian University of Science and Technology) was to test and collect data using a method for adaptively sampling fronts. Fronts are characterized by large temperature and salinity changes over relatively short distances, which can indicate layers of different water masses. The tracking and sampling of fronts are important to help increase the understanding of different oceanographic processes, but time and resources are limited, so the use of the available platform must therefore be optimized.

This is where adaptive path planning comes into play – instead of providing a complete coverage of an area, the vehicle will be attracted towards areas of interest, thus increasing the time spent sampling the important processes. The path of the robot is usually planned prior to the launch of the vehicle, and the vehicle will follow this path until the mission is completed.

This is inefficient, since the robot acquires new knowledge as the mission progresses. By utilizing this new information to alter the path of the robot, a more efficient path, with respect to the scientific objective, can be achieved. This is called adaptive path planning – the robot adapts its plan based on new information. This allows us to define scientific objectives, attracting the robot towards areas of interest, rather than defining large areas that the robot should cover, which in turn allows an increased utilization of time and sparse resources.

The developed method was applied to track an Arctic front at 82º north, where melt water from the ice and warmer Atlantic water mixed. The front that was tracked was characterized by a large temperature gradient in the upper part of the water column, with temperatures down to zero degrees.

Normally, an AUV mission consists of preprogrammed waypoints, and the vehicle follows a deterministic path. In adaptive path planning, the mission is generated online based on what the vehicle is sensing. This complicates the operation, since it induces uncertainty into the behavior of the vehicle – it is not easy to identify if the vehicle is behaving as it should, or if something has gone wrong.

An operation at Arctic latitudes is further complicated by harsh environmental conditions, severely limited communication, in addition to the possibility of drifting sea ice entering the operational area. Nonetheless, the AUV was successful in tracking the front, with an illustration of the front shown in Figure 3.

Further development of methods like this will save time and money, and may help researchers answer important questions that have previously suffered from undersampling.

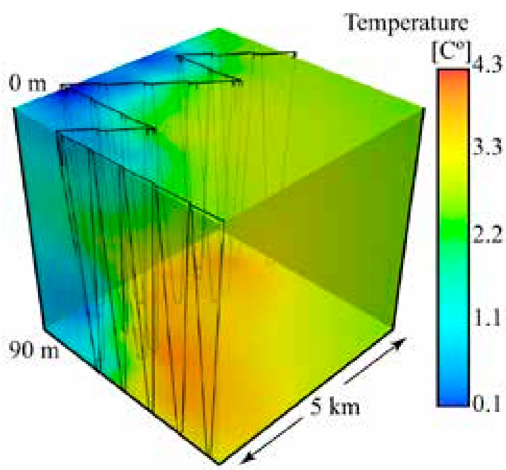


Figure 3: Path generated from measurements of the front. The cold water masses are shown as blue in the figure, and the black line illustrates the path of the robot.

INTERVIEWS WITH PHD CANDIDATES AND POSTDOCS

Helping drones navigate

Pål Holthe Mathisen is one of the new PhD candidates at AMOS, and while his project is still in its early stages, he knows that he will be focusing on developing ways to control and help aerial drones navigate.

The hope is that he and his colleagues at AMOS and NTNU will be able to create systems that allow drones to operate on their own in almost any type of environment while completing a given set of goals.

"One of the things we want to do is to make it possible to use autonomous drones to make it safer to carry out inspections and the maintenance of rooms and other confined spaces, such as oil tanks of various shapes and sizes. In order to do that, the drones have to be able to navigate properly without input from humans", explains Mathisen.

Operating indoors creates a completely new set of challenges for drones, as the control systems are unable to make use of input like GPS signals to help them orient themselves. If you want a drone to be able to operate autonomously in these conditions, you have to come up with new ways for the drone to navigate.

"The dream is that the operator only needs to throw out a few sensors that measures distance, and then the drone will be able to maneuver around on its own. This will enable the drone to operate in confines where it might be difficult, or even dangerous, for humans to move around", says Mathisen.

Mathisen has his academic background from the Department of Engineering Cybernetics at NTNU. Born and raised in Trondheim, both of Mathiesen's parents studied at NTNU, and he always expected to study there as well.

"The reason why I chose Cybernetics, among all the many options at NTNU, is that the study combines computer-programming, math and physics in an interesting way. It is also very applicable to the real world", says Mathisen.

He is certain that there is a lot of untapped potential in drones, and thinks that devoting the necessary resources to this line of research will be important.

"The industry is growing fast, and we need to be at the forefront of these developments. The potential areas of use are many, from geographic mapping, search and rescue, to industrial maintenance and surveillance."

The AMOS spin-off, SCOUT, is already developing small drones that can be used indoors, and Mathisen says that working close to the industry is paying off for everybody.

"It has been good to cooperate with companies like SCOUT. I gain valuable insight, and in a sense, the PhD candidates at AMOS are helping to build a possible future workplace."

Closing the cage

Salmon is one of the most important exports in Norway, and the value is growing rapidly, although the business has also come under fire from environmentalists, who claim that fish farms pollute the fjords and oceans, and that escaped salmon and lice are a threat to the wild salmon populations of Norway.

Closed fish cages are seen by many as one of the solutions to these problems, and Ida Strand is at the forefront of the research being done in this area. Strand just finished her PhD on closed flexible fish cages, but she will continue to work on her chosen research topic as a researcher at AMOS in the coming years. As a researcher, she will continue her work on closed cages, but will also look into other material such as concrete and steel, materials that might be better suited to some geographic areas.

"In my PhD we found that the flexible cage behaves very differently when full of water, then when only half full. If the cage is not full, the loads from currents on the mooring system can double. This has major implications for the way the cage is constructed", says Strand.

That does not mean that concrete and steel are necessarily preferable, Strand tells us. Where the currents are relatively week, and the waves are low, flexible cages may allow the industry to farm fish in areas that have been previously closed due to environmental concerns.

The advantages to closed cages are many. They greatly reduce the number of lice present on the fish, which is a recurring problem for the industry, and they also make it easier to deal with waste.

