NTNU
Centre for Autonomos Marine
Operations and Systems

# NTNU AMOS
## Centre for Autonomous Marine Operations and Systems

Annual Report 2021

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: Live Oftedahl and Asgeir J. Sørensen

# CONTENTS

# DIRECTOR'S REPORT

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

- Global challenges related to global warming, degrading ecosystems and loss of biodiversity, natural disasters, de-oxygenation of the oceans, lack of energy, food, water and minerals.
- Value creation in terms of oil and gas exploration, maritime transport, fisheries, aquaculture, offshore renewable energy, marine minerals, tourism, coastal infrastructure and urbanization.
- Governance and knowledge-based management of the oceans and coastal areas.

As we state it at NTNU AMOS: ***Sustainable economy is equal to good ecology.***

The targeted research areas at NTNU AMOS are well aligned with national and international strategies insofar as meeting the transformations for environmental sustainability, economic sustainability and social sustainability. 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.

NTNU AMOS has two research areas: Autonomous vehicles and robotic systems, and Safer, smarter and greener ships, structures and operations. The core research is 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.

The portfolio of associated projects and the launch of several new associated centres for research-based innovations (SFIs), FME and VISTA CAROS, in collaboration with national and international collaborators, enhance the societal and science impact of the research and innovation activities. The upswing through research-based education with an annual graduation of 100+ MSc and 15-20 PhDs leaves lasting traces of research originating from the NTNU AMOS research environment. The candidates leave for further careers in industry, the public sector and academia. Several of our PhDs and Postdocs have succeeded in entering into full-time professorships in Norway and abroad. I am pleased to observe that the legacy of NTNU AMOS is well entrenched.

As in the rest of society, fatigue from the pandemic in general and because of the outbreak of the COVID variants in 2021 in particular, has had increasingly negative impact on the work environment at NTNU AMOS. Nevertheless, the digital meeting arenas and remote offices have made it possible to maintain a high activity level. We have also been able to conduct most planned experimental and field campaigns. However, with less restrictions for some months this fall on social distancing, it has clearly been demonstrated how important social interaction is to stimulate creativity and a positive work spirit. We fortunately managed to have a full AMOS Day with more than 20 speakers from the different AMOS projects, together with a preview of the blockbuster movie Nordsjøen ("The Burning Sea") in the evening. Unscheduled meetings and small discussions mean a lot for the fostering new ideas and fueling inspiration into the organization. Hopefully, we will soon see an end to the pandemic.

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

It is with pride that I acknowledge that AMOS researcher groups are being recognized for their excellent research, innovation and outreach achievements.

Two prominent role models are Professors Kristin Y. Pettersen and Marilena Greco.

Kristin Y. Pettersen currently has several pronounced trusted positions in the IEEE, IFAC and EUCA. She is also a Distinguished Lecturer of the IEEE Control Systems Society. She is the 2021 recipient of the triennial NTNU Award for Outstanding Research and Artistic Activities, and was also awarded the European Research Council (ERC) Advanced Grant in 2021. A unique outreach coming from Kristin´s research group, in cooperation with the spin-off company Eelume, was the Norwegian movie Nordsjøen. Here, the snake robot is the hero.

From 1st April 2021 to 31st March 2022, Marilena Greco is covering the position as a Specially Appointed Professor (honorary position) at the Division of Global Architecture, Graduate School of Engineering, of Osaka University, Japan. This type of position targets researchers/scientists with advanced specialized knowledge or with considerable experience in a specific field to join the host university for a certain period, and perform research and/or provide a series of lectures. In this case, her expertise in marine hydrodynamics has been valued. It is also an opportunity to enlarge the footprint of female scientists in Osaka University's engineering academia, and to provide an international female-role model to the next generation of engineers. Unluckily, due to the COVID pandemic, a physical stay at Osaka University was not possible.

I will also highlight the publication of the second edition of a popular textbook that addresses guidance, navigation and the control of marine craft. In 2021, the publisher John Wiley & Sons


*Asgeir J. Sørensen with NTNU rector Anne Borg during an event at AUR-Lab in October 2021.*

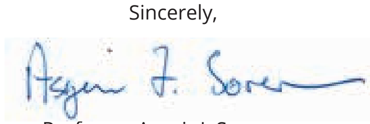
Ltd. released the Handbook of Marine Craft Hydrodynamics and Motion Control, authored by Professor Thor I. Fossen. The new edition includes autonomous vehicles, such as unmanned surface vehicles (USVs) and autonomous underwater vehicles (AUVs), in addition to ships and semisubmersibles. Hardly anyone has left such a huge academic footprint in marine craft guidance, navigation and control systems, and set such standards for vessel management as Thor.

Another great achievement was by Affiliated Professor Kostas Alexis when Team Cerberus won a highly prestigious international competition, the DARPA Subterranean Challenge, with their subterranean robots competing against top-ranked challengers. Finally, the year 2022 started with the historical launch of the Norwegian small satellite – HYPSO 1. HYPSO-1's mission is to observe plankton and algal blooms in ocean and lakes. Key people in this work are Professor Tor Arne Johansen, Professor Jan Tommy Gravdahl, Associate Professor Milica Orlandic, Evelyn Honoré-Livermore and Dr. Roger Birkeland, followed by several PhD candidates, MSc and BSc students.

In 2021, the eighth AMOS spin-off company, SentiSystems, was founded. SentiSystems offers a novel platform solution for real-time sensor data processing. SentiSystems started with sensor integration for autonomous operations, but the versatility of the platform makes it suitable for a variety of other intelligent applications, such as mapping, monitoring and surveillance systems.

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

Sincerely,



Professor Asgeir J. Sørensen
Director NTNU AMOS

# BOARD OF DIRECTORS


Photo: Asgeir J. Sørensen

The Board met twice (digital meetings) in 2021 to review progress, consider management issues and offer advice on strategic directions for the Centre.

The Board is very satisfied with the performance and activities undertaken at NTNU AMOS during 2021. We find the results very impressive considering the global lockdown and travel restrictions that has paused most physical interactions over the last year.

The Board confirms that NTNU AMOS fulfils the expectations as a Norwegian Centre of Excellence, we also acknowledge NTNU AMOS' 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.

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

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

In 2021, NTNU AMOS graduated 10 PhDs, of which 2 are female. Publication numbers include 97 papers in high-quality journals, as well as 68 conference papers, 2 books, 1 book chapter and 6 plenaries.

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The board is also pleased with the HSE performance of AMOS. There are few incidents and none 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

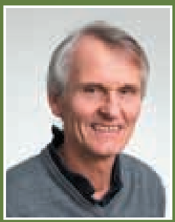
The main responsibility of the Board of Directors is to ensure that NTNU AMOS achieves its goals within the resources available, and within the research plan established by the Centre. As part of their duties, the Board members have discussed this Annual Report and endorsed it.

# 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

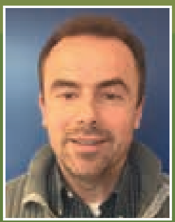

Prof.
Kristin Y. Pettersen

## Adjunct professors and adjunct associate professors


Adj. Prof.
Jørgen Berge


Adj. Prof.
Arne Fredheim


Adj. Prof.
Maarja Kruusmaa


Adj. Prof.
Claudio Lugni


Adj. Ass. Prof.
Ulrik D. Nielsen

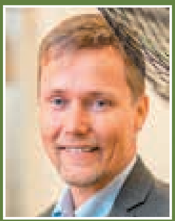

Adj. Prof.
Kjetil Skaugset


Adj. Prof.
Fred Sigernes

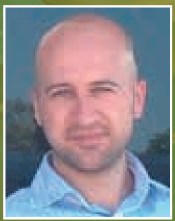

Adj. Ass. Prof.
Nadezda Sokolova


Adj. Ass. Prof.
Rune Storvold


Adj. Prof.
João Sousa


Adj. Prof.
Karl Henrik Johansson


Adj. Prof.
Kjell Larsen

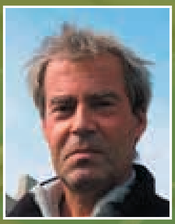

Adj. Ass. Prof.
Francesco Scibilia


Adj. Prof.
Fernando Aguado Ageleet

## Technical staff


Pedro De La Torre


Trond Innset


Pål Kvaløy

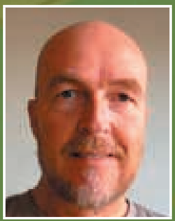

Christian Malmquist


Terje Rosten


Kay Arne Skarpnes

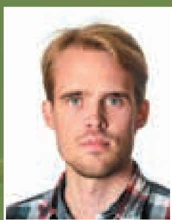

Henricus Van Rijt


Ole Erik Vinje


Frode Volden


Torgeir Wahl

## Management and administration


Sigmund Bolme


Renate Karoliussen


Knut Reklev


Live Oftedahl

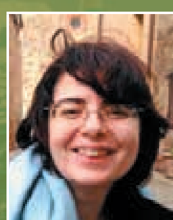
## Senior Scientific advisers


Prof. Odd M. Faltinsen


Prof. Torgeir Moan

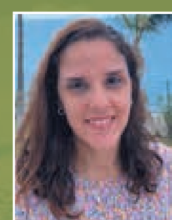
## Postdocs/researchers


Dr. Roger Birkeland


Dr. Giuseppina Colicchio

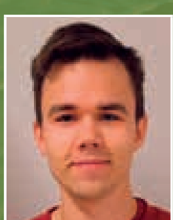

Dr. Bjørn-Olav Holtung Eriksen


Dr. Trygve Fossum


Dr. Glaucia Moreira Fragoso


Dr. Joseph Garrett


Dr. Stephen Grant

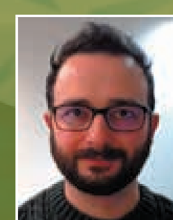

Dr. Kristoffer Gryte


Dr. Richard Hann

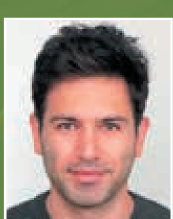

Dr. Finn-Christian W. Hanssen


Dr. Håkon Hagen Helgesen


Dr. Ravinder Praveen Kumar Jain


Dr. Alun Jones


Dr. Fredrik Stendahl Leira


Dr. Mojatba Mokhtari


Dr. Petter Norgren


Dr. Stein Melvær Nornes

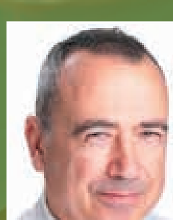

Dr. Babak Ommani

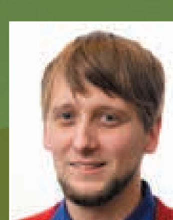

Dr. Zhengru Ren


Dr. Børge Rokseth

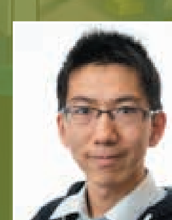

Dr. Yugao Shen


Dr. Christoph Alexander Thieme

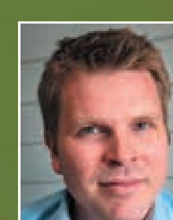

Dr. Kadir Atilla Toker


Dr. Andreas Wolfgang Wenz

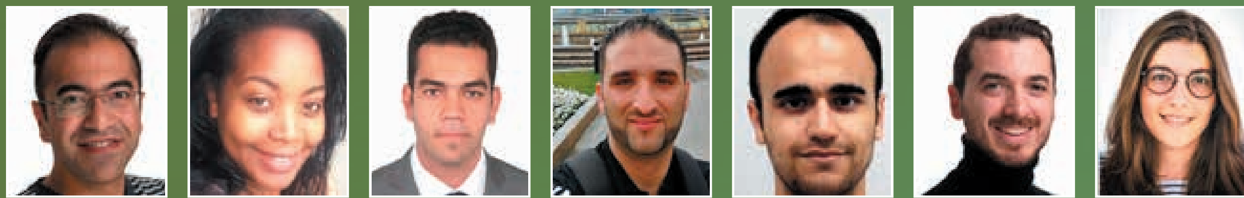

Dr. Erik F. Wilthil


Dr. Yu Zhaolong

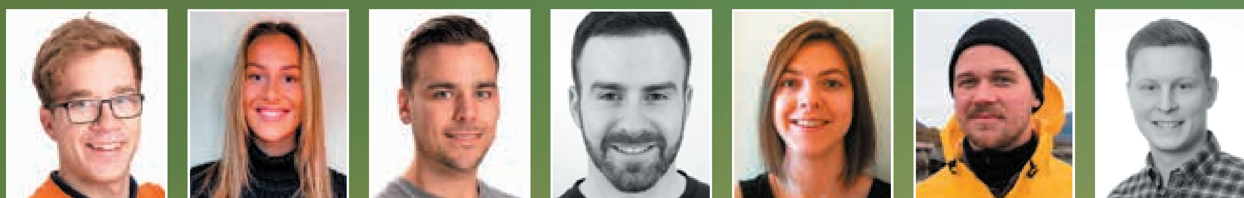

Dr. Artur Piotr Zolich


Dr. Øyvind Ødegård

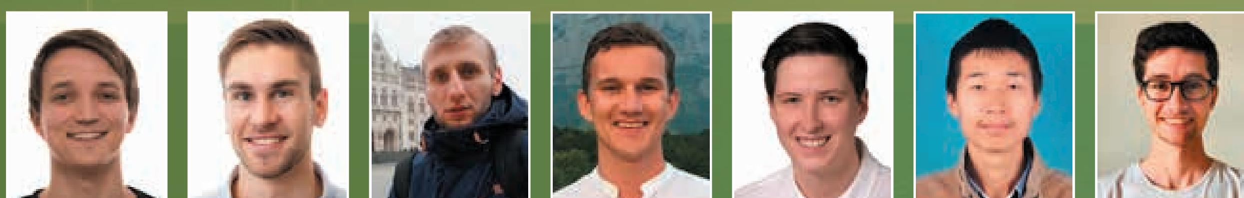
## PhD candidates



Behdad Aminian | Muram Abbadi | Serag-Eldin Abdelmoteleb | Ahmed W. Amro | Alireza Ahani | Melih Akdag | Irene Rivera Arreba

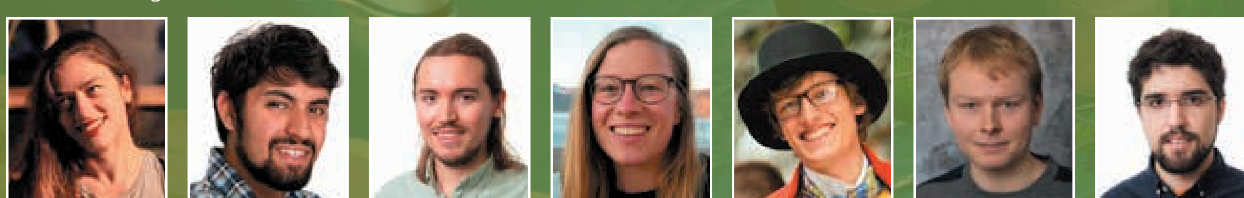


Sivert Bakken | Karoline Barstein | Erlend Andreas Basso | Glenn Ivan Bitar | Gunhild Elisabeth Berget | Tore Mo-Bjørklund | Jon Bjørnø

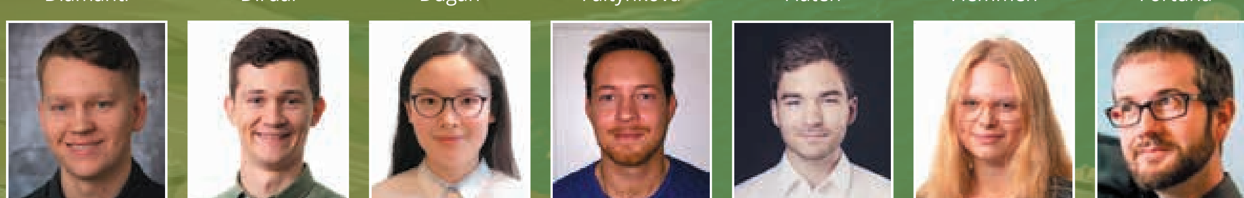


Simon Blindheim | Pål Tokle Bore | Vasileios Bosdelekidis | Jens Einar Bremnes | Eivind E. Bøhn | Chuanqui Guo | Alexandre Cardaillac

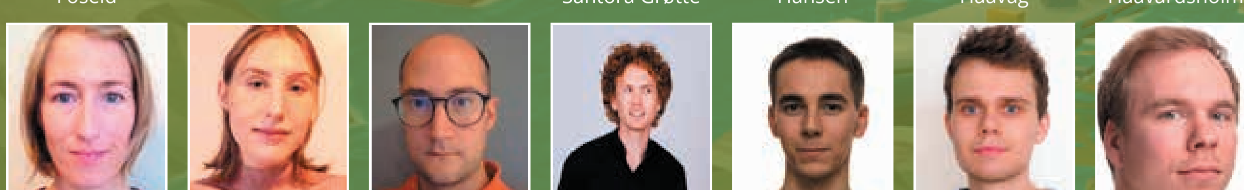
Man Ken Michael Cheung | Krzysztof Cisek | Erlend Magnus Lervik Coats | Andreas Reason Dahl | Albert Dallolio | Henrik Schmidt-Didlaukies | Gara Quintana Diaz



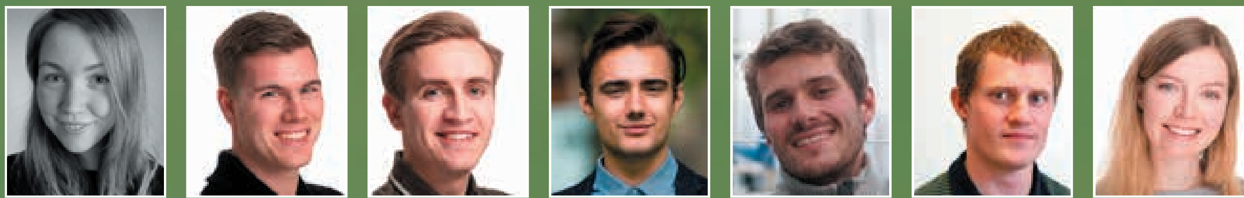
Eleni Diamanti | Johan Alexander Dirdal | Spencer August Dugan | Andrea Faltynkova | Andreas L. Flåten | Henrik Dobbe Flemmen | Joao Fortuna



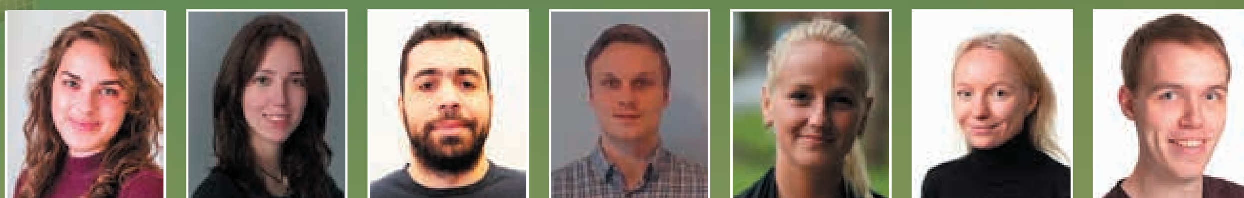
Eirik Lothe Foseid | Markus Fossdal | Fan Gao | Mariusz Eivind Santora Grøtte | Bogdan Løw Hansen | Aurora Skaare Haavag | Trym Vegard Haavardsholm



Inger Berge Hagen | Aurora Haraldsen | Oliver Kevin Hasler | Johan Hatleskog | Simen Haugo | Øystein Kaarstad Helgesen | Audun Gullikstad Hem

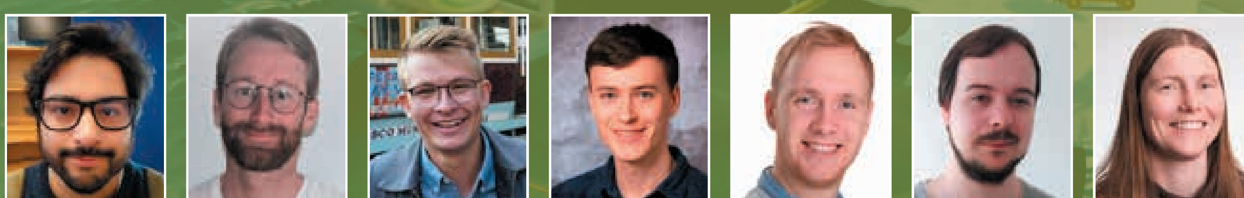


Marie Bøe Henriksen | Simon A. Hoff | Markus H. Iversflaten | Jan Henrik Jahren | Erling Rennemo Jellum | Thomas Johansen | Kristbjörg Edda Jónsdóttir

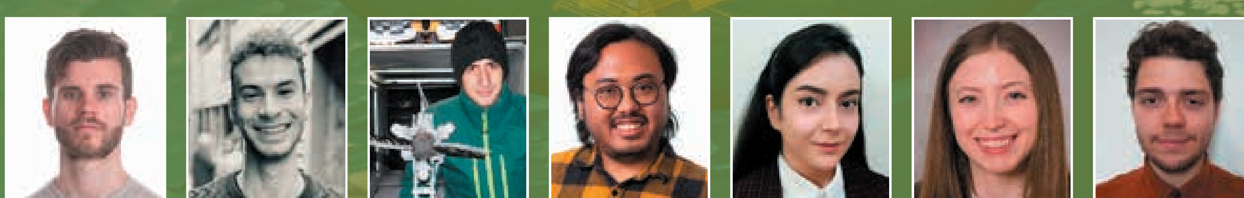


Marianna Kaminska-Wrzos | Gabriele Kasparaviciute | George Katsikogiannis | Toni Klausen | Veronica Liverud Krathe | Susanna Dybwad Kristensen | Bjørn Andreas Kristiansen

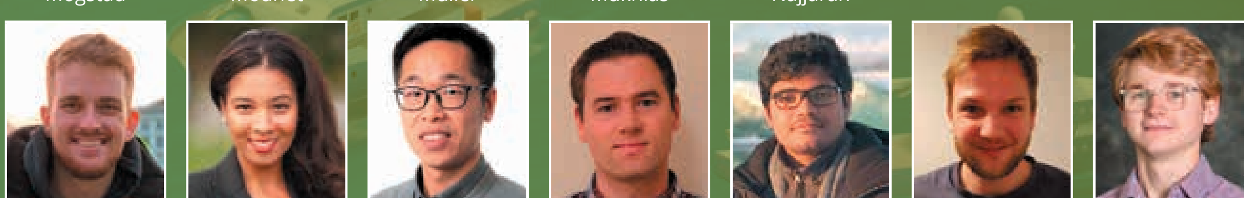
Dennis D. Langer | Martin Kvisvik Larsen | Marco Leonardi | Evelyn Livermor-Honoé | Ole Jacob Lorentzen | Håvard Snefjellå Løvås | Shaojun Ma



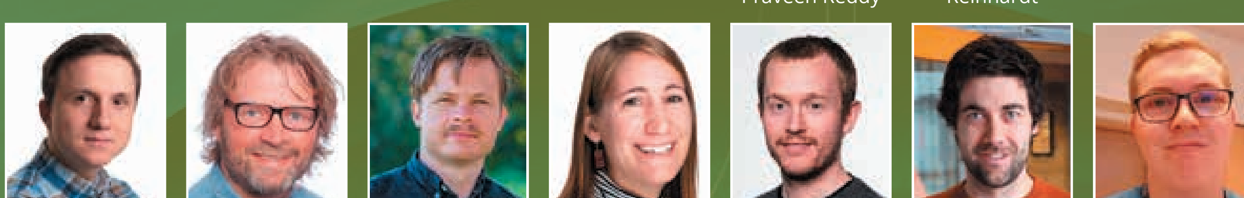
Renan Maidana | Mathias Marley | Emil Martens | Andreas Bell Martinsen | Pål Holthe Mathisen | Josef Matous | Mariann Merz



Aksel Alstad Mogstad | Raphael Mounet | Nicolas C. Müller | Muhammad Mukhlas | Samieh Najjaran | Carina Norvik | Amer Orucevic



Casper Potter | Nathalie Ramos | Xiaoming Ran | Øyvind Rabilås | Namireddy Praveen Reddy | Dirk Peter Reinhardt | Peter Rohrer

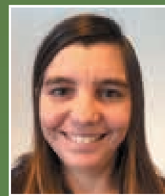


Sverre Velten Rothmund | Dag Rutledal | Simen Troye Røang | Elizabeth Frances Prentice | Robert Skulstad | Martin Slagstad | Martin Lysvand Sollie


