NTNU
Centre for Autonomos Marine Operations and Systems

NTNU AMOS
Centre for Autonomous Marine Operations and Systems

Annual Report 2019

Norwegian Centre of Excellence
The Research Council of Norway

OUR VISION

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

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

excellent – generous – courageous

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

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DIRECTORS' REPORT

We are heading into the United Nations Decade (2021-2030) of Ocean Science for Sustainable Development – *The Science We Need for the Ocean We Want*.

Norway plays an important international role as one of the main actors in the blue economy. More than ever, a holistic and sustainable approach is needed to develop competence, knowledge and innovations with relevance for:

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

As one of the major knowledge-, competence- and technology providers in Norway, NTNU has a responsibility to contribute to the transformation of the industry and public sector. Such a transformation may be a combination of incremental and disruptive developments, among others, relying on research results from NTNU AMOS.

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.

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

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

In the annual report, selected highlights of in-depth technology development and projects exemplifying cooperation between technology and science for ground-breaking research are given.

I will also pay attention to the development of a new research infrastructure and research capacity. In 2019, together with Equinor and other partners, we have installed the world's first subsea docking station at a water depth of 370 m approximately 2 km from the Trondhjem Biological Station. The docking station provides inductive electrical power and communication channels for underwater vehicles. Together with innovations on underwater vehicles and instrumentation, this is a game changer for reducing CO2 emissions from more costly ship operations, while at the same time improving safety and availability on subsea assets. In addition to this, SINTEF and NTNU were awarded with national infrastructure funding from the Research Council of Norway to an Ocean Laboratory for research and development, including the testing and verification of autonomous ships, aquaculture installations, ocean monitoring, subsea operations and e-infrastructure for ocean data. NTNU and SINTEF have also entered into a formal cooperation with REV Ocean and Ocean Data Foundation, thereby leveraging the capacity for ocean research, including the testing of new technology.

It is with pride that I acknowledge that AMOS researcher groups are being recognized for excellent research and innovation achievements. Researchers have worked on the idea of snake robots for more than 30 years, but the greatest breakthrough so far has been done by a key scientist at NTNU AMOS, Professor Kristin Ytterstad Pettersen, and her colleagues at both NTNU and SINTEF. In recognition of this work, Pettersen has been awarded the IEEE Bode Lecture Prize. The Bode Prize recognizes distinguished contributions to control systems science or engineering. Only candidates with international breakthroughs in the field are qualified for this prize. The fact that Professor Kristin Y. Pettersen received it because of the work she has done in an area, where there is intense competition between large nations, is fantastic. Pettersen is also an entrepreneur, and, together with her research group, she has used her research results to establish the underwater robotics company Eelume.

Besides this, NTNU AMOS' efforts in bringing fundamental research into innovations has also been noted and appreciated. We are grateful for receiving the Norwegian Research Council's Innovation Award for 2019. The prize is granted to a person or organization that through an exceptional use of research results has laid the foundation for research-based innovation. The innovation arenas are both existing industry and the public sector, in addition to founding a new industry. Thus far, there are six spin-off companies from NTNU AMOS all receiving the benefit of fundamental and disruptive research results. Even more important is NTNU´s role in research-based education of master's and PhDs, where we have developed a culture for innovations powered by knowledge.

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

Sincerely,

Asgeir J. Sørensen

Professor Asgeir J. Sørensen
Director NTNU AMOS


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BOARD OF DIRECTORS

The Board met twice in 2019 to review progress, consider management issues and offer advice on strategic directions for the Centre.

The Board is very satisfied with the activities undertaken at NTNU AMOS during 2019, with the results very impressive.

NTNU AMOS fulfils the expectations as a Norwegian Centre 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 centre, 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 centre has access to provides an excellent research environment.

Based on the mid-term evaluation in 2018, AMOS is focussing its research into three projects:

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

In 2019, NTNU AMOS graduated 19 PhDs. Approximately 100 journal papers were published in high-quality journals in 2019, in addition to several conference papers, book chapters and plenaries.

In their work with AMOS, Professor Kristin Ytterstad Pettersen and her colleagues at NTNU and SINTEF have made a breakthrough in the development of underwater snake robots. In recognition of this work, Pettersen was awarded the IEEE Bode Lecture Prize, which recognizes significant contributions to control systems science.

In 2019, Professor Asgeir Sørensen received the Innovation Prize from The Research Council of Norway. From the jury decision:

Asgeir J. Sørensen is close to an institution in the marine technology field. He came from industry to academia and heads the SFF AMOS - Autonomous Marine Operations and Systems at NTNU. Sørensen is a top researcher and valued lecturer, promotes talents and innovations, has a large national and international network, and is close to the maritime industry and other Norwegian business and industry.

The Board is very pleased that key persons of AMOS are recognized through such awards.

The board is also very pleased with the HSE performance of AMOS. There are few accidents and near accidents. The HSE awareness in the centre management is very good, and there is a good system for risk assessment and training for laboratory and fieldwork.

The Board's Endorsement of the Annual Report

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

NTNU AMOS STRENGTHENS NTNU

The Pro Rector at NTNU, Bjarne Foss, is full of praise when he describes the work that NTNU AMOS has done over these past eight years. Both research results and innovation through new technology and spin-offs are impressive, says Foss.

- NTNU AMOS is a centre that unites high quality research with education and innovation in an especially good way, this within the field of autonomy, a field that is very important to Norway. Our country has a large potential in this field and there are immense possibilities, both connected to, but also outside the ocean space.

- The centre is a great example of how fundamental research and innovation can be coupled, without any conflict between the two. With AMOS, we observe strong synergies between these areas.

- AMOS brings the benefits of cross-disciplinary research to us in a clear way. The cooperation between the researchers at the Department of Marine Technology and the Department of Engineering Cybernetics, and later at the Department of Biology, is a wonderful example of how interdisciplinary research creates great results, says Foss.

Asked to pick a favourite project, Foss singles out the work on snake robots that has been conducted by researchers at AMOS.
- I like this project because it shows how research driven by curiosity, and in addition working on the boundary between robotics and biology, have led to an exciting new technology with a significant commercial potential.

Improving the educational quality

NTNU aims to be a university that generates knowledge for a better world, with the Pro Rector arguing that NTNU AMOS is an important contributor towards that goal. Besides the more obvious research results, Foss directs attention to the centre's contribution to improving education at NTNU.

- On the educational side of things, AMOS educates a large number of PhD candidates, many of whom will start working in the industry. Many master's students are also involved in the work done at AMOS, and these and the PhD candidates are the people who will drive innovation and set the research agenda for the future, says Foss.

Important to NTNU

Bjarne Foss tells us that the Norwegian Research Council's Centres for Excellence programme is an instrument where NTNU wants to be a leading institution. Centres of Excellence are based on curiosity research. Despite this, AMOS has been able to attract considerable support from other external sources as well, which is quite unusual.

- That is very important and clearly shows how universities can contribute to industrial innovations.

- In many ways, NTNU AMOS is what NTNU wants to be: a research-intensive university that builds bridges between fundamental and applied research and innovation, while at the same time having attractive study programmes at both the bachelor and master's level. With that in mind, it was wonderful to see the AMOS Director receive the Norwegian Research Council's Innovation Award for 2019, It shows that we are on the right track, says Foss.

THE INDUSTRY CONNECTION

Frank Børre Pedersen joined the AMOS board in 2019. He is the Vice President and Programme Director of Oil & Gas and Ocean Space at DNV GL, and replaced Liv Hovem. He did his PhD in physics at NTNU in 1996, and he has worked at DNV GL since then.

Pedersen tells us that he jumped at the chance to join the board.

- I am very excited to be a small part of NTNU AMOS. We work closely with NTNU as a whole and are currently financing four professoriates, one of which will be part of NTNU AMOS. I am also leader of the SFI Subpro's board, so I am already more involved with NTNU than many of my colleagues, says Pedersen.

One of DNV GL's role is to verify the quality of new maritime technology and methods, with Pedersen arguing that it is therefore important to be present where the technology is being developed.

- New technology must be controlled before the industry can put it to work. The technological advances are also moving faster than regulation and standardization work, which is why one must be present from the start, and conduct quality assurance as the technology is in development. This means that it is perfect for us to be close to NTNU AMOS.

Industry and Academia

NTNU AMOS has thus far led to the creation of six spin-off companies that operate within fields from underwater drones and UAVs to autonomous ferries. This ability to create spin-offs is something that Pedersen values.

- DNV GL has previously bought companies that originated at NTNU; one example is Marine Cybernetics, and it is great to see similar spin-offs from AMOS. I think it shows how good the cooperation between industry and academy can be; we are not only employing the candidates that NTNU educates, but cooperate directly with each other on research and innovation, says Pedersen.

Seeing the whole picture

What role do you see NTNU AMOS fulfilling?
- I think AMOS is important to Norway as a nation, as it is one of the SFFs in an area where we can take a leading role internationally. This is both because the leadership at AMOS has been very active in taking this role, but also because the field is a very good fit for Norway as a nation. The adaptations that Norway must make in the coming years will make use of, and might even be dependent on, the results from AMOS, says Pedersen.

- People like to think of Norway as a country with high costs, but this is not the case when it comes to knowledge. I would argue that the combination of knowledge, and how we use it gives us a comparative advantage.

Frank Børre Pedersen highlights how AMOS, quite uniquely among other SFFs and SFIs, has delivered both cutting edge research and practical solutions within the same field.

- What we see in other organizations and centres is that they are either very good at research or innovation. When AMOS both creates and makes use of new knowledge, and even helps turning the entire Trondheim's Fjord into a test site, you have truly made use of the whole value chain, from research to innovation through pilots and finally commercialization, says Pedersen.

A GREAT OPPORTUNITY FOR MORE INSIGHT

One of two new board members at NTNU AMOS, Ingelin Steinsland is Professor at the Department of Mathematical Science, and Vice Dean at the Faculty of Information Technology and Electrical Engineering. A statistician by training, she took her master's and PhD at NTNU, and tells us she is excited to acquire a deeper understanding of the work that goes on at AMOS.

- What I really like about positions like this one is that you learn so much about new and exciting research, things I would not have learned under other circumstances. That it is within a field where Norway and NTNU have taken a leading role makes it even more exciting. I think it is important to recognize that the position that NTNU has taken within the field of Autonomy was never given, but it is very important for Norway that we have universities and research centres that are able to take a leading role. We also have to maintain this position in the years to come, she says.

Crossing disciplinary boundaries

Steinsland has extensive experience with multidisciplinary research, and she has used her knowledge of statistics to support many different fields, among others within hydrology and weather predictions.

- I worked at Sintef Energy for a while and was involved with research into hydropower and hydrology, as well as meteorology. I have also worked with quantitative genetics when I did my PhD and as a postdoc researcher. I honestly think that multidisciplinary research might be the most exciting work you can do, but I also know how challenging it can be. Simple stuff like a common vocabulary and understanding can take some time to develop, Steinsland tells us.

With those challenges in mind, Steinsland tells us that she is impressed by the results.

- Autonomy is about using data to update a decision, and that is a method I am familiar with as a statistician. Ocean monitoring, which is important at AMOS, is the same; it feels close to what I do. But to have systems that work and are genuinely autonomous, that is fascinating! I know how hard communication is in this instance. I am almost surprised that it is possible at all, says Steinsland.

Impressive innovation

Besides the fundamental research, she also mentions the amount of innovation and new companies that have originated at AMOS.

- As a centre of excellence, the amount of Innovation that has originated at AMOS is almost extreme. I had my first job at a start-up, and I know how much work it is; it is a whole other world. I am really impressed by the results achieved so far, and I am looking forward to following AMOS more closely and get an even better understanding of the work done by the researchers.

When asked what she thinks will be important for NTNU AMOS as the Centre enters its final year, Steinsland tells us that the researchers should look to how the results can be used in future centres and research projects.

- We are getting closer to the finish line, and it is important that the high quality of the research, and the high ambitions are maintained. The end should also mean new beginnings, where we can build on previous research achievements.

FROM POSTDOC RESEARCHER TO ASSOCIATE PROFESSOR

In late 2019, the former postdoc researcher at AMOS, Astrid H. Brodtkorb, took up a new position as an associate professor at the Department of Marine Technology at NTNU. With brand new responsibilities and tasks, Professor Brodtkorb will nevertheless be heavily involved with the research on autonomous ships conducted at AMOS.

- I will still contribute to AMOS, and most of my research will be under the AMOS umbrella, but I will also contribute to the ORCAS and UNLOCK projects. As AMOS draws to a close in 2023, I will keep working on developing control functionality for autonomous ships at the Department of Marine Technology, utilizing the results that we have arrived at through AMOS, she says.

Autonomy and ships

Brodtkorb has worked on autonomy for seagoing vessels from the beginning of her research career. Some parts of the field, like collision avoidance has come far, but there are still areas, such as risk-based control strategies, and cybersecurity, that require more research in order to realize completely autonomous ships, says Brodtkorb. As the technology advances, regulations and laws will also need to be simultaneously updated.

- You need to be mindful when implementing new control system functionality like this. When designing autonomous control systems, it is impossible to think of every possible scenario. Therefore, in some contexts, like unlikely combinations of failure modes, the control system may have unexpected behaviour, and it is important to discover this in the testing and verification phase. A new ship is often a massive investment by the company that buys it, and they need to be sure that the systems always work as intended. There is a large difference between designing a control system to work in most scenarios and designing a control system to never fail.

One of her latest projects is on sea-state estimation, in which the vessel's motion in waves is used to provide wave height, length and direction estimates to be used in an autonomous control system decision-making process.

- It is vital for an autonomous control system to know what kind of environment the vessel is currently operating in. An experienced captain can just look out the window and gain a pretty good idea of the waves, but a computer needs a quantitative measure to base decisions upon. In addition, human operators on land have much more difficulties in acquiring an accurate picture of the sea-state. Because of this, it is important that the control system obtains accurate input so that it can use the correct algorithms, says Brodtkorb.

The teaching role

In terms of research, Professor Brodtkorb will be engaged with the same projects and topics she is already working on, but the new position also comes with responsibilities for education, both in terms of teaching courses and supervising students.

- I am working on making the course syllabus and lectures for my own specialization topic on hybrid control theory for marine applications, which will run from fall 2020. I have previously been co-supervisor for master's and PhD students, and it will be natural to have these enrol in the classes I am teaching. This will hopefully give me a closer connection to my students and allow me to advise and teach them even better, says Brodtkorb. As an associate professor, she will also be the main supervisor for PhD candidates, with the first two scheduled to start in 2020. NTNU has provided funding for one

PhD candidate, and a new project with external partners will provide funding for a second. Both PhD candidates will work on hybrid control theory applied to autonomous ships.

- I am looking forward to the hiring process and to also being a main supervisor. Hybrid control systems is an area I know well, so supervising PhD candidates working on these kinds of systems is going to be exciting, says Brodtkorb.

Despite her excitement about her new role, Brodtkorb is also aware of some new challenges that emerge with new responsibilities.

- Finding a balance between teaching and research responsibilities will be demanding. It will be vital to quickly identify the most important activities and prioritize them. I know that the amount of time that I spend on any given task will vary throughout the year; teaching will sometimes have to be a priority, while at other times research projects will take up most of my time, she tells us.

ORGANIZATION, INTERNATIONAL COLLABORATORS, AND FACTS AND FIGURES

Organization

NTNU AMOS Board Members:

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

NTNU AMOS Management:

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

NTNU AMOS Key Scientists:

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

Senior Scientific Advisors:

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

Innovation:

- Kjell Olav Skjølsvik, Innovation Leader

Research partners:

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

Scientific Advisory Board:

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

International collaborators

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

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

Facts and figures

Personnel 2019

- 7 keypersons
- 16 adjunct prof/assoc.prof
- 30 affiliated scientists
- 2 Scientific Advisers
- 9 post docs/researchers
- 21 affiliated post docs/researchers
- 101 PhD candidates (incl. Affiliated)
- 3 Visiting prof/researchers
- 3 administrative staff
- 2 Management
- 3 technical staff

- 9 graduated PhD candidates financed by NTNU AMOS. In total 55.
- 10 graduated PhD candidates associated to NTNU AMOS. In total 43

Revenues (NOK)

• Income	62 787 000
• Costs	61 051 000
• Year end allocation	1 736 000

Publications

- 106 refereed journal articles
- 63 refereed conference papers
- 10 book chapters
- 16 international keynote lectures
- 51 news media articles and other coverage

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MAIN RESEARCH AREAS AND PROJECTS

The NTNU AMOS has two research areas:

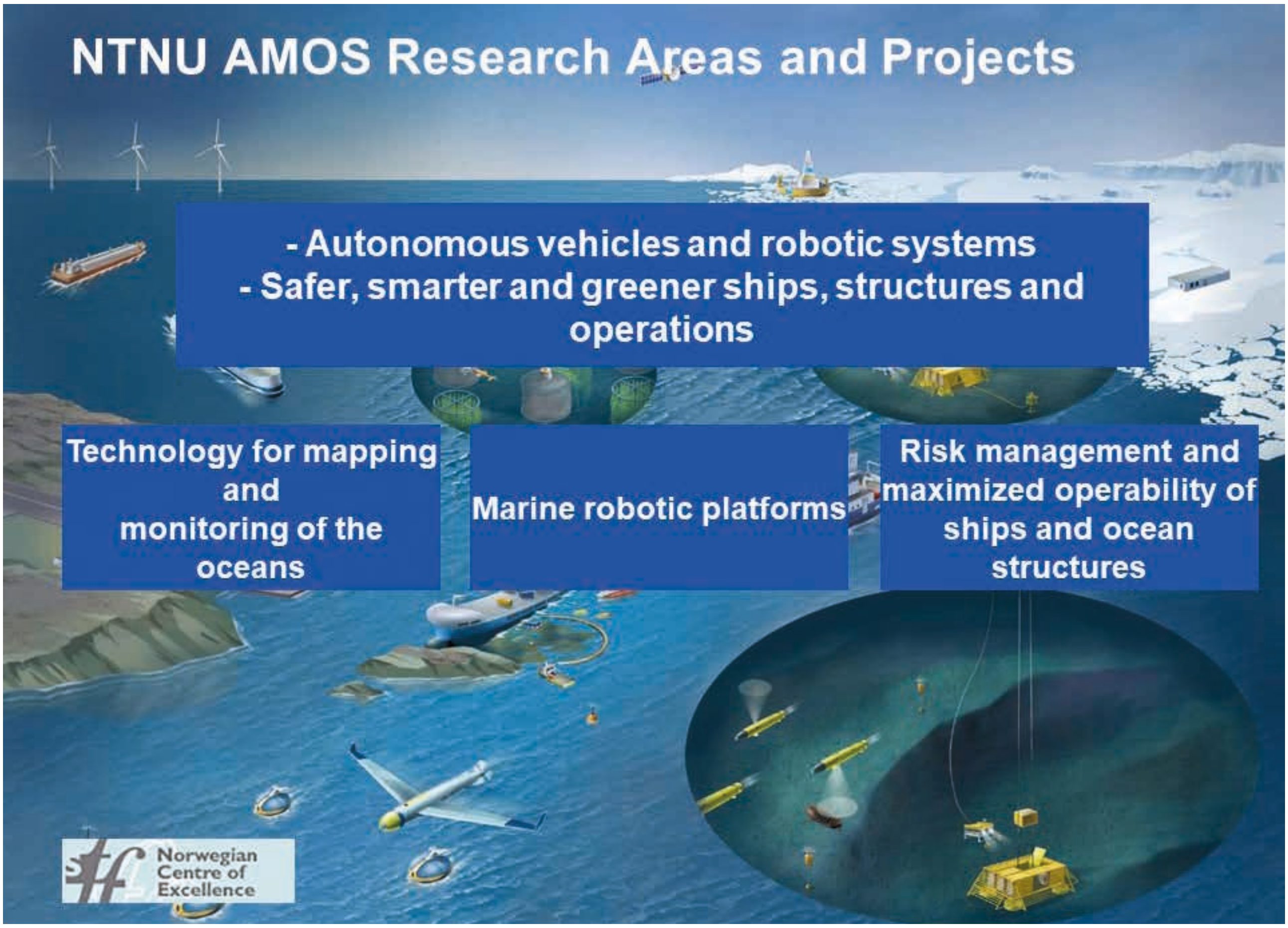
- **Autonomous vehicles and robotic systems**
  - How to develop autonomous sensors and sensors platforms – small satellites, unmanned aerial vehicles, unmanned ships and underwater vehicles, buoys - in air, sea surface and underwater for ocean mapping and monitoring?
  - How to reduce use of surface vessels with 80% in several offshore oil and gas operations?
  - How to ramp up mapping and monitoring coverage 10 times with a cost of 1/10?
  - How to enable public management agencies and industry to pilot and invest in new sensor and technology platforms?
- **Safer, smarter and greener ships, structures and operations**
  - How to design and operate hybrid power plants and propulsion systems on offshore ships using LNG, batteries and diesel engines reducing energy consumption and emissions by a fraction with 70-80% reduction of todays solutions?
  - How to safely operate at any weather condition, water depth and offshore site with 1/10 of the todays cost?
  - How to define and operate sustainable and autonomous systems for offshore renewable energy and aquaculture in shallow-to-deep waters?
  - How to contribute to standards, rules and regulations by class, authorities and industry that enables the next generation of safer, smarter and greener ships with the next level of autonomy?

We have defined the following research questions:

Q1:	How to achieve autonomous operation and vessel optimization in terms of fuel consumption, gas emissions, safety and operational efficiency?
Q2:	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?
Q3:	How to define and operate sustainable and autonomous systems for offshore renewable energy and aquaculture in shallow-to-deep waters?
Q4:	How to develop methods and fully autonomous systems for characterization, prediction, control and monitoring of marine environmental and oceanographic parameters and ecosystems?
Q5:	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, close vicinity of the sea floor, harsh weather and Arctic environments?
Q6:	How to develop intelligent marine operations to enable oil & gas field developments and marine mining in deep water and harsh environment?

Research at AMOS is organized as three major research projects

- **PROJECT 1: Technology for mapping and monitoring of the oceans.** Heterogeneous robotic platforms (underwater, surface, air and space) for mapping and monitoring the oceans in space and time.
- **PROJECT 2: Marine robotic platforms.** This project concerns the guidance, navigation and control of unmanned ships, underwater vehicles, aerial vehicles, and small-satellite systems, as well as optimization, fault-tolerance, cooperative control, and situational awareness; bio-mimics: bio-cyber-hydrodynamics, and multiscale and distributed systems for sensing and actuation are also included. The new emerging field of bio-cyber-hydrodynamics enables the development of novel concepts in marine robotics.
- **PROJECT 3: Risk management and maximized operability of ship and ocean structures.** The focus will be on the development of methods that maximize operability with improved risk management. This will be achieved by combining advanced numerical hydrodynamic and structural mechanical models for analysis, monitoring and control. Application areas include offshore wind turbines, aquaculture installations, oil and gas installations, coastal infrastructures, coupled multibody marine structures, marine operations, autonomous ships, inspections and installations.



PROJECT 1: 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), Ajit Subramaniam (Columbia University), Joe Montoya, (Georgia Institute of Technology)

Research activities:

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

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

Main results

AMOS goes to the Amazon

During the summer of 2019, two PhD candidates, Sivert Bakken and Elizabeth Prentice, and UAV pilot Pal Kvaløy, joined collaborators from the School of Biological Sciences at the Georgia Institute of Technology and the Lamont-Doherty Earth Observatory at Columbia University for a research cruise in the mid-Atlantic. The goal of the study was to complete a recurring field survey of the Amazon River plume, thus complementing a multi-year time series biological study of the region. NTNU/AMOS affiliates from the SmallSat Lab (HYPSO mission) and UAV Lab were able to piggyback on this study to test out some of their own goals: namely, how exactly can in-situ ocean sampling support a satellite mission, how well does our home-built hyperspectral imager work when targeting ocean colour gradients and can the UAV Lab's octocopter be flown from a ship successfully?

The Amazon River is the largest river in the world and discharges more than 200,000 m3/s into the Western Tropical North Atlantic Ocean. At its peak, the low salinity plume extends more than 2,000 km from the mouth and over an area greater than 1 million square kilometres. The region it covers is of particular interest, due to the diversity of the biota found there and the dynamic nature of the plume itself.

On the first two weeks of the cruise, in-situ sampling was done under the guidance of Ajit Subramaniam, Professor of Biology and Paleo Environment and a remote sensing specialist from Lamont-Doherty. Validating imagery taken from space, along with measurements taken at the water surface, is critical for the HYPSO satellite mission. In this mission, 'as mentioned in another article in this report', researchers aim to detect ocean colour targets, such as algal blooms, using an in-house hyperspectral imager and specialized on-board image processing algorithms via their 30x20x10cm CubeSat satellite. One key instrument for validating this data on the ground is a buoy, such as the one shown in Figure 1. It collects hyperspectral measurements of downwelling irradiance and water-leaving radiance using the Sky Blocked Approach (SBA) simultaneously.

Buoy data was collected by deploying the tethered instrument from the ship for approximately half an hour each day – when conditions permitted. It essentially measures the amount of light coming from both the sky and reflecting up off the water in wavelengths between 350-800nm. The measurements from the buoy were quality controlled using a tilt filter (to remove measurements that exceeded a 5-degree tilt threshold from the nadir) and an outlier filter that removed artefacts, such as the cone of the SBA being completely out of water or submerged. For the buoy, over 4,000 measurements were acquired at each station and the rigorous quality control resulted in approximately 1% of these measurements being used for subsequent analysis. The particulate and dissolved absorption spectra and HPLC diagnostic pigments were also measured at the same locations. The Quasi-Analytical Algorithm and OC4 with SeaWiFS coefficients were used to derive bio-optical parameters.

In addition to the measurements made by the buoy, the hyperspectral imager, designed for the HYPSO satellite, was tested on an octocopter UAV. This imager is a push-broom hyperspectral sensor, meaning that it must fly over its target collecting one

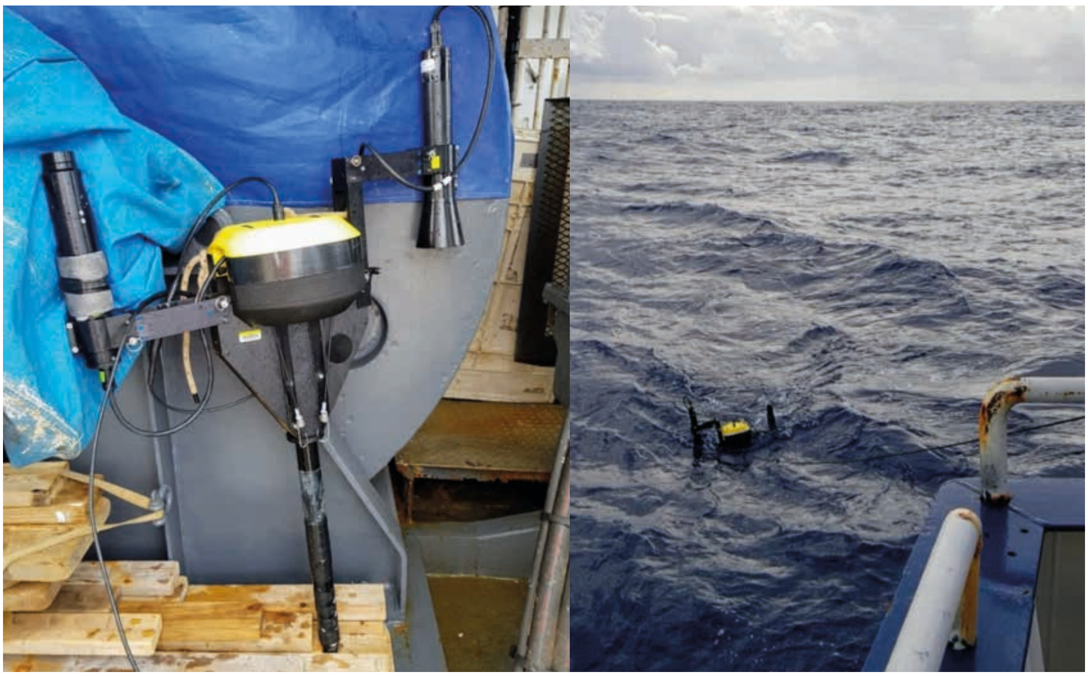


Figure 1: *SBA buoy*

Figure 2: *The R/V Endeavor docked in Barbados shipping port*

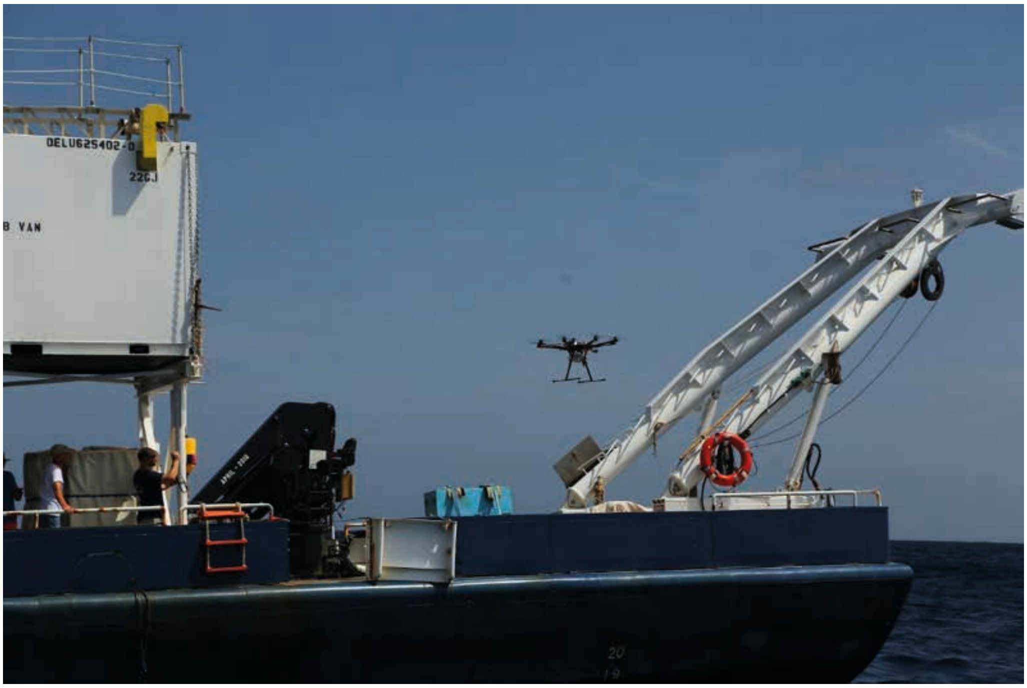


Figure 3: *The UAV with mounted HSI successfully landing on the stern of the ship*

strip of pixels at a time, and then merging them together with altitude, attitude and view angle information to acquire a spatial representation of its target. But essentially, it collects the same spectra of light (400-800nm) that the buoy does, just at a height of 50-100m above the sea surface….and the satellite, 500km above the surface.

The team managed to get two flight surveys in despite the rough Atlantic seas and high winds. During these flights, over 4,000 spectrograms (hyperspectral images) were taken of the sea surface. The Amazon plume extended so far during this time that the boat actually never left "plume" waters throughout its four-week cruise, and the team was unable to make flight passes over the gradient boundary. Regardless, the HYPSO team now has a database of ocean water spectra from the imager that will be launched into space, thereby providing data for algorithm development and testing.

A comparison with results derived from the spectra, and in situ measurements of particulate absorption coloured dissolved organic matter and diagnostics phytoplankton pigments made during this field survey, can help to make better models for the hyperspectral imaging of ocean colour for future earth observation satellites focused on aquaculture, such as the HYPSO mission.

Globally stable observers for simultaneous localization and mapping

For mobile robotics applications, it is essential to have some knowledge of the robot's position and velocity, which requires a robust and accurate estimate. Having these estimates can be especially difficult when positioning systems, such as indoor positioning systems (IPS) and global satellite navigation systems (GNSS) are not available. However, a strategy used in robotics is to mount sensors onboard mobile robots that can be used for estimating position and velocity. One of the more popular sensors for this is the camera. Its low cost, light weight, digital output and low power consumption makes it ideal for many robotics setups, particularly aerial robots. The downside is that it is nontrivial to extract positioning and velocity information from camera images. Due to the nonlinearity of the estimation problem, finding solutions with a satisfactory robustness has been an open problem with this kind of sensor setup.

We have explored two types of techniques from nonlinear observer theory, and applied them to camera-based navigation. The motivation was to design observers that could have strong stability properties theoretically proven and analysed. The first technique applied was based on representing the nonlinear system as a linear time varying system, in which sensor values were used to build the system matrices for the system. This allowed us to use classical methods from linear theory, the Kalman Filter. It was also shown how it could be guaranteed that such an observer would have globally asymptotic stability properties, and the results were confirmed with simulations. In addition, a statistical analysis of these observers was performed, and how the estimation error sensitivity to measurements noise was studied.

A set of deterministic observers for the navigation based on inertial sensors and a camera was developed, together with proofs of semi-global asymptotic stability. This was applied to the position and velocity estimation, in which two scenarios were of particular interest. In one scenario, we showed how the observer could fuse optical flow estimates from a camera with a calibrated inertial measurement unit (IMU), in order to estimate the velocity of the robot. Moreover, a scenario in which velocity measurements, camera and biased gyro measurements were combined in order to estimate the gyro bias, attitude and position of the robot. The results show how observers with theoretical proof of a global or semi-global asymptotic stability could be used to solve velocity estimation and positioning with a camera. The research was done by Elias Bjørne, under the supervision of Edmund Brekke, Torleiv Bryne and Tor Arne Johansen **[P1-R1, P1-R2]**.

Marine archaeological survey in Smeerenburgfjorden 2019

In 1693, a small fleet of four French warships under the command of M. de La Varenne was ordered by King Louis XIV to "destroy the Enemy's vessels going out to whale in Greenland [Spitsbergen]. [...] His Majesty wants that he burns or sinks, without any exception, all the ships which fly the British, Dutch or Hamburg flags and, as far as those which sail under the Danish flag, the captain will make sure that they are really Danish". This was during the Nine-year war in Europe, and the motive was to hurt the Dutch economy by hitting the prosperous whaling enterprise in the Arctic. The campaign was a success. Twenty-eight Dutch whaling ships were captured, of which 17 were sunk near Smeerenburg on the north-western edge of Spitsbergen.

In June 2019, a team of researchers from NTNU and Memorial University Newfoundland, in collaboration with the University in Tromsø, conducted a surveying expedition to look for the wrecks from the 1693 incident.

The survey areas, Sørgattet, Danskegattet and Kobbefjorden, were selected based on historical texts and maps describing anchorages, sailing routes and wreckings around the old Dutch settlement in Smeerenburg. A detailed report to King Louis XIV, including a map showing encounters between French and Dutch vessels, was the primary source of information in the planning of the survey.

The team was based on the small charter vessel MS Farm, and used Zodiac rubber boats to launch an Autonomous Underwater Vehicle (AUV) and two Blueye mini ROVs to map the seabed. The AUV, and an additional towfish, was equipped with a side scanning sonar to produce high resolution images of the seafloor. After each mission, the data were reviewed and potential objects of interest were tagged for closer inspection with ROV. The expedition was a success, demonstrating the team's ability to effectively operate light underwater robotics in a high Arctic environment. The ice edge was unusually far south this summer, and missions had to be re-planned and adapted ad hoc to ensure that both vehicles and personnel were safe at all times, accounting for ice floes, polar bears and walruses.