"With open cages, waste will be spread around the ocean by waves and current, whereas with closed cages, it will sink to the bottom of the cage where it can be collected relatively easily. With some processing, this waste could then be used as fertilizers", says Strand.

Nevertheless, Strand does not expect the industry to make a complete shift to closed cages any time soon.

"The closed cages are more expensive, and there are several risks connected to them. One is the possibility of massive fish death. New technologies coupled with biology can lead to the mass mortality of fish if something goes wrong. Research into this has shown that the advantages and possibilities are many, but there are some serious costs and risks to it as well", says Strand.

Combining the virtual and reality

Thomas Sauder finished his Msc at the Department for Marine Technology at NTNU in 2007, but waited for quite some time before he took the leap and started on his PhD.

"I think it is important to study something that you find exciting, which is why I waited for so long. I needed to find the perfect research topic for me", he says.

That research topic is the real-time hybrid testing of floating systems.

Normally, the testing of floating systems, such as oil platforms, would be carried out by testing models in tanks of various sizes. However, the Ocean basin at Tyholt is too shallow to test systems that are meant to operate in ultra-deep oceans.

"If we were to use the Ocean basin to simulate the effect that waves and wind have on these kind of structures, the models would have to be so small that the results would be too inaccurate", says Sauder.

Enter hybrid testing, a research method in which parts of the experiment are done in a conventional laboratory and the rest is replaced by virtual models. By combining the two in real-time, one can test how structures will behave, even in ultra-deep oceans.

Sauder's PhD focuses in particular on the fidelity of the results you get when you try to incorporate the real-world experiments with virtual calculations.

"My project examines the difference in results that we get by combining these two very different worlds, and looks at how we can reduce these differences as much as possible", says Sauder.

The applications for this method are many, from developing oil platforms, wind farms and floating bridges, to better power systems on-board ships.

Originally from France, Sauder has made a new home for himself in Norway, and will return to his old employer, SINTEF Ocean, now that the PhD is completed.

"It has been incredible to be allowed to work on this topic for my PhD. The work has been very challenging because no one has developed methods that we could fully rely on to analyze this problem. We are at the forefront of what we are doing. The method of hybrid testing is used in a few other fields, but is only at its beginning in Marine Technology, which is one of the reasons this is so exciting", explains Sauder.

Sauder defended his thesis December 2018, but has one piece of advice for others who want to take a PhD.

"Having worked a few years beforehand is vital in my experience. I worked eight years with SINTEF Ocean (formerly MARINTEK) before I started on my PhD, and this gave me relevant scientific experience, a very important network, and allowed me to be sure of what I wanted to study. It made completing the project easier", Sauder says.

The future is autonomous

Soon, a small passenger ferry will, hopefully, be travelling back and forth across the river Nidelven in Trondheim. The capacity is small, as only a handful of people can board the ferry at the same time, and the distance travelled is miniscule. Still, this ferry is autonomous, and represents a potential paradigm shift in the Norwegian transport system, a shift that scientists like Astrid Brodtkorb help drive forward.

Brodtkorb took her PhD at the Department of Marine Technology at Tyholt, but started working on her research topic during the final years of her master's degree.

"For me it was an advantage to start on my PhD degree straight after my master studies. This way the courses were still fresh in my mind, and I was able to keep working on the same research topics", says Brodtkorb.

Now she works as a postdoc at AMOS, and develops new methodologies for the design and verification of autonomous control systems. This is needed in order to achieve higher levels of autonomy. Both normal ships and AUVs (autonomous underwater vehicles) are areas that could make use of Brodtkorb's research.

"In autonomous ship operations, the control system needs to take over tasks that are traditionally performed by the operator. This introduces additional dynamics in the control loop, which have implications on the performance of the control system, and are therefore important to understand."

In manned ship operations today, the operator evaluates situations and makes decisions all the time. The control systems that are being developed will have to be able to do the same.

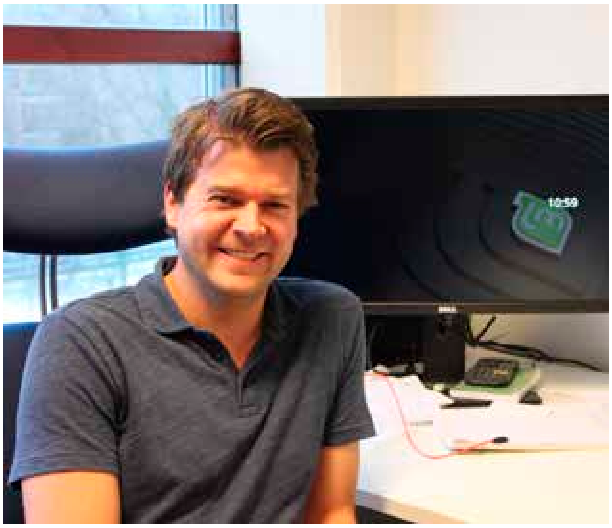
"In the case where a ferry is docking in order to load and unload passengers and cars, the ferry is not actually tethered to the docks. Instead, the captain uses the thrusters to keep the ferry in place. In order for a control system to be able to do this, it needs to have a good understanding of the vessel's surroundings in order to make the right decisions. My research will contribute to ensuring that these systems make the right decisions", says Brodtkorb.

The economic and environmental benefits are huge.

"Norway has many fjords, several of which are only crossable by large ferries. If these were autonomous, one could increase the number of ferries, while at the same time make them smaller and with electric propulsion", Brodtkorb explains.

"This would be cheaper than operating with a full crew, and could potentially be an excellent alternative to costly bridges and underwater car tunnels", says Brodtkorb.