Petter Solnør

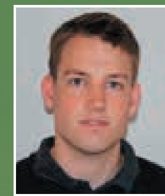

Carlos Eduardo Silva de Souza


Øystein Sture

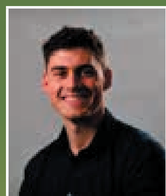

Natalie Summers


Jørgen Sverdrup-Thygeson


Eirik Svendsen


Mikkel Eske Nørgaard Sørensen


Stian Høegh Sørum


Bjørn Kåre Sæbø


Bálint Zoltán Téglasy


Emil Hjelseth Thyri

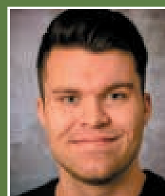

Lars-Christian Ness Tokle


Tobias Rye Torben

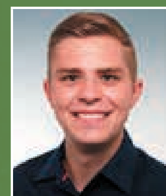

Einar S. Ueland


Anete Vagale

Kjetil Vasstein


Øystein Volden


Ambjørn Waldum


Joachim Wallisch


David Williamson


Adrian Winter


Xintong Wang

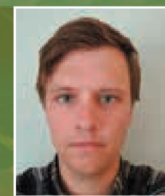

Menging Wu


Hui-Li Xu


Libo Xue


Mauhing Yip

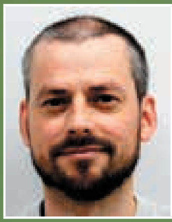

Wai Yen Chan


Henning Øvreaas

## Affiliated scientists

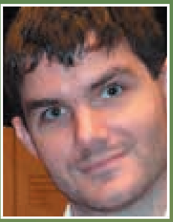

Ass. Prof. Nicole Aberle-Malzahn


Ass. Prof. Jo Arve Alfredsen


Ass. Prof. Morten Omholt Alver


Prof. Erin E. Bachynski


Ass. Prof. Morten Breivik


Ass. Prof. Edmund Brekke


Ass. Prof. Astrid Helene Brodtkorb

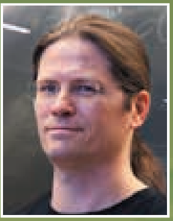

Ass Prof. Torleiv Håland Bryne


Ass. Prof. Robin T. Bye


Ass. Prof. Egil Eide


Ass. Prof. Martin Føre

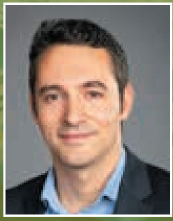

Prof. Zhen Gao


Prof. Jan Tommy Gravdahl

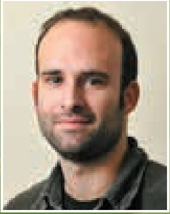

Prof. Lars S. Imsland

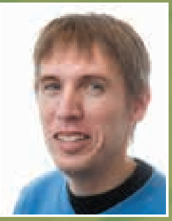

Ass. Prof. Ekaterina Kim


Prof. Trygve Kristiansen


Prof. Alexis Konstantinos


Prof. Pål Lader


Ass. Prof. Anastasios Lekkas


Prof. Martin Ludvigsen


Prof. Nguyen Trong Dong


Prof. Eilif Pedersen


Prof. Slobodan Petrovic


Prof. Yngvar Olsen

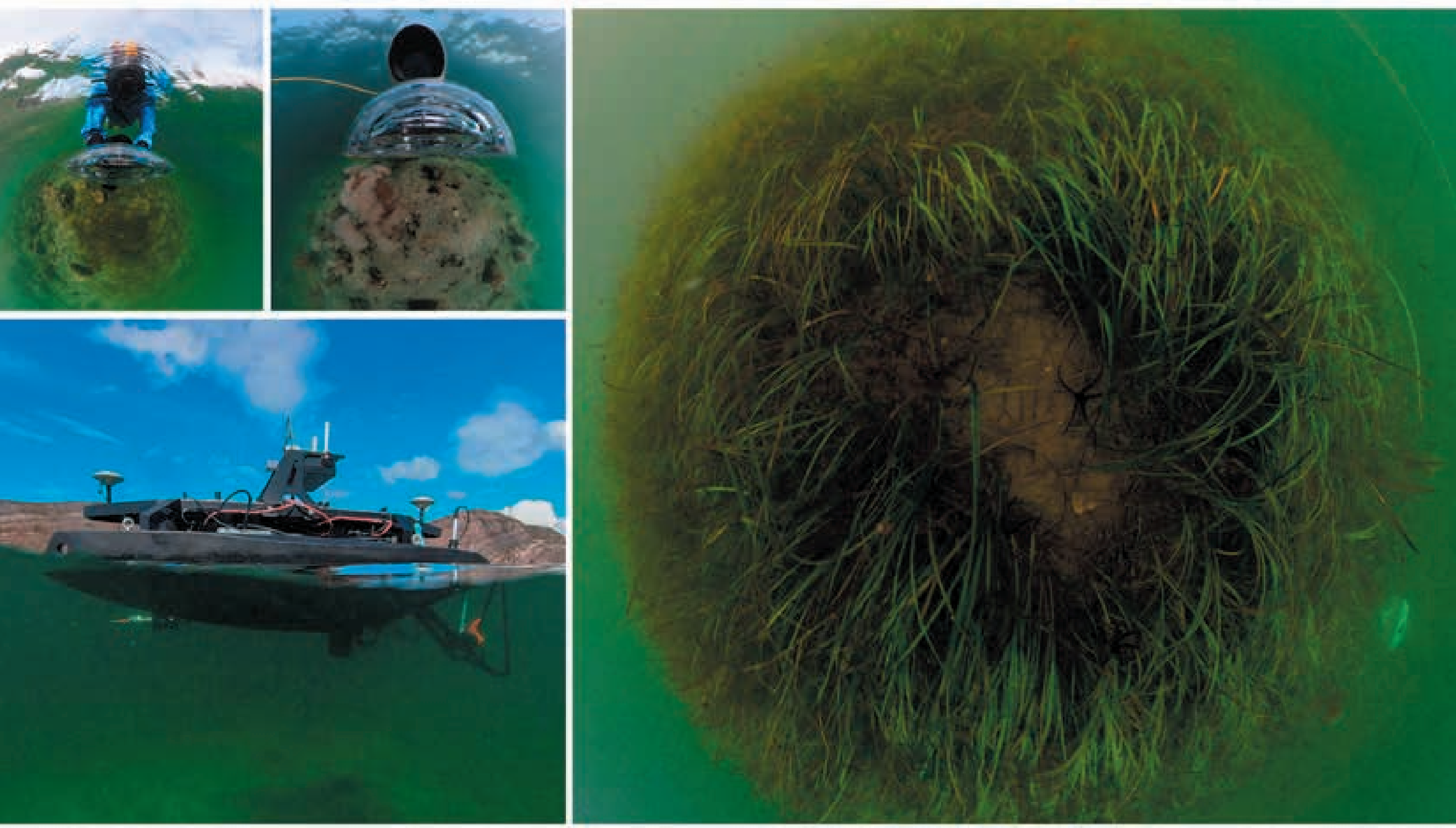

Prof. Roger Skjetne


Ass. Prof. Annette Stahl


Prof. Oleksandr Tymokha


Prof. Ingrid B. Utne


Prof. Houxiang Zhang



**Picture with 360-degree camera in Hopavågen, May 2021:** *Upper left: Human operated imaging/sampling in sea grass dominated habitat. Upper middle: Mini-ROV based imaging of habitats with anemones and brittle stars. Lower left: Unmanned Surface Vehicle (USV) as an instrument carrier for Underwater Hyperspectral Imager to identify, map and monitor organisms in a shallow habitat. Right image (large): 360 degree view of seagrass habitat. Mini ROV mapping the habitat to the right part of image.*

© Geir Johnsen

*Unmanned surface vehicle with underwater hyperspectral imager for the mapping of shallow habitats. This is part of the NFR- (the Research Council of Norway) funded National Infrastructure Project "SeaBee", for the mapping of shallow habitats along the Norwegian coast with drones.*

# IT IS TIME TO SAVE THE OCEAN THROUGH HOLISTIC OCEAN OBSERVATION

What do you get if you cross different disciplinary fields like marine biology, marine technology and engineering cybernetics? Ocean observation all the way from the bottom of the sea and up to satellite level.

The Centre of Excellence (CoE) NTNU AMOS started out with a close collaboration between engineering cybernetics and marine cybernetics in 2013, but there was a missing piece: What to research and observe? The puzzle became complete when marine biologists entered the CoE four years later. With radical climate change and the mass extinction of species happening right here and now, the need for speed in ocean observation became a crystal-clear priority.

“A large part of seabirds has disappeared due to a food and habitat loss,” says Geir Johnsen, Professor in Biology at NTNU.

AMOS’ goal is to revolutionize how we can collect data from the ocean. With small satellites, drones, UAVs (Unmanned Aerial Vehicles), USVs (Unmanned Surface Vehicles), ASVs (Autonomous Surface Vehicles) AUVs (Autonomous Underwater Vehicles), L-AUVs (Light Autonomous Underwater Vehicles), big data and artificial intelligence, the mapping and monitoring of the ocean can go from doing research in specific time periods and spaces, to a more continuous flow of data that can be analysed, and give researchers more exact knowledge on what is really taking place.

“There has been a huge development over the last 10 years in technology that carries instruments with different types of sensors and cameras,” says Johnsen, AMOS’ own Norwegian David Attenborough.

He puts it this way:
“The observation pyramid we have developed in NTNU AMOS is unique. The information we get when technology, cybernetics and biology are coupled together gives us knowledge that can’t be ignored – the ocean environment has been totally changed over the last 30 years due to habitat degradation and a warmer ocean.”

First, they have to identify, second they have to map, and third monitor the findings. Johnsen says that before the inter- and multidisciplinary collaboration, biologists would go out and collect water samples from various places, then bring it back and analyse it in very time-consuming operations:

“But the truth is that the next second or minute after you took a water sample, you would maybe have totally different results. Nothing is static, everything is in motion. Therefore, continuous observation gives us more precise and detailed knowledge.”

He mentions the long-distance remote sensing measuring of water colour, such as the spring bloom in the ocean of both phytoplankton and zooplankton.

“Of course, there are methodological challenges here as well: Do we get a good description of the reality or just fragments? We get a lot of fragments, but we also get more information than we did before, and at the same time we are working on the methodology constantly.”

How do they work together?
“We do fieldwork together, researcher and students from all different backgrounds come together and learn from each other. Time and time again, we see that it is between the borders of the different research fields that the exciting things are happening. That is what makes this research really motivating,” Johnsen says.

It is in these gaps that they discover things that have never been observed before.

“We find that this new information can be transformed into knowledge and research. And this research and education can again be used in environmental management and risk analysis.”

Johnsen continues:
“It is mind-blowing that we can get the information we all need. To go from single measuring points in time or space, to observe larger areas within larger timeframes. This is also very interesting for other nations and other international projects.”

To be more specific about the research they are doing, Johnsen talks about some of the fieldwork that has been done in 2021.

In May, researchers and students spent time in Hopavågen, a 3-kilometre landlocked bay at Agdenes in the south of Trøndelag. They used AUVs to observe the sea colour, with hyperspectral imaging and USVs and UAVs to map the seabed.

“Robots do work that people had to do before, and also map and monitor habitats that humans are not able to reach in the same way.”

In Hopavågen, they observed the seagrass where a lot of different organisms live: fish, shells, snails and macroalgae.

“Sea grass is an important habitat and an organism that produces oxygen, and it has become that there is less seagrass all over the world now. That is a stress sign indicating degraded habitats caused by human infrastructure and pollution. The mapping in AMOS can be an important part of getting people to understand what is happening."

AMOS has also done mapping of the seabed in Mjøsa, the biggest lake in Norway in 2021. Located near Mjøsa is Raufoss, a company making ammunition. Among other things, they have found a lot of bombs and grenades dumped near where water pipes bring water to people's homes.

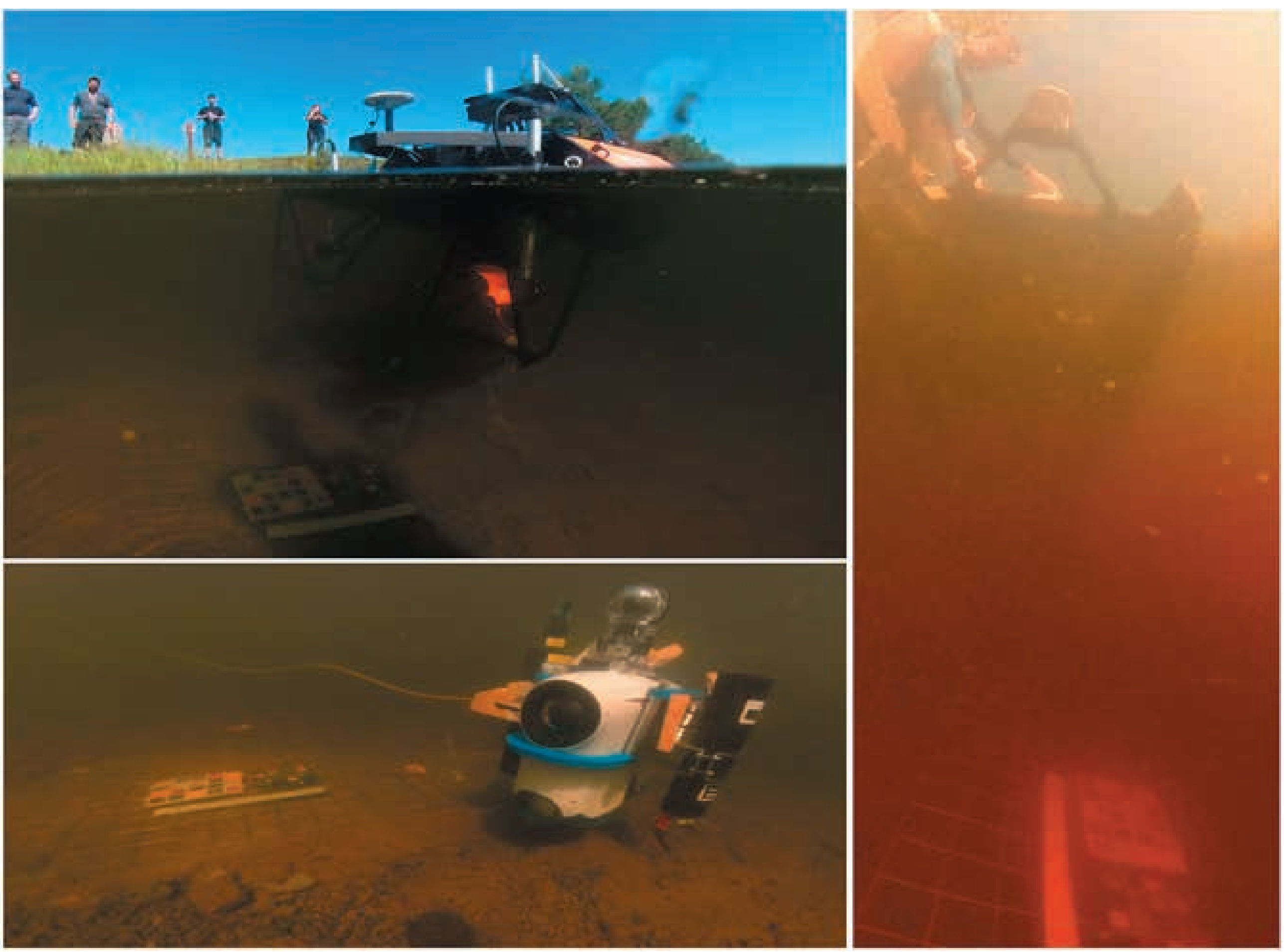
"We have used and are still using ocean and lakes as garbage dumps. Out of sight, out of mind so to say. This is the second rescue operation of Mjøsa, since our former Minister of the Environment, later Prime Minister Gro Harlem Brundtland, ordered the first rescue operation with the taking away of phosphates. It is first in later years that people react about the dumping of things in oceans and lakes."

They have also observed the colour of the water in Mjøsa. After heavy rainfall, the lake may be pretty yellow or orange.

"This orange hue is due to coloured dissolved organic matter (cDOM). With the global warming, more glaciers melt, and you get more material, sand, soil and gravel into both lakes and oceans. This is dead organic and inorganic material that affects life."

They have researched whether there is more or less plankton with cDOM, which again is species-specific and dependent on seasons.

With AMOS, they also have a course in enabling technology for marine ecology, with students from three faculties coming together.



***Picture with 360-degree camera in Mjøsa, June 2021:*** *Upper left: Unmanned Surface Vehicle (USV) with Underwater Hyperspectral Imager (UHI) mapping colour plate standard at the lake bottom with NTNU Gjøvik Colour Lab. Lower left: A mini-ROV equipped with a 360-video camera, and EcoTriplet (measuring concentration of Chlorophylla, coloured Dissolved Organic Matter and Total Suspended Matter, which is important to elucidate a correction for Inherent Optical Properties (IOP). To the left (black cylinder) is an underwater spectroradiometer for the measurement of downwelling spectral irradiance.*
*Right (large image): Shows the red hue in a small river flowing into Mjøsa. The orange-red colour is due to a high concentration of water run-off with coloured Dissolved Organic Matter (cDOM) from dissolved plant tissue from leaves and soil. This effect needs to be corrected for when doing hyperspectral imaging. Kristoffer Grøtte at the surface tuning the USV for the UHI survey.*

***Obervation Pyramid, September 2021:*** *Left: Drone image NTNU Sletvik field station (orange building in the centre of the image) at Hopavågen, with the channel to coastal water (upper right) and with Stavøya (top of image). The beach area in the central part of the image comprises a seagrass habitat with many species of brittle stars, mussels, macroalgae and anemones. Right: The pictures show a mini-ROV using a video camera to provide images of the seafloor habitat dominated by the anemone Metridium senile (sjønellik). This activity was synchronized with the aerial drone survey (equipped with a Hyperspectral Imager). USV (Unmanned Surface Vehicles) with UHI (Underwater Hyperspectral Imagers) were used for verification of the object of interest in the NFR-funded Infrastructure project called "SeaBee".*

"The majority is studying marine biology, but we also have students from marine technology and cybernetics. It is extremely rewarding to bring them together, both with theoretical lessons and practical fieldwork in finding new solutions to observe ecosystems to provide important information."

It is now more common knowledge that nature cannot cope with endless human influence.

"We have to save the earth at last," Johnsen says, but at the same time admits that the earth will probably survive human beings; it is the human beings that will not survive themselves if we continue the same path".

Text: Live Oftedahl Photo: Geir Johnsen

***NTNU course "Enabling technology for marine ecology and marine science", autumn 2021.*** *A new course with Norwegian and International students from biology, cybernetics and marine technology working together at the NTNU field station at Sletvik, October 2021. Several AMOS personnel are involved in this cross-disciplinary activity, comprising theory, lab- and field work, a hands-on project with instrument carrying robots and a project of the RV Gunnerus.*

# NTNU AMOS' FIRST SOCIAL SCIENTIST

Kate Crosman started her post-doc in Big Ocean Data at NTNU AMOS in September 2021.

NTNU AMOS has developed to be a multi- and interdisciplinary Centre of Excellence, with researchers from marine technology, technical cybernetics, marine biology and marine archeology involved and working closely together.

Until 2021, there were no social scientists involved, but this year NTNU AMOS has become even more multidisciplinary and international.

**Kate Crosman is a social scientist from the US, with expertise in the complex governance of oceans and coasts. She has been living in Norway since the autumn of 2021, working on the overall theme of "trustworthiness and trust in big data for oceans," through an André Hoffmann Fellowship in Big Ocean Data.**

## First impression

This was her first impression when she moved to Trondheim:

"I arrived in Trondheim in a torrential downpour, toting three suitcases and a crate containing a very disgruntled cat. I was exhausted after an international move and 10 days of quarantine in Oslo, and the taxi driver had a hard time finding the building. I was told that my apartment had a glorious view out over the fjord, but all I could see from the windows was the rain. And rain I am used to, having lived in Seattle, Washington for the last nine years."

She moved from Seattle to Trondheim after receiving a PhD in Public Policy and Management, followed by two years spent working as a research scientist, all at the University of Washington. The André Hoffmann Fellowship for the Fourth Industrial Revolution offers early-career academics the opportunity to work at the intersection of society, science and technology, through a joint appointment between the World Economic Forum and leading academic institutions.

The three-year fellowship is sponsored by the World Economic Forum, hosted by the Norwegian University of Science and Technology (NTNU) Department of Marine Technology and the Centre for the 4th Industrial Revolution – Oceans (C4IR Oceans), and funded in part by SFI Harvest (a Norwegian Center for Research Innovation) and NTNU AMOS.

## Big Data a huge topic

"All of us share an interest in understanding trustworthiness and trust in big ocean data, as the data move from collection to information and knowledge generation through decision-making and actions."

Crosman says that "Big Data" is currently a huge topic across scientific disciplines, with much potential for governance, as well as many potential pitfalls.

"When I saw the position posting, I knew this was an exciting opportunity to do impactful research on a salient and important topic, while applying and extending my expertise. Also: Norway. I knew I had to apply."

After her arrival she has worked on the onboarding and getting up to speed. With a lot of support from her supervisors and other Hoffmann Fellows, over the first few weeks she also scheduled meetings with all partner organizations.

"Luckily, all the partners were excited to discuss the very large topic of trust in big ocean data, and enthusiastic about the research possibilities. I also took the opportunity to begin to learn about each organization's specific interests, so that I can identify areas of focus that will be useful to everyone – and of course, interesting for me."

## Complex governance

Crosman is trained in the social sciences, with experience in interviews, surveys and experimental research into stakeholder knowledge, perceptions, attitudes and decision-making in the complex governance of oceans and climate.

"It's an excellent foundation to build on, but there's a lot to learn about the technology, ecology, and social, economic and decision-making systems of the new environments I'll be studying and working in."

She feels fortunate that there is a deep expertise available on all of this among the research partners.

She has spent her first months in Norway carefully fine-tuning her research agenda to identify and bind specific studies. That

### What is the Andre Hofmann Fellowship?

**It is a fellowship for the Fourth Industrial Revolution (4IR), which offers early-career academics the opportunity to work at the intersection of society, science and technology, through a joint appointment between the World Economic Forum and leading academic institutions. The forum tackles societal, industry and economic challenges from all angles.**

> All of us share an interest in understanding trustworthiness and trust in big ocean data, as the data move from collection to information and knowledge generation through decision-making and actions."

Photo: HUB Ocean

*Kate Crosman*

is simply part of the process in a project like this.

"How do I like Trondheim so far? It transpires that the city is incredibly charming, even in the rain, and when the sun comes out it's even better. Even the cat eventually ventures out from under the bed, and enjoys what turns out to indeed be a spectacular view, complete with both rainbows and auroras."

After almost four months as an André Hoffman Fellow in Big Ocean Data, her scope of work has started to settle into place.

"I have presented an initial research plan to all the research partners (NTNU, SFI Harvest, World Economic Forum Ocean Action Agenda and C4IR Oceans), and am ready to start moving forward."

## SFI Harvest

**is a research-based innovation centre (SFI) for developing new technology, aimed at solving the global challenges of securing enough food for a growing population in a sustainable way. SFI Harvest is run by SINTEF Ocean, CoE AMOS, the NTNU Department of Marine Technology, the Department of Engineering Cybernetics and the Department of International Business, UiT – The Arctic University of Norway and Nofima, together with 10 industry partners.**

She continues:
"At first glance, the topic may seem simple: Do we believe that the data accurately portray the characteristics of the empirical reality that we seek to describe? However, even this formulation hides a wealth of complexity."

## Characteristics of Big Data

As the first example of that complexity, consider that we are specifically talking about "Big Data" – meaning data that are high volume, rapidly accumulating, and that originate from a variety of platforms and come in a variety of formats.

"Big Data are therefore impossible to analyse using the standard statistical techniques employed in traditional data analysis, instead requiring the use of novel analytical techniques that rely on artificial intelligence (AI), aka machine learning, deep learning."

AI introduces accuracy concerns, such as algorithm selection and bias in training data, that extend far beyond – but do not supplant – the relatively simple question of whether the all the data are accurate.

## Whose trust, and to what ends?

"As a second example, consider that the simple question of, 'Do we believe that the data are accurate' omits a definition of a crucial variable: Who are 'we'? In other words, whose trust are we talking about?"

To add additional complexity, it has become clear that what is truly of interest to all research partners is not solely whether the data are accurate in the abstract. Rather, it is what trustworthiness (meaning the accuracy of data and information derived from analysis) and trust (meaning how the resulting information and knowledge are perceived and applied) mean for how the data are used.

## How are Big Data for oceans used?

Maybe we can gain some traction by working backwards. Ultimately, we are interested in using Big Data to make decisions for ocean sustainability.

For instance, Big Data could include images of water column suspended particulate, in which zooplankton have been identified and classified by a machine-learning algorithm. They could also include multibeam echosounder data from sensors on fishing vessels, as well as streaming environmental data from surface buoys.

These data might be used to better understand the systemic drivers of plankton abundance and distribution. In turn, the data could allow for the development of a sustainable fishery management of that plankton, which then might provide a sustainable source of feed for Norway's farmed salmon.

"If we were only concerned with the accuracy of the information we gain from the data (i.e. trustworthiness), we might have questions about the accuracy of the data, the appropriateness of the machine-learning algorithms, the tuning of the echo sounders and the spatial and temporal distribution of our buoys. This is just for starters. But in the above example, we can also start to see the outline of whose trust in data and decisions might bear consideration."

## Scientists and a tiny zooplankton

As her first case, Crosman will be looking at the stakeholder landscape, the data input and transformations in the information value chain, and how both sets of variables intersect to create or challenge data trustworthiness, in addition to trust in the relatively young *Calanus finmarchicus* fishery in the Norwegian Sea.

"This applied research context is an excellent jumping-off point, as it is relatively small, well-bounded and local."

Crosman's post-doc journey has almost just begun.

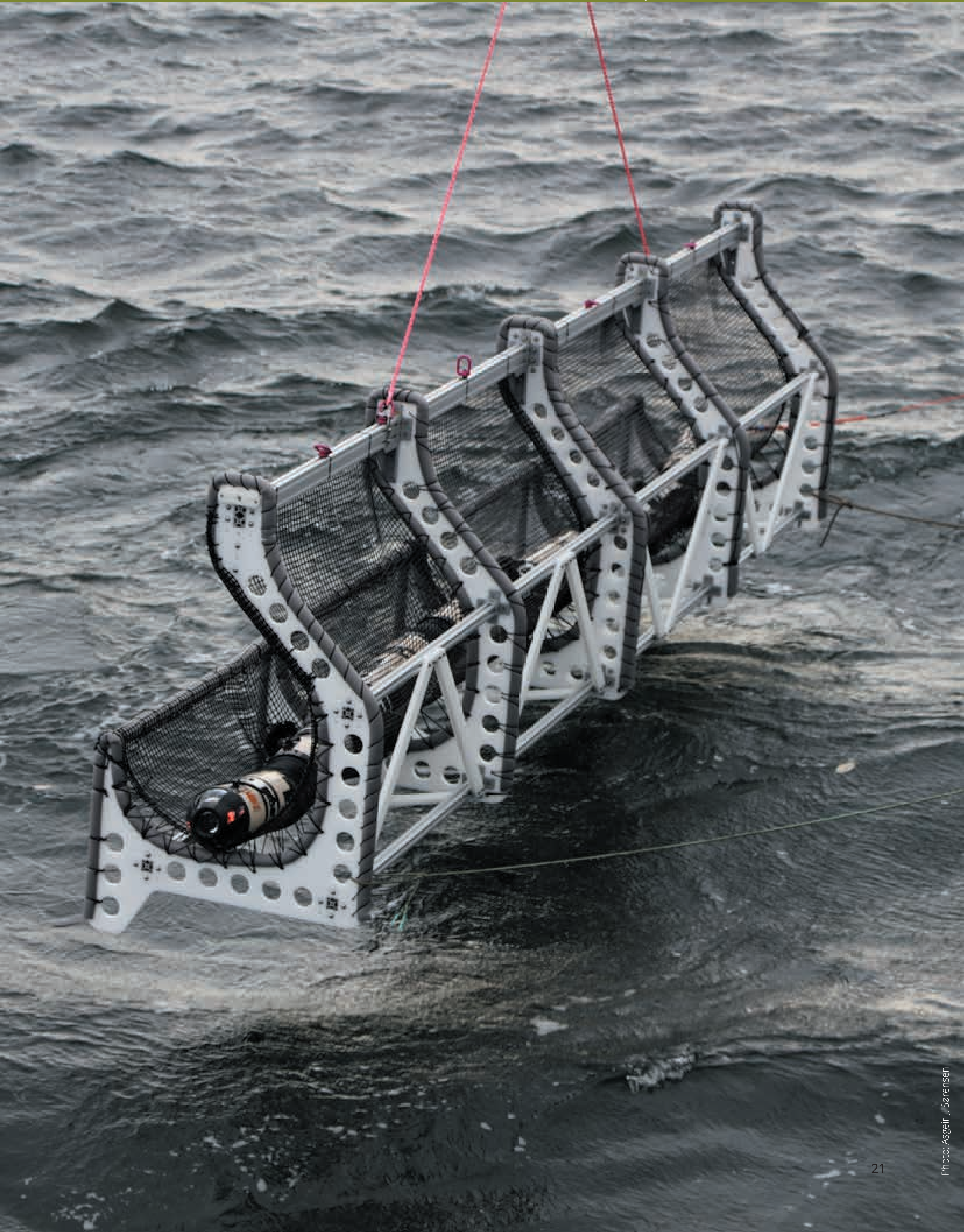


Photo: Asgeir J. Sørensen

# 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

### NTNU AMOS Management:

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

### 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
- 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 2021

| | |
|---|---|
| 7 | Keypersons |
| 14 | Adjunct prof/associated prof |
| 29 | Affiliated scientists |
| 2 | Scientific advisers |
| 8 | postdoc/researchers |
| 18 | Affiliated postdocs/resarchers |
| 27 | PhD Candidates |
| 103 | Affiliated PhD candidates |
| 5 | Administrative staff |
| 2 | Management |
| 2 | Technical staff |
| 2 | graduated PhD candidates financed by NTNU AMOS |
| 10 | graduated PhD candidates associated to NTNU AMOS |

## Publications

| | |
|---|---|
| 97 | Refereed journal articles |
| 86 | Refereed conference papers |
| 2 | Book chapters |
| 1 | Book |
| 6 | Keynote lectures |

## Revenues (NOK 1000)

| | |
|---|---|
| *Actual:* | |
| Income | 68 993 |
| Costs | 55 733 |
| Year end allocation | 13 260 |
| *In Kind:* | |
| Income | 4 979 |
| Costs | 4 979 |
| *Total:* | |
| Income | 73 972 |
| Costs | 60 712 |
| Year end allocation | 13 260 |
| AMOS 1 end allocation | 5 497 |


© Live Oftedahl

# MAIN RESEARCH AREAS AND PROJECTS


**Anders Opedal, CEO Equinor (second left) talking with Asgeir J. Sørensen (left) and rector Anne Borg (right) outside the AUR-Lab after the testing of a subsea robot in a docking station 90 meter below the sea surface.**

Photo: Live Oftedahl

# The NTNU AMOS has two research areas:

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

Research at AMOS is organized as three major research projects

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

# MONITARE: FOOD FOR THE FUTURE

Principal Investigator Glaucia Moreiro Fragoso and her research team will investigate how optical methods can be used in the growth of seaweed.