More than 10 square kilometres of seabed was mapped, covering most of the areas in the initial mission plan. Nearly 100 targets were tagged in the sonar imagery as possible wreck sites, with approximately 10 of those inspected with ROV. Preliminary results indicate that no structurally intact wrecks remain in the survey area, hence suggesting that conditions for preservation are not optimal. Wrecks in the area are likely to be buried in the sediments, and additional surveying with sensors for looking into the seabed will be required to locate and investigate this unique cultural heritage.

The project was funded by the Svalbard Environmental Fund and NTNU AMOS.

Figure 4: *Overview of survey area in Danskegattet, with Smeerenburgodden in the background (Photo: Asgeir Sørensen)*

__Figure 5:__ Team members Geir Johnsen and Asgeir J. Sørensen surveying the seabed in Kobbefjorden with side scanning sonar (Photo: Øyvind Ødegård)

Hyperspectral super-resolution

The Hyperspectral Smallsat for Ocean Observation (HYPSO) will use a hyperspectral camera to observe and monitor algal blooms in the ocean along the Norwegian coastline. The data it collects can be used to classify and investigate algae with more accuracy than is possible with traditional multispectral cameras. However, the size constraints of the small satellite platform limit the spatial resolution of the hyperspectral camera. To better understand the algal bloom dynamics, and to determine the possibility for an algal bloom to become harmful, it is helpful to enhance the spatial resolution of the data through image processing techniques, see Figure 6.

The limits to the spatial resolution of the hyperspectral camera originate from three sources: the sampling rate, its point-spread function and the signal-to-noise ratio. Even if the sampling rate is high, the point-spread function, which describes how many pixels observe one point in the scene, can cause the resulting image to

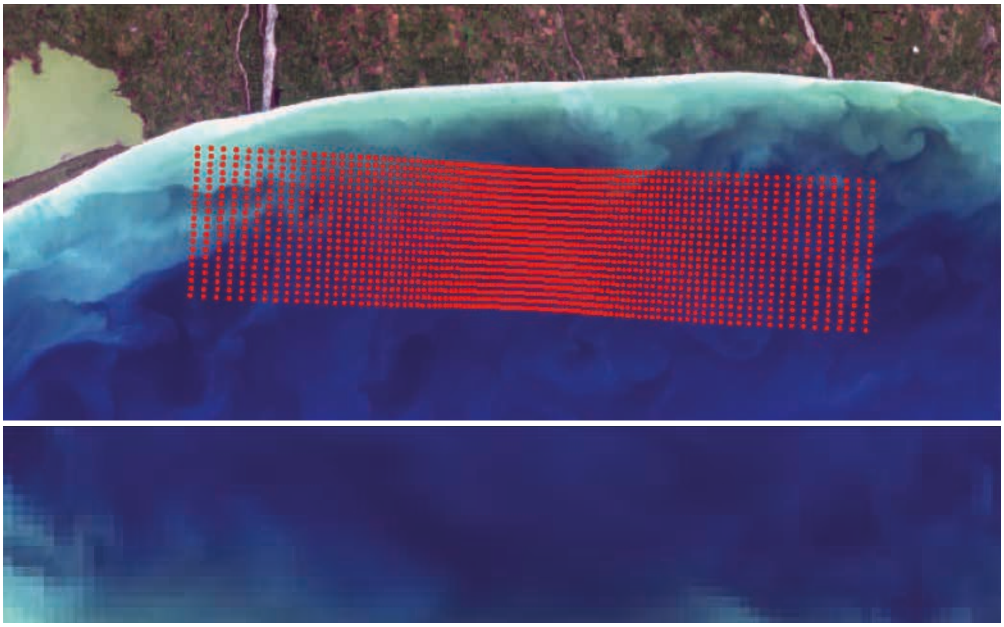


__Figure 6:__ A simulated measurement captures pixels centred at the red dots (above). The raw data are unevenly spaced and appear blurry when viewed in a grid (below). The original image of the coast near Te Waihora, New Zealand was captured by the Hyperspectral Imager for the Coastal Ocean (HICO) on 16 June 2011.

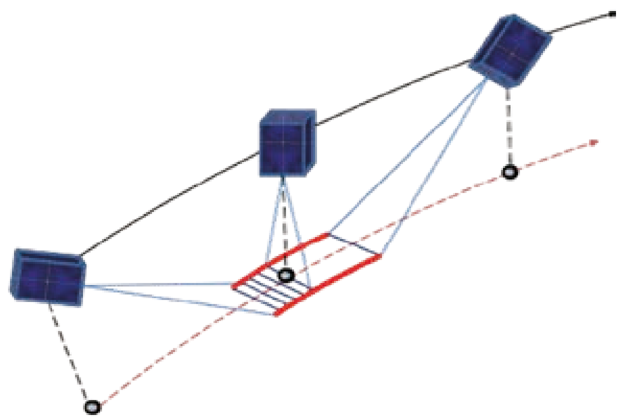


Figure 7: *A slew manoeuvre simultaneously enables HYPSO to achieve a high sampling rate and a high signal-to-noise ratio.*

be blurry. Deconvolution of the captured image can reduce the blur, but noise limits its effectiveness. If the data is too noisy, the deconvolved image can become extremely difficult to interpret.

The primary limitation to spatial resolution of HYPSO's camera comes from the width of its point-spread function in the along-track direction. To overcome this limitation, a slewing manoeuvre, see Figure 7, in which HYPSO slowly turns as images, is used so that the target region is scanned at a high sample rate, with a higher signal-to-noise ratio than would be possible with a nadir-pointing operation. The slew manoeuvre results in a high density of irregularly sampled, overlapping pixels which must be separated through image processing.

The HYPSO team tested several approaches to resolving overlapping pixels in the images. The first was the Lucy-Richardson algorithm, see Figure 8, which is a well-tested technique originally developed independently for remote sensing and astronomy. It was built into a software/hardware co-design that incorporated an FPGA **[P1-R4]**. This iterative technique is based on Bayesian inference, which interprets the point-spread function and the raw image data as probabilities. The Lucy-Richardson algorithm was shown to be very effective in low-noise environments and amenable to parallelization, though susceptible to artefacts when the noise was more significant.

Super-resolution (SR) is a collection of techniques that construct a high-resolution image from low resolution observations. SR techniques are distinguished from deconvolution techniques because they use prior knowledge about the scene itself, rather than just the imaging process, to enhance the spatial resolution. They typically also produce an image on a spatial grid that differs from the original observations. Adapting preexisting SR techniques to hyperspectral data is made difficult by the large size of the datacubes (Gbs) and the irregular spacing of the pixels. Image registration places the irregular measurements on a regular spatial grid. Yet, because traditional SR algorithms are designed for evenly-spaced measurements, it was necessary to design an interface for them to work with image registration.

Two different types of SR were compared in order to determine which sort of algorithm would meet the scientific quality standards and processing time constraints of the HYPSO mission [P1-R3]. The first of the two techniques was projection onto convex sets (POCS). In POCS, the multiple constraints on the data are each phrased as a set. For each constraint, a projection, which adjusts the scene estimate to make it consistent with the constraint, is defined. The algorithm then iterates through the projections in order to find a scene estimate that meets all constraints. Examples of constraints are a consistency of the scene estimate with a particular measurement and global non-negativity.

The second tested technique, robust SR, is based on optimization and defines a cost function that includes both a data-consistency term and a term describing prior knowledge about the scene, such as its smoothness or a spatial relationship between bands (colours). Gradient descent is then used to minimize the cost function. These two techniques were chosen for testing because many types of additional information about a scene are straightforward to incorporate into both of them.

The preliminary SR tests showed both that a spatial resolution enhancement is possible, and that it is necessary to develop new diagnostics to determine precisely how much the resolution improves, cf. Figure 9. POCS showed an approximate 3%

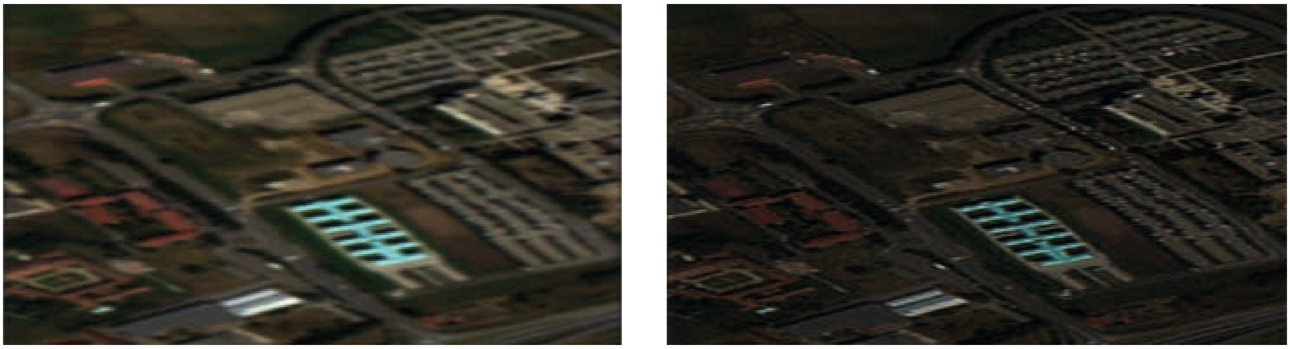


Figure 8: *The Lucy-Richardson algorithm deconvolves a blurry image (left) so that it becomes clearer (right)*

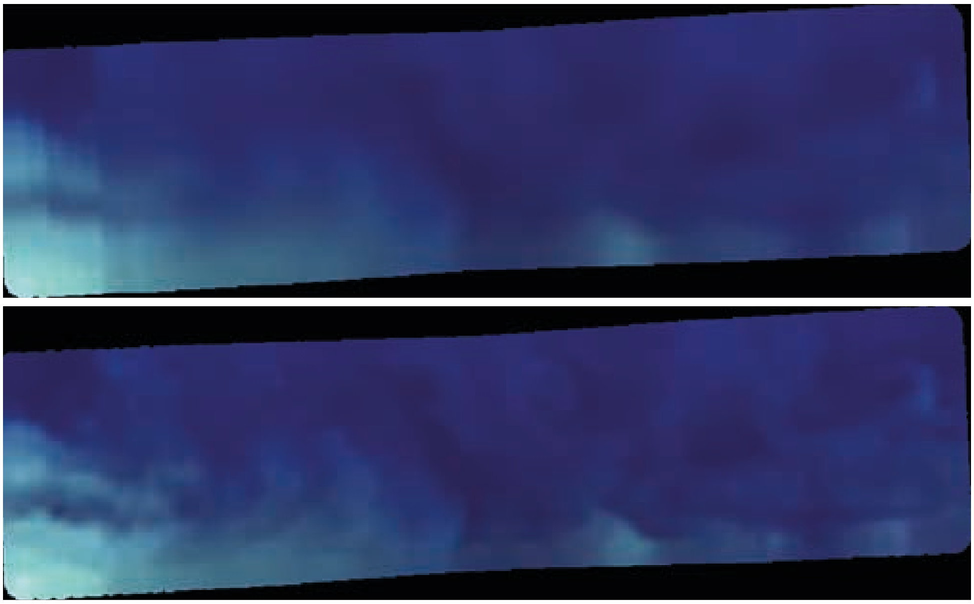


Figure 9: *The registered pixels from the simulated measurement (top); the scene after applying robust super resolution (bottom).*

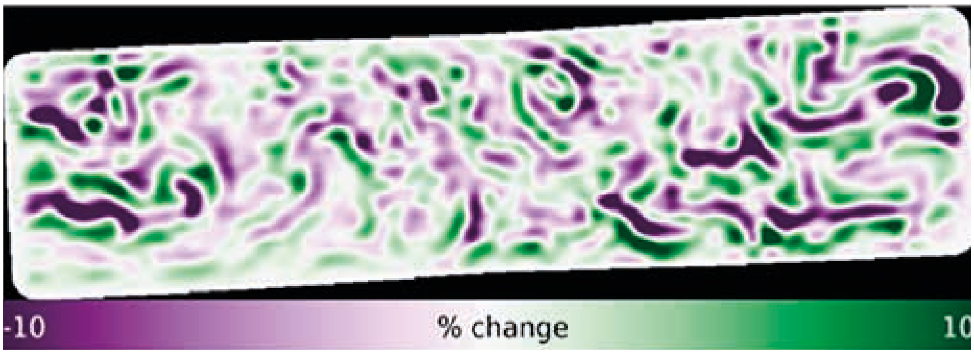


Figure 10: *The percentage change to the intensity of the green band from applying robust super resolution.*

improvement in overall accuracy over the raw registered data, with a robust SR showing approximately an 8% improvement on a small image with sparsely sampled points. An image of the adjustments of the robust SR algorithm shows spatial details (see Figure 10), but more work is necessary in order to interpret how changes in the accuracy of the simulated measurements reflect the possibility of scientific inference as short distances. A robust SR was chosen to be the target framework for the HYPSO image processing pipeline, because although it was slower per band than POCS, it was more straightforward to parallelize for multiple bands and showed a greater overall improvement.

The SR component of the HYPSO image processing pipeline is being further developed in order better accommodate real data and meet the needs of the end users of HYPSO's observations:

- The image registration and SR framework is being expanded to incorporate the asymmetric point-spread function of the hyperspectral camera. The across-track resolution is expected to meet the requirements of the science board. We want to see if the across-track spatial resolution can be utilized to improve the along-track resolution.
- UAV field experiments have been run to evaluate how well SR works on real data.
- Pan-sharpening of the hyperspectral data, the fusion of a single-band image with a lower-resolution hyperspectral image, is being investigated as a way to leverage the observations of other earth observation satellites to enhance HYPSO's spatial resolution.
- Many popular forms of SR are convolutional neural nets. The robust SR framework has been expanded to incorporate a subset of such networks. Tests are being run to determine whether robust SR is sufficient to guide the neural nets to scientifically reliable operation.
- SR is not an end to itself, but a pre-processing step to make classification and target detection more accurate. The HYPSO team is currently looking into how robust SR interfaces with different analysis algorithms, and how it can be modified to facilitate target detection and classification.

The research was done by Joseph L. Garrett, Mariusz Grøtte, Karine Avagian and Dennis Langer under the supervision of Milica Orlandic, Annette Stahl and Tor Arne Johansen.

Autonomous unmanned aerial vehicles in search and rescue missions using real-time cooperative model predictive control

Search and Rescue (SAR) is one of the fields in which the employment of UAVs brings many advantages over manned missions, such as its reduced costs, lower use of human resources and overcoming mental and perception limitations of human operators.

In order to benefit from these advantages, a multiple UAV cooperative Nonlinear Model Predictive Control (MPC) solution to search a given area was proposed in this study [P1-R5]. In MPC, the predicted control inputs are chosen with the objective of minimizing the distance between the reference trajectory and the predicted output. The technique of Particle Swarm Optimization (PSO) was used to find the control inputs that solve the MPC problem with a coordinated turn kinematic model implemented to consider the effects of wind.

The search area was divided into cells and each cell had an associated reward, which in this work was defined according to the international Search and Rescue directives of the International Aeronautical and Maritime Search and Rescue (IAMSAR) Manual. The proposed solution was tested using a Software-In-The-Loop (SITL) environment with flight dynamics simulations, see Figure 11. The results show that, for the given mission, the time to reach a 50% of probability of success is significantly reduced as the number of UAVs in the mission increases, see Figure 12.

The primary researcher was Fabio Andrade, under the supervision of Tor Arne Johansen and Rune Storvold.

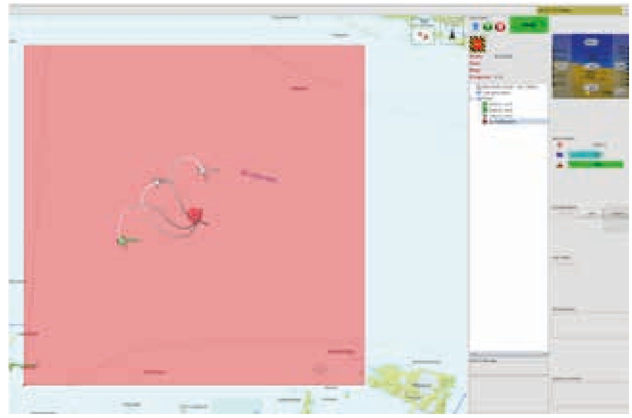


Figure 11: *A command and control software was used to visualize the UAVs' telemetry and location and to give commands to the UAVs, such as takeoff and loiter, and to start/stop the Search and Rescue mission.*

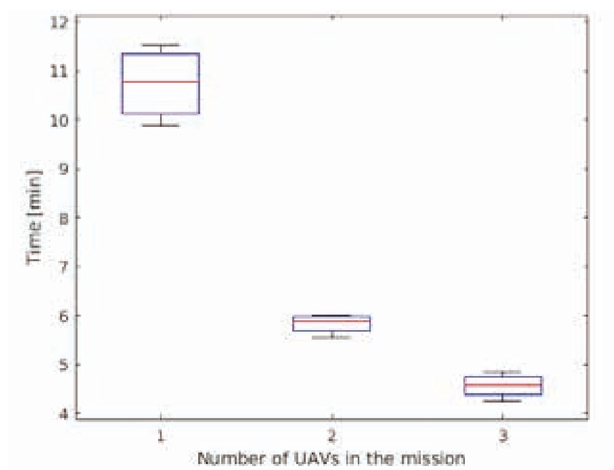


Figure 12: *Time to reach 50% probability of success as a function of the number of UAVs collaborating on the task*

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PROJECT 2: Marine Robotic Platforms

Project manager: Prof. Kristin Y. Pettersen

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

Scientists at NTNU: Profs. Odd M. Faltinsen, J. Tommy Gravdahl, Martin Ludvigsen, Edmund Brekke, Ingrid Schjølberg, Roger Skjetne, Maarja Kruusmaa, Claudio Lugni, Kjetil Skaugset, Kanna Rajan, Houxiang Zhang, Rune Storvold, Stein Nornes and Pedro De La Torre

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

Exploring the hazards of drone icing

The icing of drones is a severe hazard that significantly limits the usage of autonomous unmanned aerial vehicles. Researchers conducted experiments in an icing wind tunnel to learn more about icing to test an icing protection system.
Video: https://www.youtube.com/watch?v=jZfjtbl7mcs

This spring, researchers from the Centre for Autonomous Marine Operations and Systems (NTNU AMOS), CIRFA and UBIQ Aerospace have been visiting a special wind tunnel at the Technical Research Centre of Finland (VTT) that can simulate icing conditions. Their goal was to study ice accretion on unmanned aerial vehicles (UAVs) under laboratory conditions, and to further test and improve a UAV icing protection system called D•ICE [P2-R6]. The tests have proven the capability of the D•ICE technology, and the results will help the researchers to validate their numerical models. This will aid them in improving their system to be smarter, more reliable and energy efficient.

During the tests, the researchers collected ice shapes at different meteorological icing conditions on a UAV wing section **[P2-R5]**. This experimental data will be used to compare to numerical

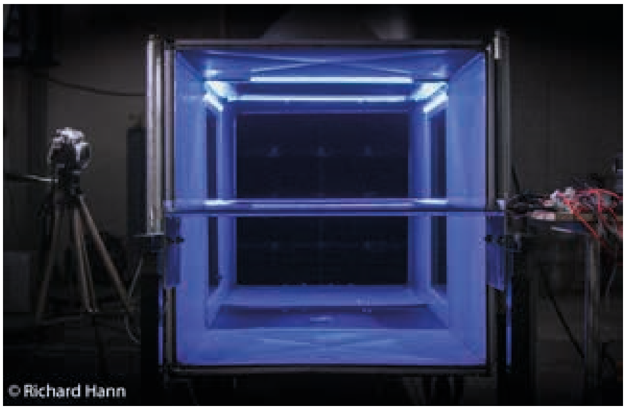

Figure 1: *Experimental setup in the VTT icing wind tunnel*

Figure 2: *Rime ice on a UAV airfoil in the icing wind tunnel.*

Figure 3: *Glaze ice on an airfoil with view inside the icing wind tunnel*

models that simulate ice accretion on airfoils. In addition, the D•ICE technology was tested to show that it can successfully prevent ice accumulation on the wing. The system mitigates harmful ice accretions by warming the surface with heating zones made of carbon fibres embedded in the wing structure **[P2-R3]**.

Atmospheric icing is a well-known phenomenon in the Nordic countries. Icing on power lines and structures is a great challenge that has been the focus of research for many years. In recent years, the topic of icing on wind turbines has become a threat to the advancement of renewable energies. In both these fields, VTT has been heavily involved with research and the development of new technologies and solutions.

Today, a new challenge with regard to icing is emerging: icing on UAVs. Drone technology is a fast-growing and emerging technology with a wide range of applications. For example, drones are used for delivering urgent medical supplies in Rwanda, to provide broadband access to remote areas, to perform search and rescue missions and to explore scientific research questions.

Icing can be a severe hazard for these applications. Research has shown that ice will accumulate on the body, wing and propeller of drones in icing conditions. The ice is disturbing the aerodynamics, which leads to a significant decrease in performance **[P2-R1, P2-R2, P2-R7]**. There are many cases where icing conditions have led to drone crashes. This is why today it is a best practice to not fly drones in bad weather conditions. However, for the success of many of the aforementioned applications, an all-weather capability is a key requirement.

Researchers at NTNU AMOS have been working on the UAV icing challenge for several years. Their goal is to understand the physics of how ice is accumulating on the drones, and how the ice affects the aerodynamics **[P2-R4]**. Furthermore, they have developed the D•ICE technology to detect and mitigate the hazards of icing. UBIQ Aerospace is a deep tech spin-off from NTNU AMOS, whose goal is to further develop D•ICE into an intelligent and effective icing protection system for UAVs.

Bio-inspired robots

The AMOS research on bio-inspired robots this year has performed real-fish experiments on behavioural and hydrodynamic advantages in fish schooling. There is an ongoing identification of fish-locomotion features for swimmers using caudal-fin propulsion based on the real-fish experiments carried out in 2018; numerical studies of fish-like hydrodynamics have been performed, with a focus on wake features and thrust production.

Many swimming fishes can be considered as underwater bio vehicles with a high hydrodynamic efficiency. Depending on their propulsion mechanisms, they can use the body caudal fin (BCF) or median-paired fin (MPF) to generate thrust. In order to transfer fish capabilities and performances to novel robotic platforms, it is essential to study real-fish behaviour. In August 2019, experiments on shiner perches, labriform swimmers primarily using their pectoral fins and caudal tail for assistance, were carried out in a Steffensen-type swim tunnel at the University of Washington (Figure 4) to study the behavioural and hydrodynamic advantages in fish schooling. Here, we highlight some findings of the ongoing analysis.

Figure 5 shows the mean fish fin-beat frequency, f, as a function of the swimming speed, U, for (A) fish in a single-fish scenario and for (B) front and (C) back fish in a pair-fish scenario. At

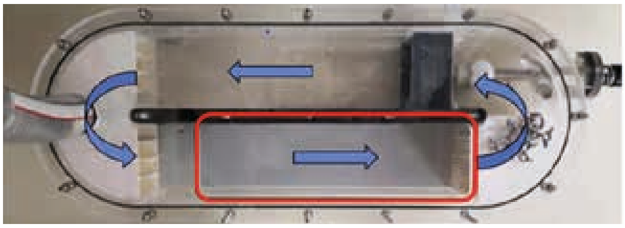

Figure 4: *Top view of the circulating channel used in the physical tests. The arrows indicate the direction of the inflow experienced by the fish placed inside the test window highlighted by the red box.*

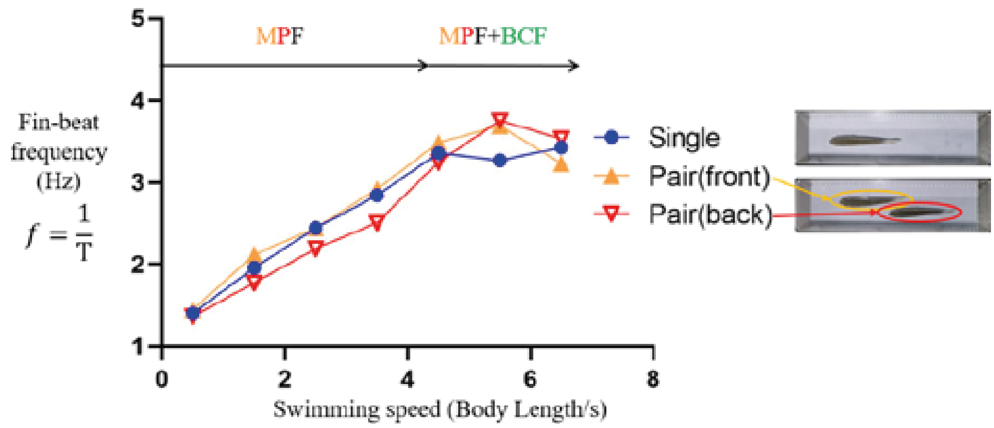

Figure 5: *Fin-beat frequency versus swimming speed for single (A), front in a pair (B) and back in a pair (C) fish case.*

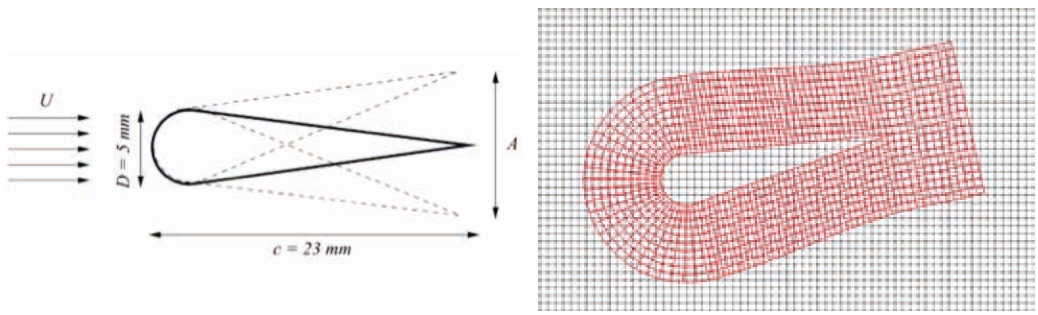

Figure 6: *Left: Schematic view of the foil profile and parameters definition. Right: Illustration of overset grid method. Black line: background mesh; Red line: body-fitted mesh.*

lower speeds, when the fish use only fins for propulsion (MPF), *f* increases almost linearly with *U* for all fish. It indicates that fish consume more energy to keep up with an increasing inflow velocity. At higher speeds, the fin-beat frequency changes little with *U* because fish also use tail propulsion (BCF) for assistance. Comparing A-C cases, *f* of the front fish is quite like the single fish case, while the back fish is associated with lower frequencies. This confirms the hydrodynamic advantages of being the back fish in schooling.

This opens for relevant research questions in connection with an optimal distance between fish and quantitative energy saving, which require further research. Because authorized labs for real-fish experiments are designed for physiology analyses, they involve limitations for quantitative hydrodynamic studies, e.g. due to lab-wall effects and errors in prescribed inflow conditions. It is also important to reveal the basic physical mechanisms of the fish hydrodynamics so as to guide the identification of reduced order models for fish robots and, more generally, for fish-inspired underwater vehicles. This pushes towards the numerical investigation of fish-like hydrodynamics. Promising results of our ongoing research are documented next. An open-source solver from the OpenFOAM simulation platform, combined with an overset-grid strategy, has been used to reproduce available experiments on a rigid foil, with a maximum thickness *D*, in two-dimensional flow conditions. The foil interacts with a steady inflow with speed *U*, and is forced to oscillate about its leading edge at frequency *f*, with oscillation amplitude *A* of its trailing edge (left side of Figure 6). In the overset grid method, two separate grids (a background and a body-fitted grid) are defined as internally static, thereby retaining their original structure and quality, but they can move relative to each other with adequate efficiency and accuracy (right side of Figure 6).

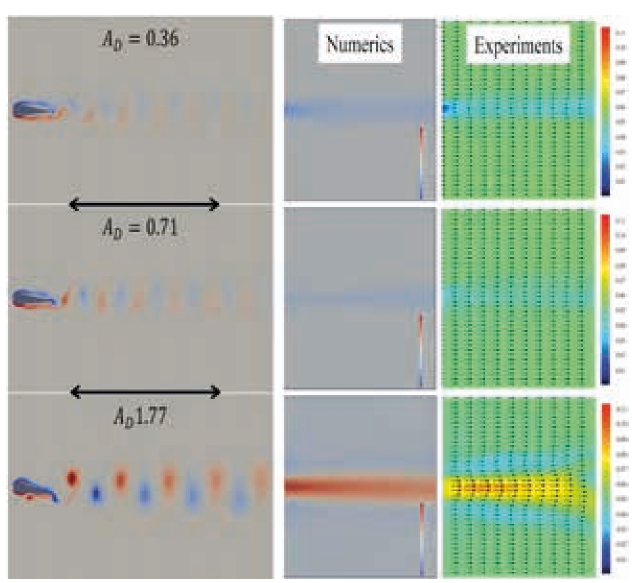

Figure 7: *Left: instantaneous numerical spanwise vorticity field. Middle: numerical time-averaged flow velocity in the horizontal-arrow region of the corresponding left plot. Right: mean experimental flow (Godoy-Diana et al., 2008).*

The left side of Figure 7 shows the numerical wake of the foil for a fixed f and an increasing A_D=*A/D*. By increasing the pitching amplitude, the von Kármán (vK) vortex street develops firstly into aligned vortices along the symmetry line of the wake, and then transforms into a reverse von Kármán wake.

Accordingly, the mean velocity behind the foil is lower than *U* at the smallest A_D, but increases with A_D and becomes higher than *U* at the largest A_D, thus leading to a jet-flow profile. The comparison of numerical results and experimental data (middle and right sides of Figure 7) is promising, indicating that the adopted method can be useful for more systematic parameter studies of the fish-like hydrodynamics.

Autonomous AUV docking

Autonomous docking is achieved by an articulated AUV learning a docking maneuver using a convolutional neural network [P2-R8]. Autonomous underwater vehicle (AUV) technology has proven to be sufficiently mature to autonomously perform a variety of underwater missions. However, the battery duration of AUVs is generally a limiting factor for a mission. This restriction adds the need of a surface support vessel to launch and recover the vehicle, something which increases the cost of the mission and makes the operational outcome more dependent on sea conditions.

A permanent docking station on the seafloor, where the vehicle could charge the batteries and transfer the results of a mission, would reduce the need for frequent launch and recovery operations at the surface, hence making the technology more cost effective, safer and more robust. It would also enable the possibility of permanently residing AUVs ready for subsea operations, which would further extend the capabilities of the AUV technology. To this end, autonomous docking is required.

Motivated by recent advances, in which neural networks have been applied to learn and perform a complex control task by themselves, and even outperforming humans, we propose a framework for end-to-end learning, obtaining data and training a convolutional neural network (CNN) for docking an AUV. The proposed CNN uses raw images from a front facing camera as input, and as output it produces the error signal that can later be fed to a controller to steer the vehicle into the docking station. In the proposed framework, the data required for training the CNN to perform a docking manoeuvre is obtained in a controlled environment, such as: A tank equipped with a motion capture system, an underwater operation where a supply vessel equipped with GNSS-USBL is present and able to provide accurate measurements, or even with a realistic 3D simulation. The external positioning system in this controlled environment allows for producing very accurate measurements of the position and attitude (*x, y, ψ*) of the vehicle during the training period. Simultaneously, and in a synchronized way, the data from the AUV's internal sensors is recorded from a large set of different states/locations, and paired with the precise data from the external sensors.

As represented in Figure 8, all the data measured by the external positioning system (EPS) is mapped through a guidance map to

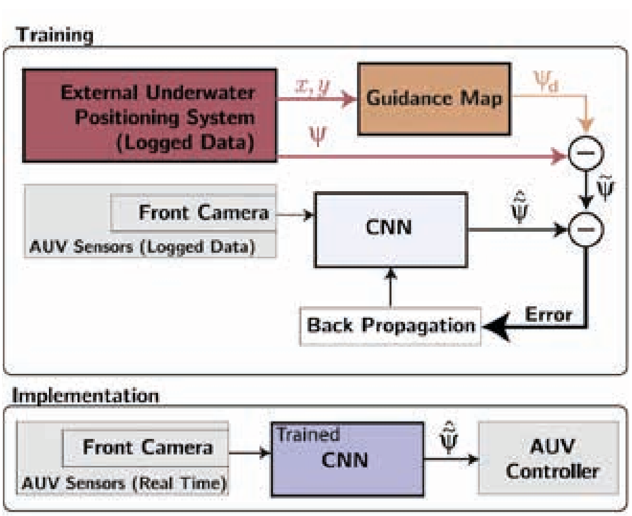

Figure 8: *Block diagram showing how the CNN is trained and the implementation after training.*

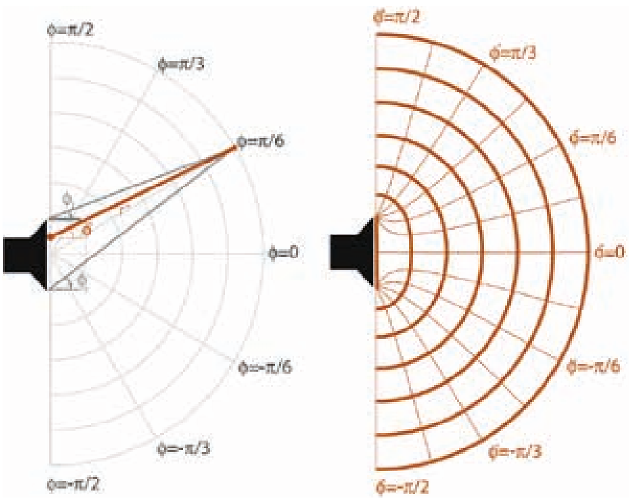

Figure 9: *Transformation of the polar coordinates.*

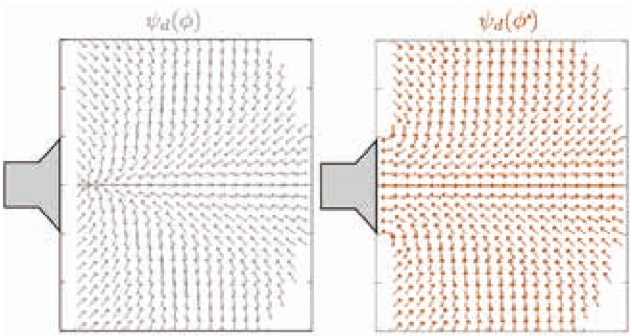

Figure 10: *Guidance map with polar coordinates (left) or the transformed coordinates (right).*

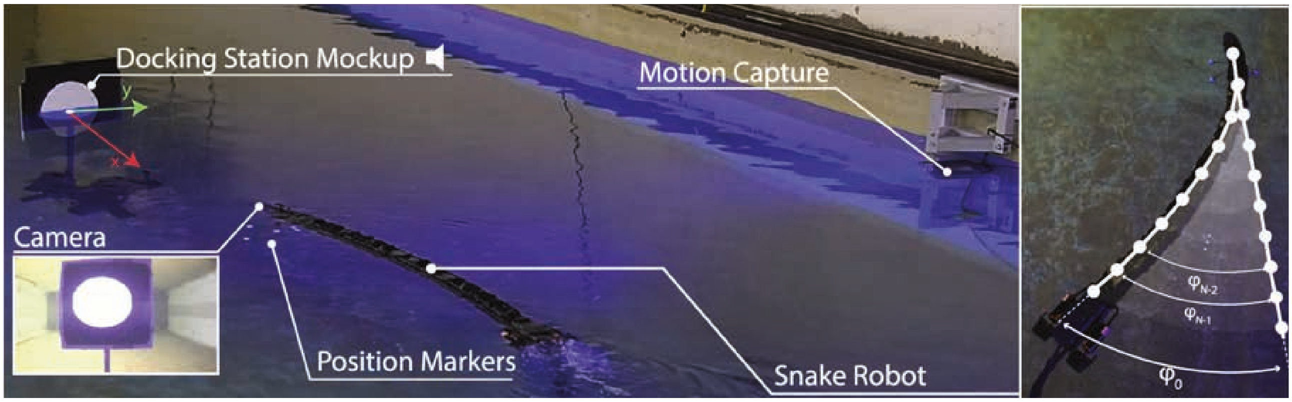

Figure 11: *The experimental setup. The direction of motion of the articulated AUV, aka a swimming snake robot, is controlled using bending, achieving remarkable manoeuvrability.*

generate a desired heading ψd that guides the AUV towards the docking station. The end goal of this application is to produce a regression from image/sensor information to an estimate of the heading error that does not use any of the external sensors. This end-to-end solution combines the detection of the docking station, navigation and guidance, all into a single network. To help achieve this, the CNN takes frames of the training dataset as input, and the output from the CNN is compared with the ground-truth values obtained from the EPS.