Navigating under the ice



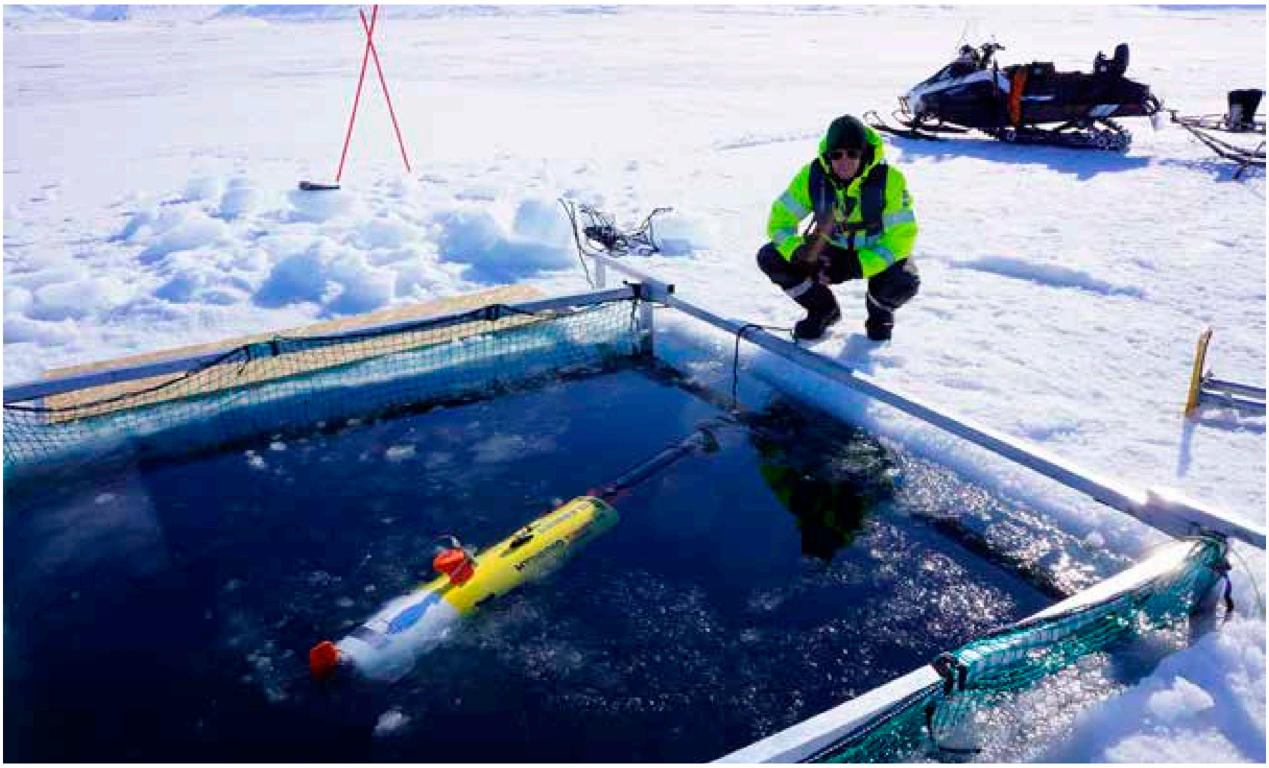
The ocean areas of the Arctic are some of the most unexplored areas on the planet, with miles upon miles of ocean hidden below a thick sheet of ice.

While more and more of the deep oceans of the world are being mapped, Arctic areas present a completely new problem: A problem that postdoc Petter Norgren is working on solving. Originally a graduate from the Department of Cybernetics at NTNU, Norgren worked on ways to use AUVs to map and monitor the sea ice in his PhD. Now the objective is to find ways for these AUVs to navigate safely below the ice.

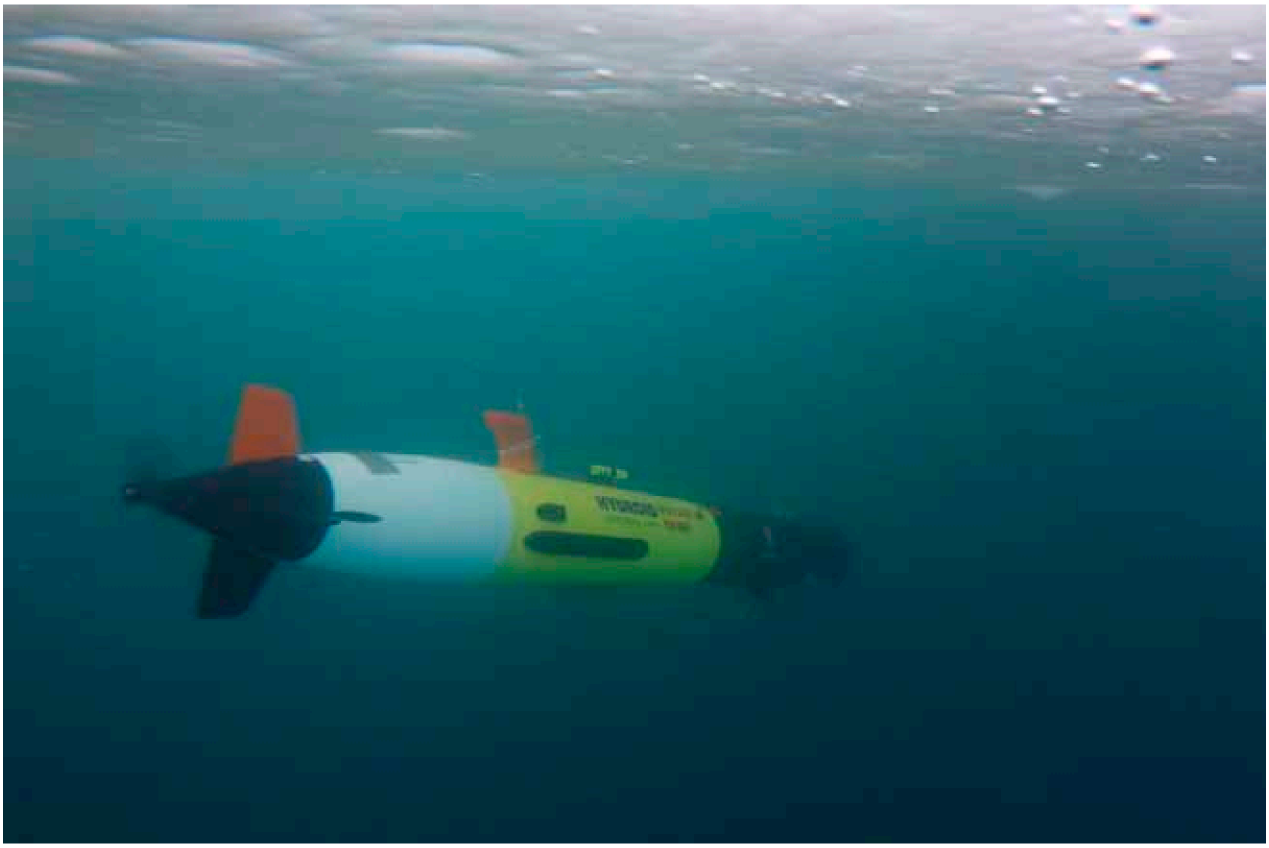
However, navigation below the ice is difficult, and traditional methods do not always work, Norgren tells us. For example, GPS is useless underwater, and as the ice keeps moving around it is difficult for the AUV to keep track of where it is. If the AUV does lose its bearings, it can be hard to get them back.