Glacia Moreiro Fragoso

> "Seaweed cultivation is one of the most sustainable types of aquaculture, with positive environmental impacts"

Seaweed cultivation is one of the fastest growing aquaculture businesses in Norway.

"It is also one of the most sustainable types of aquacultures, with positive environmental impacts, including nutrient remediation, increased biodiversity, carbon sequestration and positive impacts on local fish stocks," says Dr. Glaucia Fragoso, researcher at NTNU AMOS at the Dept. of Biology.

She is funded by the the Young Research Talent grant from the Norwegian Research Council, and the project is in association with NTNU AMOS. The four-year MoniTARE-project started last year and will continue to 2025.

## Will develop autonomous monitoring

"As commercial kelp farms continue to expand in Norway, autonomous methods for monitoring of growth, biomass and biofouling become increasingly important. This project aims to develop optical methods for these purposes," Fragoso says.

From earlier research Fragoso has experience with pigments, plankton taxonomy, bio-optics, photo-physiology and has published several research papers related to biological measurements using autonomous approaches.

Why this project? Commercial kelp farms need to be monitored regularly. During this process, measurements of seaweed biomass, growth and biofouling are taken. These measurements allow predictions to be made about the size and quality of the harvest, which can be used to optimise the biomass of future harvests.

"Current monitoring methods are labour intensive and inefficient. Automated solutions are, therefore, required as kelp farms continue to grow in scale."

***Monitoring will take place at a commercial kelp farm, run by Seaweed Solutions, on the island of Frøya in Trøndelag, Norway.***
***Photo: Seaweed Solutions.***


*Seaweed farming is one of the most sustainable and fastest growing aquaculture industries in Norway.* *Photo: Seaweed Solutions.*

## International team

The main aim of this research project is to take some major steps towards automated underwater monitoring of kelp-farms, by using cameras mounted on a remotely operated vehicle (ROV), to estimate macroalgal biomass and biofouling.

Together with Fragoso, the team consists of Geir Johnsen, one of the key scientists in NTNU AMOS at Dept. of Biology and Martin Ludvigsen, professor in marine technology and the leader of the Applied Underwater Robotics laboratory (AUR-Lab, NTNU) that will offer the infrastructure of the AUR-Lab and assist with engineering support.

The team consists also of researchers from other universities and the industry: Duncan Purdie is a professor of Biological Oceanography in Ocean and Earth Science at the University of Southampton (UK). Prof. Purdie will provide laboratory support for the analysis of phytoplankton samples through the CytoSense flow cytometer and assist in the data analysis.

Ana Borrero Santiago is the environmental research coordinator at Seaweed Solution, which is one of the companies pioneering macroalgal cultivation in Europe and the R&D provider for MoniTARE. Dr. Borrero is a chemical oceanographer and expert in environment risk assessment and ocean acidification studies.

She will provide personnel assistance in the field and the seaweed wet biomass estimations using conventional approaches for validation of the in situ data.

## Ecological monitoring in parallel

"In parallel, integrated ecological monitoring – plankton and kelp biomass and water quality - will be used by deploying environmental and biological sensors at the farm, which will help us to investigate the physical and biological factors associated with the onset of biofouling organisms in late spring," says Fragoso.

The monitoring and the optical techniques will be refined at a commercial kelp farm, run by Seaweed Solutions, on the island of Frøya in Trøndelag.

Text: Live Oftedahl

monitare
Seaweed Solutions
University of Southampton
NTNU
The Research Council of Norway

# EVELYN LED A TEAM OF MORE THAN 80 TO AN HISTORICAL LAUNCH

After four years of building and testing, the small satellite «HYPSO-1» was launched together with 104 others small satellites with a SpaceX Falcon-9 rocket from Cape Canaveral Space Launch Complex 40 in Florida, January 2022.

Photo: Kai T. Dragland

This was the first launch of a small satellite from a Norwegian university dedicated to research, and therefore historical. NTNU AMOS has pushed this project in to becoming a reality. HYPSO-1 now orbits the earth at an altitude of 500 kilometers, and uses approximately 90 minutes in one orbit, 16 rounds per day.

Using a hyperspectral camera, the plan is that HYPSO-1 can observe and reveal harmful algal blooms and pollution in the ocean, blooms that can threaten ecosystems and fish farms. The hyperspectral camera is based on a design by Fred Sigernes at the University Centre of Svalbard.

## A milestone

"This is a milestone for NTNU and Norwegian research. I hope this project can contribute to a national program for satellite research," NTNU-rector Anne Borg, said just before the launch. She is full of praise for the 80 students and researchers involved in constructing HYPSO-1 at bachelor-, master- and PhD level. Ten PhD-degrees has been based on the project.

"This was a lifetime experience," says Evelyn Honoré-Livermore, PhD-student at NTNU's Department for Electronic Systems and NTNU AMOS. She has been the project manager of HYPSO-1.

"NTNU has world-leading marine research and there is a need for hyperspectral imaging and monitoring, especially of the oceans," Evelyn Honoré-Livermore, says.

## Five years mission

Her PhD thesis is about how interdisciplinary teams, and teams with high turnover – which is the case in a university where students complete their degrees – can build such a complex thing as a small satellite in an efficient manner.

"The NewSpace paradigm challenges existing industry and standards. Universities are highly dynamic and exciting environments where we can try new approaches to building small satellites for research purposes. Figuring out how to build a strong inter-disciplinary team culture where each individual contributes to achieving mission success at a university is very interesting, especially since our team changes each semester when students graduate. The experiences the students gain from participating in small satellite projects at NTNU is extremely relevant for the current (and future) Norwegian space actors," Honoré-Livermore says.

Photo: NanoAvionics

She was in Florida at SpaceX when the Falcon-9 took off. She could hear the roar and feel the forces, and both the relief and excitement when the launch of HYPSO-1 after some minutes was successful.

According to the plan HYPSO-1 will orbit the earth for five years.

The construction of HYPSO-1 has taken four years. This is around the average time used on universities to build a small satellite, Honoré-Livermore tells. The construction of bigger satellites can take from ten to twelve years.

## Third try

Statistically the success rate has been 60 percent up until 2019 for universtity built satellites, she explains. NTNU was involved in two launches of student-developed satellites 15 years ago that failed.

"Today we have better components and information sharing. The development process is more reliable. I believe the success rates are much higher now. I am also really excited to see how far the student satellite organization at NTNU, Orbit, has gotten. They are also delivering two small satellites for launching this year. This means that at the end of 2022, NTNU will have three satellites orbiting the earth, which is a huge achievement."

So far HYPSO-1 seems to work as expected, and it remains to see if the hyperspectral camera provides the expected information.

"We are very grateful to all our collaborators, especially our partners in Lithuania, NanoAvionics, who have provided our satellite bus and supports with commissioning of the satellite and operations. We are learning new things every day, and we couldn't have achieved what we have today without their willingness and agility to respond to our requests," Honoré-Livermore says. NanoAvionics started out as a spin-off from a university in Lithuania and is now one of the leading small satellite providers in Europe and internationally."

HYPSO-1 is financed mainly from NTNU and the Norwegian Research Council with important support from the Norwegian Space Agency and ESA.

"If Norway wants to keep a position as a space nation, the infrastructure and research on small satellites have to be strengthened," says rector Borg.

Photo: SpaceX


Photo: Kai T. Dragland

Several universities are developing small satellites now.

"A huge growth is expected in the space industry in the coming years. The Norwegian industry has ambitions and a good position to compete with big international players. We want to research the technology that will be used tomorrow," Dean Ingrid Schjølberg at the Faculty of Information Technology and Electronics, says.

NTNU has now entered the new space age: "The NewSpace paradigm is about agility and willingness to take risk.

Where better to build these capacities in our future engineers than at NTNU? And, being a part of the collaborative research at NTNU AMOS is critical to delivering the capabilities and information that we need from the space assets to support a better understanding and sustainable management of our planet. The value of the research, education and services that can be provided, will soon level out the costs," Honoré-Livermore says.

HYPSO-2 is already in the making. A democratization of the space industry is ongoing.

Text: Live Oftedahl

### What is HYPSO-1?

**HYPSO** stands for **HYPer-spectral Smallsat for ocean Observation**
**HYPSO-1** is small satellite 10 x 20 x 30 cm that weighs 7 kilos with 6-liter volume.

# 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 I. Fossen

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

## 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

## ADRASSO – Autonomous Drone-based Surveys of Ships in Operation

The remote inspection of ships has the potential to increase the safety of both the ships themselves and the workers who inspect them. Inspectors will no longer need to climb by ropes or scaffolding or raft into tanks, but will instead be able to access tanks remotely by drone. Moreover, automating inspection will reduce costs and the demands on shipyard facilities, while increasing the amount of time ships are active. The environmental costs of shipping will also be reduced, as rafting surveys require releasing water from the tanks of the ship back into the ocean.

In the Autonomous Drone-based Surveys of Ships in Operation (ADRASSO) project, NTNU worked together with partners from industries relevant to remote inspection, including DNV, Norsk Elektro Optikk (NEO), Jotun, Idletechs and Scout Drone Inspection, which is an AMOS spin-off company. Activities in the project included the development of AI for crack detection with a standard digital camera, real-time hyperspectral image processing, the integration of the NTNU v4 hyperspectral camera onto Scout's drones, as well as the assessment of using hyperspectral image processing for classifying materials and identifying defects. NTNU has been involved in all portions of the project pertaining to hyperspectral imaging.

Hyperspectral imaging, which is popular in food science and remote sensing, but not yet used for maritime remote inspection, has several benefits as an inspection technology. The spectral information it reveals can be related directly to the material characteristics determined in a laboratory by absorption spectroscopy. Hyperspectral imaging does not require contact with the material, which makes drone-based measurements much simpler. Moreover, its instrumentation is relatively cheap and light compared to other materials characterization techniques, such as Raman spectroscopy, X-ray diffraction or laser-induced breakdown spectroscopy.

Because the NTNU v4 hyperspectral camera was light enough to be carried on Scout's drone, it was chosen as the hyperspectral imaging payload to be used on flights. The drone's legs were extended so that the camera could be mounted on the underside of the drone in the centre (Figure 1). Of the many different surfaces evaluated in the ADRASSO project, corroded steel panels were chosen as the target surface for the experiments to test the drone-mounted hyperspectral camera setup. Because laboratory measurements could clearly distinguish between humidity-rusted, salt-rusted and reference panels, these experiments tested the viability of the mounted camera setup. The original LEDs on the drone provided illumination only up to a wavelength of approximately 700 nm, so additional near infra-red LEDs were added (Figures 2 and 3).

The initial experiments showed that the different panels could be successfully distinguished, so long as the drone remained a constant distance from the wall (Figure 4). However, the illumination intensity changed as the distance between the drone and the wall changed, which made calibration of the camera over a whole flight trajectory difficult. Furthermore, the illumination variation across the hyperspectral slit made a consistent estimation of the reflectance difficult. In addition, although the distorted geometry of raw push-broom images (Figure 4) was overcome in this experiment by using samples with a clear geometry, it is unlikely that

***Figure 1:*** *NTNU v4 camera mounted on Scout Drone; image courtesy of Kristian Klausen of Scout Drone Inspection.*

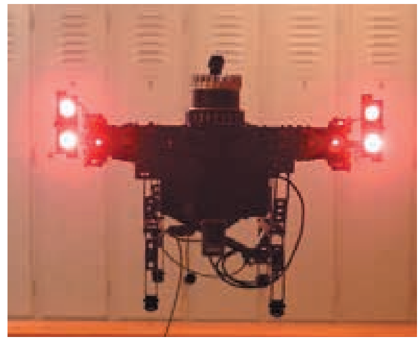


***Figure 2:*** *Scout Drone in flight with NIR lights on; image courtesy of Morten Fyhn Amundsen of Scout Drone Inspection.*

***Figure 3:*** *Camera pointed towards target with visible lights (top) or infrared lights (bottom)*

corrosion on a ship will have such a regular form, and so fusion with a traditional digital camera may be necessary. By successfully distinguishing several corroded panels from a drone-mounted camera, the ADRASSO team showed the promise of hyper-spectral remote inspection, but the difficulties encountered in the experiments show that more research is required before it could become a standard inspection tool.

NTNU also participated in the evaluation of which surfaces are worth inspecting by hyperspectral imaging. In addition to corrosion, other degradations such as pinholes and thermal aging were evaluated based on hyperspectral images acquired in NEO's laboratory, with the assistance of their state-of-the-art cameras (Figure 5). NTNU assisted scientists from Jotun in the assessment of how short-wave infrared hyperspectral images could be used to determine which binder was used in the manufacture of a coating. In particular, certain absorption lines were found to vary spatially, which suggests variation in the distribution of chemicals across the surface (Figure 6).

Hyperspectral imaging is a promising tool for remote inspection. In the ADRASSO project, we showed that it is feasible for a small drone designed for imaging inside a ship to be mounted with an even smaller hyperspectral camera, and that imaging from such a platform can distinguish between some materials. Importantly, we identified several of the problems that originate from the illumination used, which must be overcome to enable this technology. Finally, in the assessment of different use cases, we began to evaluate what sorts of materials can be distinguished with a hyperspectral imager, and what are the performance criteria a hyperspectral imager must meet to distinguish them (signal-to-noise ratio, spatial resolution, etc.).

**Contact** Researcher Joseph Garrett, Professor Tor Arne Johansen
**Media** Video: Taking drone inspections to the next level - DNV

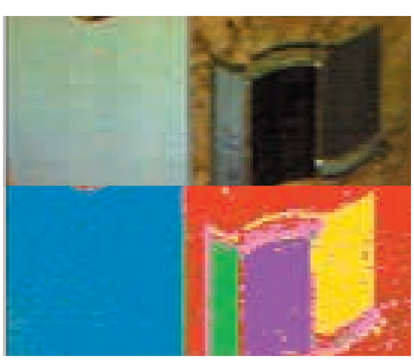


***Figure 4:*** *Top: The push-broom style of the camera leads to drift in the scan. Bottom: The pixels from the different steel panels are classified according their spectra. The purple and yellow pixels correspond to salt-rusted and humidity-rusted steel panels.*

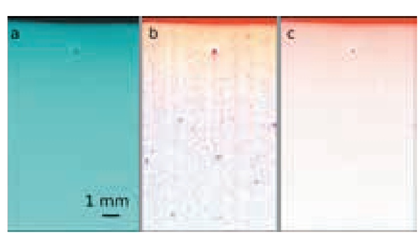



***Figure 5:*** *Sa) A possible pinhole in a coating of paint identified with hyperspectral imaging (b, c). Heat-maps of primer (red) and steel (blue) targets determined according to reference spectra and two different filters. Note that a line of primer is visible at the top of the image, above the predicted pinhole; from reference* **P1-R1**.

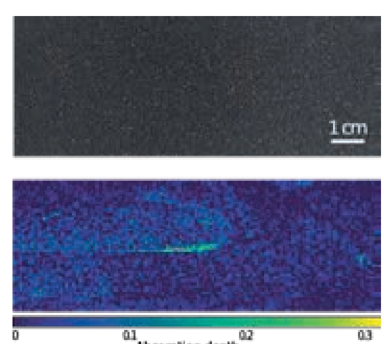



***Figure 6:*** *Top: Minimal spatial variation is visible in the false-color image of an epoxy-coated steel panel. Bottom: One absorption peak, at 2207 nm, shows spatial variation, and suggests the presence of some residual, uncured epoxy; from reference* **P1-R2**.

## Self-Organizing Maps for Clustering Hyperspectral Images On-Board a CubeSat

The hyperspectral camera on the HYPSO-1 satellite records images of the ocean in many different wavelengths of light in order to resolve fine optical details of the sea surface. However, the size of the data limits the amount of analysis that can be performed onboard, and the amount of data which can be downlinked. Clustering, or the grouping of similar pixels together, can help alleviate both problems. First, the clustered data is only approximately one hundredth the size of the raw data. Second, clusters rather than individual pixels, can be analysed, thereby vastly decreasing the number of operations.

This past year, master student Aksel Danielsen, together with his co-advisors Joseph L. Garrett and Tor Arne Johansen, investigated the possibility of clustering hyperspectral data on Self-Organizing Maps (SOMs) onboard the HYPSO-1 satellite. The neurons in the SOM network, which reside on a 2D lattice, closely approximate the data they are trained on, so they are more interpretable than deeper neural networks.

Numerical experiments on data from the Hyperspectral Imager of the Coastal Ocean (HICO) showed that the clustered representations retain much of the information in the original hyperspectral image, while vastly reducing the size of the data. In addition, SOMs require only a small subset of the total data for training and can be trained quickly, two factors that will permit them to be incorporated into the HYPSO-1, which has limited onboard processing and storage resources. Their paper also tests how the clusters can be used in classification.

**Contact** Researcher Joseph Garrett, Professor Tor Arne Johansen

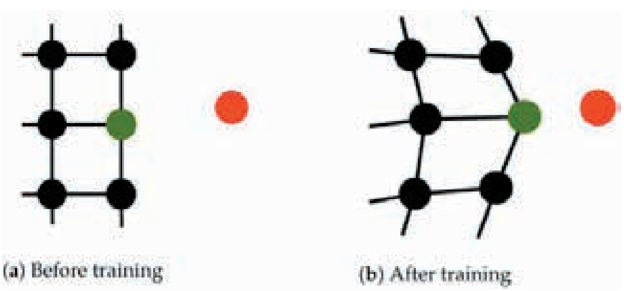



***Figure 7:*** *A Self-organizing map is trained by moving the nodes on the lattice closer to each data point (red). The node closest to the data point (green) moves the most, while neighbouring nodes are moved a shorter distance. After training, the lattice approximates the distribution of the training data; from reference* **P1-R3**.

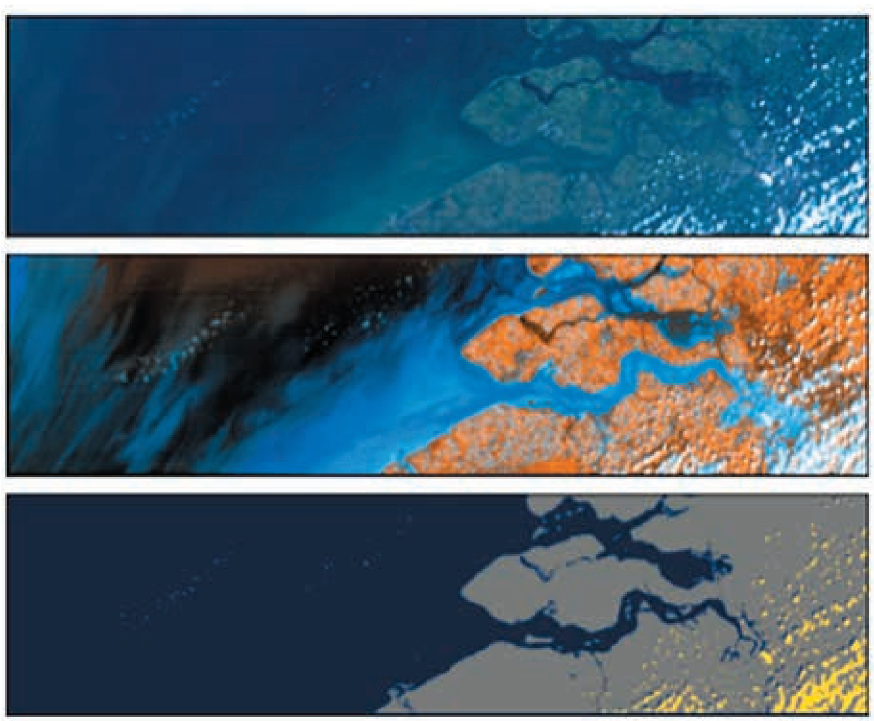


***Figure 8:*** *Top: A HICO image of the North Sea. Middle: Image clustered according to a SOM. Bottom: classification applied to the clusters of the SOM.*

***Figure 9:*** *Picture from field experiments in Frænfjorden using L-AUV Harald.*

## Adaptive Sampling with an AUV

Omya Hustadmarmor is a factory located on the shore of Frænfjorden. In this factory, a calcium carbonate processing plant has been in operation for several decades. The processing of ore from mining causes fine-ground waste called tailings, which must be disposed of. In Frænfjorden, this is done on the ocean floor in a seafill close to the factory. The discharge of such mine tailings has a high impact on the ecological status in the sea. Therefore, methods to efficiently monitor the extent of dispersion are important so that sensitive areas can be protected.

By combining underwater robotic sampling with ocean models, we can choose informative sampling sites, and adaptively change the robot's path based on in situ measurements, with the goal of optimally mapping the tailings distribution near a seafill. The adaptive sampling method was implemented on a Light-Autonomous Underwater Vehicle (L-AUV), and used to monitor the discharges in the fjord. Figure 9 shows L-AUV Harald from one of the field experiments in Frænfjorden within the INDORSE project led by SINTEF Ocean.

The method uses data from two specific ocean models (SINMOD and DREAM) developed at SINTEF. The data is used to build a simplified dynamic onboard stochastic model that approximates the spatio-temporal state of the ocean at all times. The model also has the ability to update the state belief in real-time with information from observations taken by the L-AUV. In this way, the model will have the best possible representation of the ocean state. This representation is essential when selecting the most informative sampling sites, which we define as locations with a high uncertainty in the model, and with high predicted mine tailings concentrations. New waypoints for the L-AUV are selected

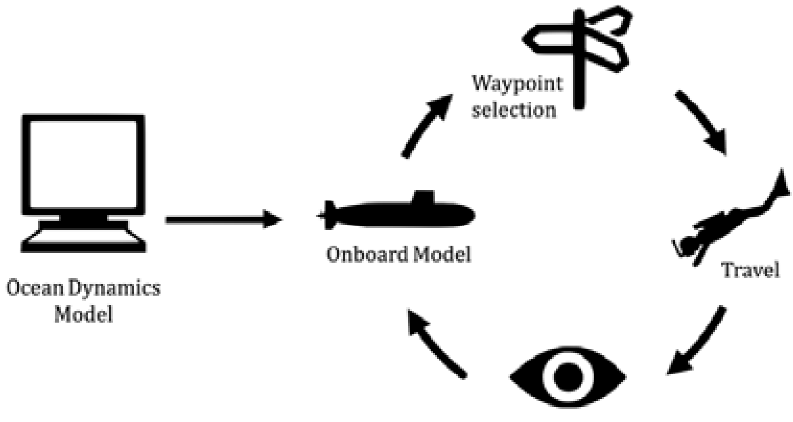



***Figure 10:*** *Overview of the adaptive sampling method*

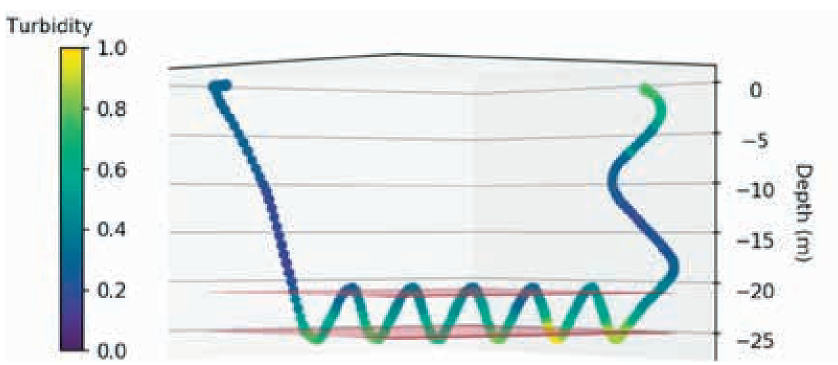



***Figure 11:*** *Showing the AUV transect between two waypoints. The colour of the transect represents normalized mine tailings concentration values.*

sequentially as the next most informative sampling location given the current state. The general steps in the adaptive sampling method are illustrated in Figure 10.

Simulation studies show that adaptive methods are preferred over simpler deterministic methods. And as a proof-of-concept, the method was tested in real-life experiments in Frænfjorden, where the method was running onboard the L-AUV Harald and giving estimates on the mine tailings field near the seafill. A transect between two waypoints can be seen in Figure 11, which shows mini tailings concentration values plotted against depth. Elevated concentrations are found at a depth of approximately 25 metres, showing that mine tailings from the discharge are found.

**Contact** The primary researcher was Gunhild Berget, under the supervision of Tor Arne Johansen, Jo Eidsvik and Morten Omholt Alver.

## Hyperspectral mapping of cold-water corals on the Tautra Ridge

Situated in the middle of the Trondheimsfjord in Norway, the Tautra Ridge supports the shallowest documented cold-water coral reefs in the world (a 39-m depth). These reefs are dominated by the scleractinian coral species *Desmophyllum pertusum*, which is known to be an important ecosystem engineer. In 2013, the ridge was declared one of Norway's first marine protected areas, but somewhat surprisingly, essential baseline information on the extent and distribution of its associated coral reefs is still lacking. In an effort to fill this knowledge gap, we decided to use underwater hyperspectral imaging (UHI), in combination with synthetic aperture sonar (SAS) imaging and multibeam echo sounding (MBES), to map the Tautra coral reef complex.

Over the past decade, UHI has emerged as a powerful technique for detailed seafloor mapping. Whereas conventional cameras render colours using a red, green and blue (RGB) waveband within the visible light spectrum, hyperspectral imagers quantify colours as contiguous spectra. This provides a substantially improved foundation for the automated identification and mapping of biogeochemical seafloor targets based on colour. Since the inception of NTNU AMOS in 2013, UHI has been applied successfully within a variety of fields, including marine biology, archaeology and geology. In 2021, we wanted to investigate whether UHI could be used to assess a three-dimensionally complex coral mound (~800 $m^2$) on the Tautra Ridge, using a novel methodology for consistent georegistration.