For convenience, the guidance and control of the vehicle are described in polar coordinates. This poses some challenges due to the singularity at the origin. Since the docking station is designed to tolerate a certain lateral offset, a novel transformation of the polar coordinates is proposed to accommodate such a tolerance and avoid large angular errors when getting very close to the docking station, cf. Figures 9-10.

The method is experimentally verified using an articulated AUV, cf. Figure 11, with the results showing that this approach enables the vehicle to reliably perform a docking manoeuvre using only a camera as a sensor.

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P2-R1. Hann, R., Wenz, A., Gryte, K., and Johansen, T. A., "Impact of atmospheric icing on UAV aerodynamic performance," 2017 Workshop on Research, Education and Development of Unmanned Aerial Systems, RED-UAS 2017, Linköping: 2017, pp. 66–71.

P2-R2. Hann, R., "UAV icing: Comparison of LEWICE and FENSAP-ICE for ice accretion and performance degradation," 2018 Atmospheric and Space Environments Conference, 2018, pp. 1–8.

P2-R3. Hann, R., "UAV Icing: Comparison of LEWICE and FENSAP-ICE for Anti-Icing Loads," AIAA Scitech 2019 Forum, San Diego: AIAA, 2019.

P2-R4. Winter, A., Hann, R., Wenz, A., and Johansen, T. A., "Stability of a Flying Wing UAV in Icing Conditions," 8th European Conference for Aeronautics and Space Sciences (EUCASS), 2019.

P2-R5. Fajt, N., Hann, R., and Lutz, T., "The Influence of Meteorological Conditions on the Icing Performance Penalties on a UAV Airfoil," 8th European Conference for Aeronautics and Space Sciences (EUCASS), 2019.

P2-R6. Hann, R., Borup, K., Zolich, A., Sorensen, K., Vestad, H., Steinert, M., and Johansen, T., "Experimental Investigations of an Icing Protection System for UAVs," SAE Technical Papers, 2019, pp. 1–9.

P2-R7. Hann, R., "UAV Icing: Ice Accretion Experiments and Validation," SAE Technical Papers, 2019, pp. 1–10.

P2-R8. A. Sans-Muntadas, E. Kelasidi, K.Y. Pettersen and E. Brekke, "AUV guidance and docking using a convolutional neural network", IFAC Journal of Systems and Control, Vol. 8, June 2019.

Selected media coverage:

- Snake robots exploring the oceans, NRK TV, 19 June 2019.
- Slangeroboter utforsker havet, By Thomas Høstad, NTNU Big Challenge Science Festival, Trondheim, Norway, 16-19 June 2019.

Plenary lectures at international conferences:

- **Pettersen, Kristin Ytterstad**. Snake robot control. Plenary lecture at Indian Control Conference (ICC), Hyderabad, India, 18-20 December 2019.
- **Pettersen, Kristin Ytterstad**. Snake robots moving on land and exploring the oceans. Keynote lecture at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, China, 4-8 November 2019.
- **Pettersen, Kristin Ytterstad**. Snake robot control. Plenary lecture at the joint IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS) and IFAC Workshop on Robot Control (WROCO), Daejeon, Korea, 18-20 September 2019.
- **Pettersen, Kristin Ytterstad**. Snake robots exploring the oceans. Keynote lecture at the Big Challenge Festival, Trondheim, Norway, 17-19 June 2019.

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

Project manager: Prof. Jørgen Amdahl

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

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

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

Research activities:

The relevant research activities carried out this year deal with:

- Wave and current induced response on a well boat operating at a fish farm with attention to the structural response of the fish farm and the mooring-line system
- Wave-induced hydroelastic analysis of a closed fish cage
- Swirling and resulting liquid mass transport during sloshing in a rigid vertical cylindrical tank
- Statistical modelling of extreme ocean current velocity profiles with an emphasis on the depth dependence
- Local – and global response of a floating fish farm subjected to ship collision
- Vertical water-entry of solid bodies with a formation of air cavities
- Impact of weather and operational uncertainties on the actual ship speed in real operating conditions and the human factor for ship speed loss in rough sea voyages
- Hydrodynamic loads and motions of a damaged mid-ship section in waves
- Modelling of the single-phase turbulent flow during the evolution of an unsteady spilling breaker
- Free-surface wave modification during propagation from deep to shallower water regions
- A nonlinear model predictive control scheme to avoid sudden peak tension and snap loads in the lifting wires during wind turbine blade lifting operations
- Wind-wave directional effects on the fatigue of bottom-fixed offshore wind turbine

Highlights

Operating marine net-based fish farms in exposed areas is promising, but will also increase the probability of service vessel, i.e. well-boat, routine operations in severe weather conditions. A well boat is a fishing vessel with a well or tank for the storage and transport of live fish, and is essential to ensure fish welfare. A typical well-boat operation can be categorized into three phases: approaching, loading/offloading and leaving. During the loading/offloading phase, the well boat is moored directly to the fish farm (Figure 1).

Large relative motion between the well boat and the floating collar makes it difficult to perform loading/offloading operations in severe sea states and strong currents. Also, the well boat has a comparable size to the fish farm; connecting the well boat directly to the net cage can significantly increase the mooring loads and the floating collar deformations, and thus endanger the structural integrity of the fish farm (see the system configuration in a current with speed U_∞ = 0.5 m/in the middle and right side of Figure 1). Therefore, there is a need to have a detailed investigation of the influence of the well boat on the fish farm, and identify the operational conditions for performing such loading/offloading operations.

Based on our numerical studies of the coupled well boat-fish farm system in current [P3-R1], the anchor loads are greatly increased by the well-boat presence. For instance, for anchor line-1 and current in x_E direction (defined in the left side of Figure 1), the steady-state load increases by more than 40% in small current velocities, and up to 90% in high current velocities due to the well boat (left side of Figure 2). Moreover, the stresses along the floating collar are affected (right side of Figure 2). The maximum

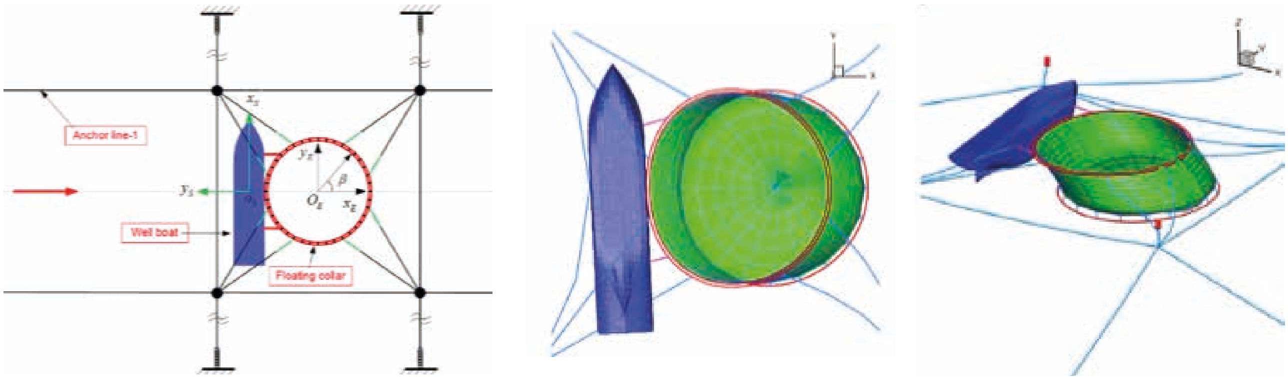
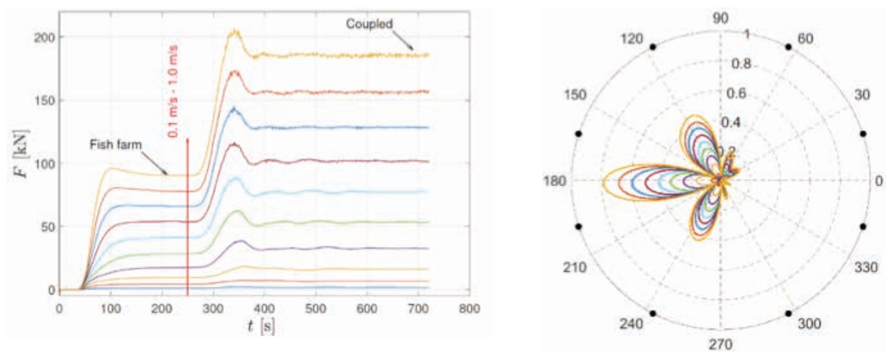


Figure 1: *Left: Fish farm with inflow in* x_E *direction (top view). Middle and Right: Steady configuration of the coupled well-boat fish farm system in current with* U_∞ *= 0.5 m/s, respectively, from bird's eye view and three-dimensional view.*

Figure 2: *Left: Time histories of loads in anchor line-1 in current only. Current velocity* U_∞ *varies from 0.1 m/s to 1.0 m/s. Right: The corresponding stress distribution along the floating collar due to horizontal deformations. The stress is made non-dimensional by the yield stress (high-density polyethylene)* σ_0*. The labels 0° – 360° represent the radial angle β (position) along the floating collar.*



stress documented is approximately 80% of the yield stress of the floater, and occurs at the region β = 180° where the well boat is in contact with the floating collar. The dynamic response of the coupled system in irregular long-crested waves and current has also been numerically analysed **[P3-R2]**. The slow-drift sway motion of the well boat matters in this scenario. As an example, the time histories of the load in anchor line-1 and the stress at β = 180° in the floating collar are shown, respectively, in the left and right side of Figure 3. The slow-drift component dominates over the wave-frequency component for both the anchor load and the stress. Additionally, the maximum stress is approximately 70% of the yield stress, while the maximum anchor load is only 17% of the breaking limit.

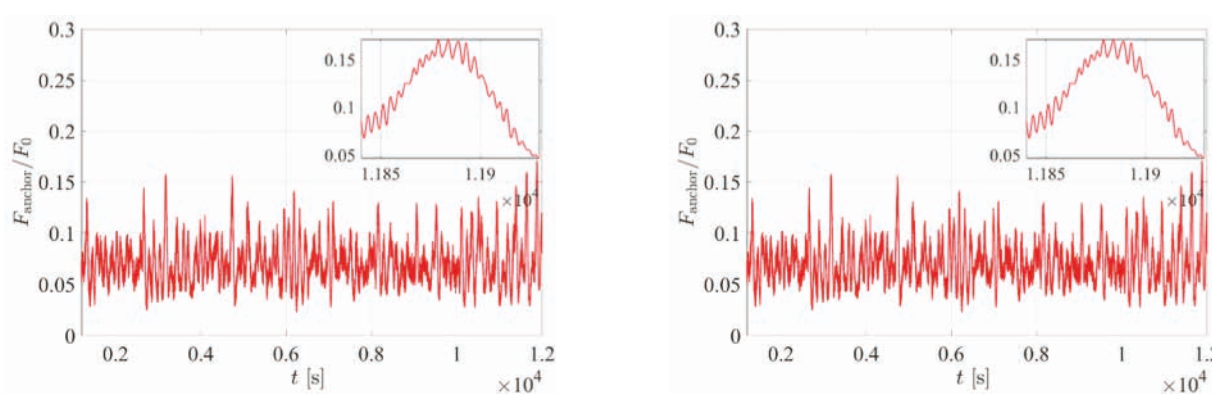


Figure 3: *Time histories of the load in anchor line-1 (left) and the stress at position β = 180° along the floating collar (right) in irregular waves and current. The force is made non-dimensional by the minimum breaking force* F_0*. The stress is made non-dimensional by the yield stress* σ_0*. A zoomed view is also given when the value reaches the largest maximum within the examined simulated time (3 hours). The significant wave height* H_s *= 1 m, peak wave period* T_p *= 5s and current velocity* U_∞ *= 0.3 m/s.*

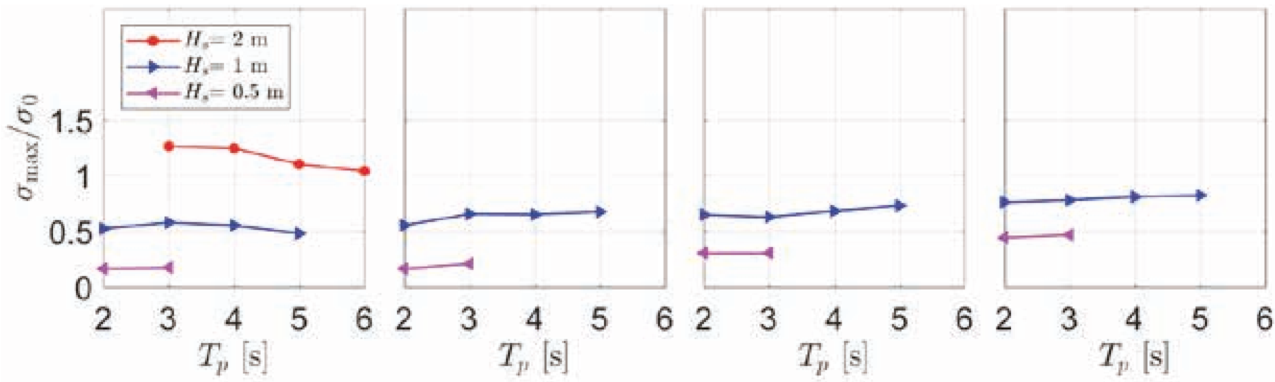


Figure 4: *Maximum value of the floating-collar stress at position β = 180° in irregular waves with different significant wave height* H_s *and peak period* T_p*. The stress is made non-dimensional by the yield stress* σ_0*. From left to right: Current velocities* U_∞ *= 0 m/s, 0.1 m/s, 0.3 m/s, 0.5 m/s.*

The operational conditions of the well boat when at the fish farm have been examined through systematic simulations. Numerical results showed that the maximum anchor load will not exceed the anchor-line breaking limit even in high exposure sea conditions, and thus it should not be of concern. The maximum stress in the floating collar would be close to the yield stress when the system operates in moderate exposure sea states, as shown in Figure 4, and should be used to determine the operational conditions of the well boat.

Closed rigid and flexible fish cages have been proposed as an alternative to the conventional net cages in order to meet ecological challenges related to fish lice and escapes. However, for both, resonant water motions inside the fish farm (sloshing) matter, and can affect the cage motions in waves. A linear mathematical model of a freely floating 2D flexible cage (CFFC) in waves (left side of Figure 5) showed that wave-induced rigid body motion responses of a flexible CFFC in sway, heave and roll are significantly different from the responses of a rigid CFFC **[P3-R3]**. For a rigid CFFC, an uncoupled sway and roll have cancellation at the first and third sloshing frequency. For the CFFC with deformable membrane in coupled sway and roll, no cancellation of the response appears at the first and third sloshing frequency. From the analysis, non-linear free surface effects must be accounted for inside the tank in realistic sea conditions. The developed method assumes that the dynamic tension in the membrane of the CFFC is always smaller than the static tension. Nevertheless, this is not always true in practice.

The right side of Figure 5 gives the ratio between the estimated standard deviation of the dynamic tension, s_t, and the static tension, T_0, as a function of the wave peak period Tp for given significant wave heights H_s. The definitions of small to high exposures are based on Norwegian standards. From this, s_t exceeds T_0 for H_s = 3 m for high exposure. If we assume a Rayleigh distribution, the most probable largest value for the dynamic tension τ exceeds T_0 for all H_s except Hs = 0.5m. For example, this indicates that bending stiffness and non-linear stress–strain relations matter for the membrane behaviour in these scenarios. Furthermore, zero tension can occur and lead to snap loads in the material with fatigue risk.

We also continued our investigation on **violent sloshing phenomena in rigid closed cages**, using an analytically-oriented approach and modelling the cage as a circular cylindrical tank with forced lateral oscillations. The focus was on swirling waves, i.e. progressive waves in the angular direction (rotary waves), thereby leading to a lower wave elevation near the tank centre and water

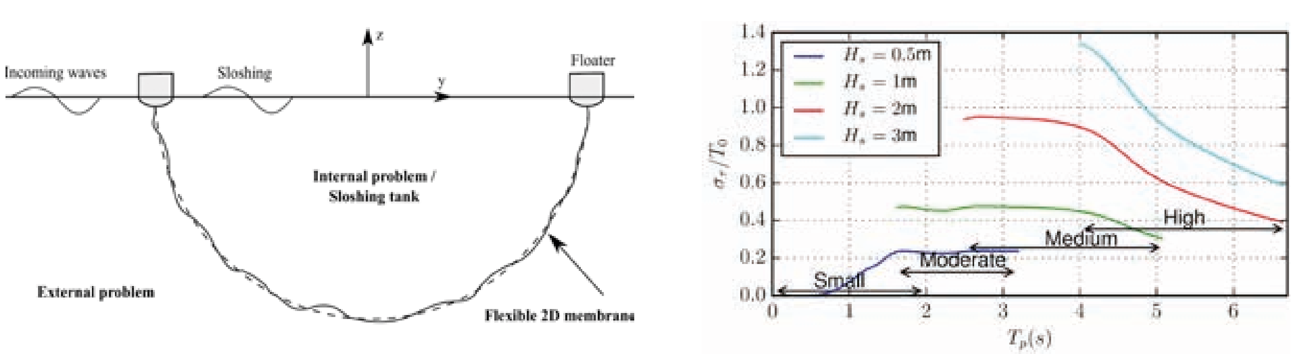


Figure 5: *Left: Mathematical model of a 2D CFFC in waves. Right: Standard deviation of dynamic tension-to-static tension ratio as a function of wave peak period for different significant wave heights. Definition of small, moderate, medium and high exposures is based on Norwegian standards.*

run-up along the vertical sides. In particular, we examined the effect of a steady flow induced inside the tank during swirling **[P3-R4]**. The comparison with available experiments documented that viscosity and associated viscous streams may play a secondary role for the mass-transport phenomenon inside the tank.

Knowledge about extreme ocean currents and their vertical structure is important when designing offshore structures, particularly in deep waters where currents may dominate the actions (loads). This is especially the case for aquaculture structures located in the coastal zone, where islands and skerries may provide shelter from severe sea states, whereas currents might retain, or even increase, their strength. Excessive simplification of the vertical velocity profile may introduce substantial errors in the calculated design actions. Motivated by the lack of accurate methods, a procedure was proposed for the **statistical modelling of extreme ocean current velocity profiles**, with an emphasis on the depth dependence **[P3-R5]**. By means of response-based estimations, a simple approach to derive more realistic design current velocity profiles was developed. The procedure provides improved knowledge of the actual extreme current conditions at the considered site, in addition to more precise predictions of current induced design loads.

The key steps of the method are summarized in Figure 6. The measured current velocities at each depth are resolved into orthogonal major and minor axis components by principal component analysis. A harmonic analysis is used to decompose the total (observed) current into the sum of (deterministic) tidal and (stochastic) residual currents (see Figure 7). A complete marginal model is then constructed for each of the residual current components. The dependence structure between the components is further characterized using a conditional extremes approach. Based on the fitted statistical model, a Monte Carlo simulation is employed to estimate extremal statistics.

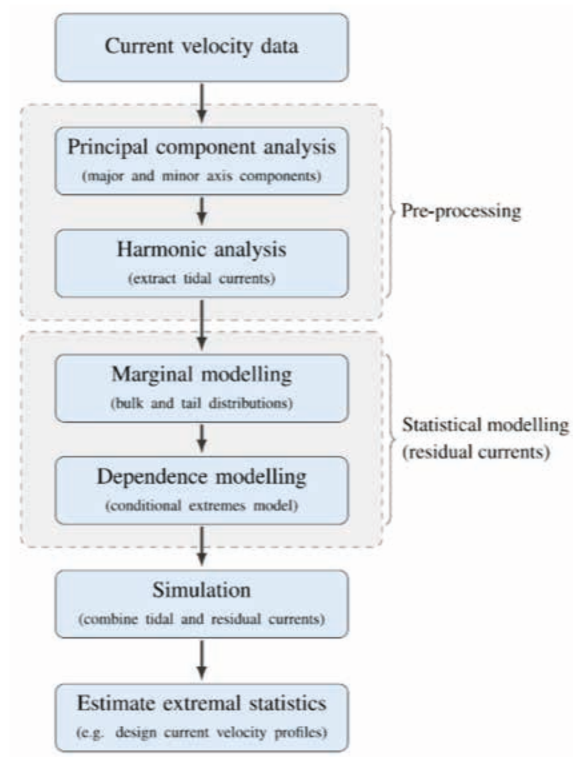


Figure 6: *Flowchart of the steps involved in the proposed method for estimation of design current velocity profiles*

The validity of the method was tested using measured current profiles at two locations along the coast of Trøndelag (Munkskjæra and Salatskjæra), covering a period of 2.5 and 1.5 years. It was shown that the method provides credible extrapolations at both

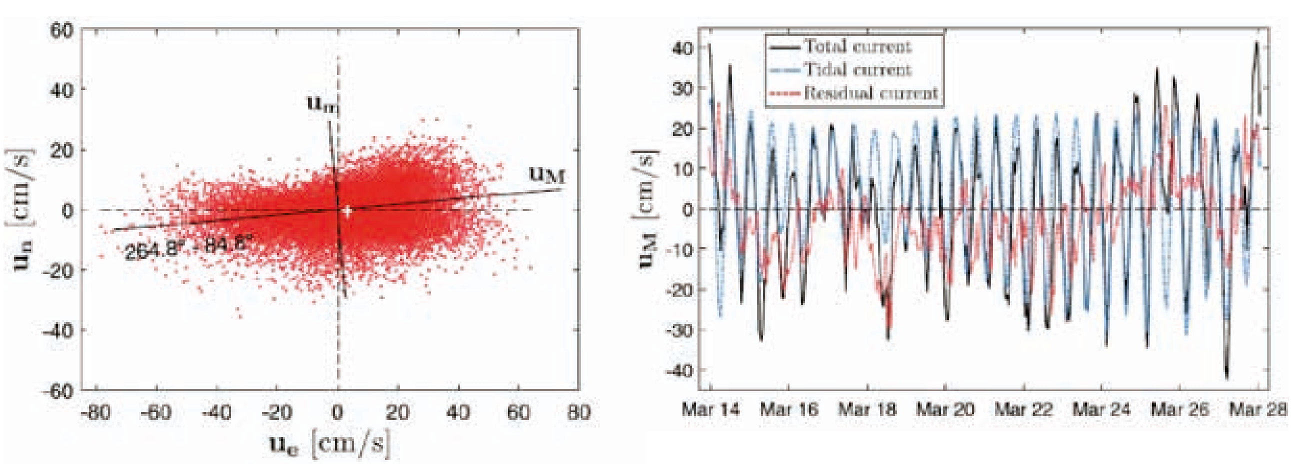


Figure 7: *Left: Measured current velocities at a depth of 4 m at Munkskjæra. The major and minor axis (uM and um, respectively) resulting from the application of principal component analysis, are indicated. Right: 14-day plot of the major axis current velocity at Munkskjæra at a depth of 4 m, and the resulting decomposition of the total (observed) current into tidal and residual currents by harmonic analysis.*

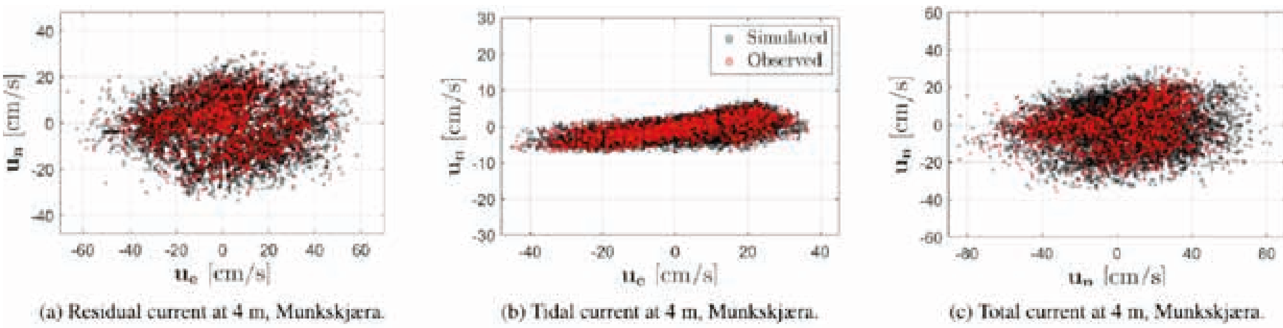


Figure 8: *10 years of simulated (grey) residual, tidal, and resulting total current velocities at a depth of 4 m at Munkskjæra compared to the observations (red).*

locations: marginally for each velocity component, jointly for the velocity components at each depth and for the full velocity profiles. As an example, 10 years of simulated residual, tidal and resulting total current velocities (based on the statistical model) are compared with measurements at Munkskjæra in Figure 8. It shows that the statistical model is capable of capturing the trends in the measured data.

Estimated 10-year design current velocity profiles for the two most critical directional sectors at Munkskjæra are shown in Figure 9 (solid black lines). The shapes agree well with those of the most extreme velocity profiles measured in the respective sectors (grey lines). It is interesting to observe the difference in the shape of the current profile for the two sectors. The depth variation of the current velocity is particularly pronounced for sector (255°, 280°).

Because the fish farming industry is going into more exposed seas, the fish cages have become larger and more fish than ever before can be accommodated. Yet, harsher environmental loads and frequent aquaculture operations emphasize the risk of **ship collisions from both service vessels and merchant vessels on an erroneous track**. The potential consequences in terms of structural damage, fish escape and associated economic loss are substantial. However, design against accidental ship collisions is not included in the present standards for fish farms.

The local and global response of an offshore fish farm subjected to supply vessel impacts on the steel structure (excluding fish net impacts) was investigated by means of on nonlinear finite element simulations [P3-R6]. The local collision analysis conducted with LS-DYNA (Figure 10) showed that the fish farm is capable of absorbing considerable energy through structural deformations. In general, the resistance of the fish cage was smaller than that of the striking vessel (especially the bulbous bow), and most of the impact energy was dissipated by the fish cage. Nonetheless, the column top with a stiffened plate represented a hard spot of the fish farm capable of significantly crushing the ship stem. The middle column and the transverse tubes were thin-walled and susceptible to local buckling and denting (Figure 10). This limited the energy that the tubes could dissipate by plastic bending or by crushing the ship's bow. The force-deformation relationships forming the local analyses were used as nonlinear springs in the

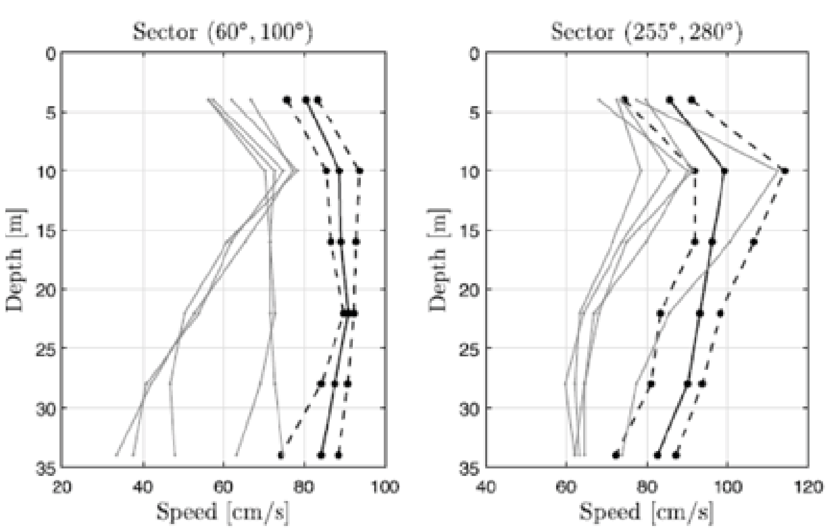


Figure 9: *Munkskjæra: estimated 10-year design current velocity profiles in the two considered critical directional sectors (solid black). Dashed black lines are 80% confidence intervals. Thin grey lines are the velocity profiles from the measurements causing the five largest forces (on a circular cylinder) in the respective sectors.*

Figure 10: Local deformation of the fish cage at different total displacements (sum of fish cage deformation and bow indentation). Local buckling of tube cross sections is illustrated.

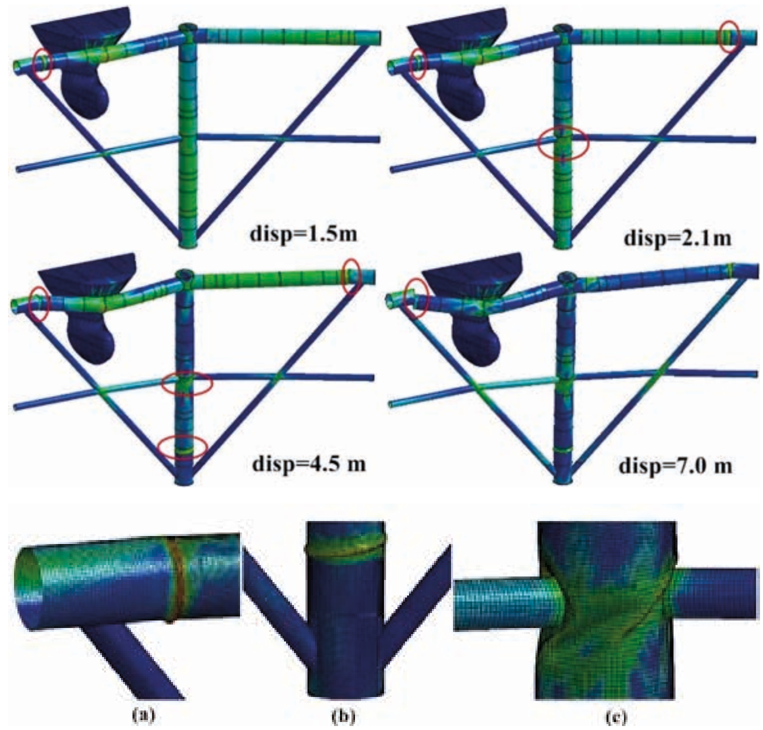
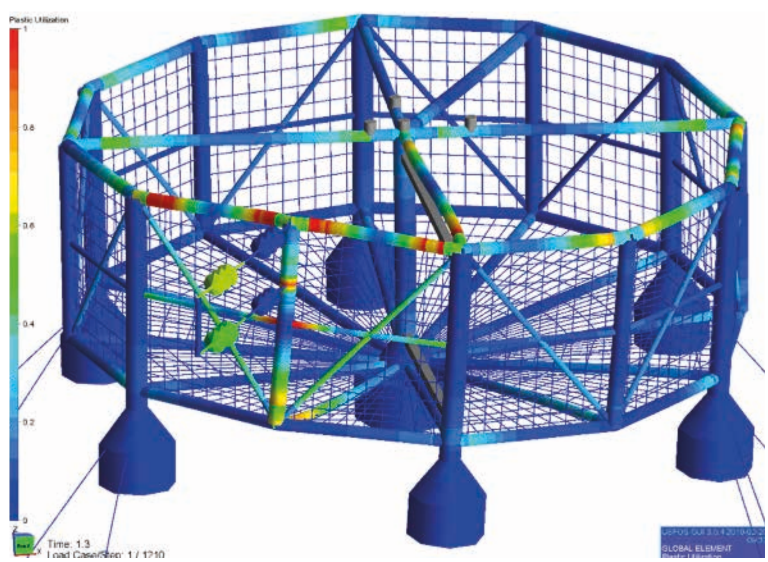


Figure 11: Deformed configuration of the fish cage at maximum collision force (deformations are magnified by three times for better illustration)



global analysis with USFOS. Figure 11 shows that the structural damage of the fish cage is primarily concentrated in the impacted region, with less damage outside the direct contact area. The analysis confirmed the major conclusions for energy absorption and structural damage from the local shell analysis. Possible acceptance criteria for designing offshore fish farms against ship collisions were discussed in view of the requirements adopted for offshore oil and gas structures.

Solid objects entering a water surface are an important research topic for several applications, e.g. freefall lifeboat drop, ship slamming, planing vessels, air-to-sea projectiles, impacting of waves on solid structures. If the water-entry speed is sufficiently large, an air cavity will be formed behind the falling body (see main stages for the vertical entry of a wedge in the left side of Figure 12). This involves complex cavity dynamics and transient features of the hydrodynamic force experienced by the body. While the former has been widely studied, very few works can be

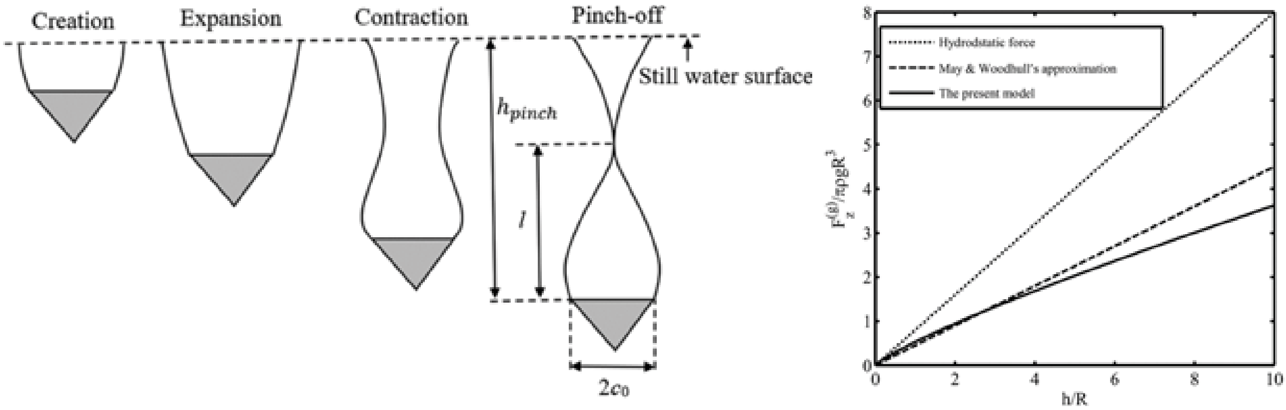


Figure 12 (above): Left: Illustration of the evolution of the air cavity for a wedge vertically entering the water surface until the cavity pinch-off. Right: Hydrostatic force, g-term force from present model and from May and Woodhull's approximation for a sphere with radius R entering the water surface. Here, h is the body submergence, r the water density and g the gravity acceleration.