"When you operate an AUV, the normal failsafe procedure is to simply surface so that the scientists can pick it up. Now, for obvious reasons, this is impossible when you are operating under the ice. When you know that these things can cost anything between 1 million and 25 million Norwegian Kroners, you realize that it is imperative that the operator is able to retrieve it if anything goes wrong", explains Norgren.

The ability to navigate AUVs safely below the ice caps are important for both the field of biology and the field of oceanography.



Norgren and the AUV REMUS. Photo: AUR-lab.



REMUS under the ice. Photo: AUR-lab.

"With this technology, we can help answer questions about how the Arctic environment is changing because of climate change. Potentially this can help save species that are dependent upon the ice cover, and tell us more about what would happen if the ice disappeared completely", explains Norgren.

Nonetheless, there are other hidden "treasures" in the Arctic regions, in some cases, quite literally.

"Another exciting application for this technology is that it can be used to hunt for and discover old shipwrecks", says Norgren.

There are areas in the Arctic where ships have been lost that have never been examined due to ice and bad weather.

"We know of wrecks that date back to at least the 16th century, and due to the cold water and unique conditions of the Arctic, these shipwrecks will be much better preserved than wrecks found in warmer waters. There are, in other words, big archaeological opportunities connected to better navigation for AUVs", claims Norgren.

Even so, before one can start to look for shipwrecks, the navigational problems will need to be solved. Norgren and his colleagues have already tested the system once, and the results were not as good as they had hoped.

"When we tried to recover the AUV, it did not manage to hit the hole, but hit the ice and kept going. We had to use an ROV we borrowed from the AMOS spin-off company Blueeye to go get it", Norgren laughs.

Nevertheless, he is confident that they will get it right the second time around.

"We are going out to try out some new solutions soon, we just need to wait for the fjord to freeze over", says Norgren.

APPENDICES

NTNU AMOS personnel and collaborators

Annual accounts and man-year efforts

PhD Graduates

Publications in 2018

NTNU AMOS personnel and collaborators

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
Wold, Sigrid Bakken	Senior executive officer	SBW

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. Pettersen, 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	Marine hydrodynamics	OF
Prof. Moan, Torgeir	NTNU, Dept.Marine Technology	Marine structures	TM

Adjunct professors and adjunct associate professors

Name	Institution	Main field of research	Acronym
Adj. Ass. Prof. Alver, Morten Omholt	NTNU, Dept. of Cybernetics	Automation in fisheries and aquaculture	MOA
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. Føre, Martin	SINTEF Ocean	Fisheries and aquaculture	MF
Adj. Prof. Kruusmaa, Maarja	Talin University of Technology	Marine robotics	MK
Adj. Prof. Lugni, Claudio	CNR - INSEAN	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. Hassani, Vahid	SINTEF Ocean	Marine control	VH
Adj. Prof. Johansson, Karl Henrik	KTH	Automation and control	KHJ

Name	Institution	Main field of research	Acronym
Adj. Prof. Larsen, Kjell	Equinor	Marine operations and structures	KL
Adj. Ass. Prof. Nguyen, Trong Dong	DNV GL	Marine control systems	TDN
Adj. Prof. Rajan, Kanna	NTNU	Artificial intelligence	KR
Adj. Ass. Prof. Scibilia, Francesco	NTNU, Dept. Engineering Cybernetics	Remote sensing and autonomy	FS

Postdocs/researchers

Name	Institution	Main field of research	Acronym
Dr. Fragoso, Glaucia	Dept biology	Phytoplankton dynamics, biodiversoty, primary production, functional groups	GF
Dr Brodtkorb, Astrid H.	NTNU, Dept. of Marine Technology	Control architecture for autonomous ships	AHB
Dr Kohl, Anna	NTNU, Dept. of Cybernetics	Underwater swimming manipulators for subsea intervention	AK
	NTNU, Dept. of Cybernetics	Multiple Object Detection and Tracking with fixed wing UAVs	FSL
Dr Ommani, Babak	SINTEF Ocean	Numerical modelling for nonlinear stochastic processes	BO
Dr Sørensen, Kim Lynge	NTNU, Dept. Engineering Cybernetics	Development of icing protection solution for small unmanned aircraft	KLS
Dr Shen, Yugao	NTNU, Dept. of Marine Technology	Limits for fish-farm operations	YS
Dr Strand, Ida Marlen	NTNU, Dept. of Marine Technology	Closed Cages in Waves	IMS
Dr Zhaolong, Yu	NTNU, Dept. of Marine Techn.	Marine Structures	UZ
Amundsen, Morten	NTNU, Dept. Engineering Cybernetics	Drone inspection	MA
Bardhyl, Hajdini	NTNU, Dept. Engineering Cybernetics	UAV icing mitigation	HB
Dr Bryne, Torleif H	NTNU, Dept. Engineering Cybernetics	Multi-stage nonlinear state estimation	THB
Bornebusch, Mads	NTNU, Dept. Engineering Cybernetics	Recovery of fixed-wing UAVs	MB
Dr Cheng, Zhengshun	NTNU, CeSOS	Characteristic Environmental Loads and Load Effects for ULS and ALS design check of floating bridges. Offshore wind turbines.	ZC
Dr. Garrett, Joseph	NTNU, Dept. Engineering Cybernetics	Superresolution techniques for hyperspectral remote sensing	JG
Dr Haring, Mark	NTNU, Dept. Engineering Cybernetics	Nonlinear filtering and observer theory	MH
Dr Jiang, Zhiyu	NTNU, Dept. of Marine Technology	Marine operation; offshore wind turbine; design of marine structures	ZJ
Dr Klausen, Kristian	NTNU, Dept. of Cybernetics	Research on drones for industrial inspection.	KL
Dr Kelasidi, Elena	NTNU, Dept. Engineering Cybernetics	Resident Robot Manipulators for Subsea IMR	EK
Dr Kufoalor, Giorgio Kwame Minde	NTNU, Dept. Engineering Cybernetics	Anti-collision for ships, funded through the Autosea project	GKK
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 Rogne, Robert J.	NTNU, Dept. of Cybernetics	Airborne gravimetry using inertial navigation systems.	RHR