The part of mapping concerned with computing earth-fixed coordinates for measurements is referred to here as georegistration. The georegistration of imaging sensor data generally requires a 3D model of the mapped surface, pose (position and orientation) measurements for the sensor and a sensor model describing the geometric configuration measurements. The method for georegistration is chosen based on the operational considerations, in particular the range and resolution of the mapping. For close-range georegistration such as for UHI, there is usually no sufficiently accurate 3D model or pose

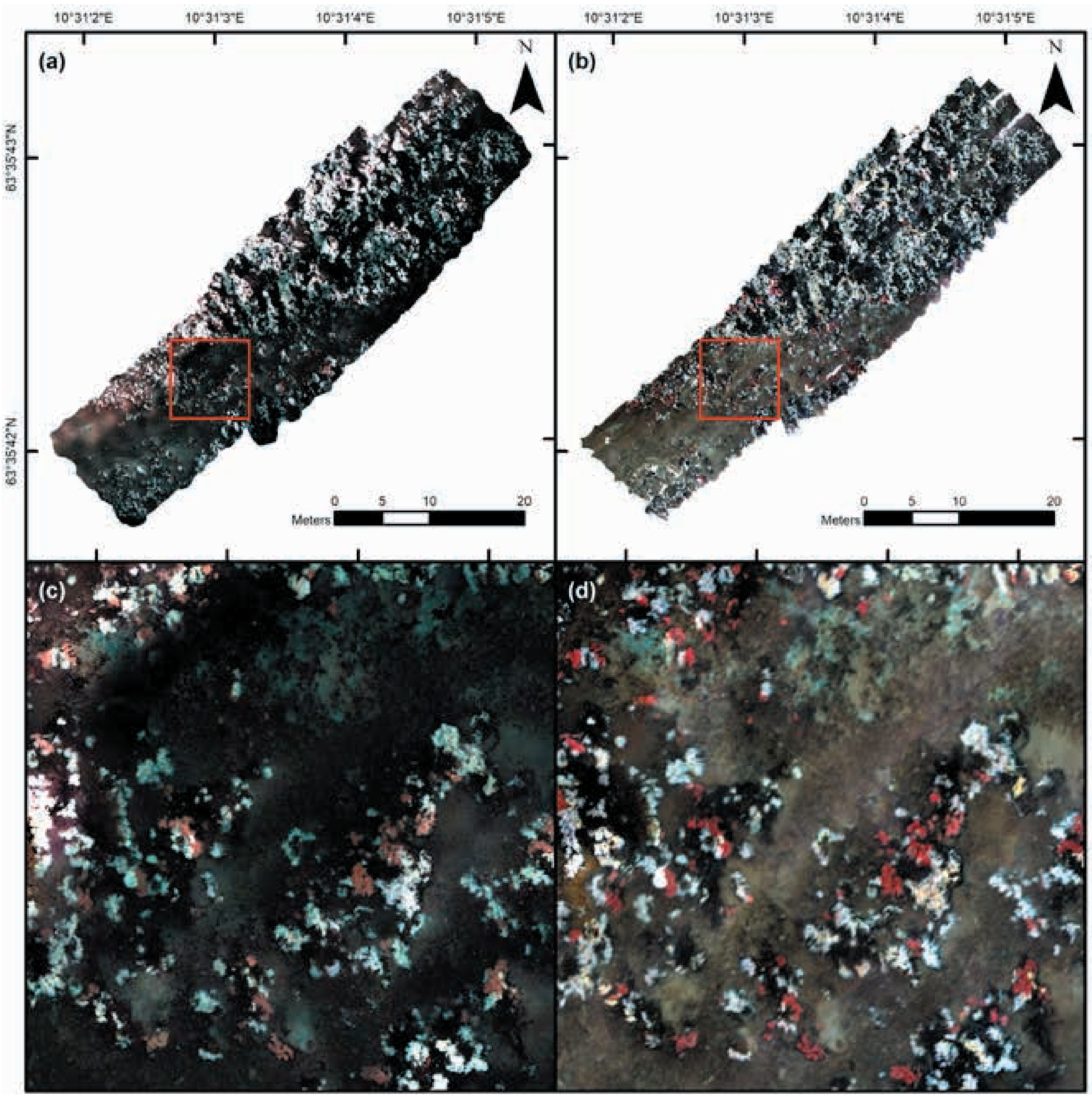



***Figure 12:*** *Orthomosaics showing georegistration. The figure shows the RGB photomosaic from the photogrammetry model in (a) and (c) with the hyperspectral mosaic in (b) and (d). The RGB visualization of the hyperspectral mosaic uses 590 nm, 530 nm and 460 nm wavebands for red, green and blue channels. The spatial resolutions of the hyperspectral mosaic and photomosaic are 1 cm and ~4 mm, respectively. The mosaics in (c) and (d) are made up from 12 transects in the North-East direction.*

(especially position) measurements available, so these should be simultaneously estimated using measurements of the 3D scene. Our georegistration methodology used a calibrated RGB camera, fixed to the hyperspectral imager (HSI), with an overlapping field-of-view (FoV). The RGB images of the seabed were used to build a photogrammetry model that simultaneously estimated the poses of the RGB camera and a three-dimensional (3D) model. Through geometrically calibrating the HSI with the RGB camera, we computed the poses of the HSI. With a calibrated line-camera model for the HSI we used ray casting to project hyperspectral measurements onto the 3D model. By projecting every hyperspectral measurement, we got a spatial reference (X, Y, Z) for each spectrum, or a point cloud in total. This gave us an estimate of the light rays' optical paths, from light source to seabed to the HSI. This allowed for a distance-based correction for the attenuation of the water column and the generation of consistent reflectance spectra invariant to optical path distance. The methodology was exemplified for UHI from a remotely operated vehicle (ROV) on the Tautra coral reef. The precision was unprecedented for georegistration in UHI, demonstrated by the first-ever spatially consistent UHI mosaic to contain multiple overlapping transects, as shown in Figure 12.

Hyperspectral classification of the georegistered UHI mosaic revealed that live coral covered approximately 17% of the surveyed coral mound. As this was in accordance with what could be expected based on previous studies on cold-water coral reefs, it firmly demonstrated the potential of UHI with respect to fast, accurate and automated coral reef mapping. Ultimately, the findings from the UHI analysis were combined with two acoustic datasets in an attempt to predict the extent and distribution of coral reefs along the entire Tautra Ridge (Figure 13). Firstly, the georegistered UHI mosaic was used to verify the identity of acoustic patterns assumed to belong to D. pertusum in a SAS dataset covering 1 $km^2$ of the Tautra Ridge. Secondly, the SAS dataset was partitioned into coral and non-coral regions using a convolutional neural network. Finally, seven geomorphometric variables derived from a 6.23-$km^2$ MBES dataset were extracted from coral- and non-coral regions, and used to predict coral reef occurrences along the ridge. Our findings suggest that the total reef extent in the area is close to 0.64 $km^2$, and that the reef distribution is linked with the patterns of the prevailing bottom currents. We believe our work illustrates the value of combining information from multiple remote sensing techniques in the quest for holistic knowledge.

**Contacts:** Håvard S. Løvås, Aksel A. Mogstad, Geir Johnsen, Asgeir J. Sørensen

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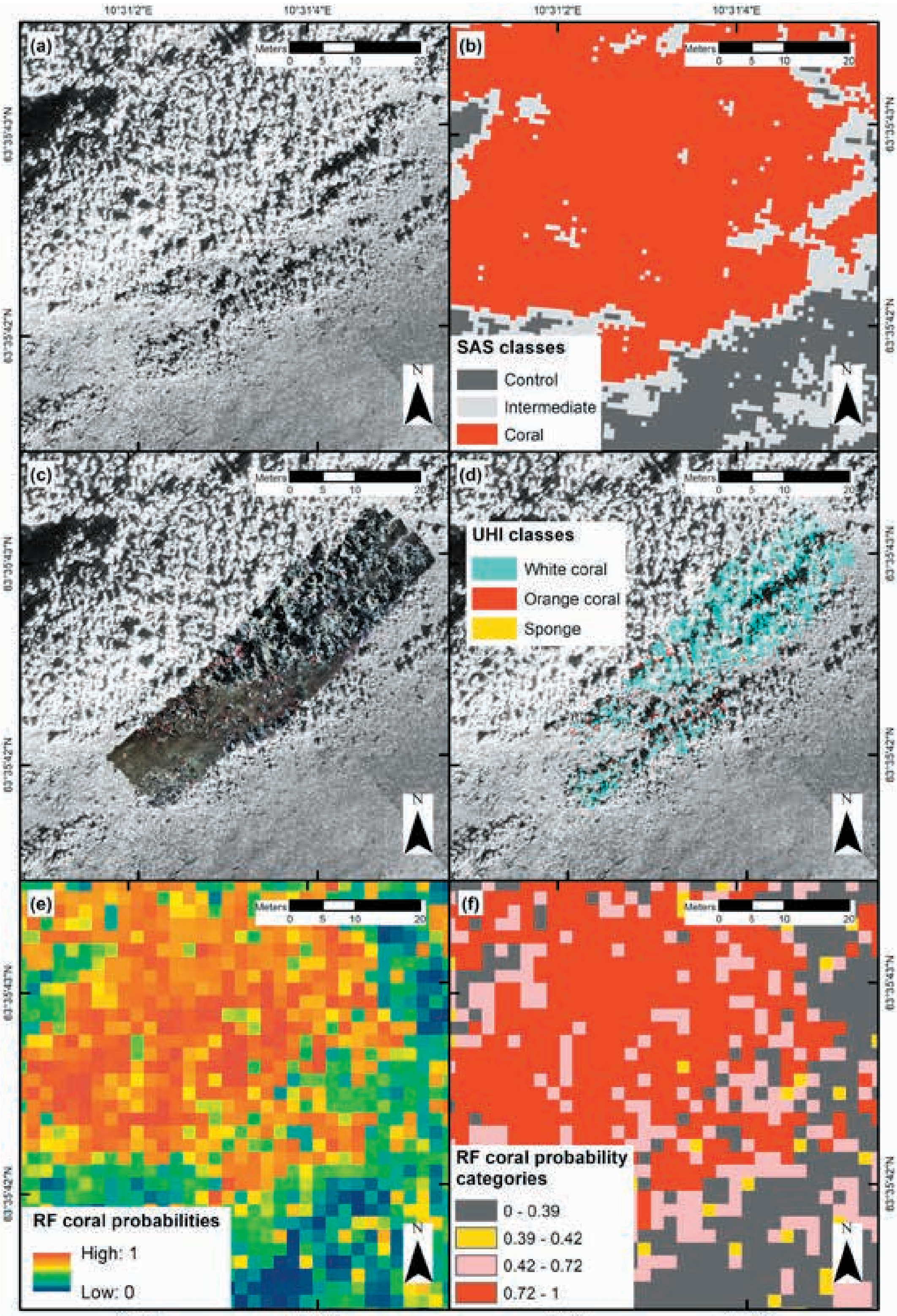



***Figure 13:*** *Comparison of different mapping techniques used on the Tautra Ridge. Panels (a) and (b) show synthetic aperture sonar (SAS) results. Panels (c) and (d) show results of the underwater hyperspectral imaging (UHI) survey. Panels (e) and (f) show results of a multibeam echo sounding (MBES)-based random forest (RF) prediction model created to estimate coral reef coverage along the Tautra Ridge. All panels correspond to the same geographic area.*

# SNAKE ROBOT PLAYS HERO IN BLOCKBUSTER MOVIE


No one could imagine that seven years after Eelume became a spin off-company from NTNU AMOS it would play a major part in the disaster film «The Burning Sea».

The snake robot Eelume started its development at NTNU AMOS and the Department of Technical Cybernetics (ITK), with Professor Kristin Y. Pettersen as the first CEO when the Eelume company was founded.

When the Norwegian production company Fantefilm searched the internet to find the coolest underwater robot in the world, to their surprise they discovered that it was being manufactured in Norway. The robot thus became the first to land a movie role in the film North Sea, which had its premiere in October 2021.

Pettersen, one of the key researchers at AMOS, has been doing research on snake robotics for many years. Pål Liljebäck, now Chief Technical Officer (CTO) of Eelume, took his doctorate in snake robotics with Pettersen as his supervisor. Based on their research, they started the company in 2015.

## Derived from differential equations

The movie world is not the only place where snake robots can be heroes. In the real world, snake robots can also play a crucial role.

For example, underwater robots can help to explore the ocean.

"Only 5% of the ocean has been mapped. A snake robot could help investigate large undiscovered areas, such as the sea under the Arctic and Antarctic," Pettersen says.

## How does a creature like this come about?

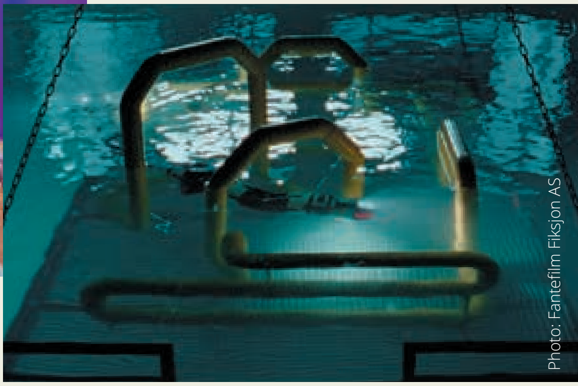
The world's most advanced snake robot for use underwater was first developed through many long math problems that Pettersen and her research group wrote out by hand. When the professors at ITK set out to create something new, differential equations on paper is a key tool.

"Getting robots to move is super fascinating. We use mathematics as a way to decode the secrets of nature. Math is an efficient language for understanding and analysing nature," Pettersen explains. She also said that the mathematical model for a robot fits on one A4 page.

## Can perform various tasks at sea

Pettersen has headed the research that led to a world breakthrough in snake robotics, for which she has won numerous awards. Many other research groups have mostly focused on mechatronics – the actual construction of joints and materials. Pettersen and her team concentrated on the "brain," or the algorithms, for how a snake robot should move.

Photo: Fantefilm Fiksjon AS


After completing his doctorate, Liljebäck became responsible for technology development in the company. With the rest of the Eelume team, he has continued to develop Eelume's snake-shaped underwater robot.

"After six years of enormous effort, Eelume is now getting ready to perform various tasks at sea. Today's robot is the third generation, and in the next few months it will carry out an autonomous inspection of pipelines," Liljebäck says.

Eelume's robot now operates wirelessly, without any tethered connection.

An advanced underwater robot like this can help detect leaks and dangerous problems in underwater installations, warn of spills and pollution or other threats, and do repairs and maintenance.

## Wireless and using AI

The team at Eelume is working hard to ensure that a snake robot like Eelume will not only consist of beautiful math equations conceived at the university, but will also benefit the world through practical uses.

"Pål has a firm grasp when it comes to mastering advanced mathematical theory and constructing the mechatronics themselves. He builds the snake robots so that they look like real creatures, such as giving them eyes that send information, and that almost humanize them. They become personalities. The way he combines a mastery of the theoretical and at the same time has the desire to put it all into practice is truly unique," Pettersen says.

Since Eelume's robot operates wirelessly, it can move completely freely in the water. Work is now continuing to develop more and more autonomous operations for the snake robot to perform. "All cybernetics is really about developing the computer's 'brain' and includes an element of artificial intelligence," Pettersen says.

## Guaranteed powerful

Fantefilm has perfected the disaster film genre in Norway with the films, *The Wave* (Norwegian: *Bølgen*) and *The Quake* (Norwegian: *Skjelvet*). Their third disaster film, *The Burning Sea* (Norwegian: *Nordsjøen*), has also become a success.

"*The Burnings Sea* shows a kind of 'worst case scenario', where we turn up the disaster volume to 11. It's guaranteed to be a powerful film," director John Andreas Andersen, who also directed *The Quake* (2018) said to Filmweb right before the premiere.

Most recently, the trade publication The Hollywood Reporter tells that the film's distributors, TrustNordic, have signed contracts to release the film in Australia, China, Greece, Portugal and New Zealand.

Text: Live Oftedahl

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

## Research activities:

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

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

## Main results

### Formation path following control of underactuated ASVs

**A significant advantage of autonomous marine vehicles is their ability to plan and execute tasks with reduced need for human interference. Some tasks may, however, be too complex to be solved by a single vehicle or be of such a nature that multiple vehicles are required to cooperate. With this, new challenges arise of how path following can be achieved while maintaining a desired overall formation [P2-R1].**

#### Background

The path following control problem for single underactuated marine vessels has been much studied in recent years. The line-of-sight (LOS) approach, by steering the vessel towards a point ahead on the path, is widely used to solve the path following problem, due to its intuitive structure and ability to counteract environmental disturbances (integral-LOS). When considering the control problem for formations of marine vessels, several leader-follower approaches have been proposed where the follower adapts its speed and position relative to the leader to obtain the desired formation. However, leader-follower methods suffer from the fact that communication is unidirectional, meaning the leader will not adapt its speed to the follower. Moreover, the existing leader-follower methods are restricted to following straight-line paths.

Another approach to the formation control problem is the null-space-based (NSB) behavioral control scheme. This guidance system decomposes the control objective into different prioritized tasks, which are solved independently of each other using a closed loop inverse kinematics (CLIK) algorithm. The solutions of each task are then combined by projecting the solution of one task into the null-space of the higher-priority task. Expressing the control objectives in terms of fundamental tasks simplifies the control system design, as the tasks can be designed independently and then assembled to compose a complex behavior which could be difficult to create with a single objective function.

### Formation of path-following control system

In [**P2-R1**], we propose a formation path following method for underactuated autonomous surface vessels (ASVs). The method handles both curved and straight-line paths and may furthermore be realized using only traditional sensors for estimating absolute velocities, such as an inertial measurement unit (IMU) and a global navigation satellite system (GNSS), which are available for most vessels. This is achieved by extending and combining the results for curved LOS path following for single surface vessels with the NSB. By replacing the barycenter CLIK control law with a LOS guidance law, we inherit the path following properties of the well-studied LOS guidance law, while the NSB control scheme is used to design the overall system behavior, thus utilizing the advantages of both methods. Contrary to the curved LOS path following result we build on, where relative velocities are used, we specify the LOS guidance law in terms of absolute velocity, eliminating the need for expensive sensors for measuring the relative velocities.

The control objective is thus to make two underactuated ASVs perform curved path following while aligning themselves such that the vector between them is perpendicular to the path with a desired inter-vessel distance. Specifically, we choose the following three tasks, sorted by priority: collision avoidance, vessel formation and barycenter path following. The first task, running at the highest priority, aims to avoid collisions between the vessels to ensure their integrity. The second task aims to control the vessels' position such that they maintain a desired cross-track distance from the barycenter, perpendicular to the path. This task will have the highest priority during regular operation when the collision avoidance task is deactivated. The last task, running at the lowest priority, aims to move the vessels' barycenter along the desired path. Consequently, this task will only take effect when the task's solution does not conflict with the so- lutions of the higher-priority tasks.

The closed-loop stability of the proposed LOS guidance law for path following of the barycenter, combined with surge and heading autopilots, is analyzed using a cascaded system approach. We show that the closed-loop system is USGES and UGAS, while the underactuated sway dynamics are proved to be bounded. The LOS guidance law is then integrated into the NSB framework, and the theoretical results are verified through both simulations and experiments

### Simulations and Experiments

The simulations present an ideal situation, and the simulation results can thus be expected to comply with and thus validate the theoretical results, as clearly seen in Figure 1. The experiments were performed using the Odin and Frigg USVs, Figure 2, which are under development by FFI. They are 11 m long and 3.5 m wide and propelled by a dual waterjet system. However,

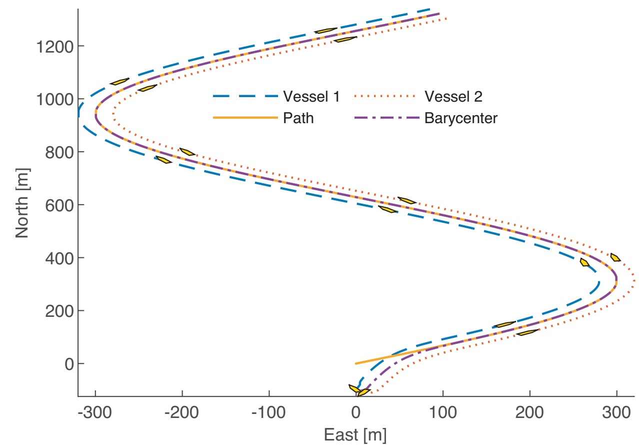



***Figure 1:*** *The simulation results show that the ASVs maintain their desired formation while making the barycenter follow the desired sinusoidal path.*

***Figure 2:*** *Odin and Frigg during the experiments.*

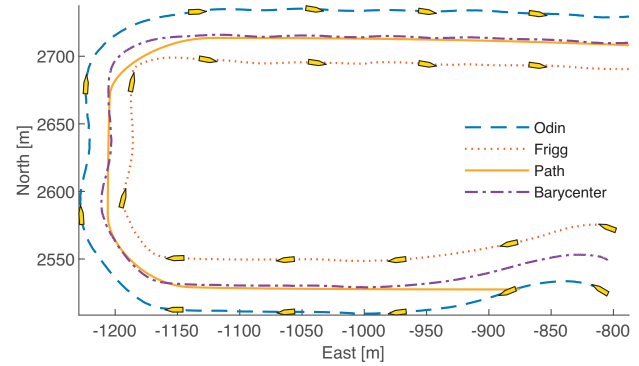



***Figure 3:*** *The ASV positions along with the desired and actual barycenter path.*

***Figure 4:*** *Top left: The lightweight autonomous underwater vehicle on a workbench, before deployment. Photo: Annecken Nøland. Top right: Mausund Field Station, Norway. The field test was a collaboration between the station and NTNU. Photo: Annecken Nøland. Bottom right: Maren Thu, from the Trondheim Biological Station, uses a Plexiglas water sampler, designed and built by NTNU researchers. The design allows fast, efficient water samples in rough seas. Photo: Geir Johnsen/NTNU. Bottom right: Annecken Nøland retrieves the NTNU-designed seawater sampler during field work close to Mausund Field Station. Photo: Maren Thu.*

at maneuvering speeds, the waterjets are linked together, rendering the system underactuated. In the experimental results performed at sea, the barycenter task errors converge to within a neighbourhood of the origin with a small steady-state cross-track error, demonstrating that the proposed method provides some robustness against the measurement noise, model parameter errors and unmodeled dynamics and disturbances including ocean currents present during the experiments. The oceant current adapting autopilots of [P2-R1] could not be implemented, and only simple PI and PD controllers were instead used for surge and heading control. Future work will include performing experiments with the adaptive autopilots to see how this can further improve the cross-track error. Future research results are also underway extending the proposed method to beyond two vessels and also to formation path following control of underactuated autonomous underwater vehicles (AUVs) in 3D.

**Contact:** Kristin Y. Pettersen

## Interdisciplinary Algal Bloom Observation Field Experiment at Mausund Field Station, Norway

Obtaining reliable phyto and zooplankton abundance and distribution data at a high spatial and temporal resolution is a very challenging research task. The RCN-funded AILARON (Autonomous Imaging and Learning Ai RObot identifying plaNkton taxa in-situ) project is an integrated effort for characterizing targeted plankton in-situ **[P2-R4]**. The robotic platform, a lightweight autonomous underwater vehicle (LAUV, cf. Figure 4) uses a camera to image microorganisms in the photic zone, process imagery in-situ, categorize and classify based on Machine Learning **[P2-R6,P2-R7,P2-R8,P2-R9,P2-R10]**, generate a probability density map and uses an advanced AI-based controller to return to the most coherent "hotspots" with respect to species of interest over the survey volume.

In April/May 2021 the AILARON team joined an interdisciplinary group of scientists at Mausund Fieldstation, Norway (Norwegian SciTech News, 2021). The researchers utilized remote sensing technologies (satellites/hyperspectral imaging), unmanned aerial vehicles (AUVs), autonomous surface vehicles (ASVs), and lightweight autonomous underwater vehicles (LAUVs) to observe the spring bloom event. The phytoplankton responds to the increased sunlight associated with the spring, and its biomass starts to be extensively productive. An early detection was anticipated by exploiting remote sensing capabilities from UAVs and satellites.

Data was analyzed from UAVs and satellites, and integrated with data from the ASVs, UAVs, an ocean modeling tool and ground truth water samplings (Figure 4), to enable and coordinate further adaptive sampling.

**Contacts**: Annette Stahl, Nicole Aberle-Malzahn, Geir Johnsen, Tor Arne Johansen

## Autonomous Robots for Ocean Sustainability (AROS) - Towards certifiable visual systems for underwater exploration

**Enabling robots to act autonomously underwater requires perception capabilities, often using cameras. While visual sensing under good visibility conditions or controlled illumination is already very advanced, e.g., in the field of automated driving or production robotics, underwater computer vision still struggles with the severely more challenging situation when there is no or only weak ambient lighting, significant turbidity and thus limited range of vision, and with distracting particles ('marine snow').**

Task-specific active lighting and automatic control of camera pose and viewing direction is mission critical. Exploration of unknown underwater environments, inspection, repair of underwater installations are typical examples of such missions.

In the RCN funded researcher project AROS plays the certifiable visual perception component a central role besides flow sensing, motion planning, and energy harvesting. The NTNU-developed underwater snake robot is the platform for our experiments and the target device for the envisaged technology (Fig. 5).

The verification of underwater visual perception algorithms is crucial for safe underwater exploration and intervention operations. Ground truth data play an important role in evaluating vision algorithms. However, obtaining ground truth from real underwater environments is in general very hard, if at all possible. Therefore, we have developed a synthetic underwater 3D environment, which means that (nearly) all parameters are known and controllable, and ground truth data can be absolutely accurate in terms of geometry.

The VAROS environment and data set [P2-R5] (example images are shown in Figures 6-7) provide highly realistic underwater video and auxiliary sensor data with precise ground truth, built around the Blender modeling and rendering environment. VAROS allows for physically realistic motion of the simulated underwater (UW) vehicle including moving illumination. The VAROS dataset version 1 provides images, inertial measurement unit (IMU) and depth gauge data, as well as ground truth poses, depth images and surface normal images.

Currently, we work on simultaneous localization and mapping (SLAM) methods that explicitly target the difficulties of underwater vision: varying illumination, time-variant shadows, turbidity, cloudiness, small-scale and large-scale dynamic clutter; all of these conditions which cause strong challenges to state-of-the-art vision methods.

The methods are both verified using the synthetic dataset as well as recordings from real missions (Figure 5) with the NTNU Eelume snake robot (Figure 7).