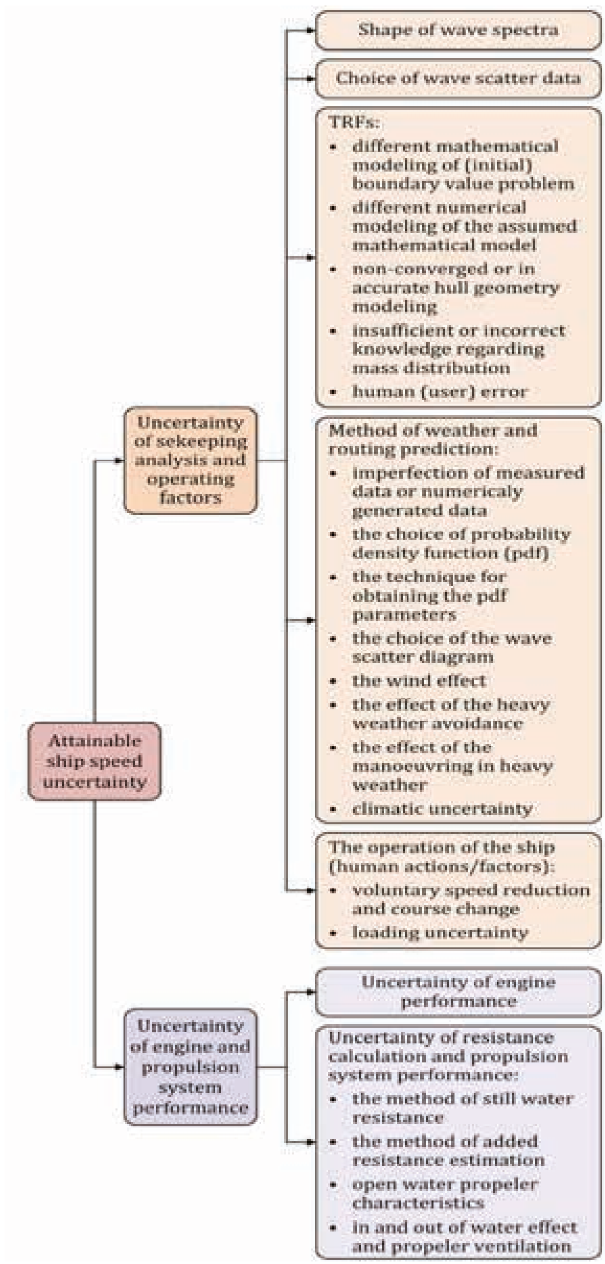


Figure 13 (left): Schematic representation of uncertainties.

found on the latter. This motivated our research, documented in **[P3-R7]**, with a focus on the vertical water-entry of two- and three-dimensional bodies. By neglecting the surface tension and air flow, the hydrodynamic force has been decomposed into the components corresponding to the following physics: (i) the body acceleration (a-term), (ii) the gravity (g-term), and (iii) the velocity of the body and the water particles (v-term). Exact physical models were proposed to represent these force components and the key physical parameters affecting them have been examined. In particular, the a-term force is equal to the high-frequency added mass times the body acceleration; the g-term force consists of a hydrostatic term and a dynamic term, with the former strongly overestimating it (see example for a sphere in the right side of Figure 12); the v-term force is modelled as a drag force.

Improving the energy efficiency of ships means increasing profits and reducing the adverse impact on the environment. In this context, a reliable method for speed-loss calculation in real environmental conditions of ship operation is essential, as speed loss can result in higher fuel consumption and emissions of CO_2 and other greenhouse gases from ships. The analysis documented in **[P3-R8]** examined the **impact of weather and operational uncertainties on the actual speed of the ship in real operating conditions** in terms of (A) seakeeping analysis and operating factors, and (B) engine and propulsion-system performance (see Figure 13). In fact, the decrease of the ship speed is a consequence of the added resistance due to the impact of weather conditions, and also due to aggravated propeller working conditions. Human factors, e.g. ship-master decisions, also matter. Moreover, the loading condition of the ship is continuously changing, which governs the basic parameters of the ship: the mass and mass moment of inertia, draft and trim, and consequently, the ship's behaviour at sea. All these parameters affect the assessment of the ship speed, and one must address their impact on the final speed value.

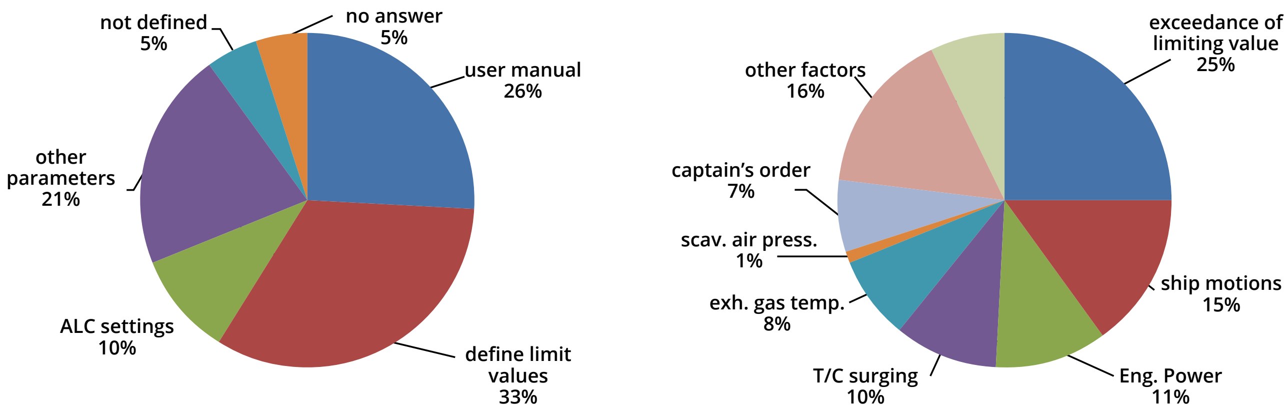


Figure 14: *Left: Setting of limiting values in emergency operations for engines. Right: Division of time for deciding engine operations*

A **speed loss analysis** was conducted in rough sea voyages **[P3-R9]** to improve the accuracy of measured data extracted from actual marine conditions, and to examine the human factors. The conventional criteria to judge the deliberate speed reduction are validated by analysing the collected data on accelerations, ship motions, navigation and engine parameters. In rough sea voyages, the airflow between the main engine and turbo charger may be reversed unless the engine speed is reduced. This is referred to as the surging phenomenon. Firstly, fuel injection is usually shifted from automatic to manual control to reduce the volume of the fuel injected. The purpose of this operation is to gradually reduce the engine speed, lowering the engine load through deliberate speed reduction. From the left side of Figure 14, the limiting value is decided from the performance curves of manufacturers (26%), the empirical values defined from their experience (33%) and the automatic load control (ALC, 10%) for ships with a controllable pitch propeller (CPP). The right side of Figure 14 shows that the slowdown operation is decided when the monitoring value approaches the limiting value in the performance curves (25%), ship motions or sea conditions become worse (15%), the engine power approaches the criteria (11%), the possibility of surging increases (10%), the temperature of exhaust gas increases (8%), communication with the captain (7 %) and other aspects.

When a ship experiences a damage event, after a collision, grounding or violent wave-body interactions, its behaviour is substantially modified from its intact conditions. Flooding occurs through the damaged opening, generally affecting the stability properties, and in the worst case causing the ship to capsize. An experimental analysis has been carried out on a model designed as a midship section with a large open deck on the side, consistent with beam-sea damage, and with nearly two-dimensional (2D) flow conditions **[P3-R10]**. The focus was on forced oscillatory heave tests in calm water, with different model-motion parameters, as well as examining both intact and damaged conditions. The results presented demonstrate the occurrence of sloshing and piston mode resonances for the water inside the damaged compartment, and their influence on the hydrodynamics loads of a damaged ship. This is documented in Figure 15, which refers to the lowest filling depth examined in the damage model.

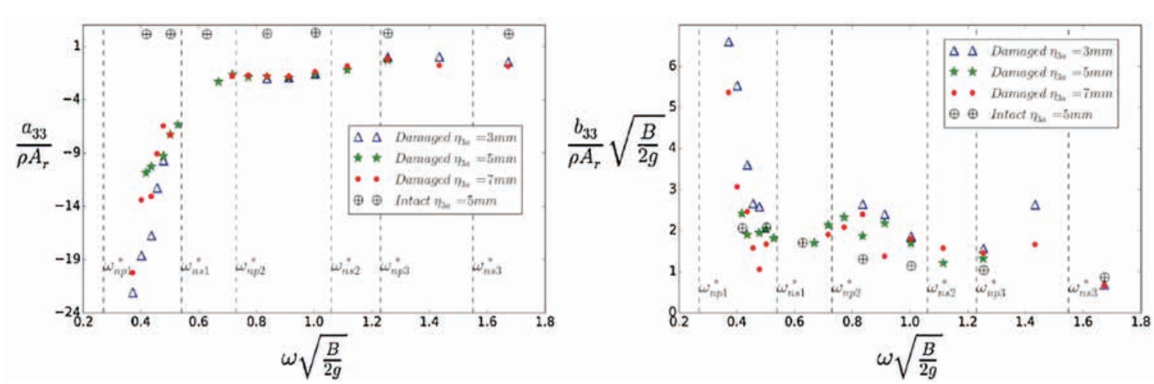


Figure 15: *Non-dimensional added mass (left) and damping (right) in heave for intact and damaged model at the lowest filling depth examined, versus the non-dimensional frequency, w*. Here, h_{3a} is the heave-motion amplitude, B is the model breadth, $A_r = Bd_T$ is the submerged cross-sectional area both for intact and damaged sections, d_T is the submergence draft, r is the water density and g is the gravity acceleration. The vertical dashed lines correspond to the non-dimensional linear natural frequencies for sloshing (s) and piston (p) modes of the water inside the damage model.*

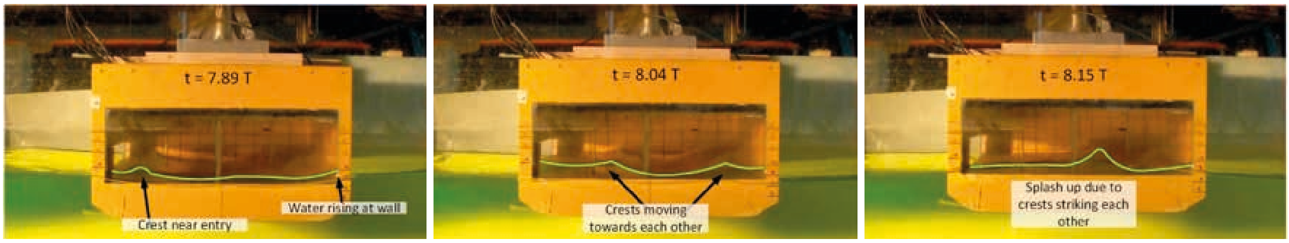


Figure 16: *Secondary splash up in the middle of the tank at w*=1.25 and h_{3a}=7mm for the lowest filling level examined. This was identified for the first time by Bouscasse et al. (2013) for a closed partially-filled tank.*

Added mass and damping coefficients in heave differ greatly from those of an intact section, especially near the first-piston mode frequency, where large negative values in added mass and peaks in damping occur for the damaged section. At higher frequencies, the damping shows a more pronounced nonlinear behaviour than the added mass. At certain heave excitation frequencies, important local loads were detected, e.g. secondary splash up as shown in Figure 16. Nonlinear effects appear dominant, especially for the lowest filling level examined, where shallow-water depth conditions occur in the damaged model.

Damage opening length clearly influences the wave systems inside the damaged compartment, while it does not show a considerable change in the hydrodynamic forces acting on the body. If the compartment is made airtight, air compressibility matters and tends to slow down the flooding inside the damaged compartment. This is especially evident near the piston mode resonance, where almost no water enters for an airtight damaged compartment. The sloshing mode remains unaffected because near the sloshing resonance the exchange of floodwater through the opening is limited anyway. Because the inflow/outflow of floodwater can be highly limited for an airtight damaged compartment, the corresponding added mass and damping in heave tend to be those of an intact section. Even so, air compressibility is associated with scaling issues and must be interpreted accordingly.

Modelling the features of the turbulent flow behind a breaking wave in open sea is challenging, yet relevant for marine applications. We continued this investigation using experimental data of a sloshing-induced, rapidly-evolving spilling breaker to help understand the specific physics of this phenomenon **[P3-R11]**. This has produced an accurate PIV measurement of the turbulent quantities in the single-phase turbulent layer below the air-water interface. Figure 17 exemplifies the estimated vorticity and turbulence kinetic energy in the shear layer, whereas Figure 18 provides the corresponding mean velocity profile at a given time of the evolution.

Such information will be used for settling a simplified theoretical model for the turbulent flow near the air-water interface to be coupled with the underneath potential flow water mass. This will enable a proper modelling of the dissipation induced by the turbulent flow.

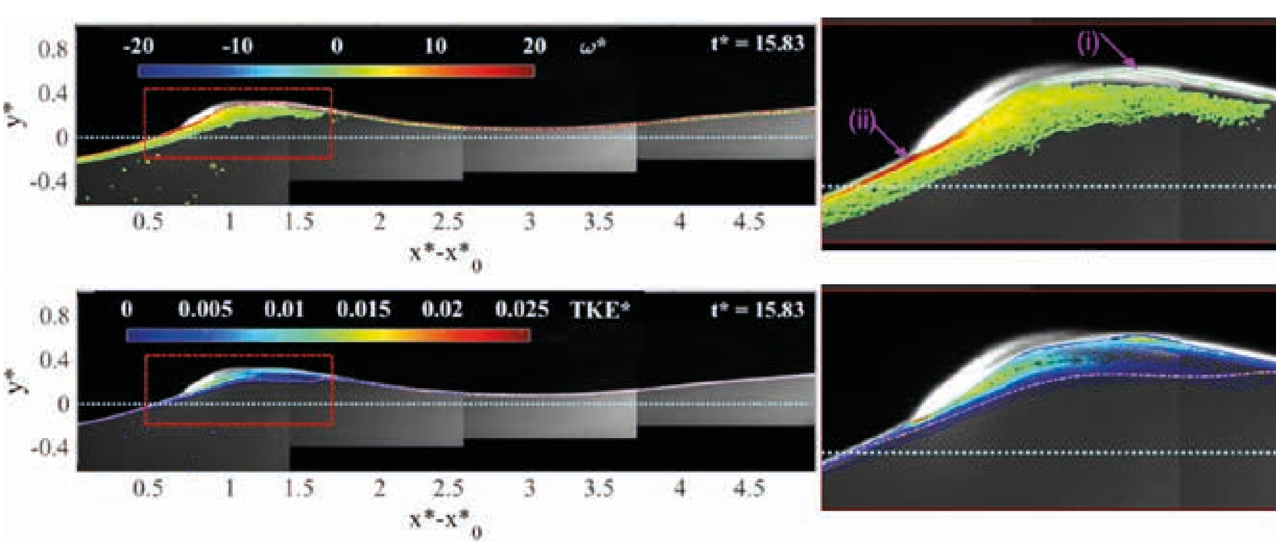


Figure 17: *Global (left) and enlarged (right) views of the vorticity (w, top) and turbulent kinetic energy (TKE, bottom) in the shear layer for an unsteady spilling breaker. In the top-right plot, (i) indicates the crest and (ii) the location of the maximum vorticity upstream of the crest. Variables are dimensionless, see [P3-R11].*

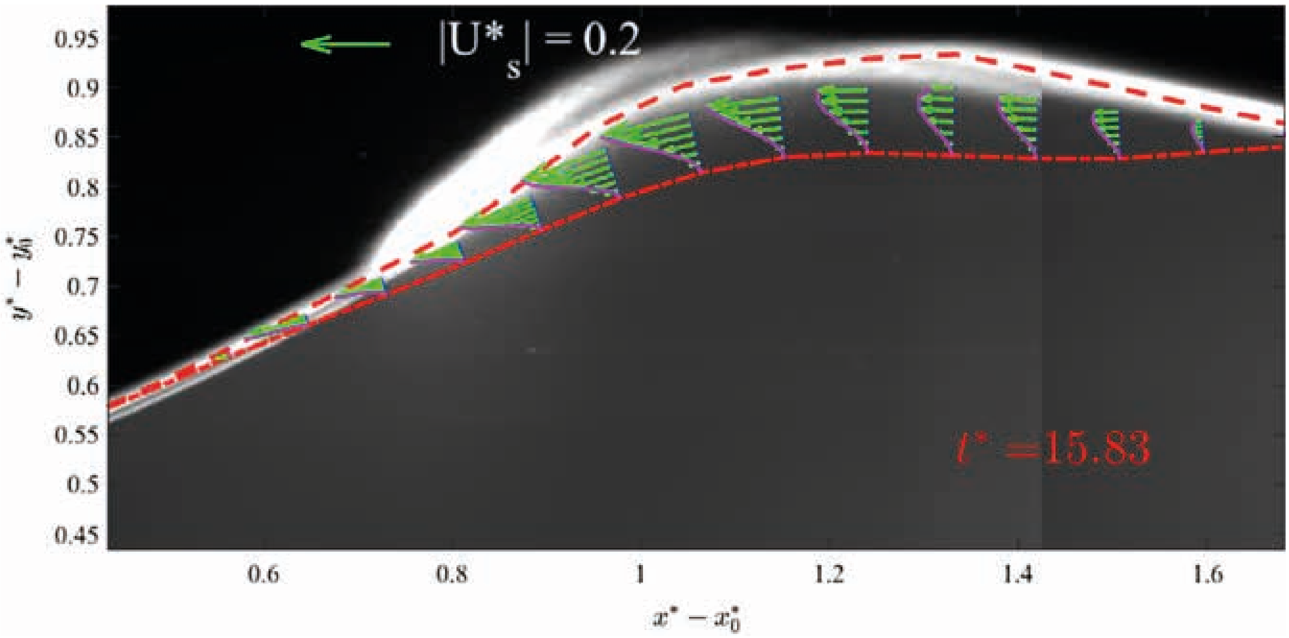


Figure 18: *Mean velocity profile in the thin single-phase turbulent layer. Variables are dimensionless, see [P3-R11].*

For marine structures operating in finite to shallow water depths, such as floating and bottom-fixed wind turbines as well as fish farms, the **accurate prediction of free-surface wave modification during propagation from deep to shallower water regions** is important for an adequate estimate of wave-induced loads on the structure. The depth-semi-averaged model previously developed preserves to a large extent the efficiency of the classic depth-averaged scheme, and includes a description of the wave vertical velocity component, so as to allow a correct modelling of dispersive effects, in addition to the linear and nonlinear shoaling of waves. This year, the model has been implemented in three spatial dimensions, and successfully validated **[P3-R12]** against available benchmark experimental data. As an example of this, the left side of Figure 19 examines the transformation of a regular wave train propagating over a submerged elliptical shoal placed over an inclined planar beach, and defines the location of eight wave-probe sections.

The right side of Figure 19 provides a snapshot of the wave elevation from the proposed method, while Figure 20 documents

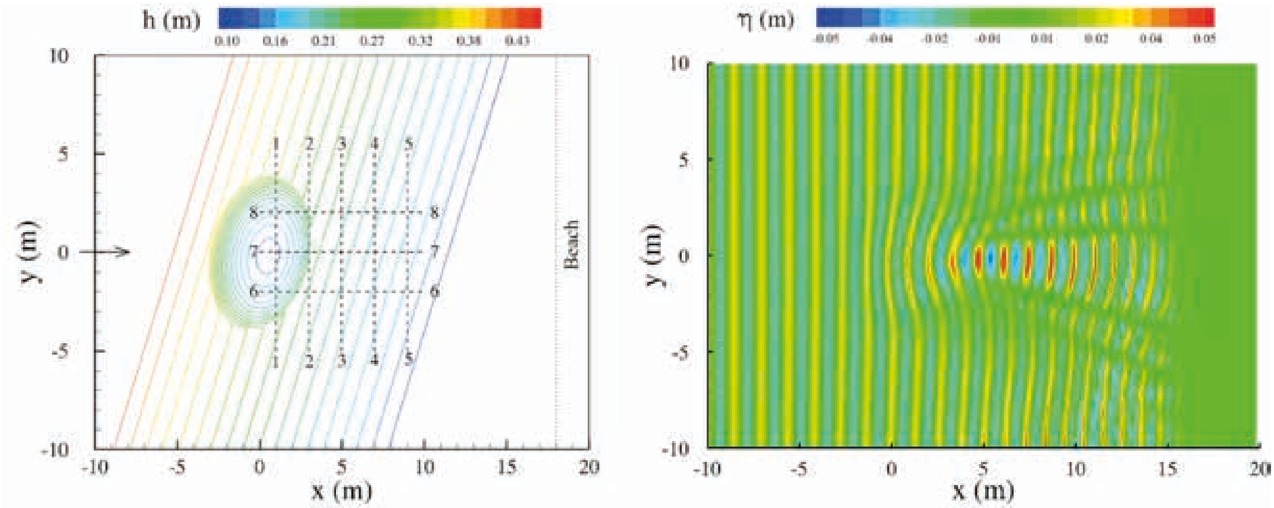


Figure 19: *Left: Contour lines of the bathymetry (h=water depth) and definition of wave-probe locations. The incident waves come from the left and the beach is on the right. Right: A snapshot of the wave elevation h from the numerical scheme.*

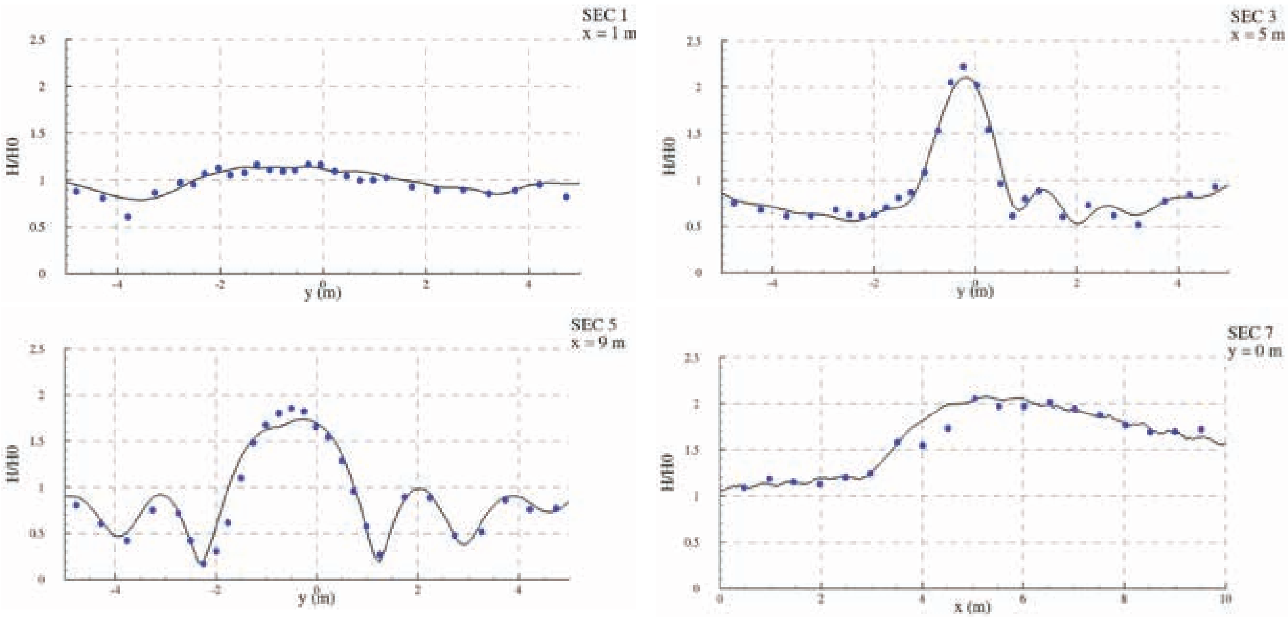


Figure 20: *Water height H-to-incident (deep-water) wave height ratio, H/H0, at four wave-gauge sections defined in the left side of Figure 19. The black solid lines and the blue dots show the numerical prediction and the experimental data from Berkhoff et al. (1982), respectively.*

the good agreement between numerical and experimental wave heights at four selected probe sections. Wave-probe sections 1, 3 and 5 are in a *y* direction, and highlight the transverse variations of the wave field resulting from the combined effect of refraction/shoaling triggered by the co-existence of the elliptical shoal and of a sloped beach. Wave-probe section 7 is in the *x* direction (placed at *y* = 0 m), and documents the wave shoaling, the focusing and the gradual decrease in the wave height after the shoal.

The wind energy's share of worldwide electricity supply is steadily increasing. Offshore wind is stronger and steadier than onshore wind, thereby yielding larger and steadier energy production.

The trend of increasing turbine size reduces the costs of installation and grid connection per unit energy produced. The growing installation height challenges the crane devices and lifting operation for most of the installation vessels. Single blade installation by means of jack-up vessels is commonly used, in which the blade is lifted by the main crane from the deck to the top of the turbine tower, where it is bolted to the rotor hub, see Figure 21. The magnitude of the blade and hub relative motions influences the severity of impact forces and the success rate of the final mating operations.

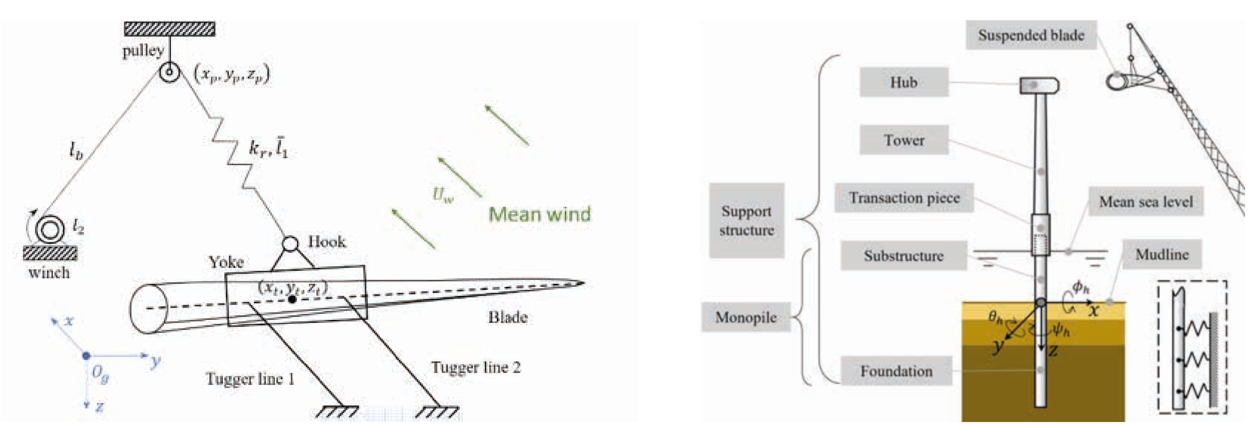


Figure 22: *Left: Simplified control model for the lifting operation. Right: Simplified control model for the hub motion estimation. The hub, tower, transition piece and piles are modelled by Timoshenko beams, and each soil layer is modelled with springs.*

Figure 21: *Single blade installation.*

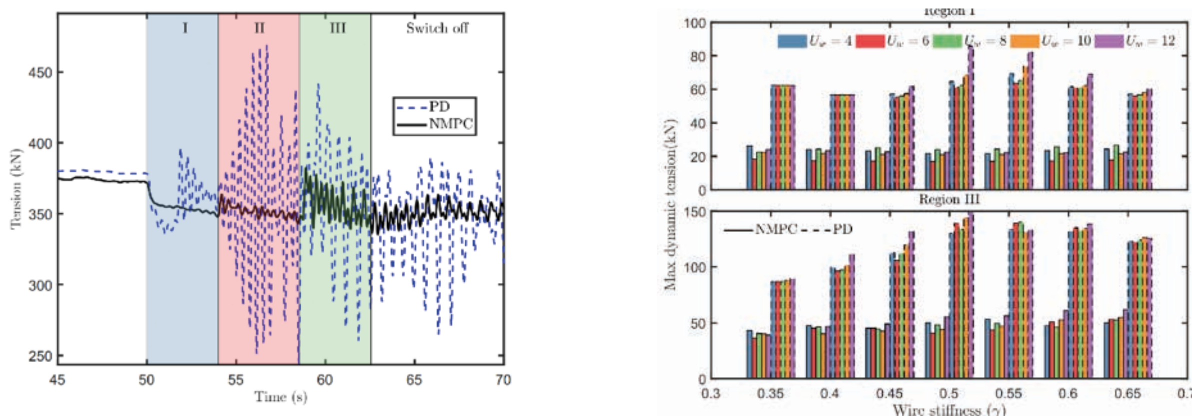


Figure 23: *Left: Time-domain performance of the NMPC. Right: Controllers as a function of the wire stiffness and mean wind speed U_w. The maximum dynamic tension is reduced by a factor of 2-3. The real value of the stiffness is γ=0.5. The performance variation of the PD controller results from significant increase of γ, while the performance variation of the NMPC controller is small for the same uncertainties.*

In collaboration with SFI MOVE, an automated and optimal lifting scheme for single blade installation has been developed, [P3-R13]. It is based on a simplified control model for the lifting operation, Figure 22 left, and a high-fidelity hub motion monitoring algorithm, Figure 22 right.

A nonlinear model predictive control (NMPC) scheme has been proposed to **overcome the sudden peak tension and snap loads in the lifting wires caused by lifting speed changes in a wind turbine blade lifting operation**. Figure 23 left shows the time domain performance of the NMPC, while the maximum dynamic tension for the NPMC controller and a conventional PD controller are compared in Figure 23 right.

The decision to perform the mating operation is based on the relative distance and velocity between the blade root centre and the hub in accordance with the weather window. Hence, **monitoring the hub real-time position and velocity** is necessary, irrespective of whether the blade installation is conducted manually or automatically. Two hub motion estimation algorithms are designed for the OWT, with a bottom-fixed foundation using sensor fusion of a global navigation satellite system (GNSS) and an inertial measurement unit (IMU) **[P3-R14]**. The hub motion estimator is sketched in Figure 24 left. The moving horizon estimator mitigates the slow GNSS sampling rate relative to the hub dynamics. The multirate Kalman filter estimates the position, velocity and accelerometer bias with a constant GNSS measurement delay. The online smoothing algorithm filters the delayed estimated trajectory to remove sudden step changes. The predictor compensates for the delayed estimate, resulting in real-time monitoring. Time histories for the horizontal position (x, y) estimates are shown in Figure 24 right. The plots show that the estimators provide a high-frequency real-time motion estimation.

As new **offshore wind turbines** are being installed in increasing water depths and the turbine size continues to increase, wave loads become more dominant for the fatigue life of monopile foundations. Consequently, it becomes increasingly important to understand which wave parameters influence the predicted fatigue design. It is known that a **misalignment of wind and waves has a considerable effect on the fatigue damage**. Design standards require that misalignment be included in fatigue

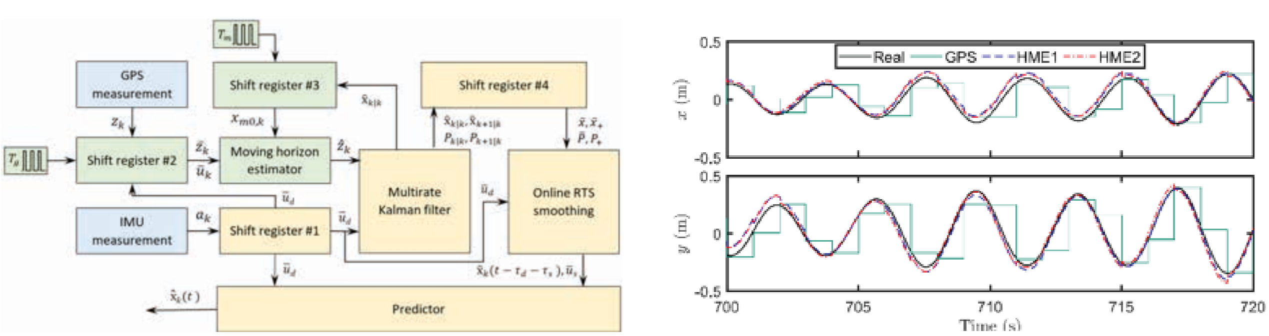


Figure 24: *Left: The diagram of a hub motion estimator (HME). Right: Time-domain estimates of the hub motion. (Real-real hub motion, GPS-GPS measurements with delay).*

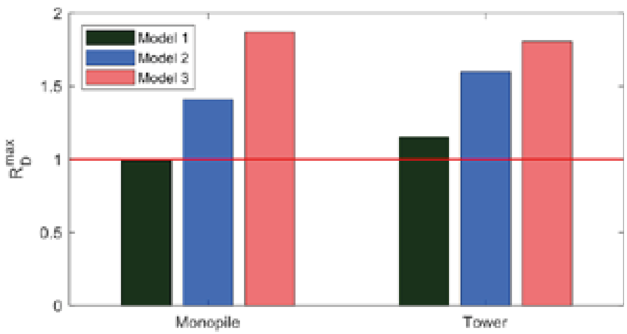


Figure 25: *Ratio of maximum fatigue damage in support structure when assuming short-crested and long-crested waves in design calculations. A value above 1 indicates that it is unconservative to assume long-crested waves in design calculations [P3-R15].*

calculations for long-crested waves, but specify no requirements for short-crested waves. Short-crested waves may both increase or decrease the misalignment in a short-term perspective. The long-term effect of neglecting waves arriving at multiple directions cannot be intuitively understood. The effect of short-crested waves on the fatigue damage was therefore investigated for three different monopile and tower designs **[P3-R15]**. As illustrated in Figure 25, it was found that for all three designs it can be **unconservative** to assume only long-crested waves during the design of the support structure.

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P3-R1 Shen Y., Greco M. and Faltinsen O. M., 2019a. Numerical study of a well boat operating at a fish farm in current, *Journal of Fluids and Structures, 84*.

P3-R2 Shen Y., Greco M. and Faltinsen O. M., 2019b. Numerical study of a well boat operating at a fish farm in long-crested irregular waves and current, *Journal of Fluids and Structures, 84*.

P3-R3 Strand I., Faltinsen O.M., 2019. Linear wave response of a 2D closed flexible fish cage, *Journal of Fluids and Structures, 87*.

P3-R4 Faltinsen O.M., Timokha A., 2019, An inviscid analysis of the Prandtl azimuthal mass transport during swirl-type sloshing, *Journal of Fluid Mechanics, 865*.

P3-R5 Bore, P. T., Amdahl, J. and Kristiansen, D., 2019. Statistical modelling of extreme ocean current velocity profiles. *Ocean Engineering*, Vol. 186.

P3-R6 Yu, Z., Amdahl, J., Kristiansen, D. and Bore, P.T., 2019. Numerical analysis of local and global responses of an offshore fish farm subjected to ship impacts. *Ocean Engineering, 194*, p. 106653.

P3-R7 Wang J., Faltinsen O.M., Lugni C., 2019, Unsteady hydrodynamic forces of solid objects vertically entering the water surface, *Physics of Fluids, 31* (2).

P3-R8 Prpić-Oršić J., Sasa K., Valčić M., Faltinsen O.M., 2019, Uncertainties of ship speed loss evaluation under real weather conditions, *Journal of Offshore Mechanics and Arctic Engineering*.

P3-R9 Sasa K., Takeuchi K., Chen C., Faltinsen O.M., Prpic-Orsic J., Valcic M., Mrakovcic T., Herai N., 2019. Evaluation of speed loss in bulk carriers with actual data from rough sea voyages, *Ocean Engineering, 187*.

P3-R10 Siddiqui M.A., Greco M., Lugni C., Faltinsen O.M., 2019. Experimental studies of a damaged ship section in forced heave motion, *Applied Ocean Research, 88*.

P3-R11 Lucarelli A., Lugni C., Falchi M., Felli M., Brocchini M., 2019. On a layer model for spilling breakers: A preliminary experimental analysis, *European Journal of Mechanics. B, Fluid*, 73.

P3-R12 Antuono M., Valenza S., Lugni C., Colicchio G., 2019. Validation of a three-dimensional depth-semi-averaged model, *Physics of Fluids, 31* (2).