Name	Institution	Main field of research	Acronym
Dr Sha, Yanyan	NTNU, Dept. of Marine Technology	Ship collision analysis of floating bridges in Ferry Free E39 Project	YS
Dr. Stovner, Bård Nagy	NTNU, Dept. Engineering Cybernetics	Nonlinear estimation and control for UAV autopilots	BNS
Dr Wenz, Andreas Wolfgang	NTNU, Dept. Engineering Cybernetics	Flight performance, optimization and fault tolerance with hybrid power and propulsion	AW

Affiliated scientists

Name	Institution	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. Brekke, Edmund	NTNU, Dept.Engineering Cybernetics	Sensor fusion	EB
Ass. Prof. Bachynski, Erin E	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	EEB
Dr. Breivik, Morten	NTNU, Dept.Engineering Cybernetics	Nonlinear and adaptive motion control	MB
Dr. Colicchio, Giuseppina	CNR - INSEAN, Italy	Mesh generation and analysis for acomputational fluid mechanics	GC
Prof. Gao, Zhen	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	ZG
Prof. Imsland, Lars	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
Ass. Prof. Kiendl, Josef	NTNU, Dept.Marine Technology	Marine structures	JK
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. Molinas, Marta	NTNU, Dept.Engineering Cybernetics	Marine power systems	MM
Ass. 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

Technical staff, directly funded by NTNU AMOS

Name	Institution, department	Acronym
Kvaløy, Pål	NTNU, Dept.Engineering Cybernetics	PK
Semb, Lars	NTNU, Dept.Engineering Cybernetics	LS
Volden, Frode	NTNU, Dept.Marine Technology	FV

Visiting researchers

Name	Institution	Main field of research	Acronym
Prof. Triantafyllou, Michael S.	Massachusetts Insitute of Technology, USA	Center for Control, Dynamical Systems, and Computation	MST
Sasa, Kenji	Faculty of Maritime Sciences, Kobe University, Japan	Integration of seakeeping, machinery and propulsion in order to estimate ship motions, added resistance, and speed loss in a seaway, as well as subsequent fuel consumption and CO2 emissions	SK
Prof. Teel, Andrew	Univ. Of california, Santa Barbara, USA	Hybrid dynamical systems	AT
Makiharju, Simo A	USA, Berkely	Marine hydrodynamics	SAM
Fiskin, Remzi	Turkey, Izmir	Autonomous systems	RF
Prof. Arcak, Murat	Univ. Of california, Berkeley, USA	Cooperative control design	MA
Du Ho Duc	Sweeden	Autonomous systems	
Tuan, Hung	Portugal	Autonomous systems	HT
Kim, Jonghyuk	Austria, Canberra	Autonomous systems	KJ
Loria, Antonio	France	Nonlinear Ccontrol	AL
Mylvaganam, Thulasi	England	Optimal control, differential games and robust control for nonlinear systems	TM
Colicchio, Giuseppina	CNR - INSEAN, Italy	Mesh generation and analysis for acomputational fluid mechanics	GC
Prpic-Orsic, Jasna	Univ. Of Rijeka, Croatia	C02 emission from ships in waves	JP

Phd candidates with financhial support from NTNU AMOS

Navn	Supervisor	Topic
Bakken, Sivert	TAJ	Coordinated oceanographic observation system with autonomous aerial/surface robots and hyper-spectral imaging in SmallSat
Brodtkorb, Astrid H.	AJS	Dynamic positioning in extreme seas
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
Eidsvik, Ole A.	IS	Design and development of unmanned underwater vehicles
Fortuna, Joao	TIF	Processing and analysis of Hyperspectral Images from unmanned systems
Fossum, Trygve	ML	Artificial intelligence for AUVs