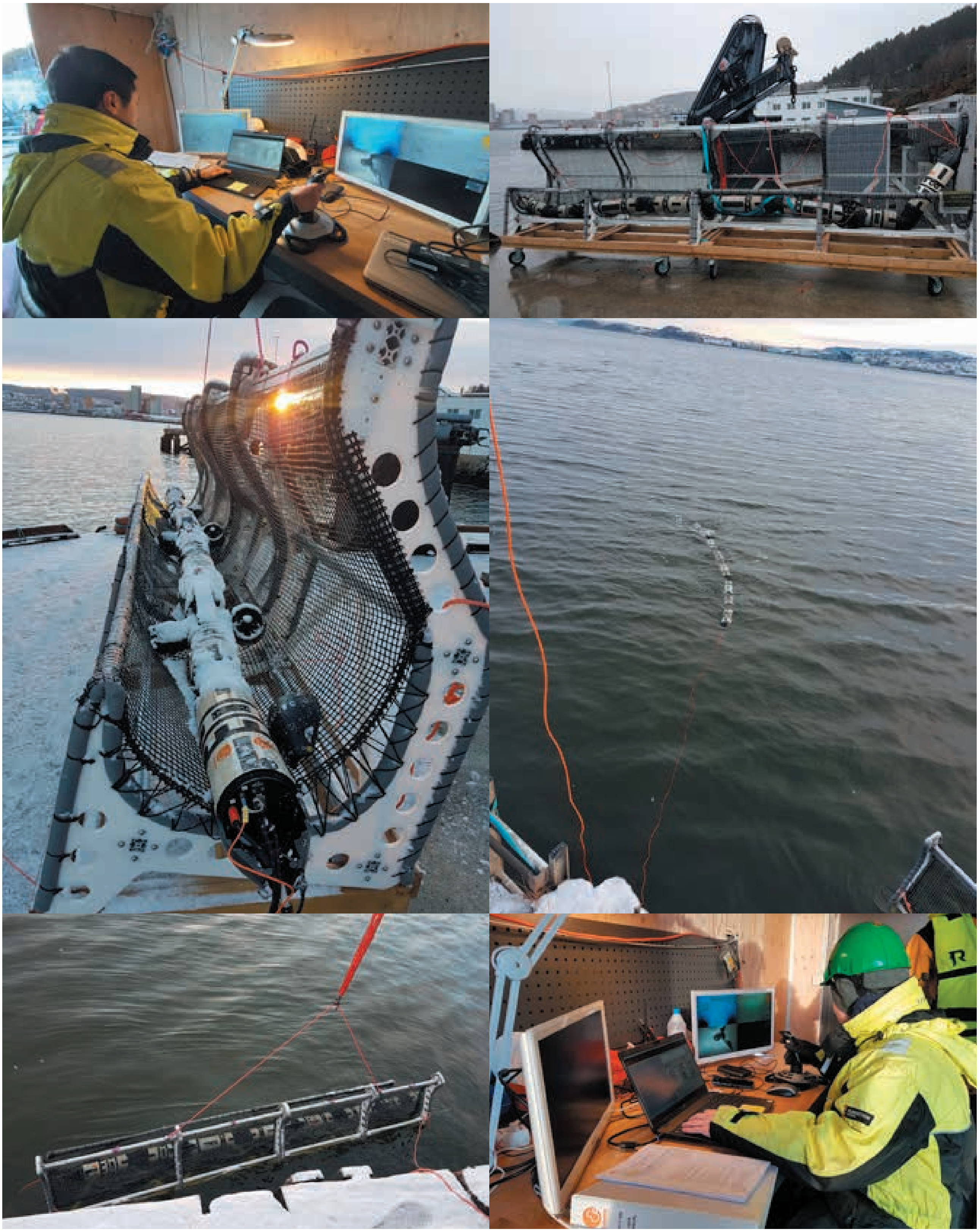


***Figure 5:*** *A typical field workday with the NTNU Eelume snake robot; Photo: Annette Stahl*

*Figure 6:* *The image types contained in the initial version of the VAROS underwater dataset: underwater images and corresponding images with uniform lighting and no water, as well as pixel-accurate surface normal and depth maps.*

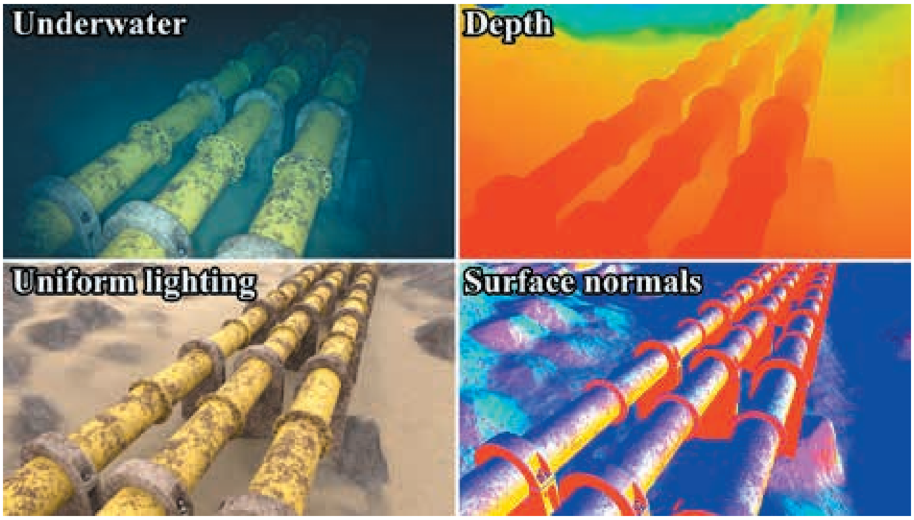



*Figure 7:* *Left: an example image from the VAROS data set [P2-R6]. Right: a real underwater image obtained during a training mission with the Eelume snake robot.*

**Link to the VAROS data set:**
https://www.ntnu.edu/arosvisiongroup/varos
**Contacts:** Mauhing Yip, Andreas Langeland Teigen, Rudolf Mester, Annette Stahl

## Bio-inspired hydrodynamic studies relevant for underwater robots

**Many fishes can be considered as highly performant underwater bio vehicles. Among them, carangiform swimmers propel themselves using body and caudal fin (BCF) locomotion with undulations mostly restricted to the posterior part of their body, within one-third of their length. Moreover, their caudal fin is typically stiff and elongated. This has inspired a systematic numerical study on rigid flapping foils to assess the influence of geometrical and motion parameters on the wake features and foil performances, documented in [P2-R11].**

Three symmetric hydrofoils with the same chord length c are examined, as shown in the left of Fig. 8. The semi-circle foil and its dimensions are consistent with the experiments by Godoy-Diana et al. (2008). Relative to this geometry, the NACA 0012 foil has a trailing edge equally sharp but has a smaller maximum thickness D; the NACA 0021 foil has the same maximum thickness but a thicker trailing edge. Each foil interacts with a steady inflow with speed U and is forced to oscillate about its leading edge at the frequency f,

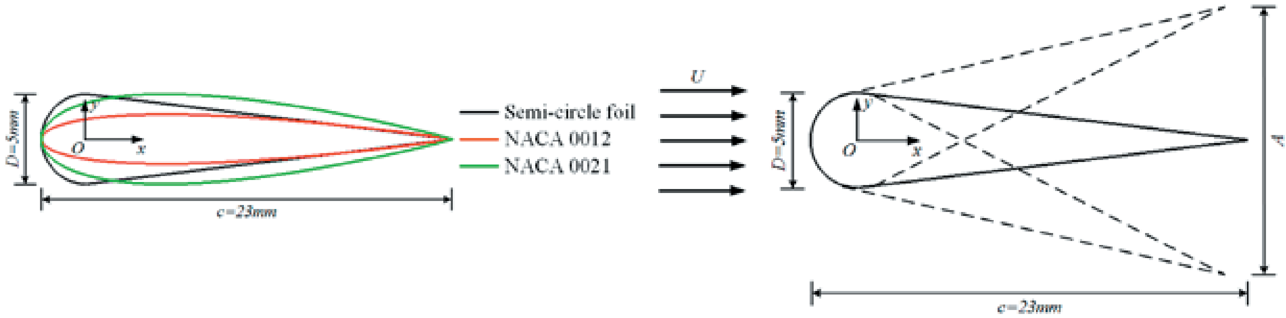



***Figure 8:*** *Left: Schematic view of the foil profiles. Right: Parameter definition of the pitching motion.*

with oscillation amplitude A of its trailing edge (right of Fig. 8) and chord-based Reynolds number Rec equal to 1173 as in the model tests. The inflow-foil interactions are studied by solving the incompressible Navier-Stokes equations with the pisoFoam solver included in the open-source OpenFOAM platform.

Fig. 9 shows the numerical (left panel) and experimental (right panel) phase diagrams of the wake features for the semi-circle foil as a function of the Strouhal number Sr=fD/U and non-dimensional amplitude AD=A/D. The results are in good agreement, supporting the use of the adopted method for further systematic parameter studies. From them, the wake is a von Karman-type (vK-type) wake at small Sr and AD, then evolves into aligned wake with the increase of Sr and AD, and enters the reverse-vK regime at sufficiently large Sr and AD. Finally, the drag-to-thrust transition does not coincide with the transition from vK

***Figure 9:*** *$A_D$=A/D vs. Sr=fD/U map for the semi-circle foil. Left: simulations. Right: experiments by Godoy-Diana et al. (2008). Blue line: transition between vK-reverse vK wake. Green line: transition between reverse vK and asymmetry regimes. Red line: predicted curve of drag-to-thrust transition. The grey region corresponds to the $Sr_A$=fA/U=0.3±0.1 interval.*

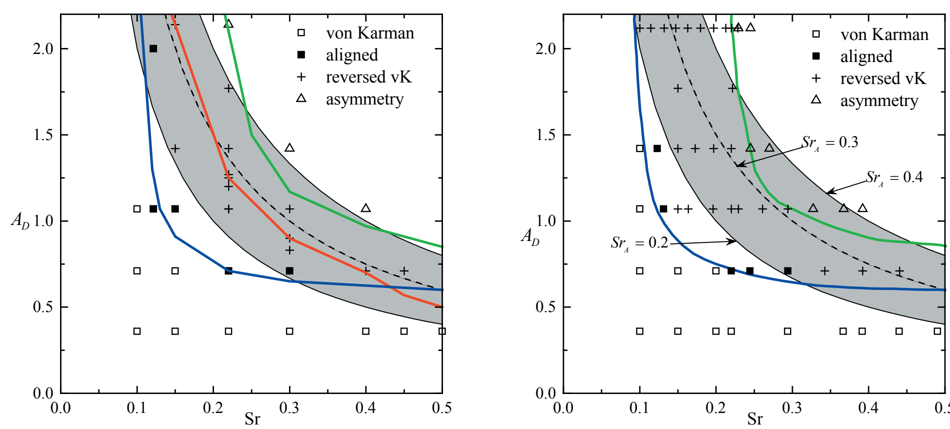



***Figure 10:*** *NACA 0012 (results in red), NACA0021(results in green) and semi-circle foil (results in black). Left: $A_D$=A/D vs. Sr=fD/U map; the solid lines correspond to drag-to-thrust transition. Right: Amplitude-based Strouhal number $Sr_A$=fA/U vs. chord-based Reynolds number $Re_c$=Uc/ν (ν is the fluid kinematic viscosity) at drag-to-thrust transition condition.*

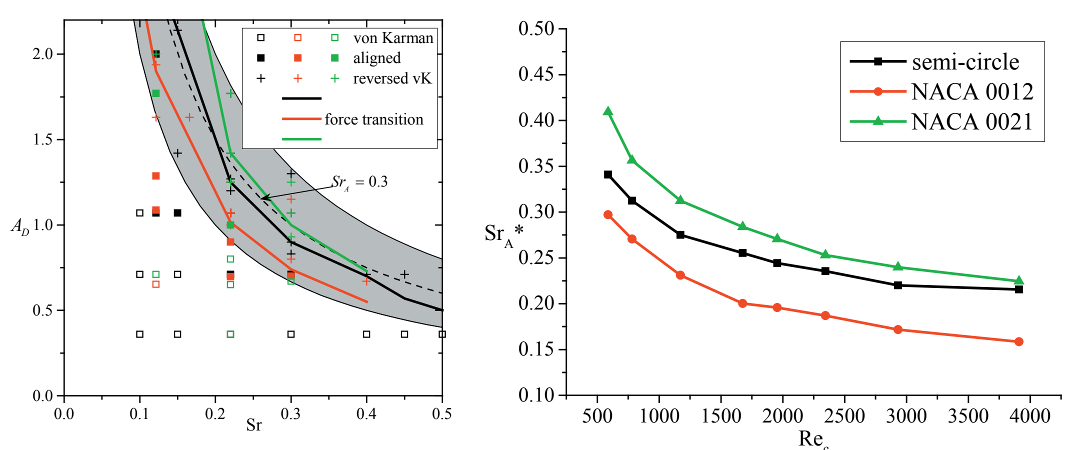


***Figure 11:*** *Forward component of the slip velocity for different undulation amplitudes dβ: (a) potential contributions; (b) vorticity contributions*

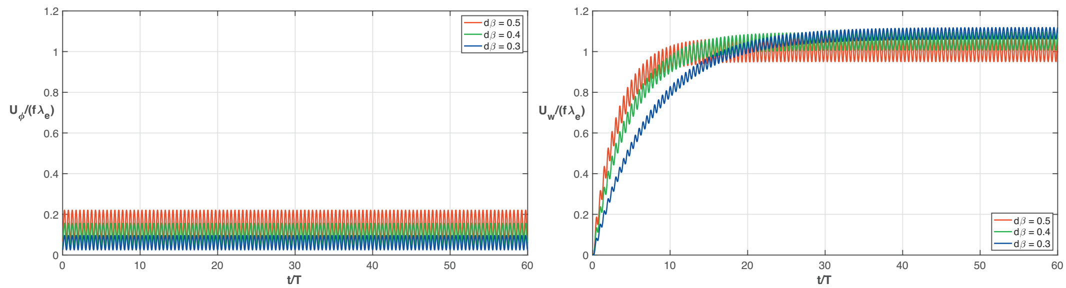
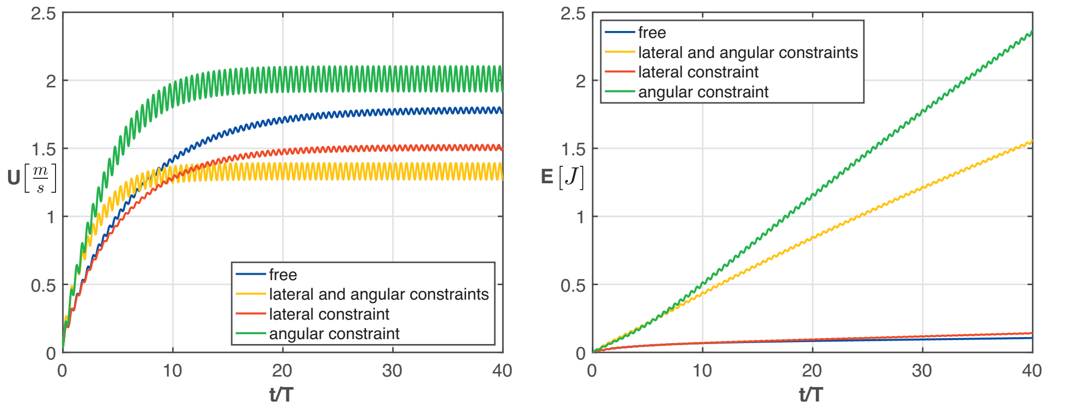



***Figure 12:*** *Time history of (a) the forward velocity and (b) the kinetic energy for free swimming (blue) and constrained gaits: lateral and angular constraints (yellow), lateral constraint (red) and angular constraint (green)*




to reverse-vK wake regime. This fact is important for propulsion and performances.

In the left of Fig. 10, the wake structures of the NACA foils show similar trends as the semi-circle foil but the wake-scenario and drag-to-thrust transitions occur at different values of the Strouhal number highlighting the importance of their shapes. The critical amplitude-based Strouhal number $Sr_A$*, i.e., the value of $Sr_A$=fA/U at which the net horizontal force changes sign and therefore the drag-to-thrust transition occurs, is not universal but depends on $Re_c$, as shown in the right of Fig. 10. $Sr_A$* is inversely related to $Re_c$ and the drag-to-thrust transition of the foil pitching at the forced oscillations approaches the vk-reverse vK wake transition curve for increasing $Re_c$.

The simulations show that when the three foils perform the same pitching motions in the same inflow, the NACA 0012 foil is associated to the largest thrust, but it also experiences the largest hydrodynamic torque, which might pose possible issue for structural integrity. The NACA 0021 foil has the smallest thrust but also the smallest torque. This has inspired ongoing research on a morphing-foil strategy, aimed to provide the best compromise between the two NACA geometries; it could serve as a basis for underwater applications provided a suitable maturity of soft or nearly soft mechatronics.

The intertwining effects of the added mass and vorticity release, embedded in the forcing terms of a CFD model, have been suitably studied within an impulse theory based on a 2D potential flow model with a concentrated vorticity **[P2-R12]**. It provides a flexible tool to cope with the complexity of the self-propelled motion accelerating from zero to a steady-state asymptotic velocity. A NACA 0012 foil with an undulatory mid-line deformation, enforced through the mid-line slope $\beta$=d$\beta$sin(2π(s/$\lambda_e$-ft)), is investigated. Here, f=1/T is the frequency and $\lambda_e$ the equivalent wavelength of the undulatory motion and s the curvilinear coordinate of the mid-line.

The study revealed that, for a neutrally buoyant swimming body, the added mass gives the instantaneous burst in the forward velocity (Fig. 11a) necessary to activate the vortex shedding into the wake which contributes to the forward speed (Fig. 11b). A larger undulatory motion amplitude dβ induces a larger potential $U_\phi$ contribution but a smaller vorticity $U_w$ contribution. However, within an ideal not dissipative system, the total slip velocity U/f$\lambda_e$ (ratio between the forward swimming speed and the equivalent phase speed ω/ke= f$\lambda_e$) keeps constant with dβ. Note that the slip velocity is larger than 1 in the free-swimming condition. This is the consequence of the recoil [P2-R13], with an additional rigid translational and rotational motion which modifies the asymptotic forward velocity. The interconnected results of the locomotion velocity (Fig. 5a) and expended energy (Fig. 5b) confirmed that the free-swimming motion enables the optimal performance of the aquatic locomotion with respect to the possible constrained motions **[P2-R13]**.

**Contacts:** Marilena Greco and Claudio Lugni

## Automatic Simulation-based Testing of Autonomous Ships using Gaussian Processes and Temporal Logic

**Autonomous ships are approaching a reality, with numerous ongoing projects ranging from small research prototypes to full-scale industrial vessels. Although several degrees of autonomy exist, autonomous ships are typically distinguished by being able to operate independently of a human operator in a non-trivial operation, requiring situational awareness and planning abilities. These characteristics have created a need for new design methodologies among autonomous ship developers, as well as a need for new methods and processes for safety assurance among regulators and classification societies. This work presents a novel methodology to automate and formalize simulation-based testing of autonomous ships [P2-R14].**

Building a compelling argument for the safety of autonomous systems has proven to be a challenge. In the maritime domain, extensive use of simulation-based testing has been proposed as a possible approach. Simulation-based testing refers to creating a simulation model, often termed a digital twin, of a system together with its operative environment and performing testing on the digital twin instead of the actual system in the real world. Simulation-based testing is attractive due to its scalability, that is, it is possible to assess system level behaviors for highly complex systems. Autonomous vessel concepts are characterized by high levels of complexity in their hardware and software systems, as well as in their interaction with the operative environment. Combined with the intrinsic challenges related to verification of autonomous functions, such as the use of machine learning components and hard-to-predict emergent behaviors, simulation-based testing stands out as a promising and key way forward. Simulation-based testing, in particular Hardware-in-the-Loop (HiL) testing, has strong traditions in the maritime industry already.

While simulation-based testing offers a great platform for verification, it is paramount that it is used in combination with valid processes for test case selection, evaluation of results and test coverage assessment. Traditionally, the selection of test cases has been a manual process based on risk analyses and experience with incidents and typical pitfalls in development and implementation. For emerging technologies, such as autonomous vessels, this approach is challenging, as the necessary experience, regulations, class notations and best practices are not yet available. Moreover, the operative environment for autonomous systems is characterized as highly dynamic, unstructured and uncertain, which gives a wide span of possible situations and failure combinations. This necessitates a large number of simulations to obtain sufficient test coverage, which calls for automation of the test case selection and corresponding evaluation of the results. Also, since simulation-based testing, in contrast to more formal methods, is almost never able to test all possible scenarios due to practical computation time constraints, the notion of confidence level in the verification becomes important. By confidence level, we refer to the probablilty that a verified system actually contains no requirement violations. Since autonomous ships are safety-critical, it is crucial to have methods to assess the confidence level in the verification efforts to build sufficient trust.

The main scientific contribution of our work is the development of a methodology for simulation-based testing which attempts to address the needs specified above. We propose to formulate the requirements to test against in the formal logic Signal Temporal Logic (STL). STL allows us to specify complex requirements to test against in a clearly defined and unambiguous language. Moreover, STL have quantitative robustness semantics. This means that evaluating a simulation against an STL requirement results in a robustness score which indicates the level of compliance the the requirement. STL therefore both gives a language to formulate formal requirement in and enables automatic quantitative evaluation of simulations against the given requirements. Furthermore, we define parametric test cases, where a more general parametric case is defined manually, and we aim to verify that all concrete subcases meet the requirements. We use

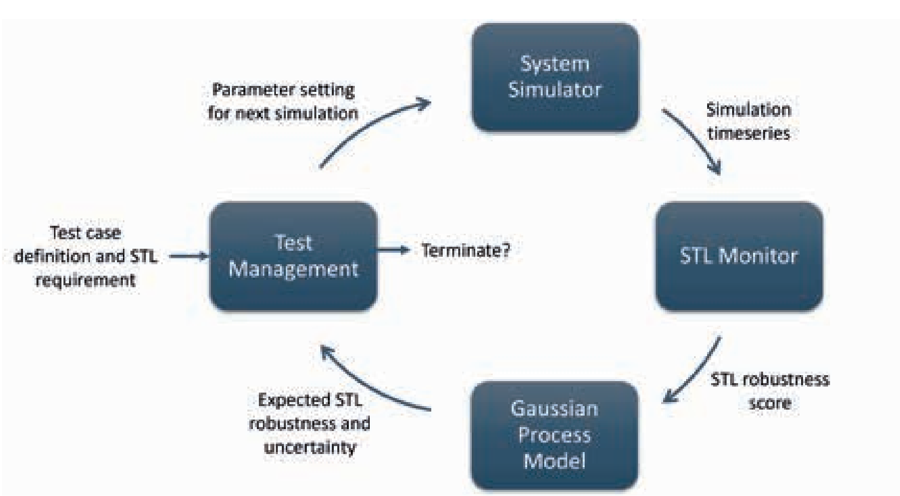
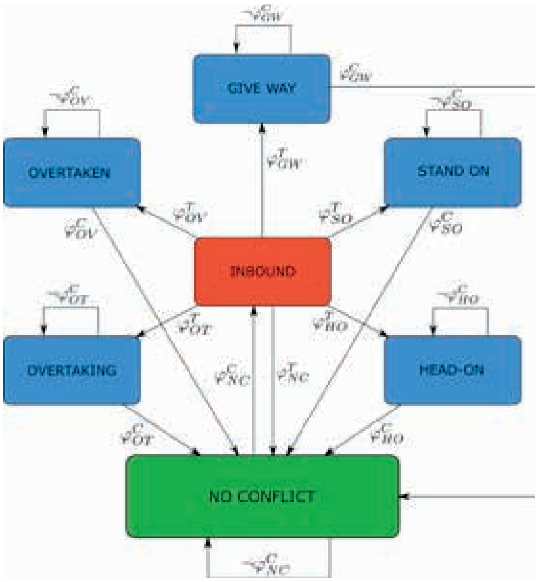



***Figure 13:*** *An overview of the main components of the proposed testing methodology and how they interact*




$$\varphi_{safety} = \Box\neg(d_i \leq d_{min})$$
$$\varphi_{mission} = \Box(e \leq e_{max})$$
$$\varphi_{colreg} = \Box(HO \rightarrow \varphi_{HO} \wedge GW \rightarrow \varphi_{GW} \wedge OT \rightarrow \varphi_{OT})$$
$$\varphi_{HO} = t_{CPA} \leq t_{CPA,turn} \rightarrow \beta_r \in [-170^\circ, -10^\circ]$$
$$\varphi_{GW} = t_{CPA} \leq t_{CPA,turn} \rightarrow d_{CPA} \geq d_{CPA,min}$$
$$\varphi_{OT} = t_{CPA} \leq t_{CPA,turn} \rightarrow d_{CPA} \geq d_{CPA,min}$$
$$\varphi^C_{OT} = \varphi^C_{OV} = \varphi^C_{GW} = \varphi^C_{SO} = \varphi^C_{HO} = t_{CPA} \leq 0$$
$$\varphi^C_{NC} = d_{CPA} \leq d_{CPA,min} \wedge t_{CPA} \leq t_{CPA,min}$$

***Figure 14:*** *STL requirements used in the case study. The left figure shows a finite-state machine for selecting the COLREG situation (HO = Head-on, GW = Give way, SO = Stand-on, OT = Overtaking, OV = Overtaken). Each situation has a trigger condition based on the sectors for the heading and bearing of an incoming vessel. To the right, the STL formulas for safety distance, mission compliance and COLREG are shown.*

a Gaussian Process (GP) model to predict the robustness and uncertainty level over the entire parameter space. The GP model is updated by running simulations and observing the resulting performance, and its estimates used to adaptively guide the test case selection towards cases with low performance or high uncertainty. The proposed testing method incrementally runs new simulations until the entire parameter space of the test case is covered to the desired confidence level, or until a case which falsifies the requirement is identified. A schematic overview of the methodology is given in Figure 13.

To demonstrate the use of the proposed method a case study has been conducted for collision avoidance of an autonomous vessel in open sea. The test object of the case study is the Branching Course Model Predictive Control (BC-MPC) collision avoidance algorithm implemented on a small high-speed vessel. We formulate three classes of STL requirements to test against: Safety distance, mission compliance and COLREG compliance. These are detailed in Figure 14.

We illustrate the use of out testing methodology on a head-on situation where the obstacle performs a predefined avoidance maneuver. The case has two parameters, the angle of the maneuver and the speed of the obstacle. The results from running the testing algorithms against the safety distance requirement is shown in Figure 15. The automatic testing method resulted in a falsification after 273 simulations as a safety distance violation was found. We also note that the robustness surface in Figure 15 illustrates the adaptivity in the test case selection well, as the simulations are much denser in areas of low robustness.

The identified safety violation appears to lie on a very sharp spike of low robustness. To validate this, and assess the overall prediction of the GP, a reference robustness surface was generated by running 2501 simulations in a 61x41 grid over the parameter space. This confirmed that the violation occurs at very narrow spike of low robustness. In fact, of the 2501 simulations, only five resulted in a safety violation, all located at this spike. This is clearly a very difficult or time-consuming safety violation to detect by manual or brute force approaches. Furthermore, it illustrates that even for such a simple case with only one obstacle in open water and perfect situational awareness, safety violations that are difficult to anticipate and detect can emerge.

We replay the simulation with the falsifying behavior to examine the cause of the safety violation. This can be very useful input for debugging and fixing the control software. The course of events is illustrated by the time-lapse in Figure 15. Ownship (blue trace) first turns starboard to do a port-port passing in accordance with COLREG Rule 14 for head-on situations. As the obstacle breaks COLREGS and turns port, ownship turns more steeply starboard to avoid a collision while still being COLREG compliant. Finally, ownship determines that a collision cannot be avoided by a port-port passing and decides to break Rule 14 and turn steeply port. At the same time, the obstacle turns starboard and a collision occurs. To better understand the cause of the safety violation and see what the sharp decision boundaries of the spike represent, simulations from both sides of the spikes were also replayed by altering the maneuver angle by +/- 1 degree. The simulations showed that for -1 degree the collision avoidance system decided to be compliant to Rule 14 throughout the encounter. For +1 degree, on the other hand, it decided early to break Rule 14 and turn port. Both of these decisions resulted in large safety margins.

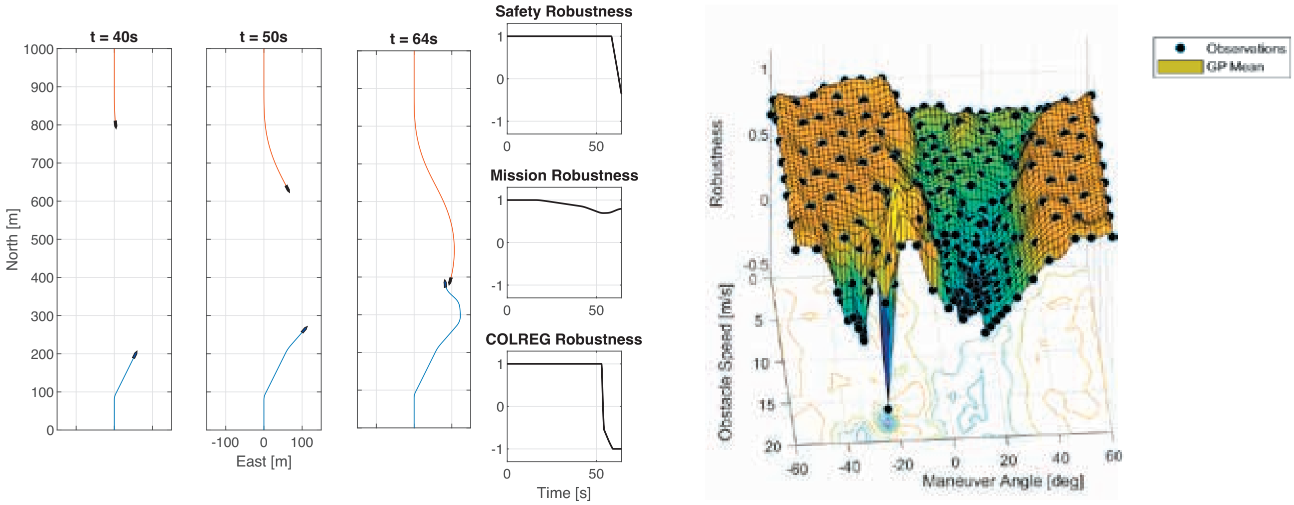



***Figure 15:*** *Example run of the automatic testing algorithms. To the right, the robustness surface is shown after a scenario which violates the safety distance requirement has occurred. To the left, a time-lapse of the identified violation is shown.*

However, in the very narrow region in between, the CA system is indecisive and switches from the first strategy to the second at the critical moment, which results in a collision.