P3-R13 Ren, Z., Skjetne, R. and Gao, Z., 2019. A crane overload protection controller for blade lifting operation based on model predictive control. *Energies, 12*(1), p. 50.

P3-R14 Ren, Z., Skjetne, R., Jiang, Z., Gao, Z. and Verma, A.S., 2019. Integrated GNSS/IMU hub motion estimator for offshore wind turbine blade installation. *Mechanical Systems and Signal Processing, 123*, pp. 222-243.

P3-R15 Sørum, S.H., Krokstad, J.R., Amdahl, J., 2019. Wind-wave directional effects on fatigue of bottom-fixed offshore wind turbine, *Journal of Physics: Conference Series*, 1356.

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NTNU AMOS PARTICIPATION IN ASSOCIATED PROJECTS

Awarded/Ongoing **Completed** **Proposed**

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	Infrastructure project of NFR funded ARCTIC ABC (ending in Dec 2019)	1-3 engineer + Lab Equipment, making ince-tethered buoy sensor syste
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
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	2015-2019	RCN MAROFF	NTNU DNV GL Kongsberg Maritime Maritime Robotics	3 PhD + 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

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
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	
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	2017-2021	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 Associated to Autoferry	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	3 MNOK	2015-2022	SFI proposal	NTNU SINTEF Ocean Equinor DNV-GL …	1 PhD
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

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
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.
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 – Polprog	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, IES, ID, IIK)	NTNU	8 PhD
Autonomous Operation of Snake-Like Robots in Challenging Environments	Kristin Y. Pettersen	0.1 MNOK	2018 – 2020	Imperial College	NTNU Imperial College	
Real-time encryption of sensors in autonomous systems. NTNU Gjøvik/Trondheim.	Thor I Fossen	8 MNOK	2020-2023	NTNU ITK/Gjøvik	NTNU	2 PhD
Autonomous ships, intentions and situational awareness	Edmund Brekke	12 MNOK	2019-2022	RCN MAROFF	NTNU DNV GL KM MR	3 PhD
Efficient stochastic dynamic response analysis for design of offshore wind turbines	Torgeir Moan	3 MNOK	2014-2020	NFR	NTNU	1 PhD

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Fault detection and diagnosis in floating wind turbines	Torgeir Moan	6 MNOK	2014-2022	NFR Equinor	NTNU, DTU, MIT Equinor	2 PhD
Dynamic response analysis of floating bridges	Torgeir Moan	6 MNOK	2016-2020	NPRA	NPRA	2 Postdoc
Safety Assesment of floating bridges	Torgeir Moan	3 MNOK	2019-2021	NPRA	NPRA	1 Postdoc
Dynamic analysis of floating submerged tunnels	Torgeir Moan S. Fu	3 MNOK	2014-2020	CSC NTNU	Shanghai Jiao Tong University	1 PhD
Num modelling and analysis of turbine blades	Torgeir Moan Z Ghao	3 MNOK	2014-2019	CSC NTNU	Fred Olsen Wind Carrier	1 PhD
Design and analysis of mooring system for floaters in shallow waters	Torgeir Moan	3 MNOK	2016-2020	CSC NTNU	Equinor	1 PhD
Real-time hybrid model testing for extreme marine environments	Roger Skjetne	3 MNOK		RCN	SINTEF Ocean	1 PhD
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
§ Rolls-Royce University Technology Center (UTC) on Ship Performance and Cyber-Physical Systems	T. A. Johansen					Extension with section on Cyber-Physical Systems
Cyber-Physical Security for Safety-Critical Aviation Operations	Nadia Sokolova, T. A. Johansen		2019-2022	NFR IKTPLUSS	Sintef Digital	1 PhD + 1 postdoc
D•ICEROTORS – Protecting the unmanned aircraft industry	T. A. Johansen	3 MNOK	2019-2022	NFR BIA IPN	UBIQ Aerospace	1 postdoc
Energioptimalisert konsept for hel-elektriske, utslippsfrie og autonome ferjer i integrerte transport og energisystemer	Morten Breivik Anastasios Lekkas	4 MNOK	2017-2020	PILOT-E (NFR Energix + Innovasjon Norge)	Kongsberg Maritime Fjellstrand Grenland Energy Grønn Kontakt NTNU	1 PhD
aFerry – An integrated autonomy system for on-demand, all-electric and autonomous passenger ferries	Egil Eide Morten Breivik Asgeir Sørensen T A Johansen	6 MNOK	2019-2021	NFR FORNY	TTO	
Realisering av en autonom byferge for passasjertransport til kommersielt bruk	T. A. Johansen	1 MNOK	2019-2021	NFR PILOT-T	Maritime Robotics mfl	
OceanEye – All-weather, high-precision intelligent payload for sea surface object detection	T. A. Johansen	1 MNOK	2019-2021	NFR MAROFF IPN	Maritime Robotics Sintef Digital PGS NORUT	

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
OceanLab Trondheimsfjorden	AJ Sørensen M. Ludvigsen ++	187,48 MNOK	2019-2023	NFR Infrastructure	SINTEF Ocean, SINTEF Digital, NTNU	
SeeBee-Norwegian Infrastructure for drone-based research, mapping and monitoring in the coastal zone	TA Johansen A Sørensen G Johnsen	83 MNOK NTNU 18 MNOK	2019-2023	NFR Infrastructure	NIVA, NTNU, NR, NINA, IMR, GA	
Autonomous Robots for Ocean Sustainability (AROS)	Kristin Y. Pettersen M Greco JT Gravdahl A Stahl R Mester	21.5 MNOK	2019-2023	NFR IKTPLUSS	NTNU	5 PhD
Navigation System Integrity Assurance for Safety-Critical Autonomous Operations	Tor Arne Johansen	3.5 MNOK	2020-2023	NFR IKTPLUSS	Sintef Digital, NTNU	1 PhD
Autonomous Underwater Fleets: from AUVs to AUFs through adaptive communication and cooperation schemes	Kristin Y. Pettersen Damiano Varagnolo Hefeng Dong Claudio Paliotta Joao Sousa	14.6 MNOK	2020-2023	NFR FRIPRO	NTNU Sintef Digital	3 PhD

New (submitted) proposals

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Machine Piloted Unmanned Systems (MPUS)	Tor Arne Johansen	1MNOK	2020-2023	NFR MAROF	Radionor, MR, Seatex, NTNU	
Unmanned Aircrafts in All Future Airspace (UAAFA)	Tor Arne Johansen	2 MNOK	2020-2023	NFR BIA	Radionor, Andøya, NTNU	1 postdoc
CORALEDNA-Developing environmental-DNA methodology to assess biodiversity in cold-water coral reef ecosystems	G Johnsen A Sørensen M Ludvigsen	0.3 MNOK	2019-2021	NFR marinforsk. Topic: ecosystem	NINA, NTNU, HI, Uni Dublin, Uni Florida,	
Deep Impact – biological surveys from lit ships in the dark – can we realistically use the results for stock assessments, ecosystem dynamics and biomass estimation of zooplankton and fish	G Johnsen	Total 10 MNOK 0,6 mNOK to AMOS	2019-2022	NFR Klimaforsk	UiT, NTNU, Uni Strathclyde, Memorial Uni St Johns Canada, Uni Delaware	
Ice-Seals: Svalbards ice associated seals in a changing Arctic	G Johnsen M Ludvigsen	0,7 MNOK	2019-2021	NFR miljøforsk	NP, NTNU, UiT	
Patterns – Phytoplankton traits and environmental relationships in the Barents Sea	G Johnsen M Ludvigsen	11,8 MNOK	2019-2022	NFR Klimaforsk	NTNU, UiT, Uni Southampton, Oxford University	1 PhD 1 post doc

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Zola- Zooplankton dynamics at thin layers	G Johnsen M Ludvigsen	8,9 MNOK total NTNU 5,6 MNOK	2019-2021	NFR marinforsk	SINTEF Ocean, NTNU, Uni Hamburg	1 PhD
fUture Proof BridgE structures Training network (UPBEaT)	Kristin Y. Pettersen	3.5 MNOK	2020 – 2023	EU ITN H2020-MSCA-ITN-2019	MIT KTH DNV-GL	1 PhD
SFI Harvest	Asgeir J. Sørensen Martin Ludvigsen M. Føre ..	40 MNOK	2020-2028	SFI	SINTEF Ocean, NTNU Aker Biomarine, PGS, Arnøytind, Scanbio, Kongsberg Maritimer Subsea, Optimar, ++	4 PhD
SFI DroSatNor Drones and small satellites for the northern areas	Tor Arne Johansen (Asgeir)	65 MNOK	2020-2028	SFI	SINTEF NTNU, Norce, Nord, ConocoPhillips ..	Xx PhD ++
SFI Autononmous Ships	Tor Arne Johansen, Thor I . Fossen, Ingrid B. Utne	?	2020-2028		NTNU, SINTEF Ocean, Kongsberg, ..	?
SFI Clean	Ingrid Schjølberg, Thor I. Fossen, Ingrid B. Utne	?	2020-2028		SINTEF Ocean, NTNU, ..	?
VigiMare	T. A. Johansen	5 MNOK	2020-2021	NFR FORNY	TTO	
SenTiBoard	T. A. Johansen	5 MNOK	2020-2021	NFR FORNY	TTO	
Digital Platform for Cost-Optimal Design and Life-Time Extension of Offshore Wind Turbines (DP-CODLTE-OWT)	Zhen Gao	4 MNOK	2020-2023	NFR IKTPLUSS (International Calls for Bilateral Project between Norway and China)	Sintef Ocean, Equinor	1 PhD
Perception & Fusion of Multidimensional Information & Cooperative Decision-making for Intelligent Diagnosis of Wind Turbine Critical Parts (InteDiag-WTCP)	Zhen Gao	4 MNOK	2020-2023	NFR IKTPLUSS (International Calls for Bilateral Project between Norway and China)	EDR & MEDESO AS, SAFETEC NORDIC AS	1 PhD

ERC plans:

- ERC Advanced Grant: Key scientist candidates: Kristin
- ERC Starting grants, Annette Stahl

Vista Centre:

- Kristin, Asgeir, Martin on Underwater robotics

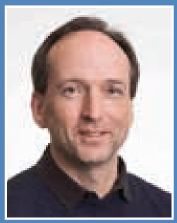
Completed Projects

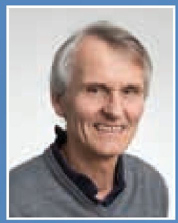
Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Design and verification of control systems for safe and energy-efficient vessels with hybrid power plants (D2V)	Asgeir J. Sørensen	18,7 MNOK	2011-2017	NFR MAROFF	NTNU Kongsberg Maritime DNV GL	5+1 PhD AJS, TAJ, RS, IU
Closed Flexible Cage (CFC)	Asgeir J. Sørensen	4 MNOK	2013-2017	NFR	SINTEF Ocean	1 PhF
Fault-Tolerant Inertial Sensor Fusion for Marine Vessels (MarineINS)	Thor I. Fossen	7 MNOK	2012-2016	NFR MAROFF	NTNU, RRM	2 PhD TIF, TAJ
Low-Cost Integrated Navigation Systems using Nonlinear Observer Theory (LowCostNav)	Thor I. Fossen	9 MNOK	2013-2016	NFR FRINATEK	NTNU, FFI, UNIK	3 PhD TIF, TAJ
Next Generation subsea inspection, maintenance and repair operations	Ingrid Schjølberg	20 MNOK	2014-2017	NFR KPN Awarded	NTNU FMC Statoil SINTEF IKT	4 PhD/Post docs IS, IBU, TIF
Autonomous Unmanned Aerial System as a Mobile Wireless Sensor Network for Environmental and Ice Monitoring in Arctic Marine Operations	Tor Arne Johansen	12 MNOK 0.9 MNOK for NTNU	2014-2016	NFR BIP Awarded	NTNU Radionor Maritime Robotics KM Seatex NTNU	Cover NTNU experimental cost, else Company research TAJ
Power management on ships	Tor Arne Johansen	3 MNOK	2014-2017	NRC Industry PhD Espen Skjong	NTNU Ulstein Group	1 PhD
Arctic Ocean ecosystems - Applied technology, Biological interactions and Consequences in an era of abrupt climate change (Arctic ABC)	Asgeir J. Sørensen Geir Johnsen	51,5 MNOK	2016-2019	Forsker-prosjekt NRC Proposal	UiT NTNU SAMS APN UiD WHOI UMA	1 PhD and Post doc for NTNU + Field experiments in the Arctic
Networked Ocean – Networked ocean and air vehicles for communications and data collection in remote oceanic areas	Tor Arne Johansen	300 kEUR	2015-2016	EEA Grant (Portugal)	University Porto NTNU FFI	Support field experiments
UAV ice detection	Tor Arne Johansen	1 MNOK	2016-2017	ERCIM / NTNU		1 postdoc
Forprosjekt design og konstruksjon av nyttelaster til NORSat	Tor Arne Johansen	250 kNOK	2017	Norsk Romsenter	Roger Birkeland, IET	
Snake Locomotion in Challenging Environments	Kristin Y. Pettersen	13.9 MNOK	2011-2015	NRC	SINTEF IKT	2 PhD + 1 Post doc
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
VISTA Post doc –Eleni Kelasidi	Kristin Y. Pettersen	3 MNOK	2016-2018	VISTA	NTNU	1 Postdoc
Assessment of operational limits for installation of OWT monopile and transition piece and development of an alternative installation procedure	Torgeir Moan	6 MNOK	2013-2016	NFR		2 PhD
Experimental and numerical study of the combined wind/wave energy concept SFC in extreme and operational environmental conditions	Torgeir Moan Zhen Gao	3 MNOK	2014-2016	NFR	NTNU	1 Postdoc
Numerical analysis of the dynamic response of an offshore wind turbine under wind and ice loads	Torgeir Moan	3 MNOK	2014-2016	NFR	NTNU	1 Postdoc
Numerical modelling and dynamic analysis of floating vertical axis wind turbines	Torgeir Moan	3 MNOK	2013-2016	NFR	NTNU	1 PHD
Dynamical analysis of anchor handling and trawling operations	Torgeir Moan	3 MNOK	2013-2016	NFR	NTNU	1 PHD

PHOTO GALLERY

Key scientists


Prof.
Asgeir J. Sørensen


Prof.
Thor I. Fossen


Prof.
Jørgen Amdahl


Prof.
Marilena Greco

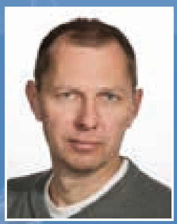

Prof.
Tor Arne
Johansen


Prof.
Geir Johnsen

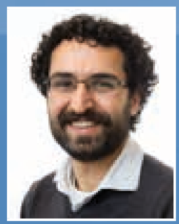

Prof.
Kristin Y.
Pettersen

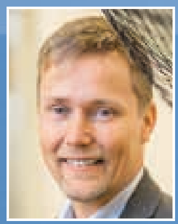
Adjunct professors and adjuct associate professors

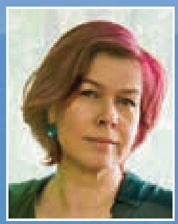

Adj. Prof.
Jørgen Berge


Adj. Prof.
Arne Fredheim


Adj. Prof.
Martin Føre


Adj. Prof.
Vahid Hassani

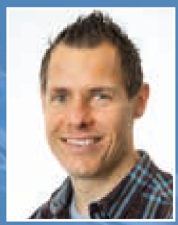

Adj. Prof.
Karl Henrik
Johansson


Adj. Prof.
Maarja Kruusmaa

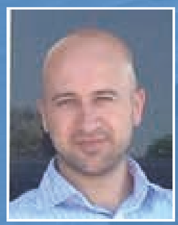

Adj. Prof.
Kjell Larsen


Adj. Prof.
Claudio Lugni


Adj. Ass. Prof.
Dong Trong
Nguyen


Adj. Ass. Prof.
Ulrik D. Nielsen


Adj. Prof.
Kanna Rajan


Adj. Ass. Prof.
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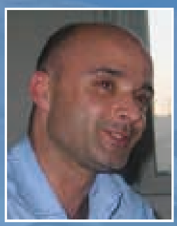
Adj. Prof.
Fred Sigernes


Adj. Prof.
Kjetil Skaugseth

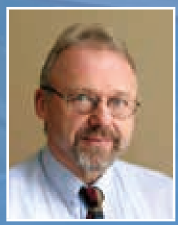

Adj. Ass. Prof.
Nadezda
Sokolova


Adj. Prof.
João Sousa

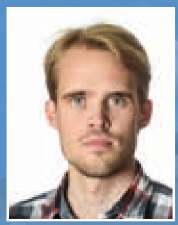

Adj. Ass. Prof.
Rune Storvold

Senior Scientific advisers


Prof.
Odd M. Faltinsen


Prof.
Torgeir Moan

Management and administration


Sigmund Bolme


Renate
Karoliussen


Knut Reklev

Postdocs/researchers


Roger Birkeland


Astrid H. Brodtkorb

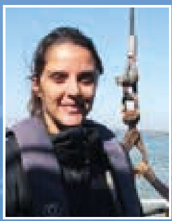

Torleif H Bryne

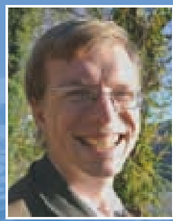

Zhengshun Cheng


Giuseppina Colicchio


Bjørn-Olav Holtung Eriksen


Trygve Fossum


Moreira Glaucia Fragoso

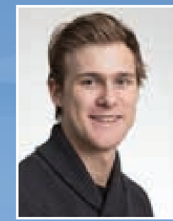

Joseph Garrett


Mark A. M. Haring


Håkon Hagen Helgesen


Ravinder Praveen Kumar Jain


Giorgio Kwame Minde Kufoalor


Fredrik S. Leira


Stein Melvær Nornes


Babak Ommani


Zhengru Ren

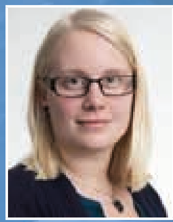

Robert J. Rogne


Børge Rokseth

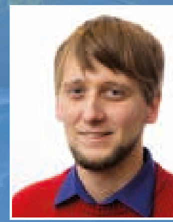

Yanyan Sha


Yugao Shen


Bård Nagy Stovner


Ida Marlen Strand


Christoph Alexander Thieme


Andreas Wolfgang Wenz

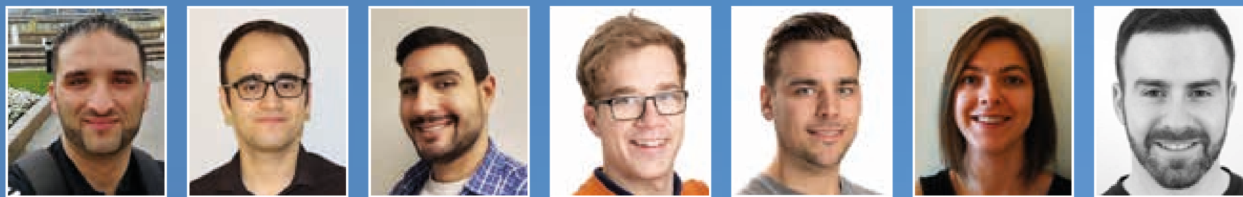

Erik F. Wilthil


Yu Zhaolong

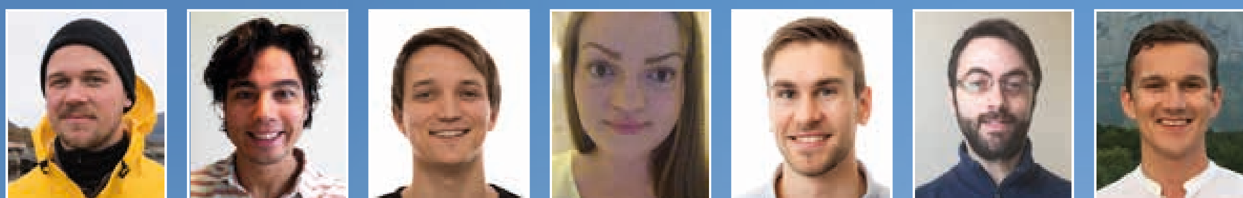

Artur Piotr Zolich


Øyvind Ødegård

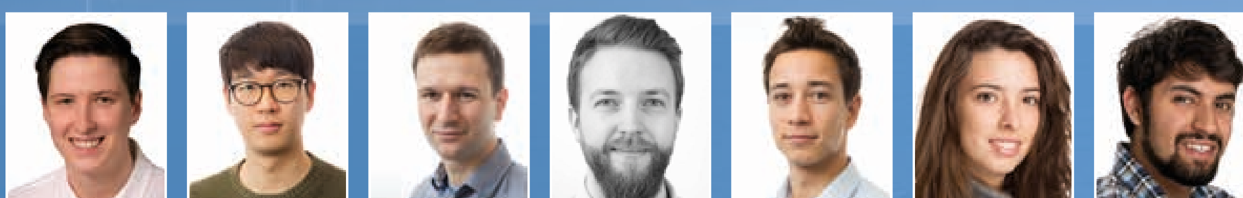
PhD candidates



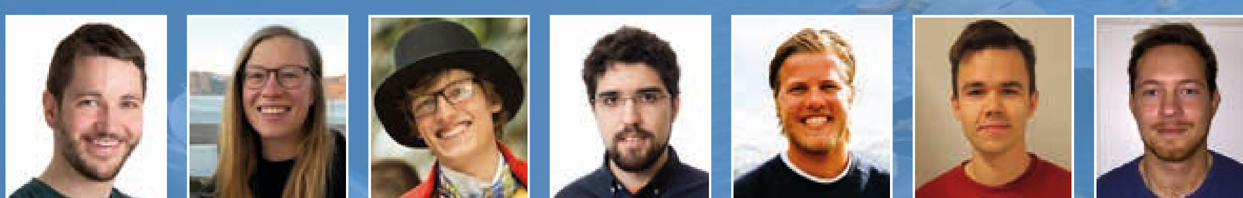
Ahmed W. Amro | Alireza Ahani | Fabio Andrade | Sivert Bakken | Erlend Andreas Basso | Gunhild Elisabeth Berget | Glenn Ivan Bitar



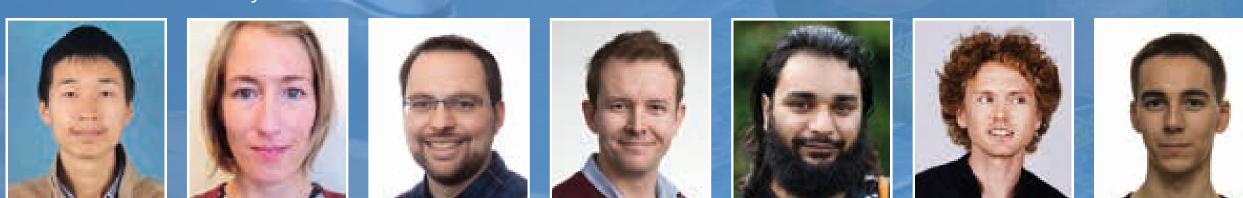
Tore Mo-Bjørkelund | Elias Bjørne | Simon Blindheim | Ida-Louise Borlaug | Pål Tokle Bore | Daniele Borri | Jens Einar Bremnes



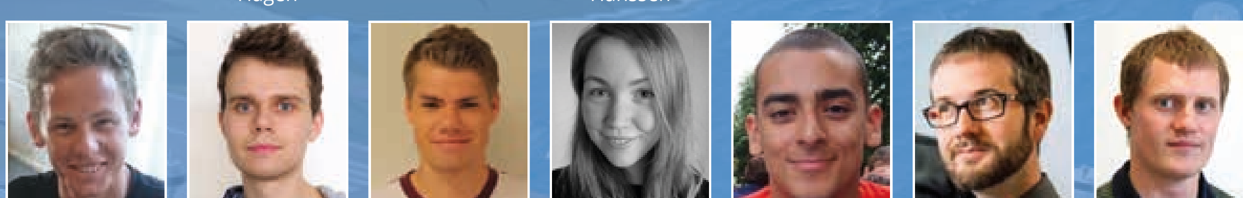
Eivind E. Bøhn | Seong-Pil Cho | Krzysztof Cisek | Erlend Magnus Lervik Coats | Andreas R. Dahl | Gara Quintana Diaz | Johan A. Dirdal



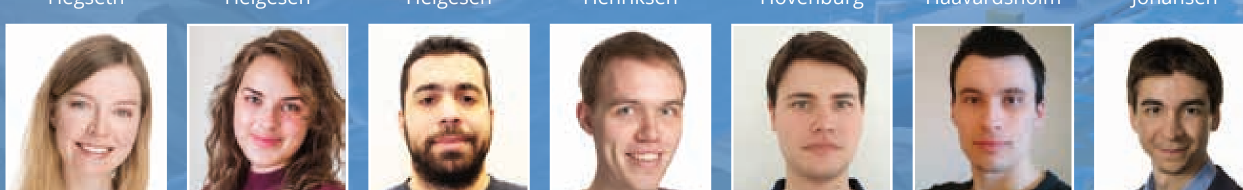
Bjørn-Olav H. Eriksen | Andrea Faltynkova | Andreas L. Flåten | Joao Fortuna | Trygve Fossum | Kristoffer Gryte | Mariusz Eivind Santora Grøtte



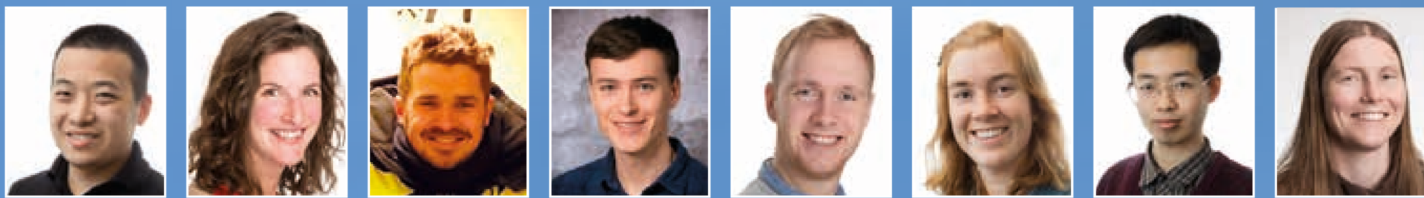
Chuanqui Guo | Inger Berge Hagen | Richard Hann | Finn-Christian W. Hanssen | Waseem Hassan | Johan Hatleskog | Simen Haugo



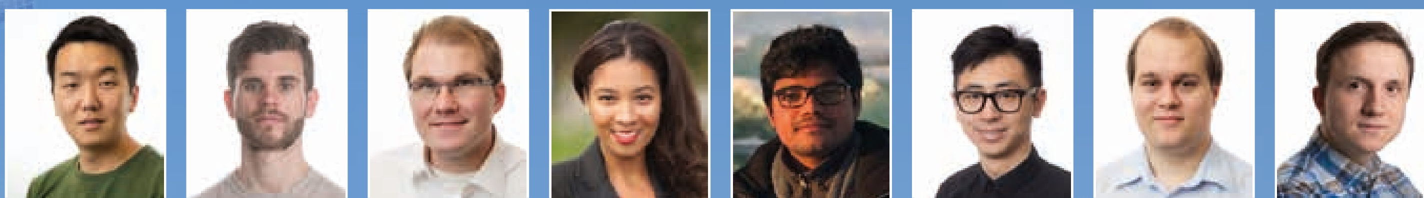
John Marius Hegseth | Øystein Kaarstad Helgesen | Håkon Hagen Helgesen | Marie Bøe Henriksen | Anthony Hovenburg | Trym Vegard Haavardsholm | Thomas Johansen



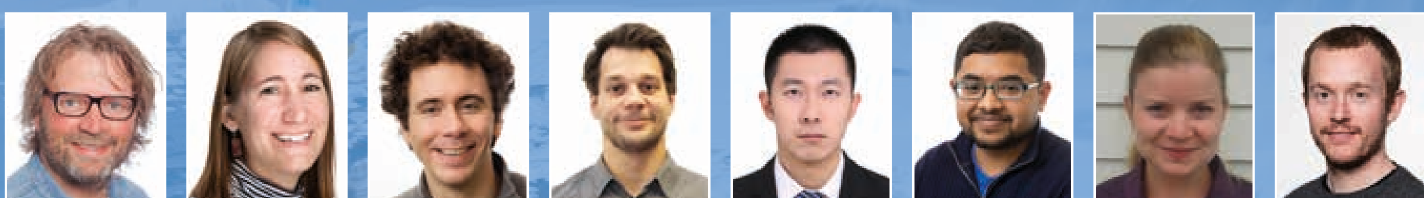
Kristbjörg Edda Jónsdóttir | Marianna Kaminska-Wrzos | George Katsikogiannis | Bjørn Andreas Kristiansen | Tord Hansen Kaasa | Dennis D. Langer | Marco Leonardi



Qinyuan Li | Evelyn Livermor-Honoé | Håvard Snefjellå Løvås | Andreas Bell Martinsen | Pål Holthe Mathisen | Siri Holthe Mathisen | Shaojun Ma | Mariann Merz

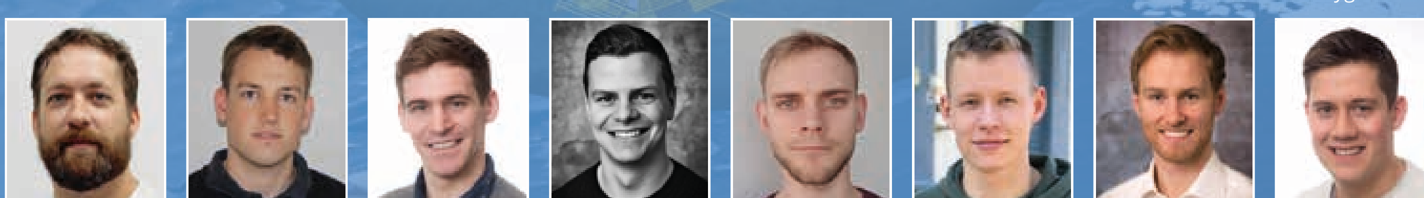


Woongshik Nam | Aksel Alstad Mogstad | Harald Lennart Jonatan Olofsson | Nathalie Ramos | Namireddy Praveen Reddy | Zhengru Ren | Christopher D. Rodin | Sverre Velten Rothmund

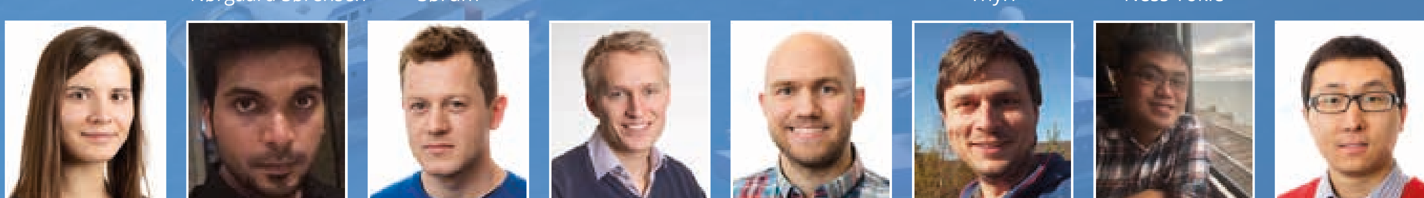


Dag Rutledal | Elizabeth Frances Prentice | Thomas Sauder | Henrik Schmidt-Didlaukies | Deng Shi | Mohd Atif Siddiqui | Tale Skrove | Robert Skulstad

Martin Slagstad | Emil Smilden | Martin Lysvand Sollie | Petter Solnør | Carlos Eduardo Silva de Souza | Øystein Sture | Natalie Summers | Jørgen Sverdrup-Thygeson



Eirik Svendsen | Mikkel Eske Nørgaard Sørensen | Stian Høegh Sørum | Trym Tengesdal | Marius Thoresen | Emil Hjelseth Thyri | Lars-Christian Ness Tokle | Einar S. Ueland



Anete Vagale | Amrit Shankar Verma | Stefan A. Vilsen | Sven Are Tutturen Værnø | Erik F. Wilthil | Adrian Winter | Chun-Deng Wang | Ling Wan

Martin Syre Wiig | Menging Wu | Hui-Li Xu | Kun Xu | Libo Xue

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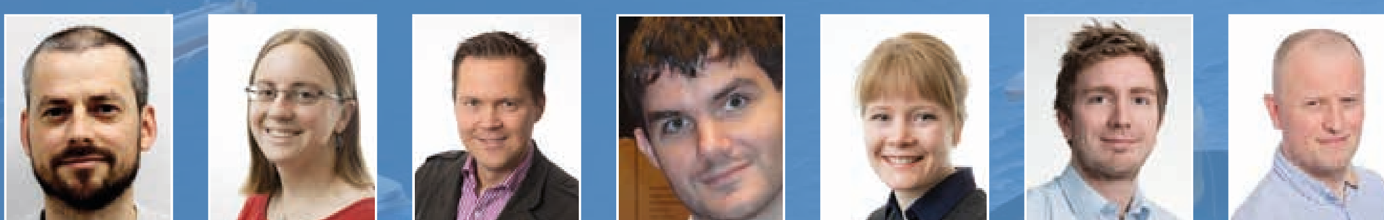
Ole Erik Vinje | Frode Volden | Torgeir Wahl

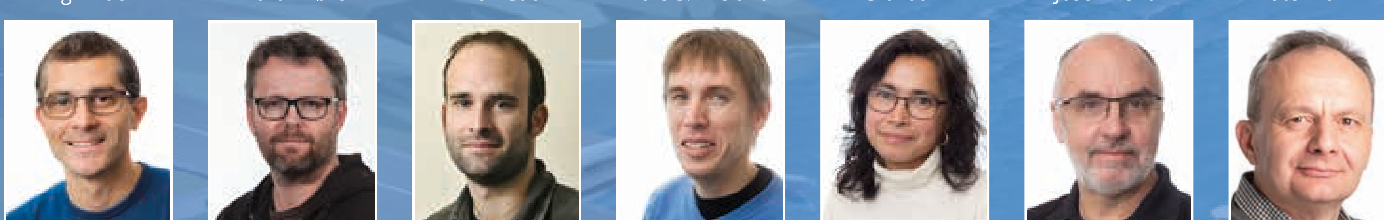
Ass. Prof. Nicole Aberle-Malzahn | Ass. Prof. Jo Arve Alfredsen

Affiliated scientists

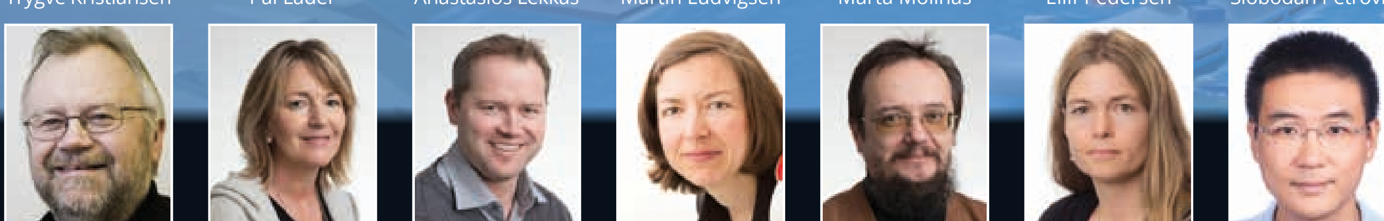


Ass. Prof. Morten Omholt Alver | Ass. Prof. Erin E. Bachynski | Dr. Morten Breivik | Ass. Prof. Edmund Brekke | Ass. Prof. Astrid Helene Brodtkorb | Dr. Torleiv Håland Bryne | Ass. Prof. Robin T. Bye

Ass. Prof. Egil Eide | Ass. Prof. Martin Føre | Prof. Zhen Gao | Prof. Lars S. Imsland | Prof. Jan Tommy Gravdahl | Ass. Prof. Josef Kiendl | Ass. Prof. Ekaterina Kim



Prof. Trygve Kristiansen | Prof. Pål Lader | Ass. Prof. Anastasios Lekkas | Prof. Martin Ludvigsen | Prof. Marta Molinas | Ass. Prof. Eilif Pedersen | Prof. Slobodan Petrovic



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

HIGHLIGHTS OF THE APPLIED UNDERWATER VEHICLE LABORATORY (AURLAB)

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

To address challenges in the ocean space, AURLab runs and maintains a park of AUVs, ROVs, instruments, samplers and navigation equipment, with support systems on behalf of partners from five different faculties. The lab represents an interdisciplinary scientific community, in which scientific questions are addressed to researchers from several scientific fields. Opportunities for faculty, researchers, PhD- and MSc students to test and experiment is provided with enhancing hypotheses and theoretical work. For 2019, some of the topics have been upper water column oceanography, particle imaging, archaeology, robotics and autonomy. The Department of Marine Technology hosts the lab, and the University Museum, the Department of Engineering Cybernetics and Department of Biology are partners.