Navn	Supervisor	Topic
Gryte, Kristoffer	TIF	Fixed-wing UAV operations from autonomous floating docking station
Hanssen, Finn-Christian W.	MG	Autonomous marine operations in extreme seas, violent water-structure interactions, deep waters and Arctic
Horn, Jan-Tore Haugan	JAM	Stochastic dynamic simulations of offshore wind turbines with integrated control and monitoring
Kaminska-Wrzos, Marianna	KYP	Free-floating intervention operations using AIAUVs
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
Muntadas, Albert Sans	KYP	Integrated underwater navigation and mapping based on imaging and hydro-acustic sensors
Nam, Woongshik	JAM	Structural resistance of ships and offshore structures sunjected to cryogenic spills
Mogstad, Aksel Alstad	GJ	Marine biological applications for underwater hyperspectral imaging (UHI)
Nielsen, Mikkel Cornelius	MB	Fault-tolerance and reconfiguration for collaborating heterogeneous underwater robots
Nornes, Stein M.	AJS	Simultaneous mapping, navigation and monitoring with unmanned underwater vehicle using sensor fusion
Ramos, Nathalie	KJ	4D printing of intelligent marine structures
Sauder, Thomas	AJS	real-time hybrid testing of floating systems.
Shen Yugao	MG	Limiting operational conditions for a well boat
Siddiqui, Mohd Atif	MG	Behaviour of a damged ship in waves
Smilden, Emil	AJS	Reduction of loads,fatigue and structural damage on an offshore wind turbine
Sørum, Stian Hoegh	JAM	Offshore Wind Turbines
Vilsen, Stefan A.	AJS	Hybrid Model Testing of Marine Systems
Wiig, Martin Syre	KYP	Reactive collision avoidance and guidance for underactuated marine vehicles
Zolich, Artur	TAJ	Autonomous control and communication architectures for coordinated operation of unmanned vehicles (UAV, AUV, USV) in a maritime mobile sensor network
Ødegård, Øyvind	AJS	Autonomous operations in marine archaeology - technologies and methods for managng underwater cultural heritage in the Artic
Xu, Hui-Li	MG	Fish-hydrodynamic study finalized to the bio-cyber-hydrodynamics

PhD candidates associated with NTNU AMOS with other financial support

Name	Supervisor	Topic
Albert, Anders	LI	Mission and path optimisation for mobile sensor network operations
Albrektsen, Sigurd M.	TAJ	Integrated observer design with a north-seeking strapdown MEMS-based gyrocompass and machine vision
Andersson, Leif Erik	LI	Iceberg and sea ice drift estimation and prediction
Andrade, Fabio	RST	Sea ice drift tracking using real time UAV path planning for maritime situational awareness
Birkeland, Roger	TAJ	Risk-based optimization of control system behavior
Bitar, Glenn Ivan	MB	Energy-optimal and autonomous control for car ferries
Berget, Gunhild	TAJ	Intelligent monitoring of drilling operations in sensitive environments
Bjorne, Elias	TAJ	Nonlinear observer theory for simultaneous localization and mapping

Name	Supervisor	Topic
Bjørkelund, Tore-Mo	ML	Adaptive and collaborative vehicle behaviour for mission management for autonomous underwater vehicles
Blindheim, Simon	TAJ	Risk-based optimization of control system behavior
Borup, Kasper T.	TIF	Model-based nonlinear integration filters for INS and position measurements
Borri, Daniele	MG	Hydrodynamics of oil spills from oil tankers
Bøhn, Eivind	TAJ	Machine learning in control and estimation
Cho, Seong-Pil	TM/ZG	Dynamic modelling and analysis of floating wind turbines with emphasis on the behavior in fault conditions
Dahl, Andreas reason	RS	Nonlinear and fault-tolerant control of electric power production in Artic DP vessels
Dahlin, Christopher	TAJ	Intelligent data acquistion in maritime UAS
Diaz, Gara Quintana	TAJ	Small satellite system communication
Eriksen, Bjørn-Olav H.	MBR	Collision avoidance for autonomus surface vehicles
Flåten, Andreas L.	EB	Multisensor tracking for collision avoidance
Fossum, Trygve	ML	Artificial intelligence for AUVs
Ghane, Mahdi	TM/ZG	Dynamic modelling and analysis of floating wind turbines with emphasis on the behavior in fault conditions
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
Haugo, Simen	AST	Computer vision methods for assisted teleoperation of unmanned air vehicles
Helgesen, Håkon Hagen	TAJ	UAV scouting system for autonomous ships
Heyn, Hans Martin	RS	Fault-tolerant control and parameter estimation for thruster assisted position mooring in Artic offshore conditions
Hovenburg, Anthony	RST	Modular design framework for RPAS operating in marine environments
Hegseth, John Marius	EB	Efficient Modelling and Design Optimization of Large Floating Wind Turbines
Katsikogiannis, George	EB	Loads and Responses of Large-Diameter Monopile Wind Turbines
Leonardi, Marco	AS	Visual odometry and servoing for 3D reconstruction
Livermor-Honoé, Evelyn	TAJ	Rapid systems engineering
Luan, Chenyu	TM	Efficient stochastic dynamic response analysis for design of offshore wind turbines
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
Norgren, Petter	RS	AUVs for subsurface monitoring of sea-ice and icebergs
Olofsson, Harald Lennart Jonatan	TIF	Bayesian iceberg risk management
Ren, Zhengru	RS	Control and Online Decision Support of Crane Operations for Fixed and Floating Offshore Wind Turbines
Rokseth, Børge	IU	A new approach for handling risk in dynamic position systems for marine vessels
Rothmund, Sverre	TAJ	Decision making under uncertainty in risk-based autonomous control
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

Name	Supervisor	Topic
Skulstad, Robert	TIF	Data-based Ship Motion Prediction in Offshore Operations
Sollie, Martin	TAJ	Autonomous ship-landing of UAVs
Souza, Carlos Eduardo Silva de	ERB	Structural modeling and optimization of floating wind turbines
Strand, Ida M	AJS	External sea loads for internal hydraulics of closed flexible cages
Sture, Øystein	ML	Autonomous exploration of Marine Minerals
Sverdrup-Thygeson, Jørgen	KYP	Motion control and redundancy resolution for hybrid underwater operations
Thieme,Christoph A.	IU	Human and organizational factors in unmanned underwater operations
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	TIF	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
Wenz, Andreas Wolf-gang	TAJ	Fault tolerant control and automatic de-icing for unmanned aerial vehicles
Wilthil, Erik F.	EB	target tracking under navigation uncertainty
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
Zhao, Yuna	TM/ZG	safety assesment of marine opetations related to installation of offshore wind turbine

Annual accounts and man-year efforts

Annual accounts

Operating income	Accountes income and costs
The research council of Norway	14 324
NTNU	22 614
Others	6 500
in kind	12 940
Sum operating income	**56 378**