In conclusion, we believe that these results show promise, by both achieving verification in feasible time and identifying falsifying behaviors which would be difficult to detect manually or using brute-force methods. An additional contribution of this work was a formalization of COLREG using temporal logic, which appears to be an interesting direction for future work.

**Contacts:** Tobias Rye Torben, Ingrid Bouwer Utne and Asgeir Sørensen

## Fluid flow-inspired guidance model for autonomous ships

**In autonomous robotics, path planning is a central problem. The objective of path planning is often to find a safe path from the agent's initial position to a destination. In the marine industry, research on autonomous ships is gaining increasing attention, as a next evolutionary step in ship technology and operations. Conflict resolution, including how to find a collision-free path, is a main issue to be addressed to achieve safe ship navigation and maneuvering [P2-R15].**

The stream function, augmented with vortex flows, is adopted to generate waypoints. The dynamic flow of fluids is used as a guidance model, where the collision avoidance in static

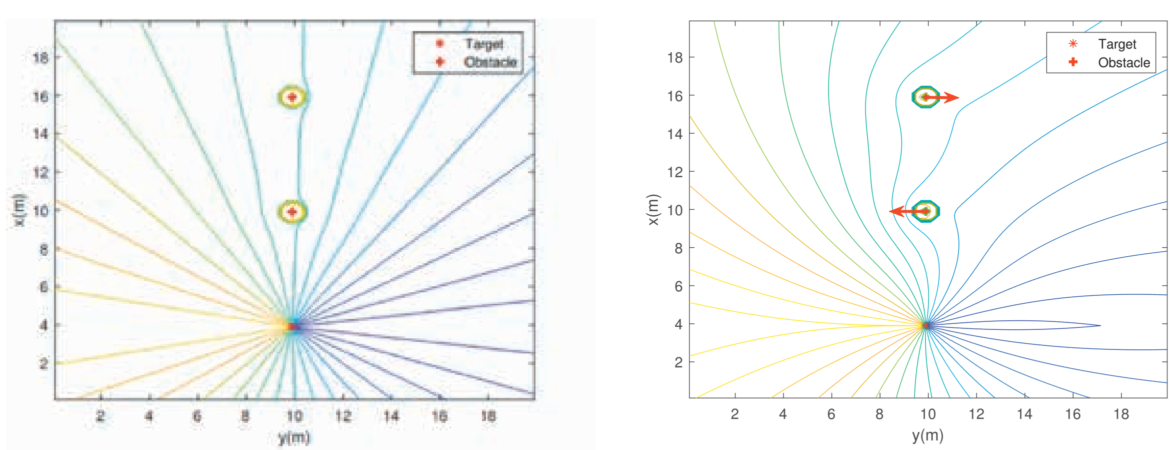



***Figure 16:*** *Avoidance of multiple moving obstacles: The flow field (left) without vortex; (right) COLREG-compliance, with a vortex strength 0:05 (counterclockwise) and 0:07 (counterclockwise)*

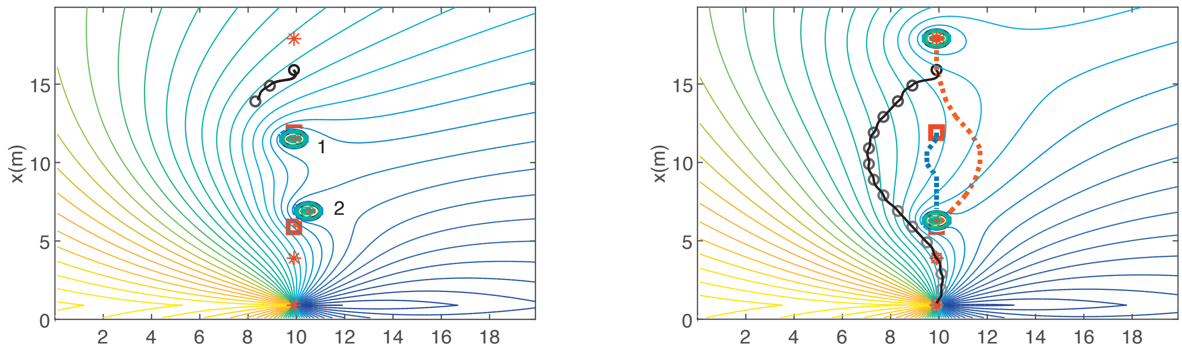



***Figure 17:*** *Obstacle avoidance simulation result of the complex situation*

environments is achieved by applying the circular theorem in the sink flow. We extend this method to dynamic environments by adding vortex flows in the flow field. The stream function is recursively updated to enable "on the fly" waypoint decisions. The vessel avoids collisions and also complies with several rules of the Convention on the *International Regulations for Preventing Collisions at Sea*. The method is conceptually and computationally simple and convenient to tune, and yet versatile to handle complex and dense marine traffic with multiple dynamic obstacles.

The algorithm was integrated with a path generation algorithm using Bezier curves, which formulates a quadratic programming problem to minimize the path length between two waypoints. The dynamics of the marine vessel is taken into account by adding constraints on path curvature. A backstepping-based maneuvering control design, resulting in a cascade structure in the error states, was performed to achieve path following. The system has been demonstrated through simulations, including overtaking, head-on, crossing, and complex situations.

**Contacts:** Zhengru Ren, Mathias Marley and Roger Skjetne

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**P2-R5.** **Olofsson Zwilgmeyer, P. G., Yip, M., Langeland Teigen, A., Mester, R., and Stahl, A.** "The VAROS Synthetic Underwater Data Set: Towards Realistic Multi-Sensor Underwater Data with Ground Truth", *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV) Workshops*, 2021, pp. 3722-3730.

**P2-R6.** **Teigen, A., Saad, A., Stahl, A., and Mester, R.** Few-Shot Open World Learner. IFAC-PapersOnLine, 2021.

**P2-R7.** **Haug, M., Saad, A., and Stahl, A.** CIRAL: A hybrid active learning framework for plankon taxa labeling. IFAC-PapersOnLine, 2021.

**P2-R8.** **Borgersen, J., Saad, A., and Stahl, A.** MOG: A background extraction approach for data augmentation of time-series images in deep learning segmentation. Proceedings of SPIE, the International Society for Optical Engineering 2021.

**P2-R9.** **Haug, M., Saad, A., and Stahl, A.** A combined informative and representative active learning approach for plankton taxa labeling. Proceedings of SPIE, the International Society for Optical Engineering 2021.

**P2-R10. Salvesen, E., Saad, A., and Stahl, A.** Robust Deep Unsupervised Learning Framework to Discover Unseen Plankton Species. Proceedings of SPIE, the International Society for Optical Engineering, 2021.

**P2-R11. Xu, H. L., Greco, M., and Lugni, C.** "2D Numerical Study on Wake Scenarios for a Flapping Foil", In International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers, Vol. 85185, p. V008T08A033, 2021.

**P2-R12. Paniccia D., Graziani G., Lugni C., and Piva R.** "On the role of the added mass and vorticity release for self-propelled aquatic locomotion", Journal of Fluid Mechanics, vol 918, A45, 2021, https://doi.org/10.1017/jfm.2021.375

**P2-R13. Paniccia D., Graziani G., Lugni C., and Piva R.** "The relevance of recoil and free swimming in aquatic locomotion", Journal of Fluids & Structures, Vol. 103, 103290, 2021, https://doi.org/10.1016/j.jfluidstructs.2021.103290.

**P2-R14. Torben, T. R., Glomsrud, J. A., Pedersen, T. A., Utne, I. B., and Sørensen, A. J.** "Automatic simulation-based testing of autonomous ships using Gaussian processes and temporal logic", Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 2022, https://doi.org/10.1177/1748006X211069277

**P2-R15. Zhou, H., Ren, Z., Marley, M, and Skjetne, R.** "A guidance and maneuvering control system design with anti-collision using stream functions with vortex flows for autonomous marine vessels", IEEE Transactions on Control Systems Technology, 2021. Accepted.

### Selected media coverage:

- A robotic microplankton sniffer dog. By Nancy Bazilchuk, Norwegian SciTech News. 27.05.2021.
- Snake robot turned movie hero, By Live Oftedahl, ScienceNorway, 20.11.2021

### Plenary lectures at international conferences:

- **Pettersen, Kristin Ytterstad**. Snake robots – bioinspiration gives efficient robots for ocean exploration. IEEE CSS Distinguished Lecture at the IEEE CSS Colombia Chapter and Plenary lecture at the IEEE Colombian Conference on Automatic Control, October 19, 2021.

Photo: Live Oftedahl

**Two PhD-students driving a Blueye outside of AUR-Lab.**

# WHAT HAPPENED TO THE CRUISE-FERRY ESTONIA?

September 28, 1994, the cruise-ferry Estonia en route from Tallin to Stockholm in the Baltic Sea capsized and sank causing 852 fatalities and only 137 survivors, making it one if the worst ship disasters in the 20th century. The official explanation of the accident was that impacts from large head waves caused separation of the bow door (the visor) from the vessel, and in that process it pulled the water-tight bow ramp open.

This in turn caused large volumes of water to flow in on the card deck jeopardizing hydrostatic stability of the vessel, which got a large list and further flooding until it eventually sank to the sea floor in a water depth of about 80 m. The bow door failed because two side locks and a bottom lock attaching the bow door to the hull were not sufficiently designed to resist the loads to which they were exposed.

Demands were raised that the entire ship be raised so that the dead bodies remaining In the wreck could be retrieved and given a burial and the true cause of the accident be determined. However citing the practical difficulties, the moral implications and the large costs of the operation the Swedish government declared the site a sanctity to prevent divers to go into the wreck and disturb the deceased bodies. They also suggested the burying the whole ship with a shell of concrete and 10000 tons of pebbles were dropped before abandoning the plans.

Several conspiracy theories have been launched about the cause of the accident; such as explosions in the bow door or ship side, impacts with other objects or submarines. It has also been argued that the Estonia could not have sunk or done that at a slower rate unless another hole had been created in the ship. It was also alleged that Estonia was used to smuggle military equipment from former Soviet Union to UK. The Swedish government admitted that this was correct in 2004, but Estonia had not been used for this purpose during the fatal voyage.

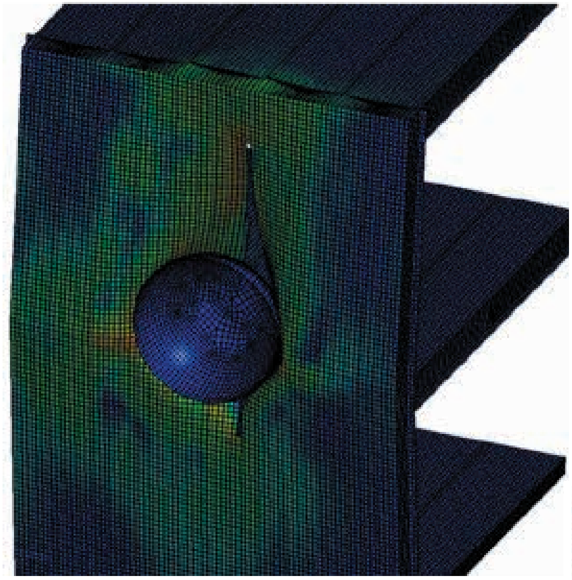
In September 2019 the Swedish journalist Henrik Evetsson lead a team from Germany (who had not signed the treaty of sanctity) to dive down to thwe wreck. They discovered a previously unknown hole in the ship starboard sign around car deck level, which obviously could have had an impact on the course of the events if it existed during capsizing. The diving to the wreck and interviews with survivors and various experts were documented in the film The Find That Changes Everything on the channel Discovery+.

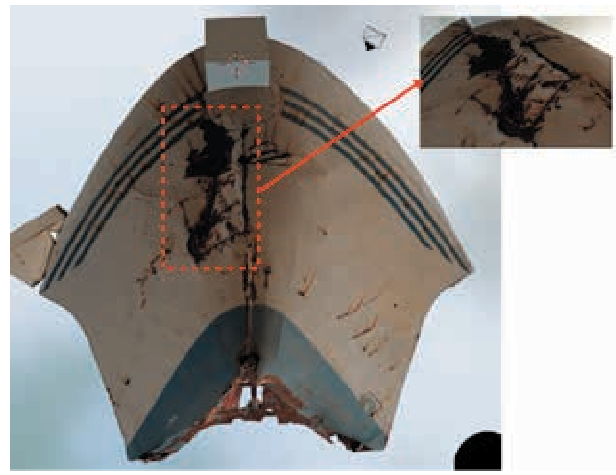
In October 2019 Prof. Jørgen Amdahl was contacted by the producer of the documentary Frithjof Jacobsen in Monster to comment upon this new evidence. He and Postdoc Zhaolong Yu further carried out nonlinear finite element analysis of the side in the damaged area with the software LS-DYNA (Figure) . On the basis of these analyses, we estimated the force required to create the damage to being in the range of 5-600 tons and the associated energy dissipation to 2.3 MJ. For illustration; this corresponds to the energy of an object with a mass of 1000 tons at a speed of 4 knots or 5000 tons with a speed of 1.9 knots. It was emphasized that the calculations were very uncertain as neither complete structural drawings of the ship side were available nor accurate dimensions of the damage level. We had also the view that further investigations be dome to clarify whether the damage was due to the impact with the seabed when the ship sank or later sliding down the sloping seabed. If not, further investigations regarding possible impacts from objects prior to sinking should be evaluated.

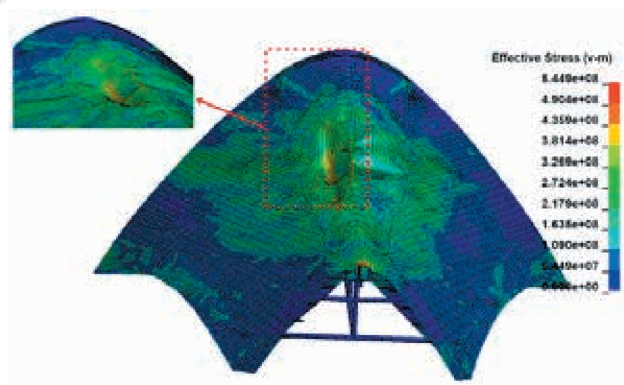
A curiosity; Monster interview and filmed Professor Amdahl in an almost empty Britannia hotel March 12 2020, one day before the heavy Covid -19 restrictions were imposed in Norway (filming at Marinteknisk senter had been planned , but was cancelled).

As a result of this work Professor Amdahl was also interviewed by Icon films Uk in conjuction with their series Mysteries of the Deep to be televised in the US.


*Estonia a) Ship wreck position b) Hole in side c) car wheels and axle.*








*Simulation of Estonia ship side penetration.*

Further investigations on the site were carried out in the summer of 2021 organized by the Swedish Authorities, but also a private expeditions lead by the former chief prosecutor of Estonia Margus Kurm on behalf of the Mare Librium Foundation In particular, the seabed conditions were surveyed. According to the Swedish investigation, hard spots (rocks) do exist in the seabed and the damage profile was between the floor close to the damaged areas. Other investigators claim that the soil basically consists of mud.

The 2019 and 2021 filming showed also that more holes exist in the hull and the damage profile was better characterized by the 2021 investigations. As structural drawings will become available, Amdahl, Yu and PhD-student Xintong Wang will conduct further analysis of the side damages, to improve the estimates of the forces and energy dissipation and elaborate on various hypothesis of the causes of the accident. Professor Manolis Samuelides of National Technical University of Athens (NTUA) will also be involved in this work, with whom Jørgen Amdahl has had a long term collaboration, including Estonia accident issues.

The loss of the visor has also attracted interest. The visor has a major vertical indentation in the front and several smaller horizontal indentations. In 2021 we conducted preliminary analyses and found that the several of damages were compatible with a fall from the main deck onto the bulbous bow.

Nevertheless, some issues remain unexplained. The bottom stringer of the visor was severely deformed and fractured. Metallographic investigations of steel samples conducted by Ass. Professor Ida Westermann, Department of Materials Science and Engineering, shows that the material locally has undergone very high temperatures (up to 1200 degrees Celsius) that cannot be explained by mechanical deformation and friction.

Full involvement in further investigations of the Estonia accident will be too time consuming considering other research and teaching obligation we do have. However, we have decided to conduct a limited and follow-up investigation of the damages in the ship side and the visor. All previous and further work (has been and will be conducted by AMOS and dept. Marine Technology. We consider it essential to maintain independence and neutrality regarding issues that potentially may be highly controversial.

Text: Jørgen Amdahl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# 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.

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

- Theoretical and experimental analysis of closed fish cages in waves.
- Comparative investigation of closed versus semi-closed fish cage in waves.
- Steady-state and stability analysis of a floating rectangular container and inner.
- Sloshing in an aquaculture closed-containment system with a rotating liquid.
- Sloshing in upright circular containers as an example of a floating fish cage.
- Steady-state and stability analysis of a floating rectangular container and inner sloshing for resonant external wave excitations, discovering a chaos.
- A 2D harmonic polynomial cell (HPC) method with immersed boundary technique for studying nonlinear wave-body interactions.
- A fully nonlinear 3D numerical wave tank using HPC for large-scale wave modelling.
- Scaling-law analysis of the maximum loads and oscillation frequency of the air cavity closed behind a 3D body during water entry.
- Understanding the discrepancies between experiments and engineering models for wave-induced low-frequency motions of floating wind turbines through CFD simulations.
- Dynamic analysis of novel gearbox configurations for offshore wind turbines.
- Developing methods for more efficient assessment of fatigue damage on large-diameter monopile wind turbines.
- Allowable sea state assessment of marine operations considering weather forecast uncertainty.
- Real Time Prediction of Operational Safety Limits for Dynamic Positioning of FPSO's.
- Structural reliability analysis of sea-fastening structures.
- Real-time hybrid model testing of ocean structures.
- Thermal analysis of structural steel subjected to cryogenic spills.

## Highlights

Salmon lice becomes an important challenge for the Norwegian aquaculture industry nowadays. The treatment of sea lice could constitute more than 10% of production costs and the high cost of delousing treatments has led to the development of preventive sea cage designs, such as closed fish cage systems (CCS). The physical contact between the infective sea lice larvae and the salmon host could be prevented by pumping and filtering water from sufficiently large depth into enclosed cages.

The station-keeping behaviour of CCS differ greatly from traditional net-based cages, involving strong coupling between the interior flow, the cage structure, and the external environment. To guarantee structural safety and fish welfare, a better understanding of the hydrodynamic behaviour of CCS is necessary. For this purpose, **wave-induced responses of a closed floating fish cage in waves** have been studied theoretically and experimentally in **[P3-R1]**. The cage model consists of a vertical circular free surface-piercing cylinder with an external toroidal floater (see Fig. 1). The focus was to investigate how the internal sloshing would influence the global response of the cage, the interior wave elevation, and the mean drift loads.

Left and middle panels of Fig. 2 show surge and pitch motions in a frequency range of primary importance for local wind generated

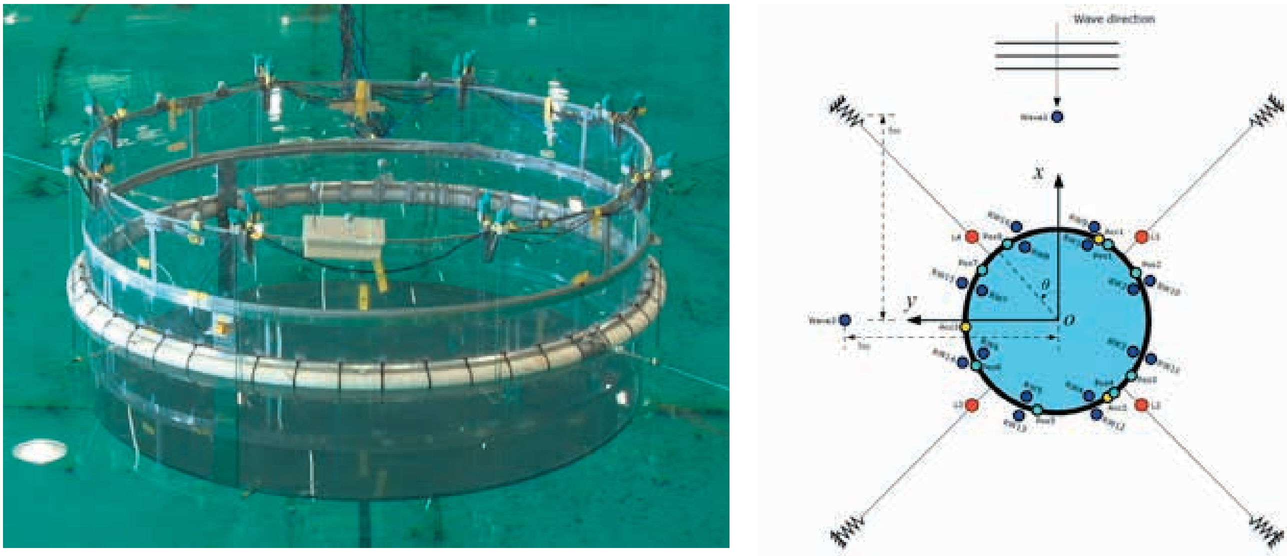



***Figure 1:*** *Left: Front-camera photo of the physical set-up. Right: sketch of the instrumentation setup from top view.*

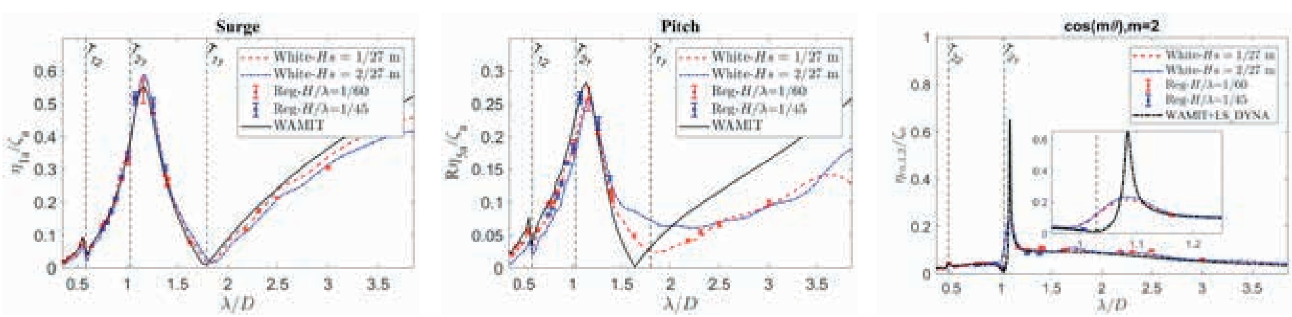



***Figure 2:*** *Transfer functions of surge, pitch and radial deformation of the ovalizing mode cos 2θ (measured at the freeboard level) for the closed cage versus relative wavelength λ/D. λ is the wavelength and D=2R the cylinder diameter.* $\zeta_a$ *is the incident wave amplitude. The black solid lines are from WAMIT calculations. Other data are based on experiments in either regular or truncated white-noise waves.* $T_{ij}$*= natural sloshing periods. A zoomed view at the sloshing natural period for ovalizing mode,* $T_{21}$*, is provided in the right plot.*

***Figure 3:*** *Left: Illustration of the radial ovalizing modes with definitions consistent with the sketch in the right side of Figure 1. Black solid line: Initial radial shape as a circle with radius R. Red dashed line: Shape with radial deformation 0.1Rcos 2θ. Blue dash-dotted line: Shape with radial deformation 0.1Rsin 2θ. Right: Non-dimensional mean wave drift force* $\bar{F}_1$ *in surge versus λ/D.*

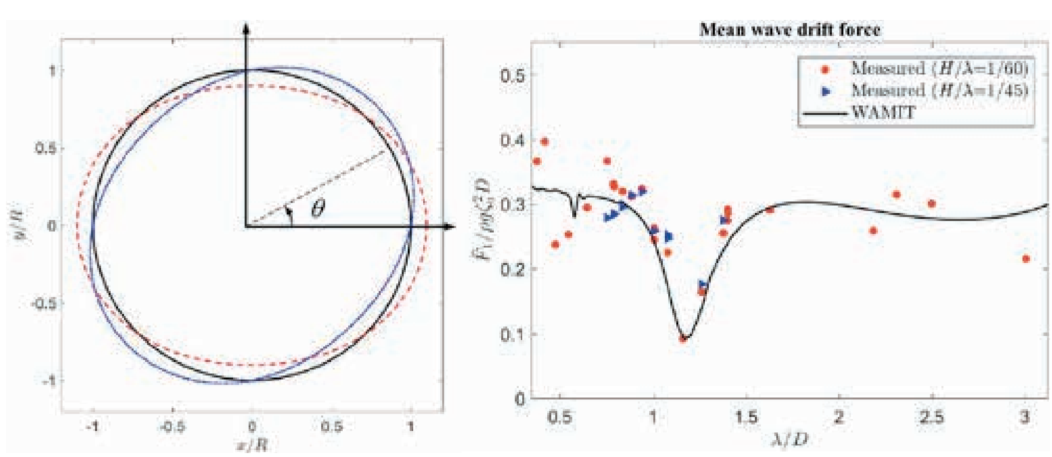
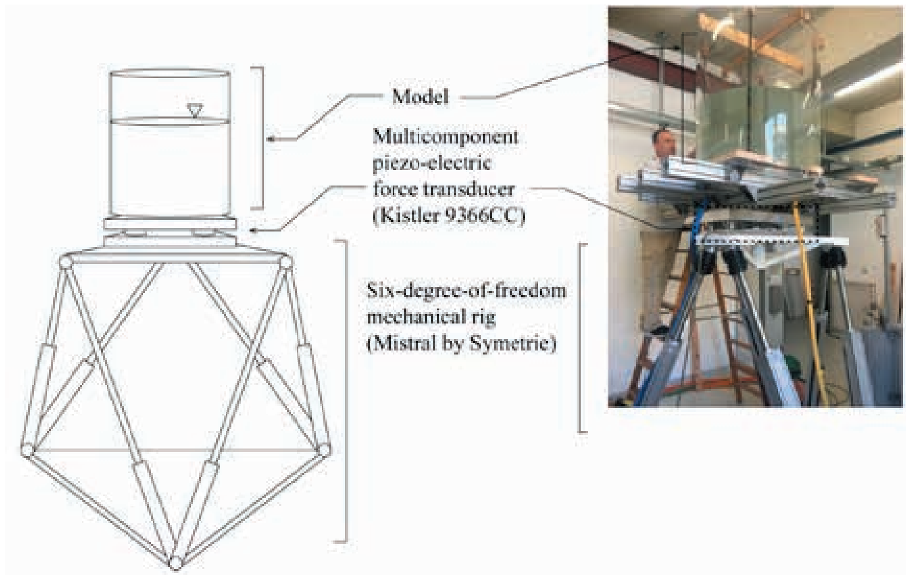


***Figure 4:*** *Experimental setup*




waves for the closed cage. Experimental data from both regular waves and the two white-noise tests are given. Numerical predictions from the linear potential-flow solver WAMIT are also provided, assuming a rigid body. There is a good agreement between the numerical and experimental results, but differences are clear for pitch in sufficiently long waves (λ/D>1.4). One reason can be large relative vertical motions at the floating collar causing nonlinearities of more importance for pitch than for surge and heave. A so-called Mathieu-type instability was also documented for pitch in long regular waves due to in and out of water of the floating collar. Right panel of Fig. 2 examines the importance radial elastic deformations of the cage (see left of Fig. 3). They were extracted from the measurements and relatively large ovalizing radial deformations are documented for wave periods close to the natural sloshing period $T_{21}$. The resonant frequencies are captured by a numerical analysis of the ovalizing modes combining the structural analysis program LS-DYNA with WAMIT, while the deformation amplitudes are affected by the involved damping. Fair agreement was also achieved between the rigid-body WAMIT predictions and experiments for the mean drift forces, despite large ovalizing radial modes involved in the experimental case (see right of Fig. 3).