Together with our industry partners, AURLab and AMOS identified the need for a subsea installation providing power and communication to test and verify solutions and concepts for future underwater operations. By providing access points on the seabed, a higher level of autonomy can also be developed for offshore operations. Together with Equinor, the company Blue Logics developed the Subsea Docking Plate (SDP), and one unit was made available to NTNU together with the required cabling to shore. After a long period of planning and preparation, the SDP was installed using RV Gunnerus and the ROV SF 30k. The installation required a landing of the system on a pre-installed suction anchor and the laying of cable to shore. No incidents or unwanted episodes were recorded during the operation, and the system is now operational at a depth of 365 metres and controlled from the facilities at the Trondheim Biological Station. The test was carried out testing the Eelume snake robot on the facility in June.

AURLab is also part of the Nansen Legacy project, with a focus on technology development and autonomous systems. An important part of this project is physical oceanography and the upper water column. In May, a special technology development cruise was

Figure 1: *The Subsea Docking Plate being installed using RV Gunnerus in May 2019.*

Figure 2: *The Eelume underwater vehicle during the testing on the SDP.*

Figure 3: *L-AUV Harald with the turbulence sensor mounted.*

scheduled together with the University of Bergen onboard the RV Kristine Bonnevie. An AUV-mounted turbulence sensor was tested together with USV, with a multi-frequency echo sounder to estimate the abundance of zooplankton. The results acquired were compared to profiling and ship-mounted equipment; the results were promising and will be further developed for Arctic application within the project.

Together with the University of Tromsø, UNIS and the Memorial University, AURLab organized an archaeological cruise funded in part by the district governor on Svalbard (Sysselmannen). The operation set out to Smeerenburg to search for a group of whaling vessels sunk by the French Navy in 1693. This part of Svalbard was an important source of oil boiled from whale blubber for Europe during this period. Due to the remote location, limited efforts have been invested in searching in this area. During our operation, one AUV and two small ROVs were deployed together with a towed sonar system. Unfortunately, we were not able to locate the wrecks, even though large areas were covered by side scan sonar. Indications of wood boring worms were found. If these waters are infested by such species, it is likely that old wooden vessels have been destroyed.

Figure 4: *Operation of the AUV close to Smeerenburg.*

HIGHLIGHTS OF THE UNMANNED AERIAL VEHICLE LABORATORY

Norwegian UAS consortium demonstrates pioneering 200km coastal long-distance flight.

An experimental flight in the summer of 2019 proves that unmanned aircraft can be used not only for short round trips, but also for long-distance operations from airfield to airfield. This opens up brand new possibilities for long-range drone applications such as surveillance, monitoring, search and rescue operations and applications within transportation.

On the morning of June 5th, a Maritime Robotics integrated Penguin-B UAV, owned by the Norwegian Defence Research Establishment (FFI), took off from Frøya on the mid-western coast of Norway. After the launch by a two-person crew from Maritime Robotics, the small unmanned aerial vehicle (UAV) flew north towards the sea, beginning its first long haul mission. As it flew

***Figure 1:** The route (red lines) from Frøya to Rørvik.*

on its 200-km route high above the rough Norwegian coast, it was always connected to the operations centre by novel long-range communication technology. The plane flew steadily through the sky on its carefully planned and monitored voyage, through different types of controlled civil airspace handled by civil air traffic control.

When the aircraft approached Rørvik, the landing operator took over control and smoothly landed the aircraft. The Norwegian University of Technology and Science (NTNU) was a part of the landing crew, providing their mobile operations station and safety pilot to assist with the final approach and landing. Upon landing, the small UAV had been in the air for 2 hours and 12 minutes, flying a route of 200 kilometres and landing approximately 170 kilometres from where it took off.

Using phased array radio systems from Radionor Communications, innovative new wireless data link technology provided reliable communications for control during the mission, and stable communications to the ground network, with range above 160 km recorded with a lightweight transceiver installed in the aircraft. This mission served to prove that it is possible to operate an unmanned aircraft not only on round trips from one base, but also for operations involving transit between multiple bases. This is a game changer for designing flexible UAV missions and services. One example is monitoring/surveillance missions (or search and rescue missions). During these missions, the main operations area might drift or move into an area far away from where the aircraft took off. This new area could be closer to an alternative landing site, and if the aircraft can land at this alternative site then it is able to stay in the air for a longer duration. Another example is freight, where it has very little effect to use UAS if the transport vehicle is not able to land at a different base from where it began.

Planning the mission involved Avinor, the company providing air traffic management for Norwegian airspace. It was clear that in order for the flight to be successful, a degree of flexibility was needed. The ability to fly in controlled airspace was essential for the mission, and fitting the UAV with a transponder (normally used for manned aircrafts) was key to giving those responsible for airspace safety confidence in the flight plan and operation. In order to effectively maintain command and control capabilities for the entire flight, the status and telemetry from the unmanned aircraft had to be accessible online. In this operation, all control was made from Rørvik or Frøya, but in principle the flight could have been controlled from specialized crew in a control room anywhere with good network access.

The experiment was a part of the research programme, Hybrid Operations in the Maritime Environment (HOME), which is a cooperation between Radionor Communications, NTNU AMOS and Maritime Robotics. This project has been funded in part by the Norwegian Research Council. In addition, the experiment was made possible due to important contributions from the Norwegian Defence Research Establishment (FFI), Norkring and Avinor.

Flying beyond-visual-line-of-sight (BVLOS) without GPS

The last decade has seen a large increase in the use of unmanned aerial vehicles that rely on positioning based on global navigation satellite systems (GNSS). However, numerous reported events in various public media outlets have emphasized the vulnerability of GNSS-based systems, as they are susceptible to both deliberate (jamming/spoofing) and natural radio frequency interference. Before unmanned aerial vehicles can be used for safety critical applications, this vulnerability must be addressed.

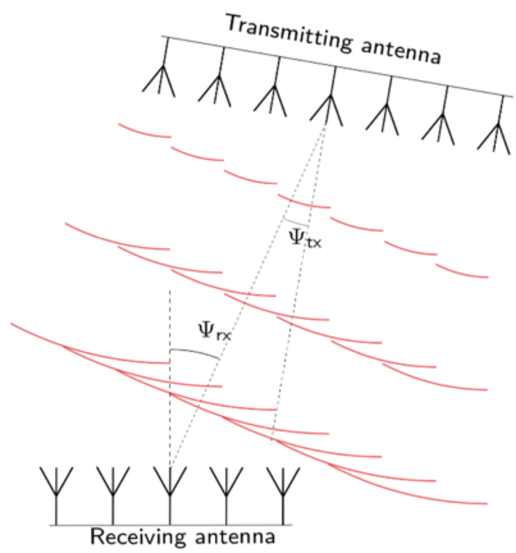


Figure 2: *The PARS uses a number of radios in which their antennas are placed in an array, where they send or receive the signal with phase differences. The phase differences allow the PARS to determine the direction of the antenna beam with a high accuracy.*

One way to mitigate this problem is by adding a second, GNSS-independent navigation system. The Trondheim-based Radionor Communications has developed a communication and navigation system based on phased array radio systems (PARS), with AMOS having studied how the performance can be improved by aided inertial navigation and filtering.

Figure 2 illustrates how the differences in the phase of the received signals at the different antenna locations can be used to determine the direction of the incoming signal. This leads to an electronically steerable highly directional antenna system. Unlike conventional mechanically steerable directional antennas, the PARS system is small, powerful and agile, and can send and receive in multiple directions at the same time in order to serve multiple moving nodes. The inherent beam-forming in the PARS can be used to locate the radio nodes onboard UAVs with a high accuracy. NTNU AMOS has worked on this problem for several years, in which the early stages (U1-R1,U1-R2,U1-R3) focused on the data collection and assessment of the data. New exciting results appeared in 2019.

First, previously collected data were used in a new algorithm to improve the positioning accuracy. This increased the confidence in the algorithm and led to a real-time implementation, which again led to two exciting demonstrations: In January 2019, we participated in a commercial demonstration with Radionor Communications, in which the PARS-based position estimate of a multirotor UAV was plotted live on a map (U1-R4,U1-R5). Then, in December, the PARS-based navigation was used in a closed-loop feedback to the flight controller of a fixed-wing UAV, flying beyond 8 km from the base antenna, without using GNSS for positioning (U1-R6).

At the heart of the new algorithm lies a multiplicative extended Kalman Filter (MEKF), which enabled the navigation system

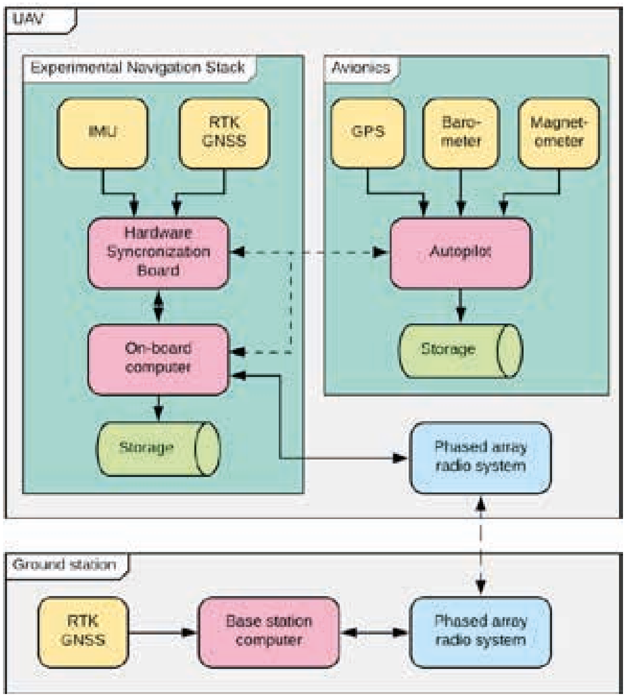


Figure 3: *Overview of the different hardware and software components.*

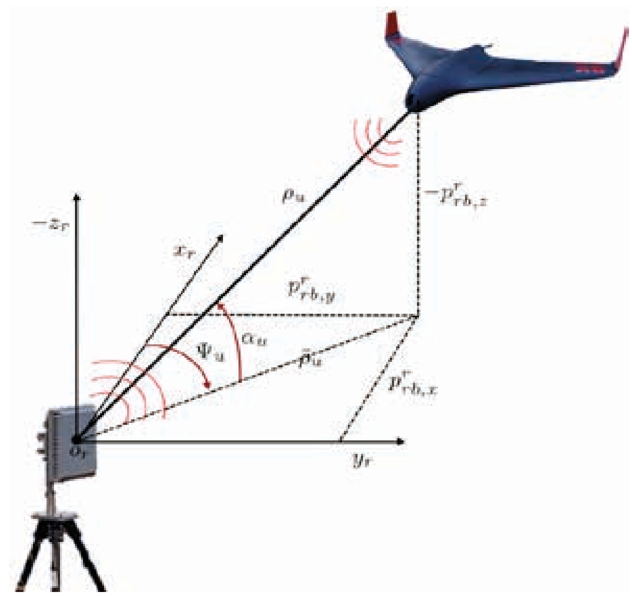


Figure 5: *PARS measurements and measurement frame. The ground antenna tracks the UAV, and can then compute its range and bearing and elevation angles to determine its position relative to the ground antenna system.*

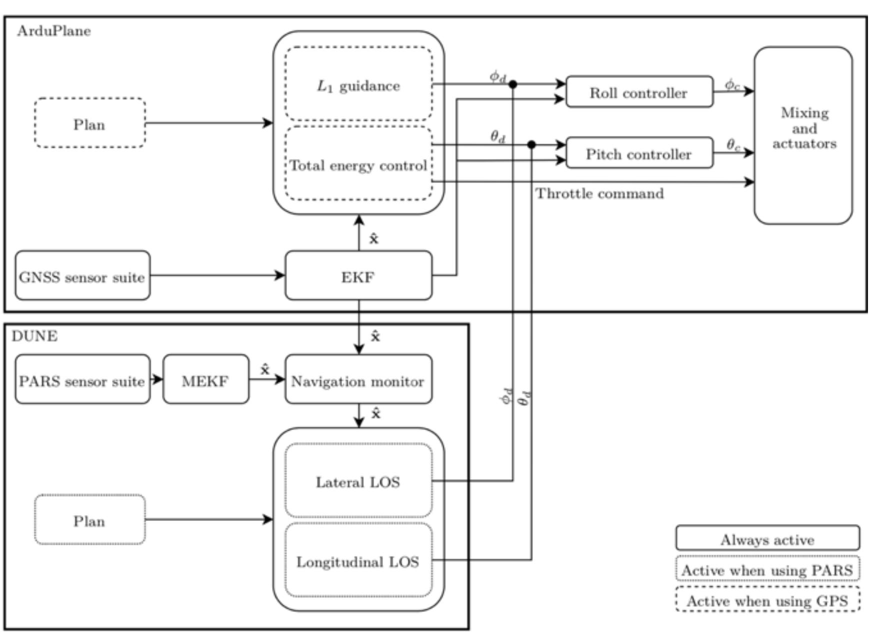


Figure 4: *Block diagram of the interconnected system.*

to determine the heading independent of a magnetometer, which uses the spherical position measurements from the PARS system, illustrated in Figure 5, and barometric height to aid the inertial navigation system, which is based on accelerometer and gyroscope measurements. An overview of the different hardware and software components, and how they are connected, is given in Figure 3, whereas Figure 4 shows more of the details of the software related to the closed-loop control.

Experiments

To evaluate the PARS-based navigation, several tests have been performed. The two presented here both performed using a Skywalker X8 fixed-wing UAV at Raudstein, 45 km north-west of Trondheim. In the first test, the data is post-processed and analysed offline in Matlab, while the results from the second test were computed onboard the UAV in real-time. For the second test, the estimates from the PARS-based navigation were used in a closed-loop feedback to the flight controller, without relying on GNSS.

Figure 6 shows the north-east position estimates of the PARS-based navigation system from the first test compared to the position estimates from a similar MEKF aided by RTK GPS instead, and against the RTK GPS position measurements, which are considered the ground truth. When comparing the PARS-based position estimates to the RTK GPS measurements, there is an error of approximately 10 metres. For the second (closed loop) test, the north-east position estimates are plotted in Figure 7. For this test, the ground truth is the internal state of the autopilot, based on multi-frequency, multi-constellation, non-RTK GNSS position measurements.

Towards a European Unmanned Traffic Management System (UTMS)

The CLear Air Situation for uaS (CLASS) project is a U-space project launched by a European Commission and SESAR Joint Undertaking in 2017. In 2019, there was a successful merger of existing technologies to build the core functions of an Unmanned Traffic Management System (UTMS). This research increases the maturity level of the primary technologies required for surveillance of Unmanned Aerial System (UAS, also known as drone) traffic.

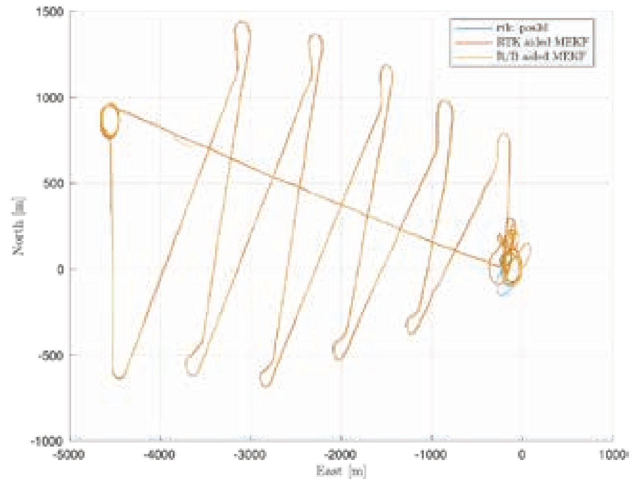


Figure 6: *North-east position estimates, post-processing results.*

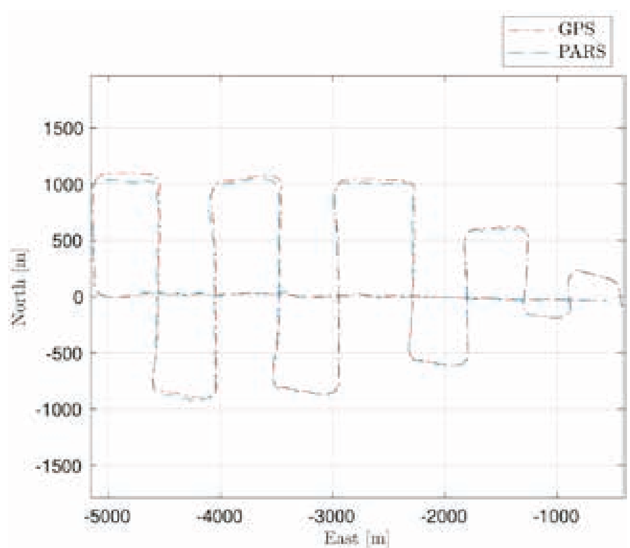


Figure 7: *North-east position estimates, closed-loop results.*

Figure 8: *The vision for the U-space is to enable complex drone operations with a high degree of automation to happen in all types of operational environments, particularly in an urban context.*

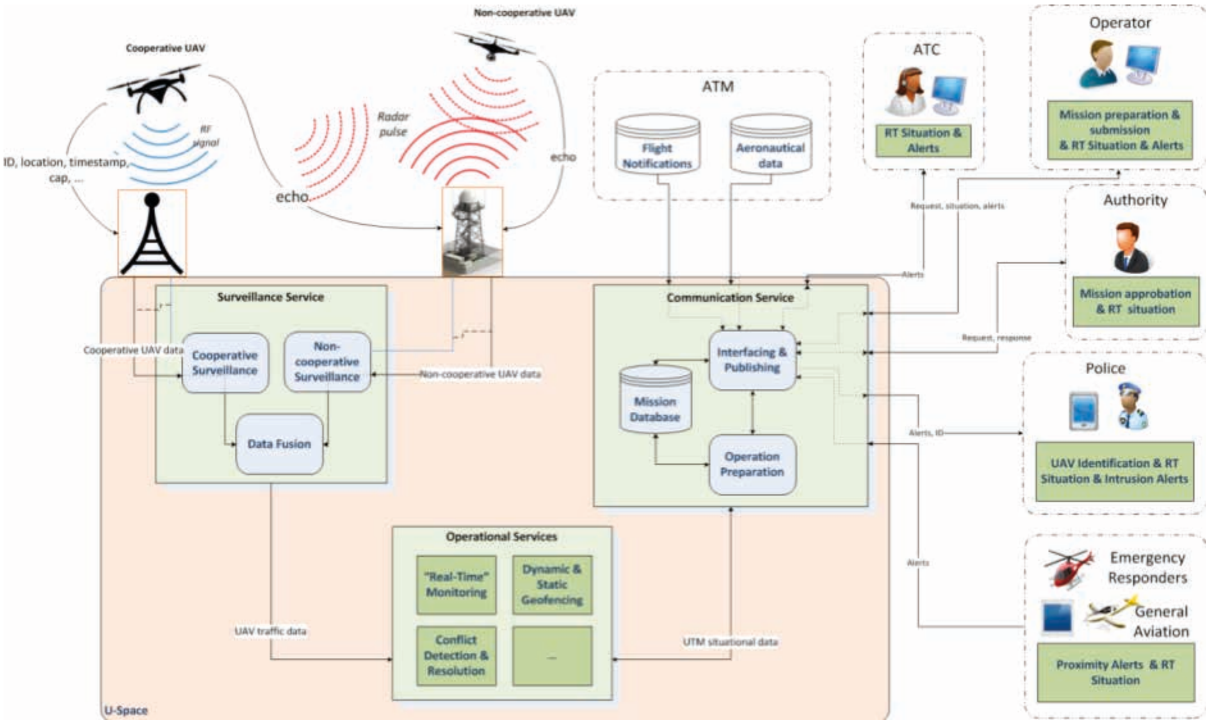


Figure 9: *CLASS concept of operations.*

The background for the project is that drone technology is on the rise and the number of drones in the air has been increasing at a rapid pace. Unfortunately, drones are hard to detect, and they often literally fly below the radar. As a result, the chances of conflicts between drones and manned air traffic (or between drones themselves) would be very high without the current restrictive regulation. However, the various stakeholders are pushing to ease this regulation. This can only be allowed if a sufficient level of safety can be guaranteed.

The project has successfully concluded it is possible to take different drone tracking technologies and present them in a single sky picture to see where the drones are and where they are going. This is a key enabler for U-space, and it supports the development of the over-arching Concept of Operations for EuRopean UTM Systems (CORUS) by identifying and de-conflicting drones operating within the airspace.

The CLASS concept of operations is illustrated in Figure 9. Project findings released in August 2019 followed earlier demonstrations, which researched real-time tracking and tactical de-confliction. Airbus managed the project, and also provided the tracker used to transmit drone ID and position data for cooperative surveillance. Aveillant provided drone surveillance technology, using its holographic radar for non-cooperative surveillance, while NTNU AMOS provided data fusion algorithms for the non-cooperative and cooperative data tracks [U2-R7]. Relevant aeronautical data was aggregated for both the sources and the data from multiple trackers (both on the drones and on the ground-based systems), and merged so that the location of all drones in the airspace could be known and displayed. ENAC designed the use case scenarios, and also flew drones during the live trials. Unifly combined the data from all sources and displayed them on screen.

Based on these functionalities, SESAR is looking to develop a real-time centralized UTMS, which will show both current and planned UAS flights.

SeaBee – Norwegian infrastructure for drone-based research, mapping and monitoring in the coastal zone

Seabee is a national research infrastructure for drone-based research, mapping and monitoring in the coastal zone that was approved for funding by the Research Council of Norway in 2019. It is led by NIVA (the Norwegian Institute for Water Research); the scientific partners are NTNU, NR, NINA, IMR and GRID-Arendal, while the industry partners are Andøya Space Center A/S and Spectrofly Aps and the data infrastructure provider is UNINETT/ Sigma2.

SeaBee will put together four state-of-the-art components in a novel interdisciplinary configuration, illustrated in Figure 10:

- Aerial drones with sophisticated sensors (RBG, multi-spectral and hyper-spectral) for collecting high-resolution environment data;
- Automated image analysis based on Artificial Intelligence (AI) for thematic mapping and targeted object detection,

Figure 10: *Organization of the SeaBee infrastructure project.*

- Automated data pipelines for the handling and storage of large datasets; and
- Cloud solutions for data sharing directly by stakeholders, including researchers, management authorities, technology industry, university students and others.

The following applications will be validated within the infrastructure project:

- Applications for benthic habitats: Develop protocol for mapping benthic habitats in the beach zone, subsurface vegetation (such as seagrass, seaweed, and kelp), seafloor substrate types and other management relevant species such as blue mussels, the invasive Pacific oyster, and opportunistic turf algae;
- Applications for marine mammals: Estimate seal population size and distribution, testing drone-based biometric measures incl. biomass;
- Applications for seabirds: Estimate breeding seabird population sizes, distribution and dynamics, and compare with existing seabird monitoring programmes, including the national SEAPOP programme; and
- Applications for surface water and ocean colour: Develop applications for surface water monitoring based on ocean colour theory, derive data on light attenuation, ocean darkening, phytoplankton biomass and harmful algal blooms. NorSOOP ship-of-opportunity data, traditional field measurements, and satellite remote sensing (Copernicus, Sentinel 2 & 3) will be included for validation.

NTNU AMOS will be involved in several activities, including establishing the infrastructure and operational procedures and capabilities for longer-distance, fixed-wing UAVs, which will cover large areas and operate beyond-visual-line-of-sight (BVLOS), the integration of instruments and field testing, and developing applications for benthic habitats and ocean colour.

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Media

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HIGHLIGHTS SMALLSAT LAB

The SmallSat Lab had its first full operational year in 2019. During the year, the ESD-protective area was taken properly into use, and new routines for work have been established. The lab is prepared to function as a safe working area for sensitive equipment and electronics, such as the payload in development and hardware-in-the-loop setup, which includes in-house developed electronics and systems connected to payload interfaces.

The HYPSO-1 (The HYPer-Spectral smallsat for Ocean observation) spacecraft is part of a larger effort towards *"... a concerted and unified cross-disciplinary focus on designing, building and operating small satellites as parts of an autonomous system for maritime sensing, surveillance and communication"*. The spacecraft is being developed in collaboration with the Department of Electronic Systems and Department of Engineering Cybernetics, with support from the Department of Mechanical and Industrial Engineering.

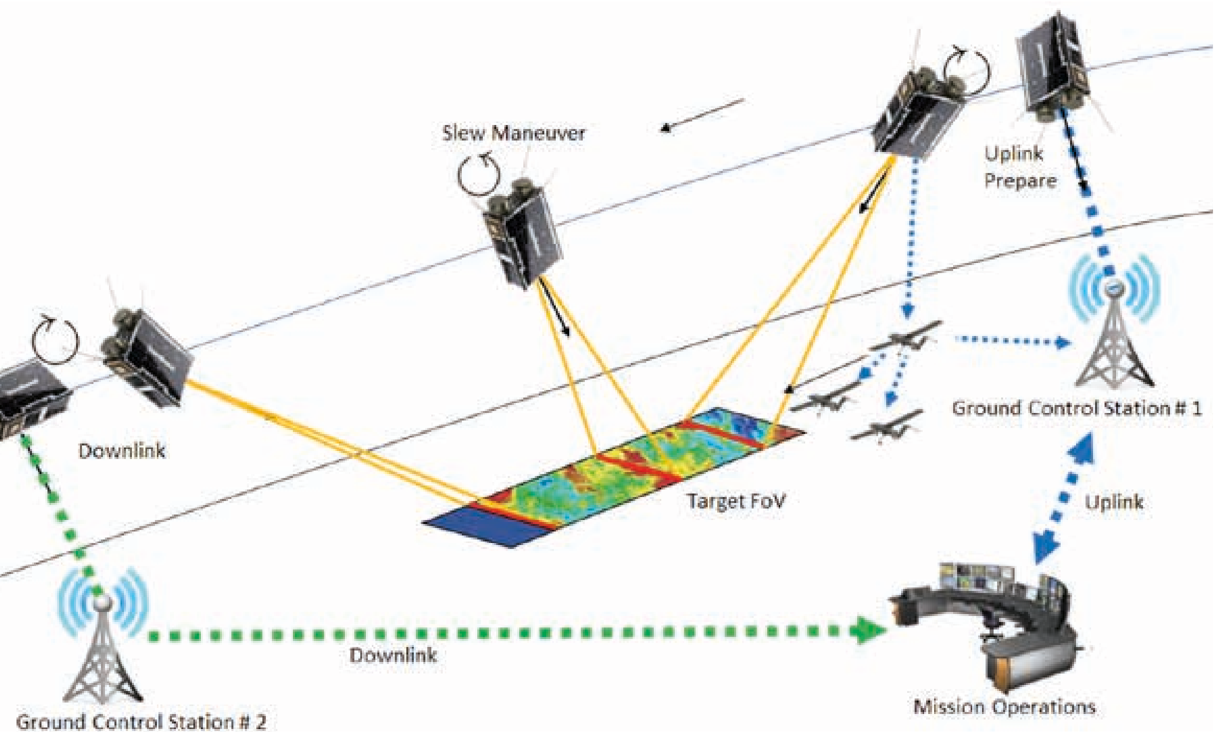
HYPSO will observe oceanographic phenomena via a small satellite with a hyperspectral camera, intelligent on-board processing and robots. Why? The ocean is of great interest to understand the effects of climate change and human impact on the world. Traditional EO satellites are very expensive, and take several years to develop and launch. Dedicated SmallSats can be used to provide images of small areas of interest with short revisit times. The information can be downloaded, and communicated to unmanned vehicles, which can further investigate areas of interest. https://www.hypso.space/

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

In 2019, the HYPSO-1 project team consisted of nine PhD fellows, two postdocs and approximately 20 MSc and BSc students, all working together in the NTNU SmallSat Lab. The work performed in 2019 included;

(1) Developing the hyper-spectral imager (HSI) designed by Fred Sigernes and the RGB camera to survive the space environment and fit a 6U CubeSat;
(2) Develop and implement on-board processing and payload control on a Xilinx System-on-Module;
(3) Finalizing the purchase of spacecraft bus from NanoAvionics, Lithuania;
(4) Installation of ground station system at NTNU;
(5) Choosing of launch planned for December 2020 on SpaceX Falcon9; and
(6) Initial planning of operations.

Figure 1



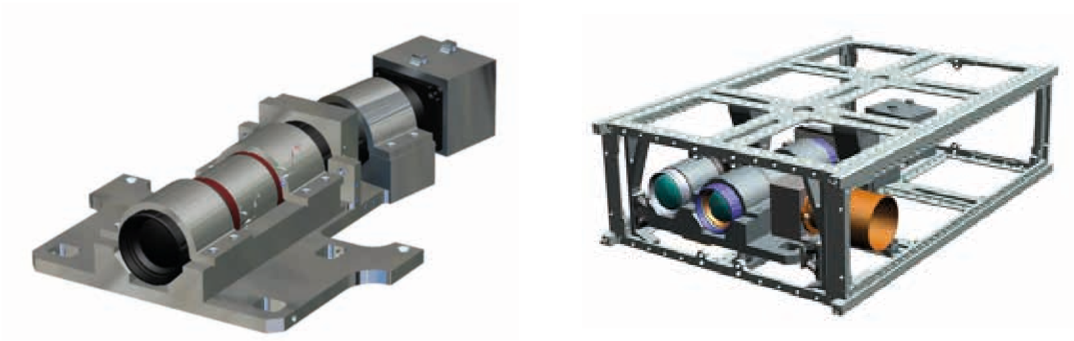


Figure 2

Several successful field experiments have been conducted to test hyperspectral imaging performance and processing methods:

- HSI flight tests were done on an oceanographic cruise off Barbados by the team in June 2019, in collaboration with Professor Ajit Subramaniam, Lamont Doherty Earth Observatory at Columbia University, USA.
- First HSI payload balloon test was completed at a 100,000 foot altitude: NASA Flight Opportunities Programme, a high-altitude balloon flight experiment was led by NASA Ames and executed by RAVEN Industries in Sioux Falls, SD in Sept 2019.
- UAV flights with HSI have been conducted in Oct 2019 to gather field data to support the testing of super-resolution image processing techniques to be implemented in HYPSO-1. The data analysis is in progress.

Figure 3

(1) Payload development

This year, the hardware team has focused on four primary tasks in preparation for launch: payload design, prototyping, environmental testing and product validation. The primary payload, or scientific instrument that will be carried by the CubeSat, is our hyperspectral imager. The "pictures" it takes will enable us to observe ocean colour from space… think algae blooms. Thus, image quality is a key part of our mission. We started by selecting commercial-off-the-shelf (COTS) components, such as lens objectives and camera sensors, which both fulfilled our quality requirements and were accessible in terms of cost and availability. The next challenge was to make these components into a working "imager". We used Computer Aided Drafting to create a working model of not only the imager, but also a platform in which the imager and other critical components could be mounted inside the satellite.

With this design, we began purchasing and prototyping with our in-house 3D printer to study how well the COTS components could be integrated with our own custom parts. We are currently in this iterative stage, and have begun the process of machining the approved 3D printed parts out of aluminum for our final flight model.

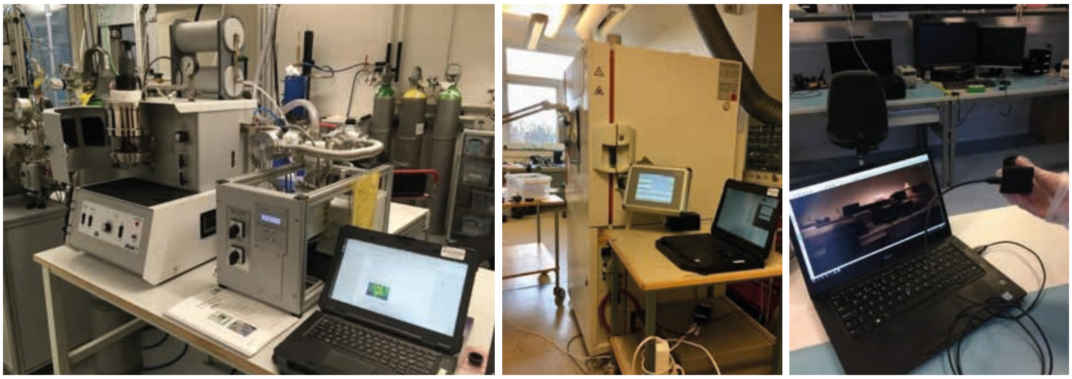


Figure 4

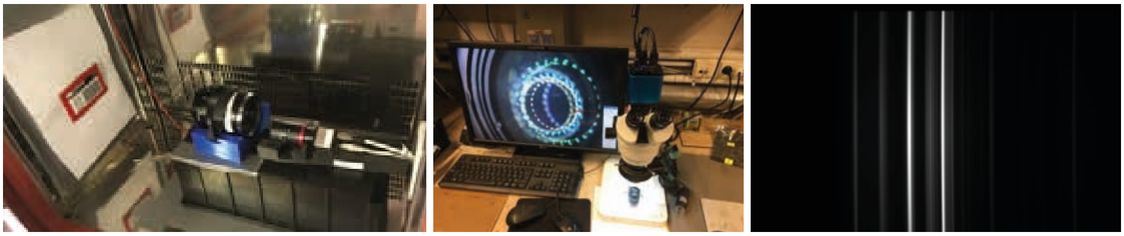


Figure 5

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

Finally, we have worked on simplified methods for evaluating image quality and imager performance prior to and after environmental testing. In this way, we are able to understand if our "images" are good enough to fulfill mission requirements, and what types of calibration and image corrections will be necessary to implement in software on the satellite and on the ground.