Operating costs	Accountes income and costs
Salary and social costs	34 419
Equipment investments	2 386
Procurement of R&D servises	1 032
Other operating costs	4 715
in kind	12 940
Sum operating costs	**55 492**

Year end allocation	886

Opening balance 20180101	5 497
Closing balance 20181231	6 382

Total man-years efforts

Man-years	2018
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	3,30
Affiliated prof/scientists	5,78
Scientific advisor	0,50
Postdocs	6,62
Postdoc (affiliated)	12,63
Visiting researchers	0,63
PhD candidates	16,49
PhD candidates (affiliated)	36,34
Total research man-years	**88,49**

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	Administrative staff*)	Sum
Norwegian	6	8	12	2	12	-	24	42	7	
Other nationalities	1	9	10	-	17	13	17	36	-	
Sum	7	17	22	2	29	13	41	78	7	-
Man-years	**3,50**	**3,30**	**5,78**	**0,50**	**19,25**	**0,63**	**16,49**	**36,34**	**2,20**	**87,99**

PhD Graduates

PhD degrees 2018

Supervised by Key Scientists at AMOS

Name		Topic	Supervisor
Albrektsen, Sigurd Mørkved	September 25	Sensor Synchronization and Navigation in GNSS-Denied Environments for Unmanned Aerial Vehicles	TAJ
Kauko, Hanna	September 21	Light response and acclimation of microalgae in a changing Arctic	GJ
Nornes, Stein Melvær	June 21	Guidance and Control of Marine Robotics for Ocean Mapping and Monitoring	AJS
Ødegård, Øyvind	June 20	Towards Autonomous Operations and Systems in Marine Archelogy	AJS
Jørgensen, Erlend Kvinge	March 19	Navigation and Control of Underwater Robotic Vehicles.	IS
Muntadas, Albert Sans	June 7	Path-Planning, Guidance and Navigation tools for Docking of Underactuated AUVs	KYP
Nielsen, Mikkel Cornelius	May 25	Modular Underwater Robots – Modeling and Docking Control.	MB
Horn, Jan Tore Haugan	December 11	Statistical and Modelling Uncertainties in the Design of Offshore Wind Turbines	JAM
Shen, Yugao	November 23	Operational limits for floating-collar fish farms in waves and current, without and with well-boat presence	MG
Sauder, Thomas	December 7	Fidelity of Cyber-physical Empirical Methods. Application to the Active Truncation of Slender Marine Structures	AJS
Strand, Ida Marlen	February 28	Sea Loads on Closed Flexible Fish Cages	AJS
Wenz, Andreas Wolfgang	November 20	Inflight Estimation of Airflow Variables, Wind Velocities and Aerodynamic Coefficients for Unmanned Aerial Vehicles	TAJ
Zolich, Artur Piotr	November 23	Systems Integration and Communication in Autonomous Unmanned Vehicles in Marine Environments	TAJ

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

Name		Topic	Supervisor
Ghane, Mahdi	October 3	Fault Diagnosis of Floating Wind Turbine Drivetrain- Methodologies and Applications	TM
Luan, Chenyu	June 1	Design and Analysis for a Steel Braceless Semi-Submersible Hull for Supporting a 5-MW Horizontal Axis Wind Turbine	TM

Supervised by Affiliated Scientists at AMOS

Name		Topic	Supervisor
Albert, Anders	August 17	Unmanned Aerial Vehicle(s) Trajectory Planning for Target Searching and Track.	LI
Andersson, Leif Erik	June 8	Short-term Iceberg drift estimation and predictioc	LI
Borup, Kasper Trolle	September 29	Air Data Estimation for Small Unmannes Aircraft	TIF
Norgren, Petter	September 3	Autonomous Underwater Vehicles in Arctic Marine Operations: Arctic marine research and ice monitoring.	RS
Thieme, Christoph	November 2	Risk Analysis and Modelling of Autonomous Marine Systems	IU
Rokseth, Børge	April 12	Safety and Verification of Advanced Maritime Vessels: an Approach Based on Systems Theory.	IU
Hedge, Jeevith	February 26	Tools and Methods to manage Risk in Autonomous Subsea Inspection, Maintenance and Repair Operations	IS
Stovner, Bård Nagy	February 21	Aided Inertial Navigation of Underwater Vehicles.	IS

Publications in 2018

Journals

Ahmadi Moshkenani, Parisa; Johansen, Tor Arne; Olaru, Sorin. Combinatorial approach toward multiparametric quadratic programming based on characterizing adjacent critical regions. *IEEE Transactions on Automatic Control* 2018 ;Volum 63.(10) s.3221-3231

Albert, Anders; Imsland, Lars Struen. Combined Optimal Control and Combinatorial Optimization for Searching and Tracking Using an Unmanned Aerial Vehicle. *Journal of Intelligent and Robotic Systems* 2018

Albert, Anders; Imsland, Lars Struen. Survey: Mobile Sensor Networks for Target Searching and Tracking. *Cyber-Physical Systems* 2018 ;Volum 4.(2) s.57-98

Albrektsen, Sigurd Mørkved; Johansen, Tor Arne. Reconfigurable Sensor Timing and Navigation System for UAVs. *Sensors* 2018 ;Volum 18. s.1884-1891

Alsos, Hagbart Skage; Faltinsen, Odd Magnus. 3D motion dynamics of axisymmetric bodies falling through water. *Ocean Engineering* 2018 ;Volum 169. s.442-456

Andersson, Leif Erik; Scibilia, Francesco; Copland, Luke; Imsland, Lars Struen. Comparison of statistical iceberg forecast models. *Cold Regions Science and Technology* 2018 ;Volum 155. s.69-89

Antuono, Matteo; Lugni, Claudio. Global force and moment in rectangular tanks through a modal method for wave sloshing. *Journal of Fluids and Structures* 2018 ;Volum 77. p. 1-18

Blanke, Mogens; Nguyen, Dong Trong. Fault-tolerant Position-Mooring Control for Offshore Vessels. *Ocean Engineering* 2018 ;Volum 148.(jan) s.426-441