For a full comprehension of **the effect of the water exchange forced in the closed cage** and vital for fish growth and welfare, a **unique study on sloshing in an aquaculture closed-containment system with a slowly rotating liquid** is done in **[P3-R2]**.

It focuses on the effect of liquid rotation (with angular velocity Ω) on the fundamental sloshing modes; the amplitudes of sloshing waves, their damping and possible suppression due to rotation and the overall effect of sloshing on the hydrodynamic loads on a circular-cylindrical tank with radius R, undergoing a sinusoidal forced motion with amplitude A and frequency f, is investigated. Both laboratory experiments with a scaled physical model (Fig. 4) and numerical models are implemented. Two theories were used in the analysis: a weakly nonlinear multimodal theory for sloshing in a non-rotating liquid and a linear theory for a rotating liquid.

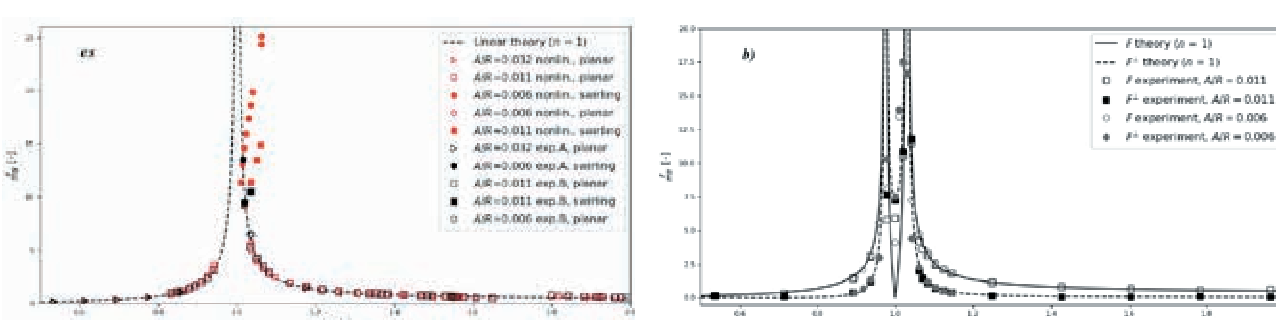


***Figure 5:*** *Nondimensional sloshing-induced force on the tank along the excitation (F) and transverse ($F^{\perp}$) direction. a): Non-rotating liquid sloshing case, i.e., Ω = 0. The transverse force is not plotted since $F^{\perp}$ = F at swirling regimes and 0 otherwise. b): rotating liquid sloshing case at Ω $(R/g)^{0.5}$= 0:07.*

The most important effect of the rotating flow is the splitting of the natural frequencies for the non-rotating liquid, leading to sloshing regimes not observed for the non-rotating case. Transverse liquid oscillations causing swirling can be excited linearly in a wide range of frequencies when liquid rotation is forced (Fig. 5b). This contrasts with resonant sloshing in non-rotating liquids, where swirling is attributed to nonlinear effects as, e.g., near the lowest natural frequency $f_1$ (Fig. 5a). However, nonlinear resonant swirling regimes can also be observed in a rotating liquid, but they occur near each of the pair frequencies split by rotation and not necessarily at $f_1$ (Fig. 5b). Further, the violent sloshing flows characterizing the non-rotating liquid case at $f_1$, tend to be suppressed for a quite large angular velocity of the rotating liquid. This observation suggests a possible damping mechanism to be used in small containment systems under forced oscillations; in larger cages, similar angular velocity would lead to flow velocities too high for fish.

Bearing in mind **sloshing in fish cages**, a book **[P3-R3]** has been published focusing on mathematical fundamentals on sloshing in an upright circular cylindrical tank with an emphasis on semi-analytical solutions resulted from implementation of the multimodal method. By utilizing the nonlinear Narimanov-Moiseev–type (asymptotic) modal equations equipped with the linear damping terms, the book demonstrates how to analyse the resonant steady-state wave regimes and their stability. The corresponding steady-state (periodic) solutions are classified versus the forcing type and frequency. The sway/surge/roll/pitch periodic tank excitations are, to within the highest-order quantities in the steady-state solution, equivalent to a sort of the horizontal elliptic (orbital) tank forcing. The latter means that the resonant steady-state waves can be studied, qualitatively and quantitatively, as a function of the semi-axes ratio of the ellipsoidal trajectory. A series of examples shows how to do that for the most practically important cases. A series of physical phenomena is analytically described. The results are in a good agreement with experimental data (measurements).

**The natural frequencies for sloshing without coupling with lateral tank motions differ from the natural sloshing frequencies with coupling**. A consequence is that the nonlinear multimodal sloshing theory for prescribed tank motion should be revised when studying the liquid sloshing dynamics in connection with marine structures in ocean waves. The needed revisions are done for a rectangular rigid tank with a finite liquid depth [P3-R4]. Steady-state resonant solutions of the constructed nonlinear modal equations are derived to analytically describe the coupled resonant sloshing and sway of a floating rigid body in regular incident deep water waves with two-dimensional flow conditions at the lowest coupled sloshing–sway natural frequency.

The analysis implies constructing an analytical solution of the nonlinear problem and studying its stability. The latter makes it possible to distinguish multiple solutions and detect chaotic motions of the complex dynamic system if occurs. The steady-state analytical results are validated in Fig. 6 by comparing them with the model tests by Rognebakke & Faltinsen (J. Ship Res., vol. 47, issue 3, 2003, pp. 208–221). Comparative analysis shows a good agreement for stable steady-state motions and confirms occurrence of an instability frequency range in two experimental cases by Rognebakke & Faltinsen (2003, panels a and b in Fig. 6) who documented an 'unstable situation' when 'the sway amplitude shifts and thus two steady-state responses take place during one run'. The literature contains alternative numerical simulations in this frequency range which have always failed to achieve a clearly steady-state wave regime. According to P3-R4, the irregularity/

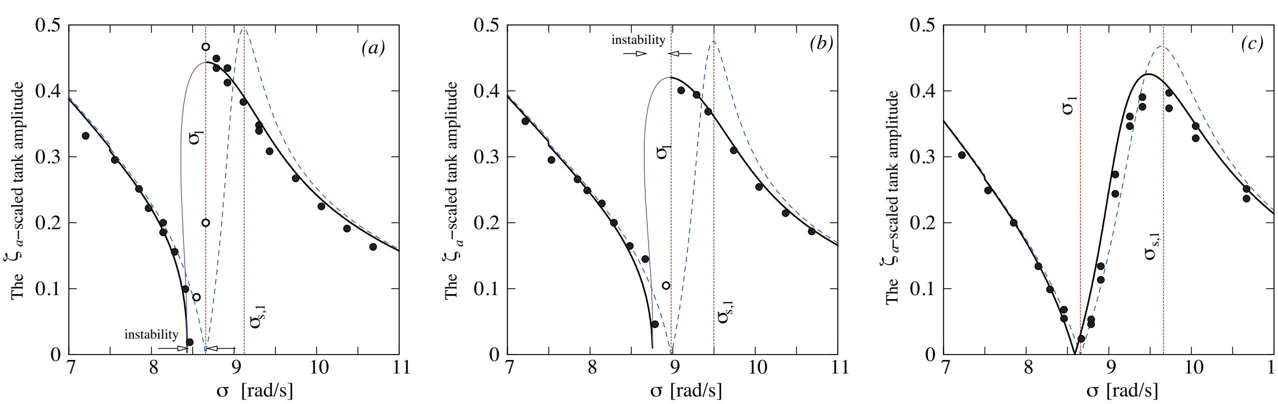



***Figure 6:*** *The linear/nonlinear theoretical and experimental maximum tank amplitude scaled by the incident wave amplitude ζa. Panels (a), (b) and (c) correspond to experimental Cases I, II and III by Rognebakke & Faltinsen (2003), respectively. Circles represent the measurements. The blue dashed lines result from the quasi-linear analytical solution. The theoretical frequency $\sigma_{s,1}$ is the first non-Stokes natural sloshing frequency in sloshing-affected containers. The frequency $\sigma_1$ is the first natural Stokes frequency. The solid lines show the Narimanov–Moiseev analytical steady-state approximation, which accounts for the viscous damping effect for sloshing. The solid bold black lines imply stable steady-state solutions but the thin magenta lines – instability. The Narimanov–Moiseev theory detects a frequency range (marked as 'instability') where theoretical steady-state solutions are unstable, and chaos can be discovered. Experimental values in this range are marked by the empty circles. Two measurements at $\sigma_1$ in the case (a) give contradictory results, which are mentioned as 'unstable situation' by Rognebakke & Faltinsen (2003). The third measurement in this range may be a result of the instability or, contrarily, caused by damping, which is not precisely predicted in the present simplified mathematical model.*

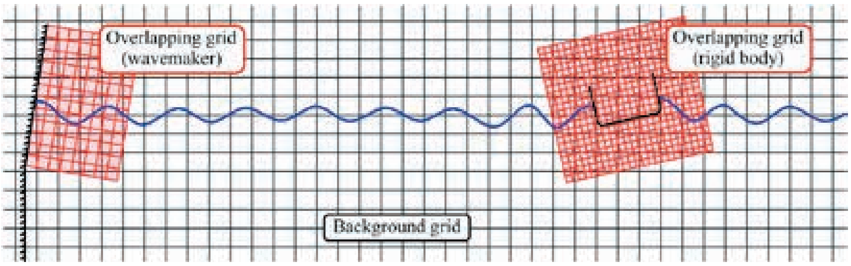



***Figure 7:*** *Schematic overview of immersed-boundary overlapping grid modelling*

chaos could be an attribute of the resonant coupled motions. If this happens numerical solvers become inapplicable for certain input data.

A numerical framework for studying **nonlinear wave-body interaction in 2D** has been proposed and rigorously validated **[P3-R5]**. Inviscid flow is assumed, and the harmonic polynomial cell (HPC) method is used to solve the governing Laplace equation. To deal with complex boundaries such as the free surface, an immersed boundary technique is used, combined with overlapping grids to refine the solution locally (see example in Fig. 7). This combined method, denoted as an immersed-boundary overlapping grid method (IBOGM), represents a novel development demonstrating one possible way to utilize the HPC method favourable properties in nonlinear problems.

A challenge in nonlinear wave-body interaction problems is to model the motion of the wave-body intersection points, especially when the structure has non-vertical geometry near these points.

As seen in Fig. 8, the IBOGM simulates this behaviour in good agreement with a reference solution for the challenging case of a semi-submerged circular cylinder undergoing forced oscillatory heave motions.

Accurate, efficient, and robust prediction of wave elevations and wave loads in storm waves is important for safe design and operation of marine structures. Aiming to develop a practical numerical tool for this purpose, **a fully nonlinear 3D numerical wave tank for large-scale wave modelling has been developed**, where the numerical techniques proposed to study nonlinear wave problems in 2D have been extended to 3D. Moreover, to improve numerical efficiency, an adaptive grid refinement (AGR) strategy, as shown in the examples in Fig. 9, has been implemented. With the AGR, simulations can be run in the order

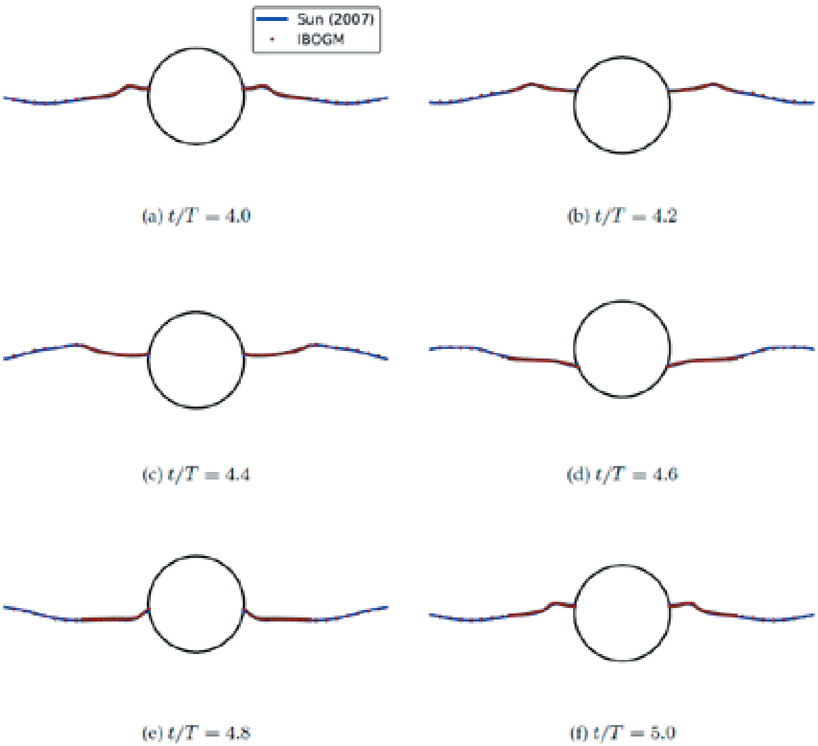



***Figure 8:*** *Snapshots of a wave profile for a semi-submerged circular cylinder at different time instants t relative to the forced harmonic heave period T. IBOGM results compared with a numerical solution by Sun (2007).*

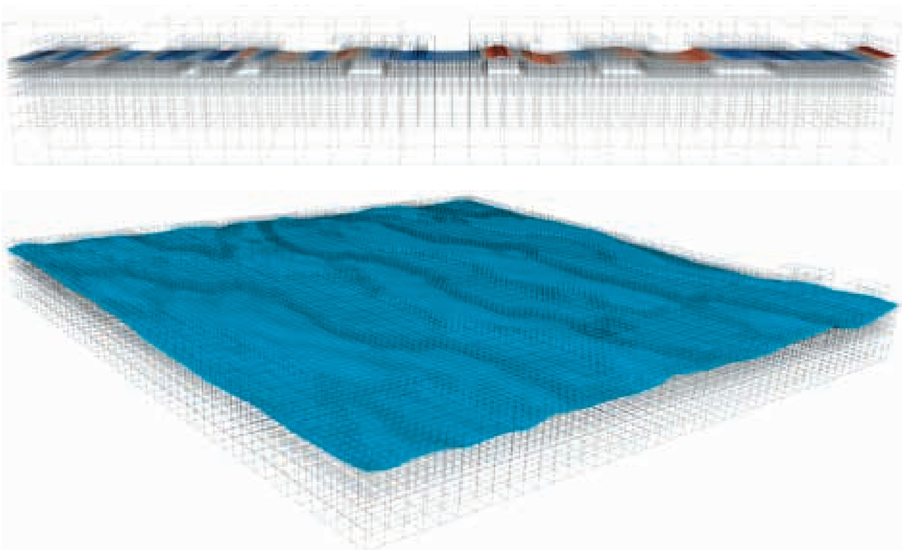
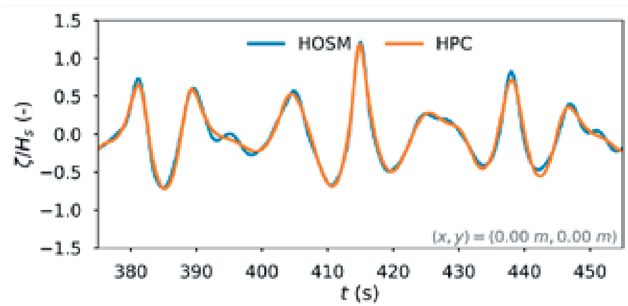


***Figure 9:*** *Example of numerical wave tank with AGR. Top: Long-crested irregular waves, in which the colour shading of the free surface indicates the water particle velocity. Bottom: Short-crested irregular waves on a large computational domain.*



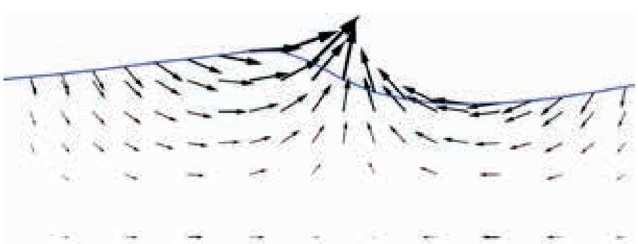



***Figure 10:*** *Example of numerical wave tank results. Left: Time series of wave elevation compared with an accurate reference solution. Right: Water particle velocities under a steep wave crest*

of 10-20 times faster than using a uniform grid on a standard laptop without compromising the accuracy. As a result, large-scale scenarios with short-crested irregular waves, which may be required to study realistic ocean-wave phenomena, can be simulated.

The work, initially presented in **[P3-R6]**, has been carried out in close cooperation with DNV and DTU, and detailed results will be submitted for journal publication in the first months of 2022. Simulated free-surface elevations compare well with reliable reference results, and the variables that can be calculated include the water particle velocities in the water below the free surface (Fig. 10).

The numerical code will be owned by NTNU but will be made publicly available as an open-source tool. The purpose of openly sharing the code is that interested parties can 1) make directly use of the tool or 2) optimize the tool to their specific assignment or continue to further develop the tool by adding functionality.
**The water entry of a body** is of interest in several marine applications, from the slamming of ship bows or the launch of life boats up to the projectile and missile entering the water for military purposes or solid objects unexpectedly falling into the sea as a consequence of a marine operation failure.

The problem is complex from the physical point of view because it involves several challenging phenomena common to marine flows, from the impulsive loads during the slamming stage up to the multi-phase flows in the jet and the cavity evolution behind the body, which require a different scaling depending on the physical phenomena involved. For the first time, **the experimental scaling of the maximum loads occurring on the body and induced by the cavity oscillation** has been assessed in **[P3-R7]**, emphasizing the mutual role of the Froude and Euler numbers. The depressurized channel facility available at CNR-INM has been used; an ad-hoc and sophisticated setup for a free-falling cone, able to support and ensure the proper measure, has been designed and realized (Fig. 11).

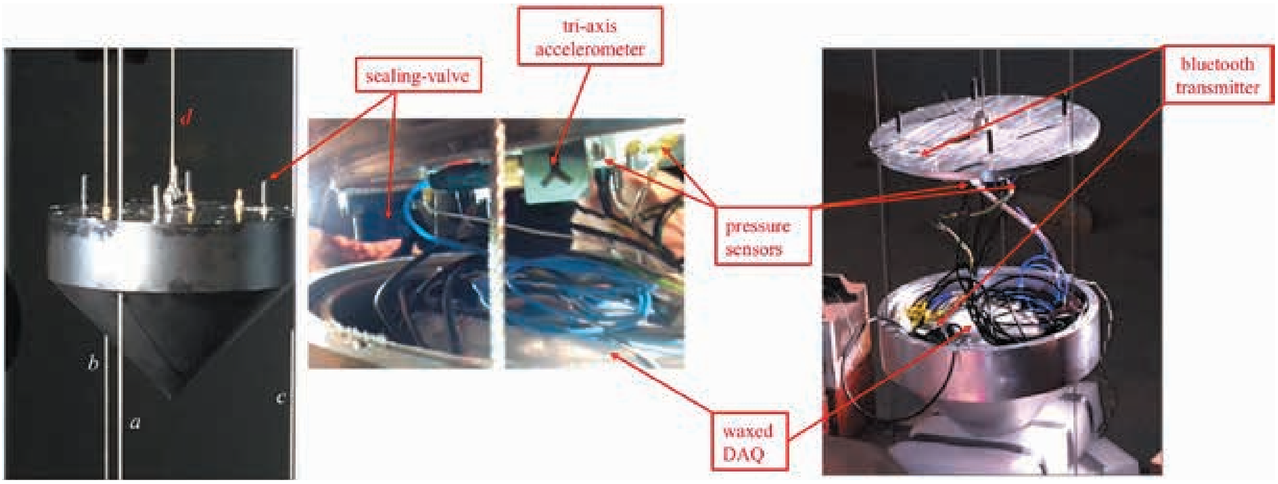



***Figure 11:*** *View of the cone used in the experiments*

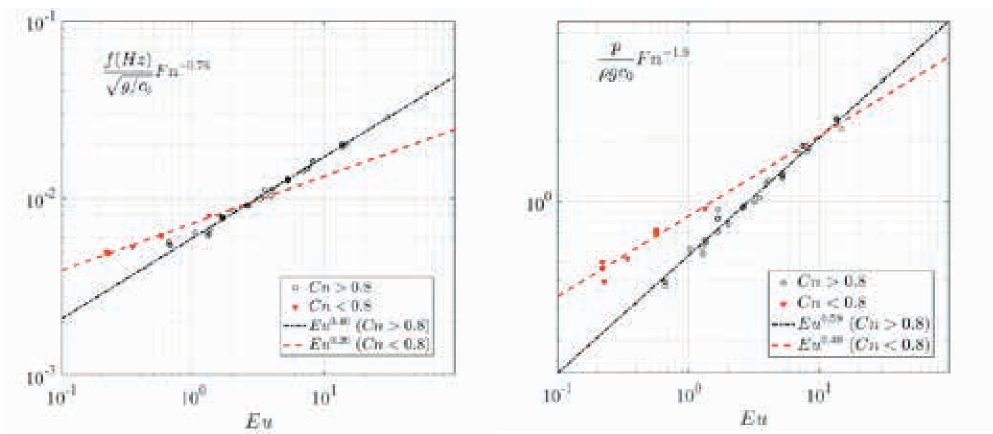


***Figure 12:*** *Left: Scaling behaviour of the oscillation frequency of the cavity. Right: Scaling behaviour of the maxi- mum pressure at the first oscillation peak of the cavity. Cn indicates the cavitation number.*

The contribution of this study to the stage after the closure of the cavity is highly relevant. This stage is characterized by the cavity oscillations and by a relevant effect of the air compressibility, which provides the restoring contributions. The cavity natural frequency scales as $Fn^{0.76}$ $Eu^{0.46}$ (left panel Fig. 12); the Eu scaling resembles the previous findings for the oscillation of the cavity entrapped in the wave-impact problem. A scaling that $Fn^{-1.9}Eu^{-0.59}$ has been found for the maximum pressure in the cavity (right panel Fig. 12). However, it is crucial to avoid the cavitation phenomena on model scale; since they do not occur on the prototype for the case of our interest, their occurrence in the model tests can modify the scaling and the physical evolution of the flow field. This is relevant for a proper choice of the scale factor for the model test applications. The analysis also revealed the scaling of the time evolution of the flow before and after the closure of the cavity.

**Bottom-fixed offshore wind turbines** are currently being installed at a record pace, with the industry swiftly moving toward larger turbines and larger support structures. Monopile support structures remain the preferred choice, given their long industry

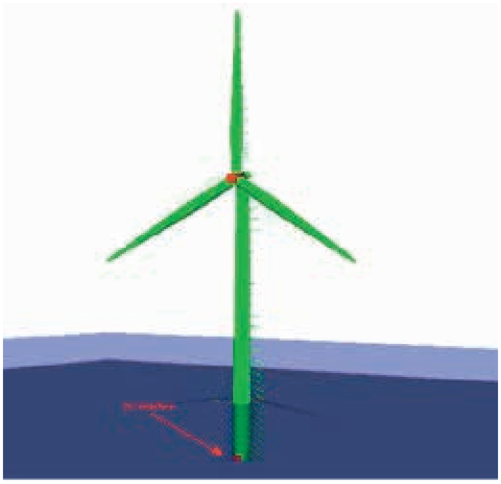


***Figure 13:*** *Aero-hydro-servo-elastic model of a monopile, including a macro-element model for the soil-structure interaction via DLL **[P3-R8]***

experience and well-developed supply chain. Extensive load calculations with non-linear time-domain, aero-hydro-servo-elastic simulation tools are needed for assessing the fatigue life of these large, flexible structures (Figure 13). Reducing the number or computational cost of such simulations has the potential to enable more efficient design studies:

Previously, methods for "environmental lumping" – the grouping of short-term sea states into a single sea state for simulation – either disregarded the correlation between wind and waves, disregarded the dynamics of the system, disregarded the wind loads and aerodynamic damping, or did not consider the damage along the full length of the support structure. A damage-equivalent contour line method for monopile wind turbines in operating conditions has been developed and compared to a full long-term fatigue assessment for a 10MW wind turbine [P3-R8].

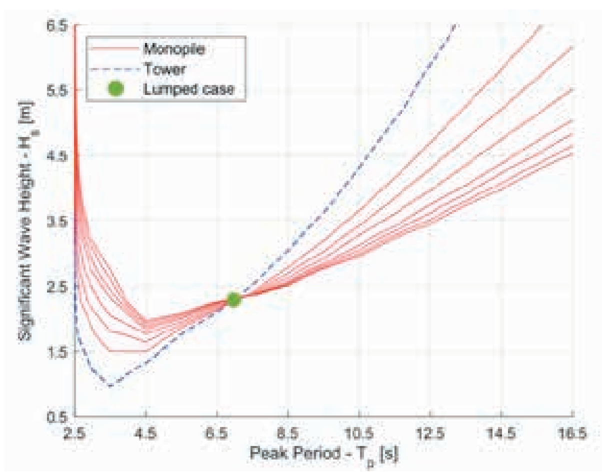



***Figure 14:*** *Damage-equivalent contour lines for hub-height wind speeds 14-16 m/s* ***[P3-R8]***

The damage-equivalent contour line for a given wind speed represents all the combinations of significant wave height and peak period, which result in the same damage at a given location along the structure. If these contour lines can be found for damage levels that represent the total fatigue damage contributions for all sea states associated with a given wind speed, the intersection of contour lines from different locations along the substructure can be used to choose a single lumped sea state.

For this method to be useful, the approach for estimating the target damage level must be computationally efficient. In a study by Katsikogiannis et al. **[P3-R8]**, transfer functions for the wave-induced responses are obtained from aero-hydro-servo-elastic time-domain simulations of the monopile wind turbine considering white noise waves and constant wind. This "frequency domain" approach allows the effects of the mean thrust (which are important for soil stiffness and damping) and aerodynamic damping to be included in the estimate of the wave-induced responses. Figure 14 shows the damage-equivalent contour lines for a given wind speed obtained using the frequency domain approach. A single contour line is seen for all points along the tower, while the contours vary along the monopile. The lumped load case is chosen as the intersection point for a representative location on the monopile and at the base of the tower, and – for the studied designs – corresponds well to the intersection of all of the contours.

As illustrated in Figure 15, the lumped load cases estimated the damage within ± 13% for individual wind speed classes, and within 6% for the total fatigue damage compared to the full scatter fatigue assessment. The approach significantly improves the computational efficiency: 55 1-hr time-domain simulations (five were carried out for each lumped load case to reduce statistical uncertainty) instead of 800 (full scatter analysis).