(2) Software and firmware development

The software and firmware team, led by Sivert Bakken and Joseph Garrett, has been focusing on developing the necessary reliable camera control and integration with the NanoAvionics spacecraft. Because of the short schedule until launch, the focus has been on reliable firmware and software for camera control, and for implementing the support of in-flight upgrades of firmware and software. During the commissioning of the payload, it is expected that the software and firmware must be updated, and that new on-board processing algorithms can be uploaded. The future on-board processing pipeline will include synchronized image acquisition, data calibration and correction (radiometric, spectral, keystone, smile, atmosphere), image registration, geo-referencing,

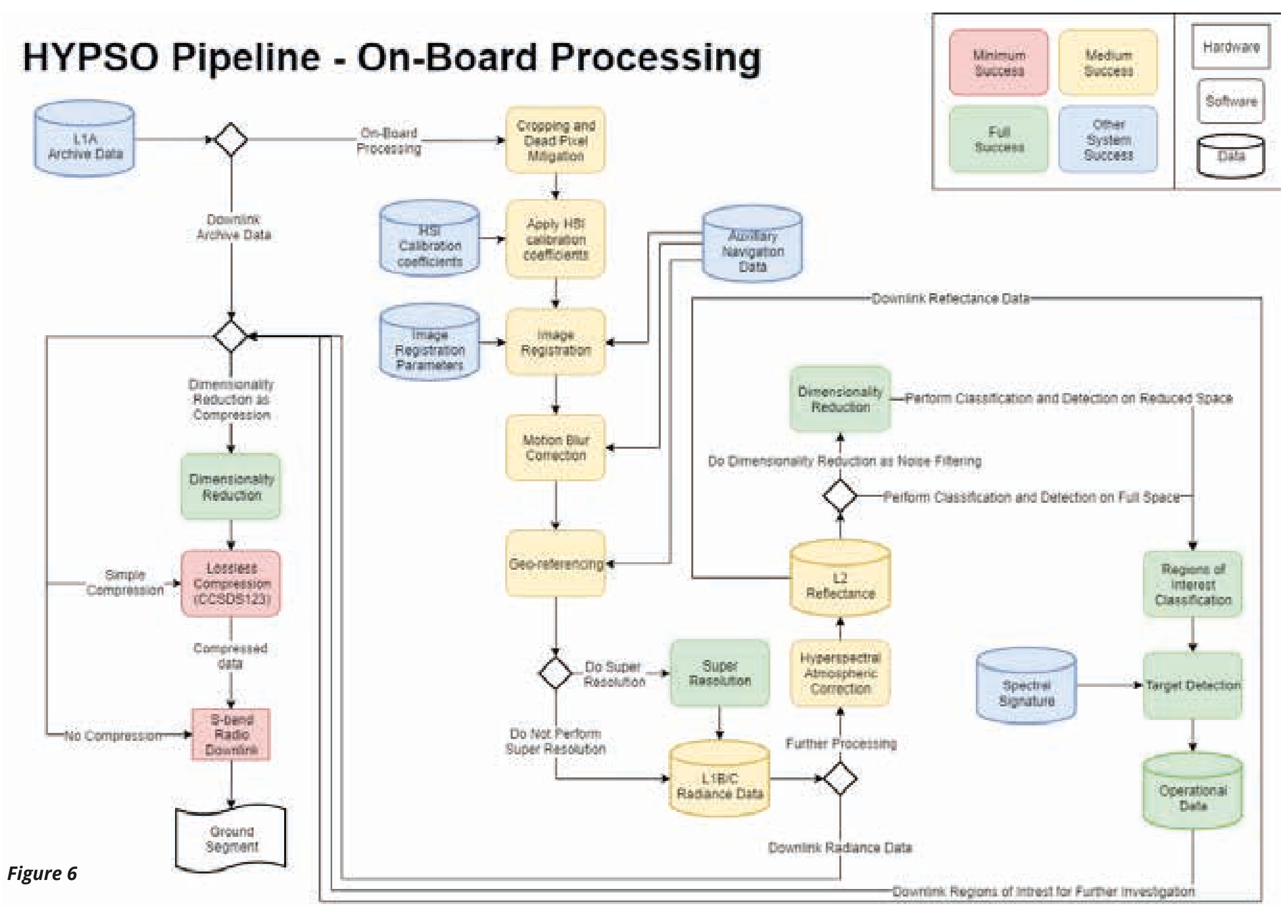


Figure 6

super-resolution processing, dimensionality reduction, compression, target detection and classification using AI/machine learning, data storage and communication.

(3) The spacecraft bus

The spacecraft bus was procured from NanoAvionics, and a Site Acceptance Test has been performed. The integration of payload and spacecraft is expected in Q2 2020. Working with NanoAvionics has included numerous hours of support and calls, as well as a training session on the FlatSat on the NTNU premises in Q1 2019. This allows for easier Hardware-in-the-Loop testing.

(4) Installation of ground station

In November 2019, an S-band ground station (S-band: A frequency around 2200 MHz used for downloading payload data and uploading commands and new settings to the satellite) was installed at NTNU. The station was delivered by NanoAvionics and their partner SatLab. The installed system, together with the S-band in the satellite will be able to deliver a data link with a rate of up to 1 Mbps during each pass. There will be between 5–8 visible passes per day from Trondheim.

Figure 7: *S-band antenna installed at NTNU*

Parts for an upgraded multi-band UHF-station were also procured in 2019. The station will be installed in 2020. This station is designed to cover two UHF frequency bands: one that will be used by HYPSO, in addition to the amateur radio band that will be used by the Orbit student satellite.

HYPSO-1 will make use of this ground station, as well as stations at Tromsø (KSAT), Svalbard (KSAT), Denmark, Vilnius and possibly locations in Spain.

(5) Launch

In the final part of the year, a launch agreement was reached with NanoAvionics as the launch broker. The HYPSO-1 spacecraft is planned to launch with SpaceX in December 2020. This will give a sun-synchronous orbit, from North-to-South. It is not the ideal orbit conditions for the mission, but this has given the team knowledge in how a mission is developed and iterated on depending on the constraints that arise.

(6) Operations

From Q1 2020, there will be several students working on developing the operations architecture and implementation, with the goal of developing an operations control centre and a spacecraft control centre. The operations control centre will be designed with the goal of integrating operations between the HYPSO-1 spacecraft and other autonomous assets, namely the AutoNaut as being developed by Alberto Dallolio.

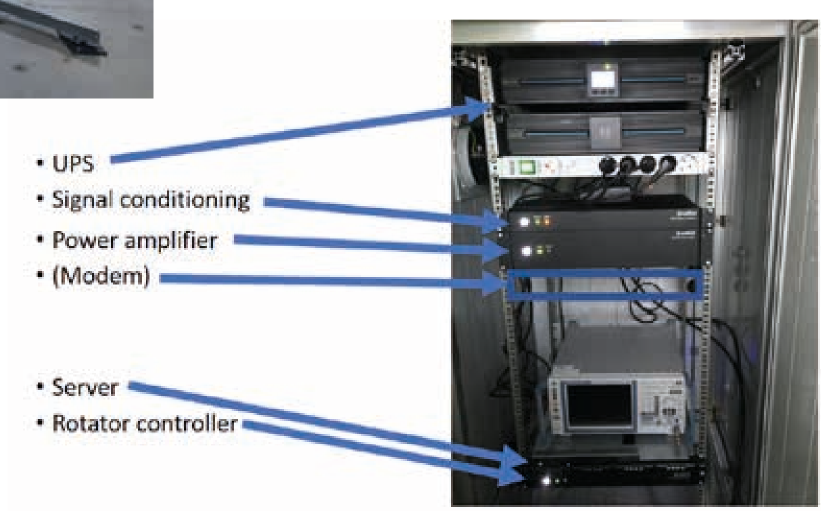


Figure 8: *Installed equipment*

AWARDS AND HONOURS 2019

Key scientist at AMOS, **Kristin Y. Pettersen** has been awarded the Bode Lecture Prize for her work on snake robots. The Bode Prize recognizes distinguished contributions to control systems science or engineering. Pettersen's colleagues argues that it is the closest you get to a Nobel-prize within the field of Cybernetics.

PhD candidate at NTNU AMOS and the Department of Engineering Cybernetics, Erlend Andreas Basso, has won the NFEA's prize for best master thesis 2019 with the thesis "Dynamic Task Priority Control of Articulated Intervention AUVs. Using Control Lyapunov and Control Barrier Function based Quadratic Programs".

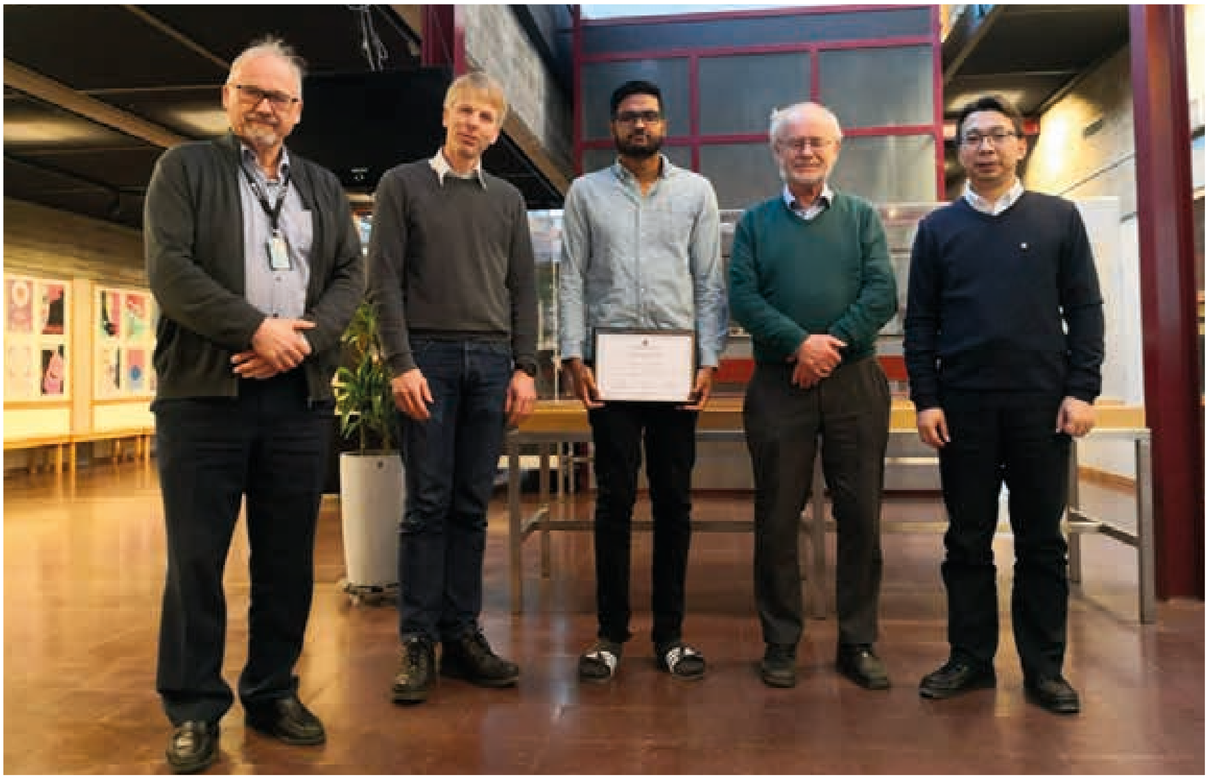
PhD candidate at AMOS, Richard Hann, has received an outstanding oral presentation award from the SAE for their International Icing conference 2019.
Hann gave two talks on his papers on "Experimental Investigations of an Icing Protection System for UAVs" and "UAV Icing: Ice Accretion Experiments and Validation".
Hann and his colleagues are doing research on icing on unmanned aerial vehicles (UAVs) and developing icing protection systems for it.

Photo: Odd Richard Valmot, TU

The Director of AMOS, Professor Asgeir Sørensen, has received the Norwegian Research Council's innovation prize for 2019. The price is granted to a person or organization that through exceptional use of research result have laid the foundation for research-based innovation.

Key scientist at NTNU AMOS, Marilena Greco, has been named 2019 Reviewer of the Year by the ASME Journal of Offshore Mechanics and Arctic Engineering. The Reviewer of the Year Award is given to reviewers who have made an outstanding contribution to the journal in terms of the quantity, quality, and turnaround time of reviews completed during the past 12 months

Professor Emeritus, Torgeir Moan, was been elected "a Foreign Member of the Chinese Academy of Engineering (CAE)" in 2019. Li Xhiaohong, the President of the CAE, writes that Moan was elected member due to his "distinguished contributions to marine engineering and civil engineering and his promotion of China-Norway exchanges and cooperation in those fields".



Senthuran Ravinthrakumar at NTNU received the Moan-Faltinsen Best Paper Award on Marine Hydrodynamics 2019. The awarded paper is 'A Two-dimensional Numerical and Experimental Study of Piston and Sloshing Resonance in Moonpools with Recess', which was published in Journal of Fluid Mechanics and authored by Senthuran Ravinthrakumar, Trygve Kristiansen, Bernard Molin and Babak Ommani.

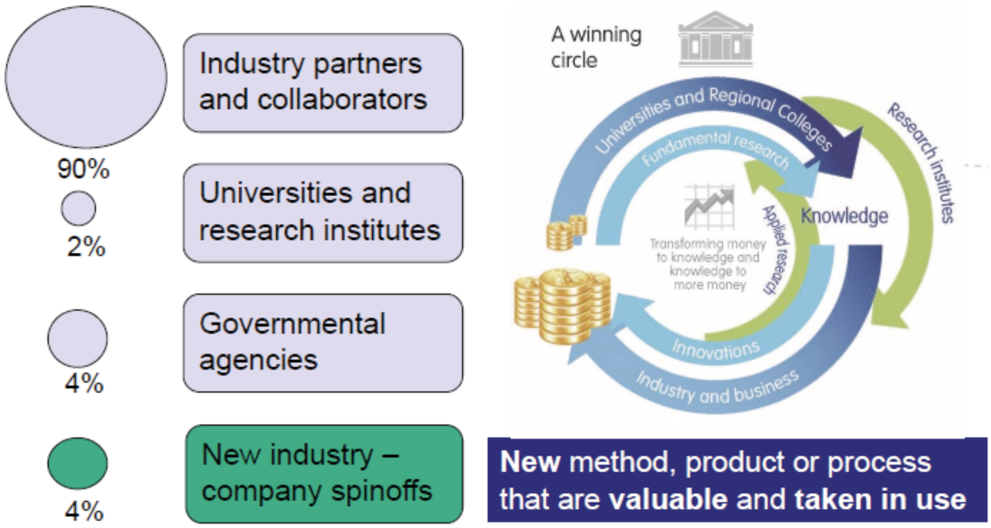
RESEARCHER-DRIVEN INNOVATION AT NTNU AMOS

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

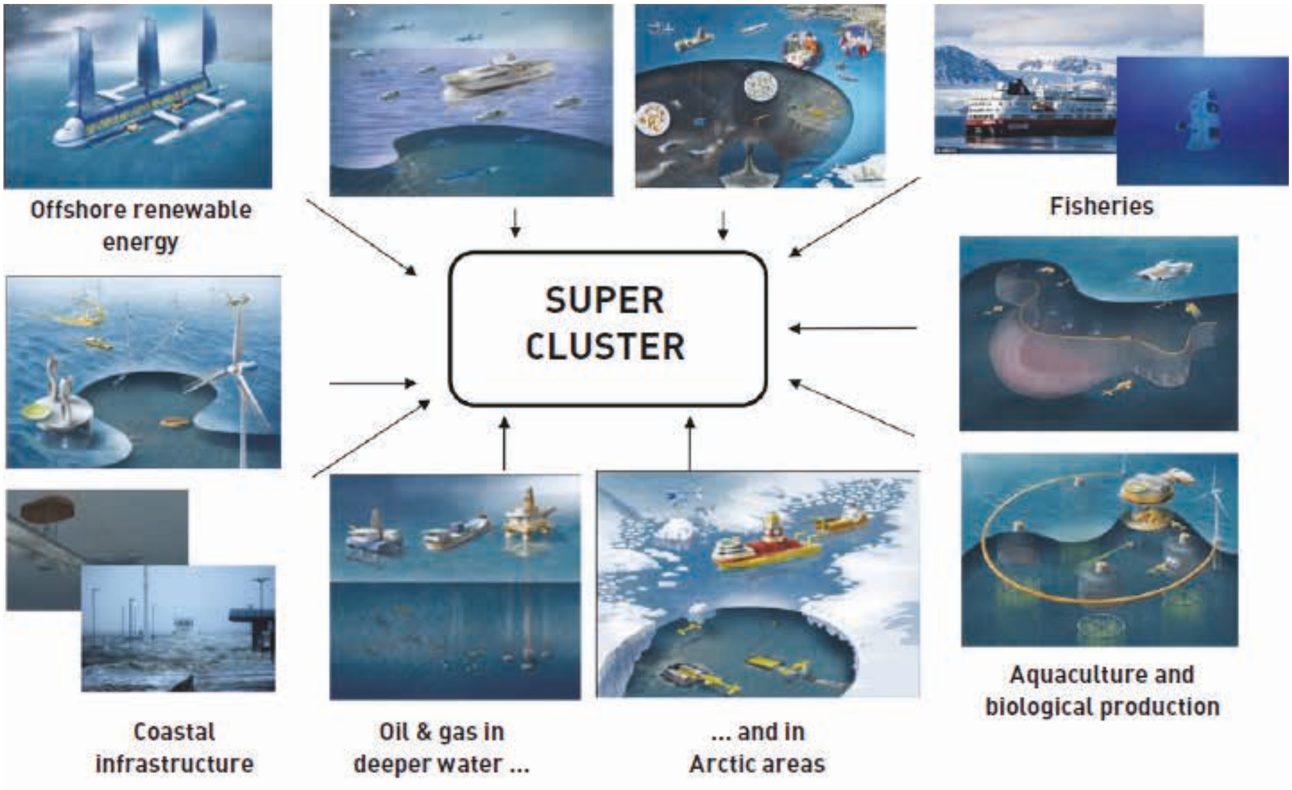
Key scientists hypothesized the importance of these topics 3-5 years before they become "hot¨ in Norway and elsewhere. This is also one reason for the great interest and rapid growth of AMOS in terms of funded PhDs and affiliated scientists. AMOS research topics have become an important part in the Norwegian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

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

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



Innovation arenas at the NTNU AMOS



The blue economy that comprises a super cluster over Norway.

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

PRESTIGIOUS PRIZE TO PROFESSOR KRISTIN YTTERSTAD PETTERSEN

Researchers have worked on the idea of snake robots for more than 30 years, but the greatest breakthrough thus far has been achieved by a key scientist at NTNU AMOS, Professor Kristin Ytterstad Pettersen, and her colleagues. In recognition of this work, Pettersen has been awarded the Bode Lecture Prize.

The Bode Prize recognizes distinguished contributions to control systems science or engineering. Pettersen's colleagues argue that it is the closest you get to a Nobel prize within the field of Cybernetics.

The director of NTNU AMOS, Professor Asgeir J. Sørensen, has known Pettersen for many years, and they have worked together for the last 15.

- Only candidates with international breakthroughs in the field are qualified for this prize. That Kristin got it on account of the work she has done in an area where there is intense competition between the large nations is simply fantastic, says Sørensen.

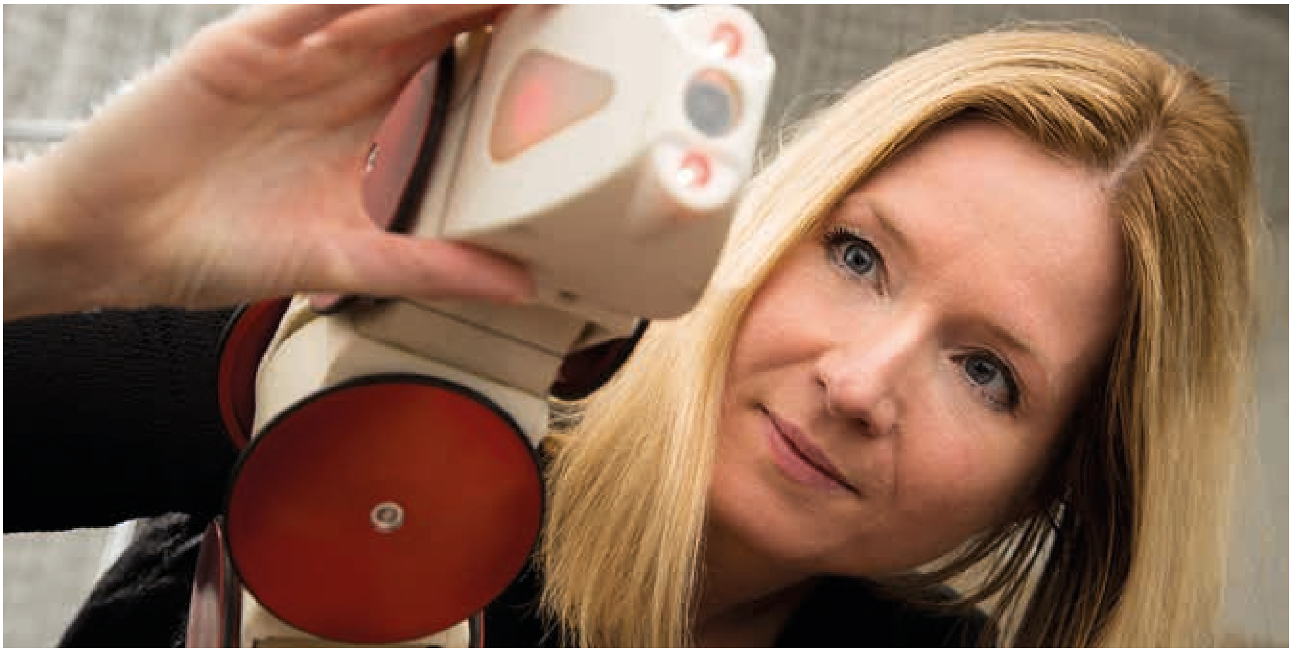
Sørensen says that he is very proud to have the first Norwegian to receive the prize as a colleague.

A robot that mimics a biological snake

For several years, the research team at NTNU has been working on developing an underwater robot that is flexible and slim enough to conduct complex operations in confined spaces, very much like a real sea snake. The result is a flexible snake robot, with motorized joints that can change its form as needed, just like a real snake.

¬- Because of this, the robot is capable of conducting a wide spectrum of inspections and surveys under water in places where we have previously struggled to obtain access. It is also capable of gripping and manipulating tools and objects, just like an operational underwater drone, says Professor Petersen.

Petersen is both humble and somewhat surprised to be awarded the prize.



- Only the great pioneers within this field have received this prize before, so I feel very humbled to be placed among their ranks. I never even suspected I would get it, so I was very surprised when I learned that it would be awarded to me, explains Petersen.

Petersen is the first Norwegian to get the prize, and only the second woman. She confirms that the field is still very dominated by men.

- Luckily, a lot has happened in our field since I started almost 30 years ago, and it is very inspiring to see the growing interest for cybernetics and robotics, she says.

Even though the prize was awarded to her personally, Petersen is adamant that this is a prize that also recognizes her colleagues at NTNU.

- No one can conduct projects of this size on their own, so it is as a representative for the unique research environment at NTNU that I receive this award, she says.

Petersen is a professor at the Department of Engineering Cybernetics, a key scientist at the Centre for Excellence NTNU AMOS, and a professor II at the Norwegian Defence Research Institute.

Puts Norway on the map

This might be the most prestigious international scientific recognition one can receive within the field of Control Engineering – a large and important area within ICT. That Kristin and NTNU receives an award like this in a generic field is exceptional, and it really shows what a brilliant scientist she is, says Asgeir Sørensen.

Kristin Ytterstad Pettersen is also an entrepreneur, and, together with her research group, she has used her research results to establish the underwater robotics company Eelume.

- This is also great recognition for the Department of Engineering Cybernetics and to NTNU AMOS. It really puts Norway on the map, says head of department Morten Breivik at the Department of Engineering Cybernetics at NTNU.

He also recognizes the importance of Sintef as a partner in the development of generic underwater robots over several years, particularly in connection with the early prototypes to be developed.

- The work that has led to this award spans more than 15 years of focused and systematic research, with everything from developing prototypes, modelling, analysis and simulation to control, experimental verification and commercialization. This is very much in line with NTNU's vision of "knowledge for a better world", in which knowledge, in the form of more sustainable products and services, is provided to the world, says Breivik.

The world's largest engineering society

The prize is named after Hendrik W. Bode, one of the founders of modern cybernetics, and is awarded by The Institute of Electrical and Electronics Engineers (IEEE), which, with more than 400,000 members, is the largest engineering society in the world.

Every year, a select few members who have achieved extraordinary results are named fellows. Pettersen was named a fellow three years ago, being the first Norwegian woman to achieve the honour.

This is what the Control Systems Society has to say about this year's prize:

The Bode Lecture Prize is the most prestigious award given by the Control Systems Society (CSS) and is accompanied by a plenary address at the Society's largest conference, the Conference on Decision and Control (CDC).

This is the technical highlight of the conference, and is avidly attended. Kristin's address will take place at the CDC 2020 next December at Jeju Island, Republic of Korea.

The basis for judgment is "the technical merit of distinguished contribution to control science or engineering." The awardee is selected by the CSS President after consultation with senior figures in the field. This small-group selection process is designed to identify an individual whose contributions have true depth, breadth and significance.

In Kristin's case, the technical contribution has extended from fundamental theory through implementation, application and commercialization, which describes a broad arc of achievements and impact in the science, engineering and technology of control systems. CSS is very proud to count her as one of our own.

NTNU AMOS RESEARCHERS GET THE COVER OF SCIENCE ROBOTICS

The front-page article of the 2019 February issue of Science Robotics was written by researchers at NTNU AMOS.

The article “Toward adaptive robotic sampling of phytoplankton in the coastal ocean” by Fossum et al., looks at how we can gain a better understanding of our oceans using robots.

Very efficient

Modern robotic technology presents new ways to map the oceans and gather data, in a far more efficient and cost-effective way, then previously possible.

The autonomous underwater vehicles are able to cover a larger area than ships and stationary sensors. They are also able to make their own decisions on where to move in order to get the best possible samples.

These new methods are important if we are to gain a better understanding of the complex ecosystems of the oceans. More knowledge will hopefully help us make the best decisions on how to maintain and preserve the health of the oceans and their vital ecosystems.

Difficult conditions

The research team conducted their experiments in the coastal waters near Runde Island, Norway. This area is affected by strong winds, ocean currents, and freshwater runoff from land. Fossum et al. used a light autonomous underwater vehicle (LAUV) to survey the edges of predefined volumes, and the resulting data allowed the robot to identify interior areas with high concentrations of subsurface chlorophyll a for additional, detailed sampling.

LAUV results were confirmed with data from remote sensing and shipboard samples. The combination of a real-time data analysis, in addition to accurate, adaptive robotic sampling, will help improve our understanding of marine food webs and their dynamic, heterogeneous environments.

Article abstract

Currents, wind, bathymetry and freshwater runoff are some of the factors that make coastal waters heterogeneous, patchy and scientifically interesting—where it is challenging to resolve the spatiotemporal variation within the water column.

We present methods and results from field experiments using an autonomous underwater vehicle (AUV) with embedded algorithms that focus sampling on features in three dimensions. This was achieved by combining Gaussian process (GP) modelling with on-board robotic autonomy, allowing volumetric measurements to be made at fine scales. A special focus was given to the patchiness of the phytoplankton biomass, measured as chlorophyll a (Chla), an important factor for understanding biogeochemical processes, such as primary productivity in the coastal ocean.

During multiple field tests in Runde, Norway, the method was successfully used to identify, map and track the subsurface chlorophyll a maxima (SCM). Results show that the algorithm was able to estimate the SCM volumetrically, thereby enabling the AUV to track the maximum concentration depth within the volume. These data were subsequently verified and supplemented with remote sensing, time series from a buoy and ship-based measurements from a fast repetition rate fluorometer (FRRf) and particle imaging systems, as well as discrete water samples that cover both the large and small scales of the microbial community shaped by coastal dynamics.

By bringing together diverse methods from statistics, autonomous control, imaging and oceanography, the work offers an interdisciplinary perspective in the robotic observation of our changing oceans.

NTNU OPENS LABORATORY 370 METRES BELOW THE SURFACE

Right now, more than 300 metres under the surface of the Trondheim Fjord, new technology is being developed at Norway's deepest subsea laboratory, the only one of its kind in the world.

The lab was officially opened in May 2019 at the 25th anniversary of Equinor's research centre at Rotvoll in Trondheim by former rector at NTNU, Gunnar Bovim, and Executive Vice President at Equinor, Anders Opedal.

Before the opening, Asgeir Sørensen, the director of NTNU AMOS, and Kjetil Skaugset from Equinor told the audience how the collaboration between NTNU and Equinor is changing how drones are used, not just under water, but also on the surface and in the air.

Its purpose is to test new underwater drones, and it will allow NTNU, Equinor and other partners to develop new radical solutions and innovations for underwater operations. In addition to NTNU, the first user is Eelume and their snake robots. The lab's subsea docking station is the first of its kind in the world, and it will provide the future "janitors of the ocean" with a test-site where they can be refined and improved upon in realistic conditions. This is work that is necessary if snake robots are to become the efficient underwater workers that Eelume and Equinor envision.

Among the areas that will be explored is the possibility of having robots that live permanently on the ocean floor. Offshore maintenance, repairs and inspections today require ships and specialist equipment that can be expensive to operate.

Besides the oil and gas sector, other businesses like aquaculture, shipping and offshore-wind energy production can all benefit from cheap and efficient inspection and maintenance work.

If robots like this can be put into action on a large scale, they can provide considerable cost reductions, quicker response times and fewer emissions of gases such as CO_2, NOX and SOX. They will also contribute to an increased safety and regularity for the industry that operates them.

The lab is operated by NTNU, but will also be available for businesses, research centres and other universities, cementing NTNU and Trondheim's position as a world leading research hub for subsea technology and underwater robotics.

INTO THE DARK

The research being done at AMOS is opening new ways of understanding the world, but knowledge is only useful if people are aware of it, and when you want to reach a larger audience, what better way than to make a movie?

Over this past year, AMOS professor 2 Jørgen Berge and key scientist at NTNU AMOS, Geir Johnsen, participated in the movie project “Into the Dark”, which attempts to unravel the mystery of the polar night.

The movie premiered at a film festival in Tromsø on 16 January 2020, where it was shown several times, filling the movie theatre each time.

- Because so many wanted to see it, we who participated in making it had to have our own showing at the University in Tromsø on the 17 of January. We simply could not get seats at the regular screening, Johnsen laughs.

Life in the dark

The movie, whose audience will be able to enjoy at several film festivals in the coming year, is based on the work done by Johnsen and his colleagues over these last 10 years. The researchers have looked more closely at the biological organisms that thrive in the polar night. The movie mostly follows the work of Jørgen Berge, who is heading this Polar Night project, which is the basis of the film, with David McKee (University of Strathclyde, Glasgow) and Geir Johnsen.

- The film director, Michael Snyder, managed to get the best from us, and the team was brilliant. They followed us closely, and were very thorough in making sure that the science was presented correctly, stating the take home messages to a larger audience globally, says Geir.

Light pollution

In the middle of the polar night, most organisms in Arctic waters are expected to be in a state of dormancy. However, the team from NTNU and UIT discovered organisms reacting to light levels as low as one millionth that of daylight, including algal cells that entered a photoactive state a full six weeks before the return of sunlight.

These organisms, from algae to fish, can be very sensitive to light, something which poses problems for all those who try to understand ocean life in the High North during a period of darkness for the human eye.

- Even the light from a research vessel, or a vessel estimating the stock size of zooplankton and fish, can influence organisms down to 200 metres below the ocean surface. They can either be attracted to the light or flee from it. All of this makes it very difficult to say anything accurate about behaviour or populations, and stock assessments of fish may be influenced by this at nighttime all over the world, says Johnsen.

- Because of this, the methods that we use are very important. Our best solutions right now are to use autonomous robots that don’t need any artificial light and will give us information that is not affected by artificial light, says Johnsen.

The need for knowledge is growing quickly, as Arctic sea ice is melting faster than at any time in recorded history, and growing human activity in the Arctic, with respect to fisheries, oil and gas, mineral extraction, new transport routes and tourism, is rapidly increasing in the region. Consequently, light pollution is pouring into the Arctic, and is now thought to be among the fastest growing sources of pollution in the region. The long-term consequences of this may be far reaching. So far, they remain largely unknown, but thanks to researchers like Johnsen and his colleagues we are getting closer and closer to an understanding of these complex environments and the life that exists and thrives there.

AUTOSEA AND AUTOSIT

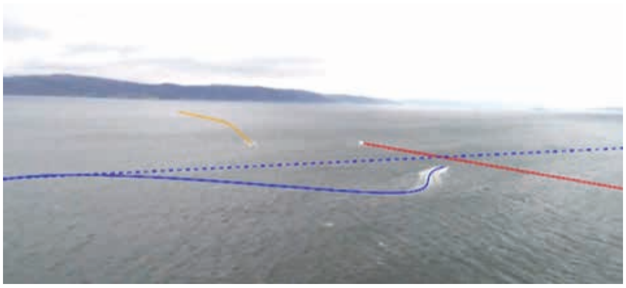
Unmanned ships can only be commercially viable insofar as legislators, classification societies and the public opinion acknowledge this technology as safe. On the one hand, reducing human interference will reduce the number of mistakes caused by human operators. On the other hand, a ship must have sophisticated systems for interpreting its environment and executing actions and responses in order to safely operate on its own. Most importantly, the ship must be trusted not to collide with its surroundings.

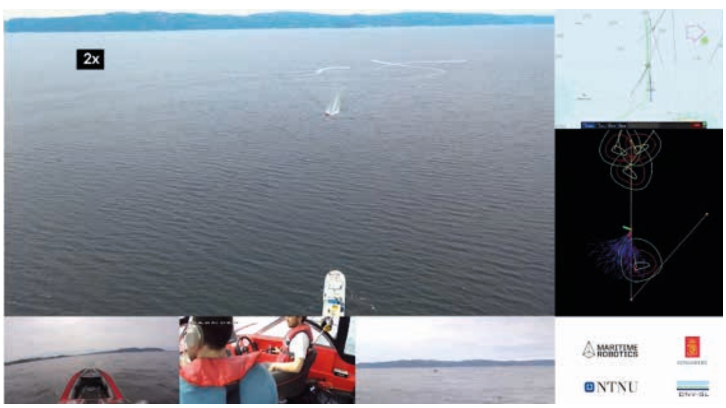
The competence-building research project, “Sensor Fusion and Collision Avoidance for Autonomous Surface Vehicles” (Autosea, 2015-2019), funded by the Research Council of Norway, DNV GL, Kongsberg and Maritime Robotics, has developed and investigated systems for collision avoidance for unmanned ships. The fundamental premise for the Autosea project has been that the main building blocks for a collision avoidance system are a multi-target tracking system that keeps track of potential obstacles and a collision avoidance method that overrides the nominal motion control commands when necessary.

In multi-target tracking, the project has led to new understanding and methods for dealing with safety-critical sensor imperfections such as false alarms and misdetections. In motion control, the project has developed several collision avoidance methods based on ideas from model-predictive control (MPC). These methods are capable of utilizing a very rich information picture in their decision-making.

The Autosea project has always had a strong focus on real world validation. The collision avoidance systems have matured through a series of full-scale experiments involving test vessels from the consortium partners. The systems have used both radar and data from the automatic identification system (AIS) to obtain information about the location and motion of obstacles. All the experiments, including the final demonstrations on 14 June 2019 (reported in Adressa and Teknisk Ukeblad), were conducted with arbitrary traffic (passenger ferries, RIBs, etc.) passing through the test area.

The breakthroughs in autonomous marine navigation achieved in the Autosea project are already paving the way for related





activities at a higher technology readiness level (TRL) at NTNU and in the consortium partners. The autonomous ferry half-scale model Milliampere is serving as a testbed for research on autonomous ships at NTNU. Based on this, a new spin-off company, Zeabuz, aims to provide autonomous electric passenger ferry services in urban waterways.

The Autosea consortium continues its collaboration in the new competence-building project, "Autonomous ships, intentions and situational awareness" (Autosit, 2019-2023), which will deliver algorithms for a situational awareness that enables autonomous vessels to understand, interpret and predict the intentions of other vessels.