Borlaug, Ida-Louise Garmann; Gravdahl, Jan Tommy; Sverdrup-Thygeson, Jørgen; Pettersen, Kristin Ytterstad; Loria, Antonio. Trajectory tracking for underwater swimming manipulators using a super twisting algorithm. *Asian journal of control* 2018, Vol. 21 No. 1 pp.1-16

Brekke, Edmund Førland; Chitre, Mandar. Relationship between Finite Set Statistics and the Multiple Hypothesis Tracker. *IEEE Transactions on Aerospace and Electronic Systems* 2018;Volum 54.(4) s.1902-1917

Brodtkorb, Astrid H.; Nielsen, Ulrik Dam; Sørensen, Asgeir Johan. Sea state estimation using vessel response in dynamic positioning. *Applied Ocean Research* 2018 ;Volum 70. s.76-86

Brodtkorb, Astrid H.; Værnø, Svenn Are Tutturen; Teel, Andrew R.; Sørensen, Asgeir Johan; Skjetne, Roger. Hybrid controller concept for dynamic positioning of marine vessels with experimental results. *Automatica* 2018 ;Volum 93. s.489-497

Bryne, Torleiv Håland; Rogne, Robert Harald; Fossen, Thor I.; Johansen, Tor Arne. A virtual vertical reference concept for aided inertial navigation at the sea surface. *Control Engineering Practice* 2018 ;Volum 70. s.1-14

Cheng, Zhengshun; Gao, Zhen; Moan, Torgeir. Hydrodynamic load modeling and analysis of a floating bridge in homogeneous wave conditions. *Marine Structures* 2018 ;Volum 59. s.122-141

Cheng, Zhengshun; Gao, Zhen; Moan, Torgeir. Numerical Modeling and Dynamic Analysis of a Floating Bridge Subjected to Wind, Wave, and Current Loads. *Journal of Offshore Mechanics and Arctic Engineering* 2018 ;Volum 141.(1)

Cheng, Zhengshun; Gao, Zhen; Moan, Torgeir. Wave load effect analysis of a floating bridge in a fjord considering inhomogeneous wave conditions. *Engineering structures* 2018 ;Volum 163. s.197-214

Cheng, Zhengshun; Svangstu, Erik; Gao, Zhen; Moan, Torgeir. Field Measurements of Inhomogeneous Wave Conditions in Bjørnafjorden. *Journal of waterway, port, coastal, and ocean engineering* 2018 ;Volum 145.(1)

Cho, Seongpil; Gao, Zhen; Moan, Torgeir. Model-based Fault Detection, Fault Isolation and Fault-tolerant Control of a Blade Pitch System in Floating Wind Turbines. *Renewable Energy* 2018 ;Volum 120. s.306-321

Cristofaro, Andrea; Polycarpou, Marios M.; Johansen, Tor Arne. Fault-Tolerant Control Allocation for Overactuated Nonlinear Systems. *Asian journal of control* 2018 ;Volum 20.(2) s.621-634

Dumke, Ines; Ludvigsen, Martin; Ellefmo, Steinar Løve; Søreide, Fredrik; Johnsen, Geir; Murton, Bramley J. Underwater Hyperspectral Imaging Using a Stationary Platform in the Trans-Atlantic Geotraverse Hydrothermal Field. *IEEE Transactions on Geoscience and Remote Sensing* 2018

Dumke, Ines; Nornes, Stein Melvær; Purser, Autun; Marcon, Yann; Ludvigsen, Martin; Ellefmo, Steinar Løve; Johnsen, Geir; Søreide, Fredrik. First hyperspectral imaging survey of the deep seafloor: High-resolution mapping of manganese nodules. *Remote Sensing of Environment* 2018 ;Volum 209. s.19-30

Dumke, Ines; Purser, Autun; Marcon, Yann; Nornes, Stein Melvær; Johnsen, Geir; Ludvigsen, Martin; S**øreide, Fredrik.** Underwater hyperspectral imaging as an in situ taxonomic tool for deep-sea megafauna. *Scientific Reports* 2018 ;Volum 8.(1)

Eguiraun, Harkaitz; Casquero, Oskar; Sørensen, Asgeir Johan; Martinez, Iciar. Reducing the number of individuals to monitor shoaling fish systems-Application of the Shannon Entropy to construct a Biological Warning System model. Frontiers in Physiology, ISSN: 1664-042X

Faltinsen, Odd Magnus; Shen, Yugao. Wave and Current Effects on Floating Fish Farms. *Journal of Marine Science and Application* 2018 s.1-13

Ferreira, Antonio Sergio; Costa, Maria; Py, Frédéric; Pinto, Jose; Silva, Monica A.; Nimmo-Smith, W. Alex M.; Johansen, Tor Arne; Borges de Sousa, Joao; Rajan, Kanna. Advancing multi-vehicle deployments in oceanographic field experiments. *Autonomous Robots* 2018 s.1-20

Fjeldtvedt, Johan Austlid; Orlandic, Milica; Johansen, Tor Arne. An Efficient Real-Time FPGA Implementation of the CCSDS-123 Compression Standard for Hyperspectral Images. I*EEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 2018* ;Volum 11.(10) s.3841-3852

Fossen, Sindre; Fossen, Thor I.eXogenous Kalman Filter (XKF) for Visualization and Motion Prediction of Ships using Live Automatic Identification Systems (AIS) Data. *Modeling, Identification and Control* 2018 ;Volum 39.(4) s.233-244

Fossum, Trygve Olav; Eidsvik, Jo; Ellingsen, Ingrid H.; Alver, Morten; Fragoso, Glaucia Moreira; Johnsen, Geir; Mendes, Renato; Ludvigsen, Martin; Rajan, Kanna. Information-driven robotic sampling in the coastal ocean. *Journal of Field Robotics* 2018 ;Volum 35.(7) s.1101-1121

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Approved by the
NTNU AMOS Board of Directors March 2019

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Science and Technology

Annual Report for NTNU AMOS 2018

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