While situational awareness is typically understood as something that pertains to human operators, and often treated in highly abstract and conceptual terms, the Autosit project will make more tangible building blocks of situational awareness for automated decision-making. Such technology will enable autonomous ships to enter more congested areas such as harbours, canals, inland waterways and areas close to the seashore in general.

The Autosit project consists of four work packages:
(1) Long-term vessel prediction,
(2) Fusion between AIS and exteroceptive sensors,
(3) Pose estimation and extended object tracking and
(4) Experiments and validation.

The rationale behind the first work package is that different data sources such as sensor data, historical data and physical constraints, as well as models of reasonable behaviour (e.g. COLREGS compliance), must be fused together to get reliable predictions over longer time horizons (e.g. minutes and beyond). The second work package will develop rigorous and robust solutions to important but non-standard sensor fusion problems that have been largely unexplored in the scientific literature. As for the third work package, humans understand that when a ship in motion changes its heading, then it is probably also changing its course, and this is indeed a key rationale for the COLREGs guideline that manoeuvres should be readily observable. To enable this capability for autonomous systems, the Autosit project will combine several recent advances in sensor fusion, computer vision and machine learning.

NOT JUST WORLD-CLASS RESEARCH

At NTNU AMOS, we try to create a bridge between different fields and methods, between fundamental research and innovation, and between different departments and universities. But what of the social bridges that connect people?

In 2019, the NTNU AMOS Social Committee was created to strengthen teamwork and friendship among PhD candidates, but also any other researchers who want to participate. The hope is that social activities will help foster friendships across research areas and departments that may lead to further collaboration and exciting new research results.

Einar Ueland, Jens E. Bremnes and Sverre Velten Rothmund are, together with Chripstoph Thieme, Elizabeth Prentice, and Stian Høegh Sørum, all PhD candidates and postdocs at NTNU AMOS and members of the social committee. Below are some of their thoughts on this initiative.

- Our goal is to improve the interaction between researchers at Gløshaugen and researchers at Tyholt. It has previously been a challenge to get these two groups to get to know each other. Thus far, we are organizing one social activity per month, and have also provided input on how the AMOS days conference should be organized, says Einar.

- The committee is also providing ideas on how the networking part of the AMOS spring seminar can be a success, Sverre adds.

Points of contact

The idea for the committee was born at the 2019 AMOS Seminar, where several AMOS PhD candidates talked about how they missed more contact among themselves. Some of them followed up on the discussion by creating the Social Committee, with Director Asgeir Sørensen providing some funds to get it all started.

The committee began its work in the summer of 2019, and by the end of the year have already organized eight different activities: bowling, hiking, minigolf, climbing, cabin trips, board game nights, a Christmas event and a swing dance course.

- Even though a lot of people were sceptical about the dance course, it turned out to be one of the most fun events, says Sverre, Jens and Einar.

More fun, better research

While the activities are meant to create a stronger connection within NTNU AMOS, the committee, when suitable, allows all members of the various departments to participate.

- At the Department of Engineering Cybernetics, there is no real divide between researchers connected to AMOS and those who are not; everyone at the department is therefore invited to most of the events to ensure that nobody is left behind, says Sverre.

- It's all about multidisciplinary cooperation, if people get to know each other, that will make it easier to cooperate. We also want to make the work even more fun, and activities like this might give the PhD candidates a better work experience, which can further motivate them in their research. Of course, this result would be a great help for NTNU AMOS as well, Jens tells us.

The events for the spring are already planned out, and the committee will keep working to bring AMOS researchers together in a social setting, thereby hopefully strengthening the centre's research in the process.

SMALL, EFFICIENT AND WITH ZERO EMISSIONS

Another spin-off from the AMOS research community was launched in 2019. This time the focus was on small green ferries, perfect for modern urban centres with usable waterways.

The new company, Zeabuz, seeks to develop effective and climate-neutral mini-ferries that can be a cheap and climate-friendly alternative to bridges and traditional ferries in cities.

Making use of the waterways

With more and more of the world's population concentrated in the cities, finding new, sustainable and efficient methods for transportation is a considerable challenge. Zeabuz says that they will hopefully help provide some of tomorrow's transportation solutions by "building mobility solutions on top of world-leading technology expertise".

Among the people behind the company is NTNU AMOS director Asgeir Sørensen, who thinks these ferries can be a great alternative to footbridges in modern cities.

- This could be a better idea than to build expensive footbridges, and the new company is called Zeabuz, where the "Z" stands for zero emissions. I definitely think there will be a market for these ferries, especially in the future, says Sørensen.

Autonomous solutions

Zeabuz will be based in Trondheim, but the concept envisions a system where most of the ferry is built on-site. The ferry will also be autonomous, thereby driving down costs, with NTNU hard at work developing solutions to ensure that the autonomous operations of ships and boats like these are safe.

- Autonomy fits like a glove with electric ferries. This enables better control, optimal operation, safety and maintenance, says Sørensen.

While originally envisioned as a solution for cities, the autonomous electric mini-ferries will also be available for smaller settlements along coasts and rivers. The company hopes that the combination of cooperation with both industry and NTNU will be a winning formula.

- Our autonomy solution is world-leading and can enable self-driving ferries that safely manoeuvre among other boats, dock to the quay by themselves and handle passengers safely. We are working with DNV GL, the Norwegian Coastal Administration and the Norwegian Maritime Directorate to test two prototypes in Trondheim. The unique technology has been developed at NTNU and will be made available to the company, says Susanne Jäschke, interim CEO of the company.

IMPROVING STRUCTURAL SAFETY

Dr. Zhaolong Yu is currently working as a postdoctoral research fellow at the Department of Marine Technology and NTNU AMOS. Originally from China, he obtained his PhD on "Hydrodynamic and Structural Aspects of Ship Collisions" at NTNU, with Professors Jørgen Amdahl and Marilena Greco as his supervisors.

- Many Chinese students choose to apply to study at NTNU because of the famous professors here who work within the field of marine technology. Many people recommended NTNU to me. I think professors Moan and Faltinsen in particular are pulling many students to the university, says Yu.

Yu himself applied for a position at AMOS because the project description for the PhD was similar to his master's thesis. He also knew of Jørgen Amdahl, and had met him at a conference as a master's student. Looking back, Yu is happy he chose NTNU.

- I think my time here has been well spent. The course quality has been high, and the feedback from my supervisors has been very good.

Icebergs and impact

At the moment, Yu is working on assessment of structural accidental loads. Or, as he explains, attempting to measure how much extra unexpected loads a given ship or offshore structure can handle. Loads may be ship collisions, grounding, slamming (the wave impact on the offshore structures) and ice collisions.

- I am currently working on an ice collision project with Jørgen and SamCot, where we are doing simulations and analyses on how ice impacts will affect ships and structures, says Yu.

As global warming speeds up, the melting icecaps will make more and more resources like oil and minerals available for extraction, Yu tells us. This means more activity and more risk. The melting ice will also lead to more icebergs and floating ice in more southernly waters during the summer months, which increases the chance that offshore structures and ships will be hit.

- We have delivered three reports on this to the PTIL (Petroleum Safety Authority in Norway) so far. We have quite a lot of findings here. The PTIL was very happy to receive them, and hopefully this will lead to new regulations that are more suited to this new environment, says Yu

Damage from waves

Another project is with Marilena Greco, where they look at slamming and try to combine the fields of hydrodynamics and offshore structures. The project began because of an incident in 2016 when a platform in the North Sea was impacted by a steep wave. One person was killed and three were injured. This phenomenon has attracted a lot of attention. Accidents like this have serious costs in terms of both human lives and monetary costs for the operator of the structure.

According to Yu, this is a very novel approach to the problems, as previously the people who worked on this project have primarily been working on the hydro-elastic response of structures. In this case, the focus is not only on elastic.

- We initiated an analytical solution for the hydro-plastic coupling to predict the structural damage. When the wave hits the structure, the deformation will influence the hydrodynamic force of the wave, which will again change the deformation on the structure. We developed an analytical solution and published two papers on this, thus validating our solution with simulations. This area of hydro-plastic slamming is pretty new, and nobody has considered it in a coupled way before, says Yu.

As with the ice impact project, Yu hopes that his research will help keep people and structures safe, since we can expect even rougher weather in the North in the coming years.

TAKING SNAKE ROBOTS FURTHER

Underwater snake robots are one of the great innovations that originated at AMOS, and even as the first commercial models are being tested in the Trondheim Fjord, researchers at NTNU are hard at work developing more advanced and sophisticated models and control systems.

One of those researchers is Marianna Wrzos-Kaminska, a PhD candidate at the Department of Engineering Cybernetics.

- We are developing a new method on how to control the robot in a precise and robust way, in order to make sure that external conditions like tide and current don't disturb its work, she explains.

Wrzos-Kaminska and her research group are planning to conduct experiments this summer, in which they will test how well the new upgrades does in difficult conditions. The experiment will be conducted in the Marine Cybernetics Laboratory at the Department of Marine Technology, and Wrzos-Kaminska is excited to see how well the new upgrades work.

- When we conduct simulations, we know all the numbers and parameters, but in the real world it can be harder to predict such behaviours. This experiment will help us with that, and as cybernetics engineers it is great to be able to draw on the expertise of other research fields like hydrodynamics and marine technology.

PhD was an easy choice

Wrzos-Kaminska is originally from Bærum in the south of Norway, but she took her master's at the Department of Engineering Cybernetics at NTNU, where she worked on robot snakes. As her education progressed, she realized the she wanted to learn even more about her research topics.

- The end to the classes came too quickly for me, and I wanted to keep learning. I also had a summer job in the Norwegian Defence Research Institute, where I had been allowed to work on problems and try to figure out how to solve them on my own. This really suited me, says Wrzos-Kaminska.

She also tells us that the work done by Kristin Y. Pettersen was important in her choice to go for a PhD.

- I knew that I wanted to do a PhD quite early in the master's studies, and right before we were supposed to choose our master's project I read an interview with and about Kristin in Teknisk Ukeblad. The interview helped inspire me to choose to work on snake robots.

- It really helps to have somebody who has already walked the road you want to take, and that you can look up to. There aren't that many women who work in my field, and Kristin is a great role model, says Wrzos-Kaminska.

The robot for the future

Advanced snake robots are meant to make underwater operations more efficient and safer. The goal is to remove humans from the loop as much as possible, since underwater operations can be both difficult and dangerous. Wrzos-Kaminska also hopes that more efficient operations will lead to a better utilization of resources.

The advantages to using snake robots are many. Wrzos-Kaminska tells us that robots are more manoeuverable than traditional ROVs, they can move like snakes and get into small spaces and they are also equipped with thrusters, which makes them fast if needed.

- Right now, the big market for these robots is in the oil and gas sector, but looking ahead, I think there is a large potential in the maintenance of ocean-based wind energy, as well as several other areas. Exploration and archaeology are two, while the maintenance of fish farms is another, she says.

FINDING THE RIGHT PATH

Have you ever wondered how autonomous drones are supposed to find their way home?

Unlike pigeons, arguably the first "drones" used by humans, drones do not have any instinct telling them where to go. Existing drones are often controlled directly by humans, but autonomous solutions could drastically reduce costs and improve efficiency.

This is what PhD candidate Siri Gulaker Mathisen works on, drone pathfinding and guidance, as well as autonomous aerial recovery. In simple terms: How can we get the drone and its cargo from point A to point B in the most efficient way, with as little human interaction as possible?

Getting down is the hardest part

Helicopter drones are perhaps the image of a drone that is foremost in people's minds when they think about drones. They are also the drone-type most suited to precision manoeuvres, but they are not made for long-distance trips, rough weather, or to carry heavy loads. To accomplish this, you need fixed-wing drones that are faster and can carry more. However, fixed-wing drones come with their own problems, as they are often dependent on a long landing strip, something which is not always available.

Enter autonomous aerial recovery systems, which make it possible to land drones and cargo, even in difficult conditions.

- Autonomous aerial recovery can mean the recovery of an object that the drone is carrying, or the drone itself. I am working on two distinct methods for this. The first is precision drops. The idea is pretty basic, as we calculate how air resistance, speed, height and wind will affect the object that we want to deliver. We have already proved that this method can work during tests at Brekken in Røros. This is one of the great things about NTNU AMOS; we can prove that something works under certain conditions, and then we, or others, can later develop the method and technology to the point where it works under almost any conditions.

- The second method is deep stall landing. Here, we minimize the speed to the point where the drone starts to drop. The idea is that the drone will drop with low speed at a relatively steep angle. If we time it correctly, we will hit the target and land the drone, says Mathisen

Wide range of application

Drones can be used for surveillance, aerial mapping, military purposes and the delivery of goods. Mathisen is particularly interested in their application in search and rescue work.

- Right now, I am working on ways to deliver emergency aid and supplies to areas that are difficult to reach by conventional means, all under the search and rescue umbrella. But autonomous drones are also relevant for other things such as mapping. They are able to bring sensors and map anything from biological phenomenon to ice. This is very relevant today, where we see that nature and climate change, and we need data to fully understand those changes. This data is often found in places difficult to reach, but an UAV can reach it much more effectively than a human can, she says.

Mathisen is nearing the end of her PhD project, and when this annual report is published, she will have moved on to a new position at SINTEF, something she is very much looking forward to.

- The PhD period has been extremely gratifying, but I am happy that I am close to the finish line, as five years can be a long time to work on the same project. It will be interesting to conduct research outside of academia. That said, it has been nice to be able to really dig into a topic, not to mention being a part of the UAV lab, which is a wonderful research environment with immense knowledge of UAVs.

APPENDICES

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

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 adjuct associate professors

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Adj. Prof. Berge, Jørgen	UiT, The Artic University of Norway	Marine biology	JB
Adj. Prof. Fredheim, Arne	SINTEF Ocean	Fisheries and aquaculture	AF
Adj. Prof. Kruusmaa, Maarja	Talin University of Technology	Marine robotics	MK
Adj. Prof. Lugni, Claudio	CNR - 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, DEPARTMENT	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, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Dr Ommani, Babak	SINTEF Ocean	Numerical modelling for nonlinear stochastic processes	BO
Dr Leira, Fredrik S.	NTNU, Dept. of Cybernetics	Multiple Object Detection and Tracking with fixed wing UAVs	FSL
Dr Zhaolong, Yu	NTNU, Dept. of Marine Technology	Marine Structures	UZ
Dr Brodtkorb, Astrid H.	NTNU, Dept. of Marine Technology	Control architecture for autonomous ships	AHB
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.Fragoso, Moreira Glaucia	NTNU, Dept. of Biology	Marine primary production: Bio-diversity, bio-geography, enabling technology for marine ecology	GF
Dr.Ødegård, Øyvind	NTNU, Dept. of Marine Technology	Use of underwater robots and sensors in marine archaeology, including the integration of autonomy in scientific knowledge production	ØØ
Dr. Colicchio, Giuseppina	CNR - INM	Mesh generation and analysis for acomputational fluid mechanics	GC
Dr Bryne, Torleif H	NTNU, Dept. Engineering Cybernetics	Multi-stage nonlinear state estimation	THB
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. Helgesen, Håkon Hagen	NTNU, Dept. Engineering Cybernetics	Autonomous ships	HHH
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
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

NAME	INSTITUTION, DEPARTMENT	MAIN FIELD OF RESEARCH	ACRONYM
Dr Wenz, Andreas Wolfgang	NTNU, Dept. Engineering Cybernetics	Flight performance, optimization and fault tolerance with hybrid power and propulsion	AW
Dr. Thieme, Christoph Alexander	NTNU, Dept. of Marine Technology	Online risk modelling for autonomous systems	CAT
Dr. Birkeland, Roger	NTNU, Dept. of Electronic Systems	Mission-oriented autonomous systems – with small satellites for maritime sensing, surveillance and communication	RB
Dr. Fossum, Trygve	NTNU, Dept. of Marine Technology	Intelligent autonomy, data-driven sampling, and planning for marine robotics.	TF
Dr. Eriksen, Bjørn-Olav Holtung	NTNU, Dept. Engineering Cybernetics	Robustifying control and collision avoidance systems for autonomous ferries	TOF
Dr. Jain, Ravinder Praveen Kumar	NTNU, Dept. Engineering Cybernetics	Machine learning methods for adaptive sampling and control	PRJ
Dr.Wilthil, Erik F.	NTNU, Dept. Engineering Cybernetics	Situational awareness for autonomous urban ferries	EW
Dr. Ren, Zhengru	NTNU, Dept. of Marine Technology	Control methods for more efficient offshore wind installation	ZR
Dr. Zolich, Artur Piotr	NTNU, Dept. Engineering Cybernetics	Coordination of unmanned vehicles in marine environment	APZ

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. Alver, Morten Omholt	NTNU, Dept. Engineering Cybernetics	Automation in fisheries and aquaculture	MOA
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
Ass.Prof. Brodtkorb, Astrid Helene	NTNU, Dept.Marine Technology	Marine Cybernetics	AB
Adj.Prof. Bryne, Torleiv Håland	NTNU, Dept. Engineering Cybernetics	Navigation systems	THB
Ass. Prof. Bye, Robin T.	NTNU, Dept.Of ICT and Natural Sciences	Cyber-physical systems and AI	RTB
Ass. Prof. Eide, Egil	NTNU, Department of Electronic Systems	Navigation of autonomous ships	EE
Ass. Prof. Føre, Martin	NTNU, Dept.Engineering Cybernetics	Fisheries and aquaculture	MF
Prof. Gao, Zhen	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	ZG
Prof. Imsland, Lars	NTNU, Dept.Engineering Cybernetics	Automatic control, optimization	LI
Prof. Kristiansen, Trygve	NTNU, Dept.Marine Technology	Marine hydrodynamics	TK

NAME	INSTITUTION	MAIN FIELD OF RESEARCH	ACRONYM
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
Prof. Zhang, Houxiang	NTNU, Dept. of Ocean Operations and Civil Engineering	Robotics and Cybernetics	HZ
Prof. Petrovic, Slobodan	NTNU, Dept. of Information Security and Com.Techonolgy	Information Security	SP
Prof. Gravdahl, Jan Tommy	NTNU, Dept.Engineering Cybernetics	Control Engineering	JTG

Technical staff, directly funded by NTNU AMOS

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

Visiting researchers

NAME	INSTITUTION	MAIN FIELD OF RESEARCH	ACRONYM
Fiskin, Remzi	Turkey, Izmir	Autonomous systems	RF
Arcak, Murat	Univ. Of california, Berkeley, USA	Cooperative control design	MA
Colicchio, Giuseppina	CNR - INM	Mesh generation and analysis for acomputational fluid mechanics	GC

Phd candidates with financial 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
Basso, Erlend, Andreas	KYP	Motion Planning and Control of Articulated Intervention-AUVs
Borlaug, Ida-Louise	KYP	Robust control of articulated intervention AUV
Bore, Pål Tokle	JAM	Structural design of reliable offshore aquaculture structures
Cisek ,Krzysztof	TAJ	Multi-body unmannes aerial systems
Dirdal, Johan	TIF	Sea-State and Ship Response Estimation
Fortuna, Joao	TIF	Processing and analysis of Hyperspectral Images from unmanned systems
Fossum, Trygve	ML	Artificial intelligence for AUVs
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
Henriksen, Marie Bøe	TAJ	Hyperspectral imaging in drones and small satellites
Kaminska-Wrzos, Marianna	KYP	Free-floating intervention operations using AIAUVs
Kristiansen, Bjørn Andreas	JTG	Energy optimality for spacecraft attitude manoeuvres
Langer, Dennis D.	AJS	Hierarchical Control of Heterogenous Robotic Systems from Satellites.
Løvås, Håvard Snefjellå	AJS	Classification and Detection of Microorganism Including Plastics in the Oceans Using Optical Methods
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
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)
Ramos, Nathalie	KJ	4D printing of intelligent marine structures
Sauder, Thomas	AJS	real-time hybrid testing of floating systems.
Schmidt-Didlaukies Henrik	AJS	Modeling and Control of Hyper-Redundant Underwater Manipulators
Siddiqui, Mohd Atif	MG	Behaviour of a damged ship in waves
Slagstad, Martin	JAM	Advanced and rational analysis of steel fish farms in exposed waters
Smilden, Emil	AJS	Reduction of loads,fatigue and structural damage on an offshore wind turbine
Sørum, Stian Høegh	JAM	Offshore Wind Turbines
Tengesdal, Trym	TAJ	Risk-based COLREGS compliant collision avoidance for autonomous ships
Vilsen, Stefan A.	AJS	Hybrid Model Testing of Marine Systems
Værnø, Sven Are Tutturen	RS	Topics in motion control of offshore vessels
Wiig, Martin Syre	KYP	Reactive collision avoidance and guidance for underactuated marine vehicles
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
Amro, Ahmed W.	SK	Communication and cybersecurity for autonomous passenger ferry
Ahani, Alireza	MG	Local structural response due to wave slamming
Andrade, Fabio	RST	Sea ice drift tracking using real time UAV path planning for maritime situational awareness
Bitar, Glenn Ivan	MB	Energy-optimal and autonomous control for car ferries
Berget, Gunhild	TAJ	Intelligent monitoring of drilling operations in sensitive environments
Bjørne, Elias	TAJ	Nonlinear observer theory for simultaneous localization and mapping
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
Borri, Daniele	MG	Hydrodynamics of oil spills from oil tankers
Bremnes, Jens Einar	AJS	Risk-based planning and control of AUVs
Bøhn, Eivind	TAJ	Machine learning in control and estimation
Guo, Chuanqui	SH	Risk analysis and management for autonomous passenger ferry
Cho, Seong-Pil	TM/ZG	Dynamic modelling and analysis of floating wind turbines with emphasis on the behavior in fault conditions
Coates, Erlend Magnus Lervik	TIF	Nonlinear Autopilot Design for Operation of UAVs in Extreme Conditions
Dahl, Andreas Reason	RS	Nonlinear and fault-tolerant control of electric power production in Artic DP vessels
Rodin, Christopher D.	TAJ	Intelligent data acquistion in maritime UAS
Diaz, Gara Quintana	TE	Small satellite system communication
Eriksen, Bjørn-Olav H.	MBR	Collision avoidance for autonomus surface vehicles
Faltynkova, Andrea	GJ	Detection of microplast using new optical tools
Flåten, Andreas L.	EB	Multisensor tracking for collision avoidance
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
Hassan, Waseem	MF	Real-time acoustic telemetry for fish behaviour monitoring in aquaculture
Hatleskog, Johan	TAJ	Autonomous Industrial Inspection in a Contextualized Environment
Haugo, Simen	AST	Computer vision methods for assisted teleoperation of unmanned air vehicles
Helgesen, Øystein Kaarstad	EB	Sensor fusion for autonomous ferry
Helgesen, Håkon Hagen	TAJ	UAV scouting system for autonomous ships
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
Johansen, Thomas	IU	Risk Modeling for Supervisory Risk Control
Jónsdóttir, Kristbjörg Edda	JAA	Dynamics of waterflow and turbulence in large-scale aquaculture sea cages
Kaasa, Tord Hansen	JAM	Aluminium Ship Design with Extruded Panels
Katsikogiannis, George	EB	Loads and Responses of Large-Diameter Monopile Wind Turbines
Leonardi, Marco	AS	Visual odometry and servoing for 3D reconstruction
Li, Qinyuan	TM	Long-term extreme response prediction for offshore wind turbines
Livermor-Honoé, Evelyn	EE	Rapid systems engineering
Martinsen, Andreas Bell	AL	Reinforcement learning methods for guidance, navigation and control
Mathisen, Siri Holthe	TAJ	Embedded Optimization for Autonomous Unmanned Aerial Vehicle Mission Planning and Guidance

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

ANNUAL ACCOUNTS AND MAN-YEAR EFFORTS

Annual accounts

OPERATING INCOME	ACCOUNTES INCOME AND COSTS
The research council of Norway	17,536
NTNU	25,911
Others	6,400
in kind	11,976
Sum operating income	**61,823**

OPERATING INCOME	ACCOUNTES INCOME AND COSTS
Salary and social costs	39,019
Equipment investments	3,966
Procurement of R&D servises	441
Other operating costs	4,685
in kind	11,976
Sum operating costs	**60,087**

Year end allocation	1,736

Opening balance 20190101	6,382
Closing balance 20191231	8,118

Total man-years efforts

MAN-YEARS	2019
Centre director	0.30
Co-director	0.20
Adm.personnel	1.40
Technical staff	1.10
Summary	**3.00**

Key professor	3.50
Adjunct prof/ass.prof	3.10
Affiliated prof/scientists	6.50
Scientific advisor	0.50
Postdocs	5.42
Postdoc (affiliated)	11.37
Visiting researchers	0.25
PhD candidates	14.04
PhD candidates (affiliated)	45.8
Total research man-years	**93.48**

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

NATIONALITY	KEY PROFESSOR	ADJUNCT PROF/ ASS PROF	AFFILIATED SCIENTIST	SCIENTIFIC ADVISOR	POSTDOC/ AFFILIATED POSTDOC	VISITING PROFESSOR/ RESEARCHER	PhD	Assc PhD	ADMINISTRA-TIVE STAFF*)	SUM
Norwegian	6	7	21	2	16	-	22	38	5	
Other nationalities	1	9	9	-	14	3	10	31	-	
Sum	**7**	**16**	**30**	**2**	**30**	**-**	**32**	**69**	**5**	**-**
Man-years	3.50	3.10	6.50	0.50	16.79	0.25	14.04	45.80	2.00	92.48

PhD degrees 2019

Supervised by Key Scientists at AMOS

NAME	DATE	TOPIC	SUPERVISOR	YEAR
Helgesen, Håkon Hagen	December 13	Detection and Tracking of Floating Objects using UAVs with Optical Sensors	TAJ	2019
Rodin, Christopher Dahlin	December 4	Applications of High-Precision Optimal Systems for Small Unmanned Aerial Systems in Maritime Environments	TAJ	2019
Bjørne, Elias	December 6	Globally Stable Observers for Simultaneous Localization and Mapping	TAJ	2019
Smilden, Emil	November 22	Structural Control of Offshore Wind Turbines – Increasing the role of control design in offshore wind farm development	AJS	2019
Ren, Zhengru	August 21	Advanced Control Algorithms to Support Automated Offshore Wind Turbine Installation	AJS	2019
Hanssen, Finn-Christian Wickmann	June 7	Non-Linear Wave-Body Interaction in Severe Waves	MG	2019
Vilsen, Stefan Arenfeldt	May 25	Method for Real-Time Hybrid Model Testing of Ocean Structures – Case study on Slender Marine Systems	AJS	2019
Wiig, Marting Syre	April 8	Collision Avoidance and Path Following for Underactuated Marine Vehicles	KYP	2019
Olofsson, Harald Lennart Jonatan	January 10	Multi-UAS Sea Ice Monitoring	TIF	2019

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

NAME	DATE	TOPIC	SUPERVISOR	YEAR
Zhao, Yuna	June 26	Numerical Modelling and Dynamic Analysis of Offshore Wind Turbine Blade Installation	TM	2019
Ghamari, Isar	February 2	Numerical and Experimental Study on the Ship Parametric Roll Resonance and Effect of Anti-Roll Tank	OF	2019
He, Zhao	January 31	Hydrodynamic study of a moored fish farming cage with fish influence	OF	2019

Supervised by Affiliated Scientists at AMOS

NAME	DATE	TOPIC	SUPERVISOR	YEAR
Andrade, Fabio	November 29	Real-time and offline path-planning of Unmanned Aerial Vehicles for maritime and coastal applications	RS	2019
Werma, Amrit Shankar	November 25	Modelling, Analysis and Response-Based Operability Assessment of Offshore Wind Turbine Blade Installation with Emphasis on Impact Damages “	ZG	2019
Wilthil, Erik Falmår	October 2019	Maritime target tracking with varying sensor performance	EB	2019
Eiksen, Bjørn-Olav Holtung	August 30	Collision avoidance and motion control for autonomous surface vehicles	MBR	2019
Macías, Juan Alberto Ramírez	August 19	Dynamics and motion control of underwatyer remotely operated vehicles and highly flexible rods	RV	2019
Fossum, Trygve Olav	Juni 2019	Adaptive Sampling for Marine Robotics	ML	2019
Heyn, Hans-Martin	May 15	Motion sensing on vessels operating in sea ice: A local monitoring system for transit and stationkeeping operations under the influence of sea ice	RS	2019

PUBLICATIONS

Journals

Abdollahpouri, Mohammad; Batista, Gabriel; takacs, gergely; Johansen, Tor Arne; Rohal-Ilkiv, Boris.
Adaptive vibration attenuation with globally convergent parameter estimation. Mechanical systems and signal processing 2019 ;Volume 114. pp.512-527

Abdollahpouri, Mohammad; Quirynen, Rien; Haring, Mark; Johansen, Tor Arne; Takacs, Gergely; Diehl, Moritz; Rohal-Ilkiv, Boris.
A homotopy-based moving horizon estimation. International Journal of Control 2019 ;Volume 92.(7) pp.1672-1681

Andersson, Leif Erik; Imsland, Lars Struen; Brekke, Edmund Førland; Scibilia, Francesco.
On Kalman filtering with linear state equality constraints. Automatica 2019 ;Volume 101. pp.467-470

Andersson, Leif Erik; Scibilia, Francesco; Imsland, Lars Struen.
An iceberg forecast approach based on a statistical ocean current model. Cold Regions Science and Technology 2019 ;Volume 158. pp.128-142

Andrade, Fabio; Hovenburg, Anthony Reinier; de Lima, L. N.; Rodin, Christopher D; Johansen, Tor Arne; Storvold, Rune; Correia, Carlos; Haddad, Diego.
Autonomous Unmanned Aerial Vehicles in Search and Rescue Missions Using Real-Time Cooperative Model Predictive Control. Sensors 2019

Andrade, F. A. A.; A. R. Hovenburg; L. N. de Lima; C. D. Rodin; T. A. Johansen; R. Storvold; C. A. M. Correia; D. B. Haddad,
Autonomous Unmanned Aerial Vehicles in Search and Rescue missions using real-time cooperative Model Predictive Control, Sensors, Vol. 19, 4067, 2019;

Antuono, M; Valenza, S; Lugni, Claudio; Colicchio, Giuseppina.
Validation of a three-dimensional depth-semi-averaged model. Physics of Fluids 2019 ;Volume 31.(2) pp.1-17

Bachynski, Erin Elizabeth; Eliassen, Lene.
The effects of coherent structures on the global response of floating offshore wind turbines. *Wind Energy* 2019 ;Volume 22.(2) s. 219-238

Belleter, Dennis Johannes Wouter; Braga, Jose; Pettersen, Kristin Ytterstad.
Experimental Verification of a Coordinated Path-Following Strategy for Underactuated Marine Vehicles. Frontiers in Robotics and AI 2019 ;Volume May.

Belleter, Dennis Johannes Wouter, Mohamed Maghenem, Claudio Paliotta and Kristin Y. Pettersen,
"Observer Based Path Following for Underactuated Marine Vessels in the Presence of Ocean Currents: A Global Approach", Automatica, Vol. 100, Feb. 2019, pp. 123-134.

Berget, Gunhild Elisabeth; Eidsvik, Jo; Alver, Morten; Py, Frédéric; Grøtli, Esten Ingar; Johansen, Tor Arne.
Adaptive Underwater Robotic Sampling of Dispersal Dynamics in the Coastal Ocean. Springer Tracts in Advanced Robotics 2019

Binder, Benjamin Julian Tømte; Johansen, Tor Arne; Imsland, Lars Struen.
Improved predictions from measured disturbances in linear model predictive control. Journal of Process Control 2019 pp.86-106 NTNU

Bjørne, Elias; Brekke, Edmund Førland; Bryne, Torleiv Håland; Delaune, Jeff; Johansen, Tor Arne.
Globally Stable Velocity Estimation Using Normalized Velocity Measurement. The international journal of robotics research 2019

Bore, Pål Takle; Amdahl, Jørgen; Kristiansen, David.
Statistical modelling of extreme ocean current velocity profiles. Ocean Engineering 2019 ;Volume 186:106055. p. 1-22

Borup, Kasper Trolle; Fossen, Thor I.; Johansen, Tor Arne.
A Machine Learning Approach for Estimating Air Data Parameters. IEEE Transactions on Aerospace and Electronic Systems 2019

Borup, Kasper Trolle; Stovner, Bård Nagy; Fossen, Thor I.; Johansen, Tor Arne.
Kalman Filters for Air Data System Bias Correction for a Fixed-Wing UAV. IEEE Transactions on Control Systems Technology 2019

Brekke, Edmund Førland; Wilthil, Erik Falmår; Eriksen, Bjørn-Olav Holtung; Kufoalor, D. Kwame Minde; Helgesen, Øystein Kaarstad; Hagen, Inger Berge; Breivik, Morten; Johansen, Tor Arne.
The Autosea project: Developing closed-loop target tracking and collision avoidance systems. Journal of Physics: Conference Series 2019 ;Volume 1357.(1)

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 2019 ;Volume 141.(1)

Cheng, Zhengshun; Svangstu, Erik; Gao, Zhen; Moan, Torgeir.
Field Measurements of Inhomogeneous Wave Conditions in Bjørnafjorden. Journal of waterway, port, coastal, and ocean engineering 2019; Volume 145.(1)

Cheng, Zhengshun; Svangstu, Erik; Moan, Torgeir; Gao, Zhen.
Long-term joint distribution of environmental conditions in a Norwegian fjord for design of floating bridges. Ocean Engineering. 2019

Dahlin Rodin, Christopher; de Alcantara Andrade, Fabio Augusto; Hovenburg, Anthony Reinier; Johansen, Tor Arne.
A survey of practical design considerations of optical imaging stabilization systems for small unmanned aerial systems. Sensors 2019 ;Volume 19:4800.(21) pp.1-20

Dumke Ines, Ludvigsen Martin, Ellefmo Steinar, Søreide Fredrik, Johnsen Geir, Murton BJ.
Underwater hyperspectral imaging using a stationary platform in the Trans-Atlantic geotraverse hydrothermal field. Transactions on Geoscience Remote Sens, IEEE. DOI: 10.1109/TGRS.2018.2878923. 2019 57:2947-2962.

Eriksen, Bjørn-Olav Holtung; Breivik, Morten; Wilthil, Erik Falmår; Flåten, Andreas Lindahl; Brekke, Edmund Førland.
The branching-course model predictive control algorithm for maritime collision avoidance. Journal of Field Robotics 2019 ;Volume 36.(7) pp.1222- 1249

Faltinsen, Odd Magnus; Timokha, Alexander.
An inviscid analysis of the Prandtl azimuthal mass transport during swirl-type sloshing. Journal of Fluid Mechanics 2019 ;Volume 865. pp.884-903

Ferreira, A. S.; M. Costa, F. Py, J. Pinto, M. A. Silva, A. N. Smith, T. A. Johansen, J. Sousa, K. Rajan,
Advancing Multi-Vehicle Deployments in Oceanographic Field Experiments, Autonomous Robots, Vol. 43, pp. 1555–1574, 2019;

Fossum, Trygve Olav; Fragoso, Glaucia Moreira; Davies, Emlyn John; Ullgren, Jenny; Mendes, Renato; Johnsen, Geir; Ellingsen, Ingrid H.; Eidsvik, Jo; Ludvigsen, Martin; Rajan, Kanna.
Toward adaptive robotic sampling of phytoplankton in the coastal ocean. Science robotics 2019 ;Volume 4.(27)

Fossum, Trygve Olav; Ryan, John; Mukerji, Tapan; Eidsvik, Jo; Maughan, Thom; Ludvigsen, Martin; Rajan, Kanna.
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