**Floating wind turbines are promising solutions for harvesting wind energy in deep water.** Numerous simulation tools have been developed and compared against each other, and against experimental results in international projects. One of the main findings of the OC5 project (carried out through the IEA) was

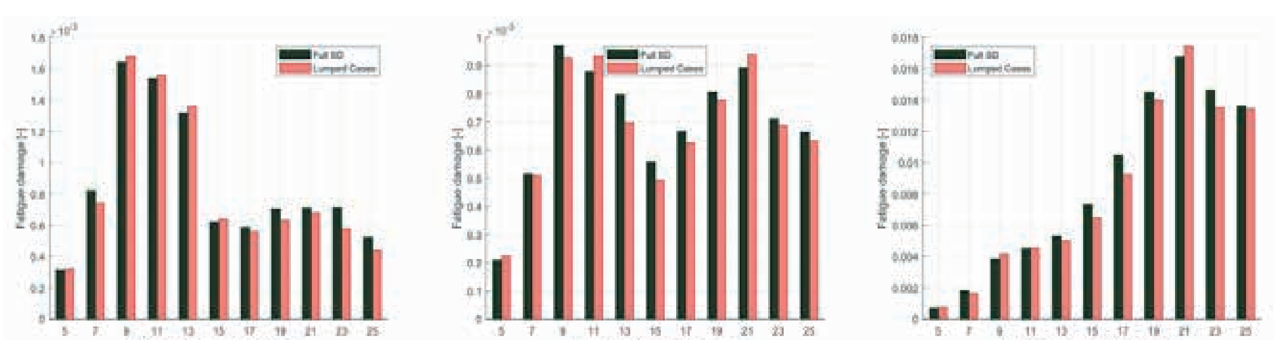



***Figure 15:*** *Contribution of individual wind speed classes to total fatigue damage for the full long-term calculation (black bars) and for the lumped load case approach (red bars) for the tower base (left), 15 m above mudline (middle), and 8.25 m below mudline (right)* ***[P3-R8]***

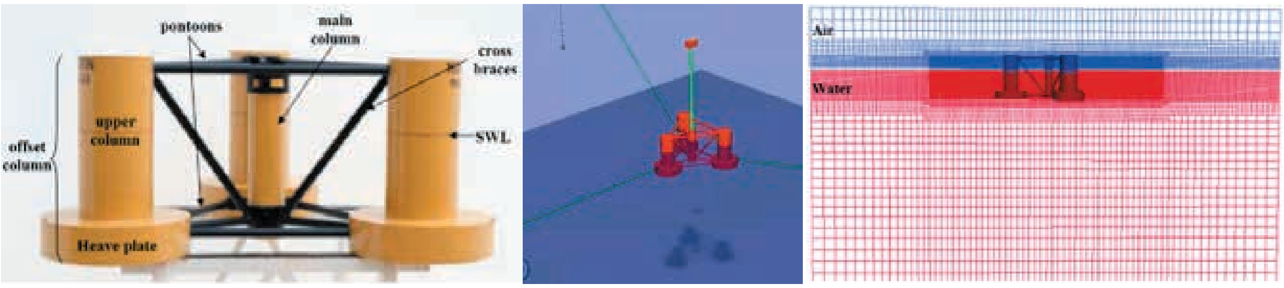



***Figure 16:*** *The OC4 semi-submersible in experiments (Definition of the Semisubmersible Floating System for Phase II of OC4, Robertson et al. 2014), SIMA simulations and CFD (images from: Experimental and numerically obtained low-frequency radiation characteristics of the OC5-DeepCwind semisubmersible, Haoran Li et al., Ocean Engineering, 2021*

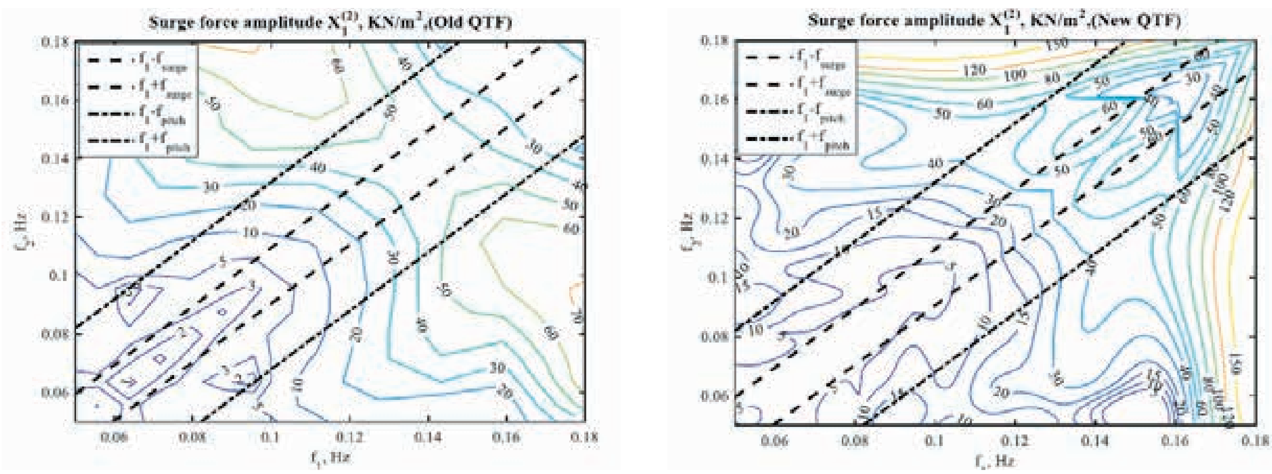



***Figure 17:*** *Comparison of the quadratic transfer function before and after modification based on biochromatic wave simulations using CFD* ***[P3-R9]***

that none of the simulation tools could accurately capture the low-frequency pitch motions of a given semi-submersible floating wind turbine. The hydrodynamic models of the "engineering" tools in the study were based on first- and second-order potential flow theory, combined with Morison's equation for modelling both slender members and viscous forces.

A systematic approach to improving these engineering tools through targeted CFD simulations has been proposed **[P3-R9]**. Improved estimates of the low-frequency added mass and (linear and quadratic) damping are obtained through forced oscillations in the CFD model in still water, see Figure 16. In general, the CFD simulations suggest that the potential flow results underestimate both the added mass and damping at low frequencies. Improved estimates of the second-order excitation are obtained by carrying out CFD simulations with biochromatic waves, and updating the second-order quadratic transfer function (QTF) by incorporating this information at those specific frequency combinations (after corrections for viscous effects which are incorporated in Morison's equation). The biochromatic waves are chosen such that the difference frequencies correspond to the surge or pitch resonance frequencies. Figure 17 illustrates the effect of these modifications on the surge QTF.

In general, improved results from the modified engineering tool are seen when comparing to the experiments. However, it should be noted that modifications in added mass, damping and excitation should all be included simultaneously to achieve these improvements: added mass and damping modifications tend to decrease the (underestimated) responses at low frequencies, while modifying the QTFs alone tends to result in an overestimation of these responses. Estimates of damage-equivalent loads in the mooring lines and tower also tend to improve after the proposed modifications.

**During the execution of marine operations** (for example the onsite installation of offshore wind turbines), **a go or no-go decision is made** based on the comparison of the operational sea state limit (often represented by significant wave height Hs) and the short-term sea state forecast data. Using Hs criteria only has a strong limitation for operations involving floating vessels, for which the spectral peak period plays an important role in the

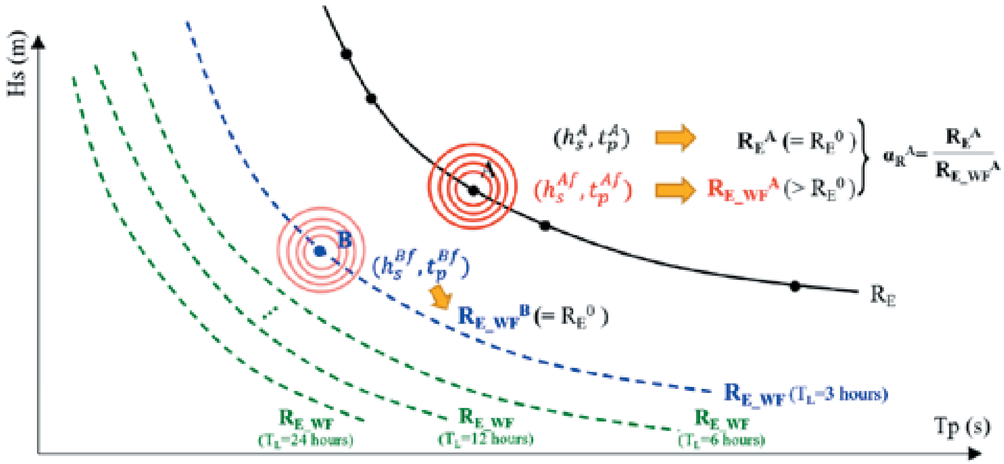



***Figure 18:** Illustration of the operational sea state limits with and without the consideration of wave forecast uncertainties. Black solid line: sea state limits with no consideration of wave forecast uncertainty. Blue dash line: sea state limits with consideration of wave forecast uncertainty for a 3-hour forecast ahead. Green dash lines: sea state limits considering the wave forecast at different lead time. Red curves around point B: the probabilistic distribution of the true sea state when the forecast sea state is B. R_E and R_E_WF represents the characteristic values of the maximum responses for the given sea state, and when the forecast uncertainty is considered, respectively. Alpha_R is the response-based alpha factor.*

dynamic responses of the vessels. A methodology using response-based criteria is developed to determine the operational sea state limits, in which the uncertainty in wave forecast data is explicitly considered **[P3-R10]**. Figure 18 illustrates the derivation of the operational sea states (in solid line) when the forecast uncertainty is not considered, and the operational sea states (in dash lines) when the forecast uncertainties for different forecast horizons are considered, as well as the so-called response-based alpha factor. To help illustrate this methodology, a case study **[P3-R12]** considering the installation of a single offshore wind turbine blade using a semi-submersible floating installation vessel is performed as shown in Figure 19, in which a physics-based machine learning approach for short-term wave forecast is developed, and the forecast uncertainties are quantified against the historic wave data **[P3-R11]**. The physics-based machine learning approach for wave forecast considers the current wave and future wind conditions as input and the forecasted future wave statistics (significant wave height, spectral peak period) as output, and adopts the ANN (Artificial Neural Network) algorithm:

**The Deepwater Artificial Seabed (DAS) system** is proposed as a new alternative field development solution for petroleum production in ultra-deep water, which works in concert with dynamic positioning (DP) FPSO. Nonetheless, critical DP failures, which have the potential to cause the drift-off scenario for the FPSO, pose a serious threat to the structural safety of the DAS system. Therefore, it is crucial to establish operational limits for the DP FPSO to prevent such accidents. In view of this, a probabilistic model of the DP FPSO, TLP/mooring and flexible riser is established to predict the operational safety limits of the DP FPSO **[P3-R13]**. To reduce the computational efforts in the generation of large statistical samples of the response, a surrogate model is established by the Support Vector Machine (SVM) algorithm. Three limit states are used to describe the emergency

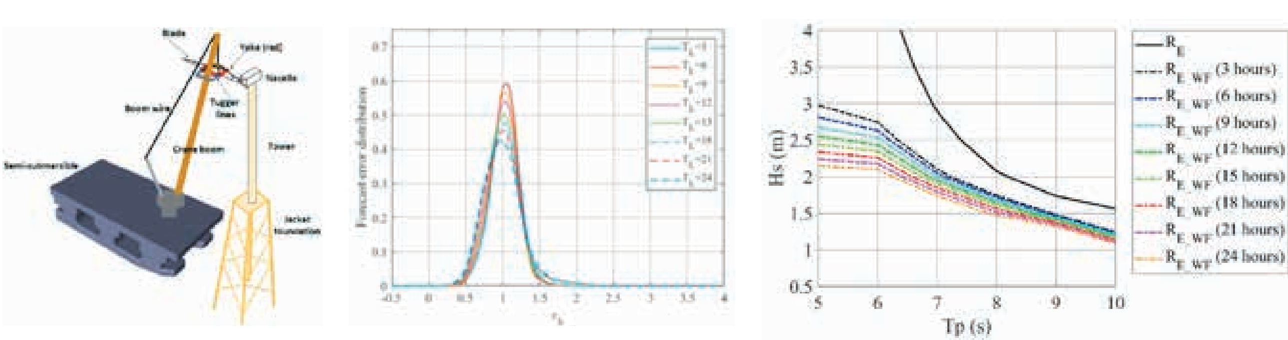



***Figure 19:** Left: Illustration of a semi-submersible installation for single turbine installation considering the blade root motions as the limiting response parameters. Middle: Probabilistic distributions of forecasted significant wave heights with different forecast lead time using a physics-based machine learning approach. Right: Operational sea state limits considering wave forecast uncertainties for different forecast lead time.*

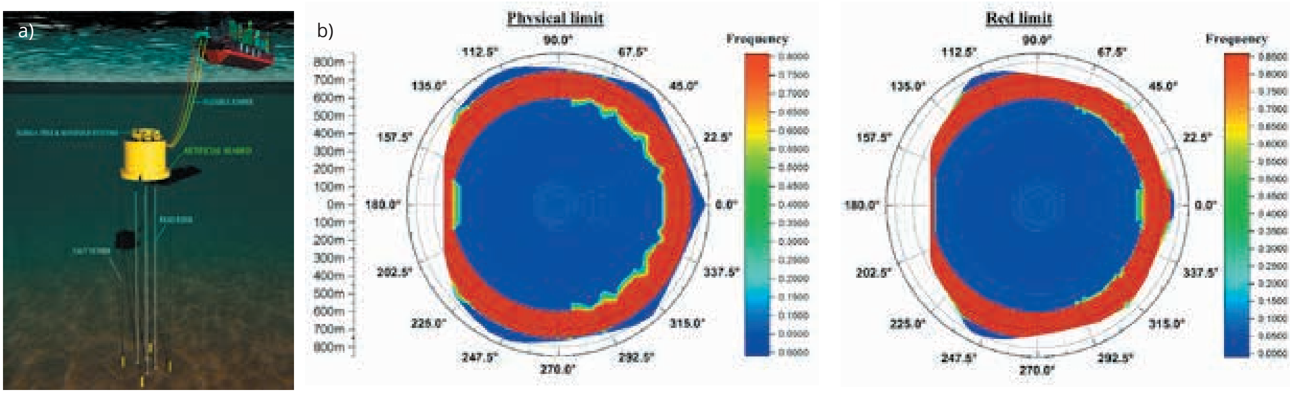
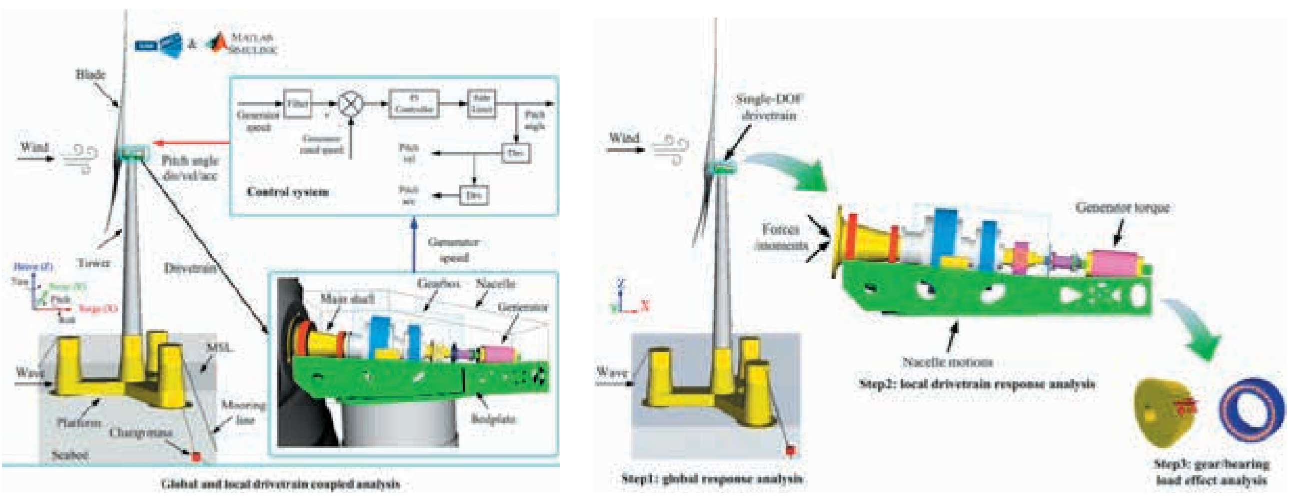



*Figure 20: Deepwater Artificial Seabed (DAS) system a): Frequency contours of operational safety limits of DP FPSO in DAS system b). The red limit indicates that the emergency disconnection should be executed. The physical limit indicates that the safety integrity of one or more components of DAS system exceeds the allowable value. Frequency is referred to the occurrence rate of the operational safety limits.*




a) Fully coupled method

b) De-coupled method

*Figure 21: Fully coupled and decoupled methods for 10-MW wind turbine drivetrain analysis*

quick disconnection, especially of the flexible jumper, which is an important safety barrier, namely: preparing, initiating (yellow limit) and executing disconnection (red limit). The statistical distribution of the operational safety limits is simulated by the proposed methodology. Most of the operational safety limits are concentrated in two specific areas (near end and far end) along the radius that encircles the safe moving range of the DP FPSO (see Figure 20). By this information the operator has got sufficient time for decision-making, and hence contributes to the safety of DP operations of floating production units in an efficient manner.

Traditionally, drivetrain responses have been obtained by a de-coupled analysis, which first involves a global analysis with a simplified representation of the drivetrain, followed by a detailed analysis of the drivetrain with the input of the global response on the drivetrain interface. As the wind turbine size increases, it is questionable as to whether this de-coupled analysis method yields sufficiently accurate results. To help address this question, a comparative study of **the drivetrain dynamic behaviour obtained by a fully coupled method and a de-coupled one**, as illustrated in Figure 21, was conducted **[P3-R14]**.

Natural frequencies of the fully coupled model were studied, and showed that for large offshore wind turbines, the drivetrain resonance risk is higher in the non-torsional directions than in the torsional direction. Generally speaking, the percentage difference of 1-h fatigue damage of bearings and gears of the 10-MW drivetrain calculated by the fully coupled and de-coupled methods was less than 5%. The study concluded that the de-coupled method could provide accurate results of the drivetrain fatigue damage if the natural frequencies of the drivetrain are sufficiently separated from that of the “global system”. In the case

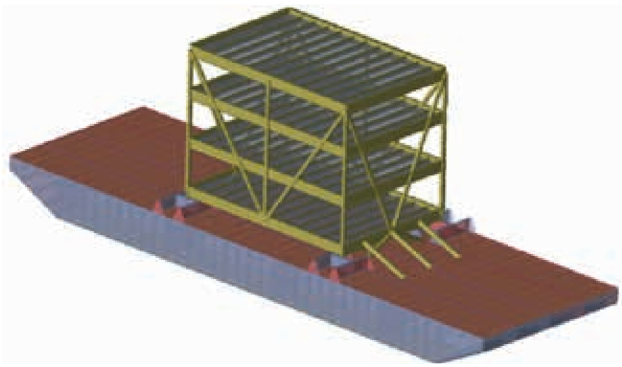


*Figure 22: Typical towed barge with grillage and sea-fastening (roll and pitch stoppers) and the transported object (only structural steel is shown, not the mechanical equipment or outfitting structures)*

that the drivetrain has resonance in the fully coupled model, the de-coupled method should not be used. The 10-MW drivetrain is at the borderline of resonance, as non-torsional resonance checks should be made for larger offshore turbines.

The safety of marine operations related to a **sea-fastening system for the transport of large objects** on a towed barge, see Figure 22, was studied, and a structural reliability approach to accommodate the uncertainties affecting design checks was developed **[P3-R15]**. The probability of structural failure through the use of design standards for assessing marine operations was investigated by means of structural reliability analyses in order to shed light on the implicit reliability levels of such standards. A structural reliability model that included the effect of uncertainty in the weather forecasts of significant wave height was established. The reliability analyses showed that the method to account for forecast uncertainty as defined in the standards compensates well for that uncertainty, with the failure probabilities in the case studies between $10^{-4}$ and $10^{-3}$ per operation. A reliability model that included the long-term statistical distribution of the environmental conditions was also established; this model is applicable for operations with a duration longer than three days, i.e., not relying on weather forecasts. The failure probability was calculated for execution in several months of the year, showing the dependency on the time of the year (seasonal variations) and the duration of the operations. The failure probabilities were on the order of $10^{-4}$ per operation.

**Real-time hybrid model testing** (ReaTHM testing) is a method for emulating ocean structures that combines numerical methods with traditional hydrodynamic model testing. This is done by partitioning the target ocean structure into numerical and experimental substructures, which are then recoupled through sensors and actuators, and tested in real-time in an ocean laboratory. In this way, the method enables the emulation of systems, in which neither a purely numerical simulation nor a purely physical model testing is feasible within satisfactory performance levels. See Figure 23 for the method applied to the testing of a moored ship.

The developments presented in the dissertation by Einar Ueland **[P3-R16]** are aimed at ReaTHM testing, in which the numerically computed load vector is calculated based on measurements of the experimental displacements, and thereby actuated onto the physical substructure via a configuration of distributed cabled winches. One of the major research objectives of this PhD project was to ensure that load actuation in ReaTHM testing can be performed with minimal errors, and without a significant degradation of emulation performance.

In **[P3-R17]**, novel methods for real-time force allocation, that is, determining each actuator's appropriate target cable forces, are proposed. These methods guarantee a continuous differentiability of the resulting cable forces. The article also shows that an implementation of Newton's method specialized for the resulting optimization problem can be used for practical real-time applications. The results are beneficial for ReaTHM testing because of the method's flexibility, and also because it is expected that smoother cable force trajectories can be more accurately tracked. Moreover, the presented slack formulation may increase the applicability and robustness of basin-specific standardized

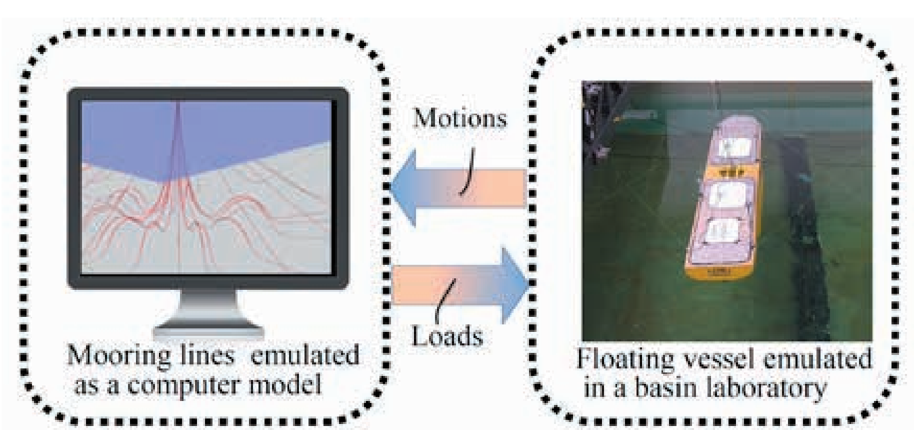



*Figure 23: ReaTHM testing of a moored ship in the MC-LAB, NTNU. Notice the four nylon strings used to apply the numerically calculated forces onto the ship.*

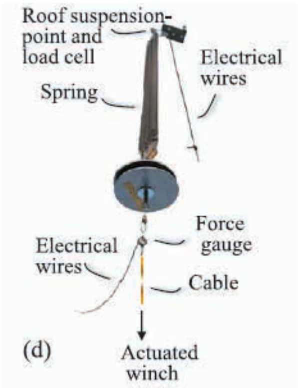



***Figure 24:*** *Actuator control test system*

ReaTHM testing setups, by allowing errors in low-priority DOFs, when this does not cause a loss of accuracy.

In **[P3-R18]**, a framework for the optimal placement of actuators, which prioritizes load actuation accuracy while ensuring that the numerically calculated loads can always be applied according to predefined workspace specifications, is presented. No other such guidelines were previously found for ReaTHM testing.

In **[P3-R19]**, an actuator control system design is developed and demonstrated, based on feedforward, prediction and adaptive compensation, to accurately track forces on moving objects using actuated winches. The study emphasizes ReaTHM testing by focusing on relevant use cases, force magnitudes and frequency ranges. The results are supported by extensive experimental testing on the setup shown in Figure 24.

With these results, the thesis **[P3-R16]** concludes that it met its overall goal to further improve the ReaTHM testing methodology as part of a research effort to make it a well-documented, accepted and valued practice that accurately identifies and predicts the behaviour of ocean structures in realistic marine environments. The results from the thesis are currently being applied in commercial projects by SINTEF Ocean.

It is well-known that **steel becomes more brittle as the temperature decreases**, as experienced by ships operating in the Northern Sea Route. Liquid natural gas (LNG) vessels carry cryogenic cargo at a temperature of -163°C. If a leakage of LNG to unprotected steel occurs by human error or an accident, it may result in an embrittlement of the steel, fracture initiation and a propagation. This may further lead to a progressive degradation of the structural integrity after the initial accident.

To help increase the knowledge of the structural performance of steel subjected to cryogenic temperatures, liquid spills tests were conducted with six unstiffened EH36 steel plates 560 mm wide and 8 mm thick **[P3-R20]**. A local pool with liquefied nitrogen (LN2) was built into the plate, see Figure 25. The plate was preloaded to a nominal tensile stress of 20 MPa, then kept fixed against inward displacements in the pool boiling stage, during which the stress increased to 75 MPa due to thermal contraction. The plate had an initial crack of approximately 20 mm in the centre. One plate fractured in this cooling stage, but for the other specimens the stress had to be increased to 80 -120 MPa after a steady state situation had been attained to initiate brittle fracture, see Figure 26.

The first step in the response assessment of cryogenic spills consists of a transient heat transfer analysis **[P3-R21]**, consisting of convection to the boiling liquid and heat conduction within the steel plate influenced by convection from the ambient air to the bare steel. The convection and conduction coefficients, as well as the specific heat capacity, are highly temperature-dependent. Figure 27 shows experimental and calculated temperature histories for two locations in the steel plate. The second analysis step – the prediction of crack initiation and propagation – will be reported on in a separate paper.

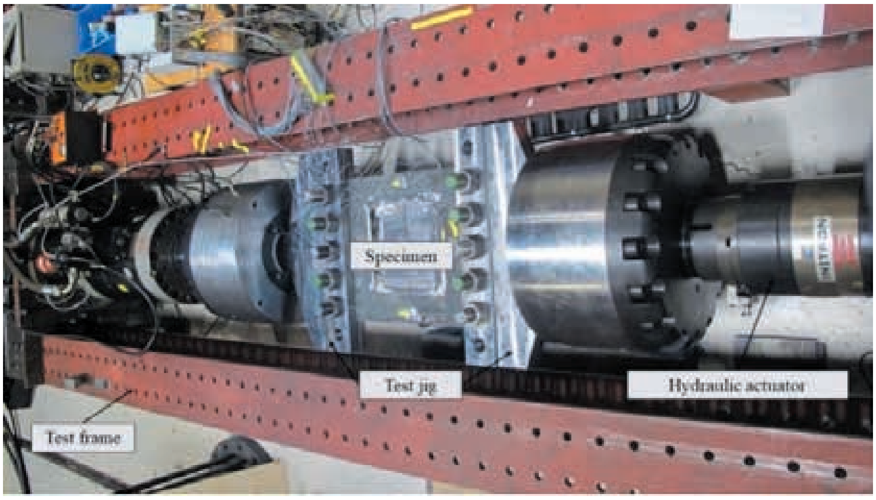



***Figure 25:*** *Test setup*

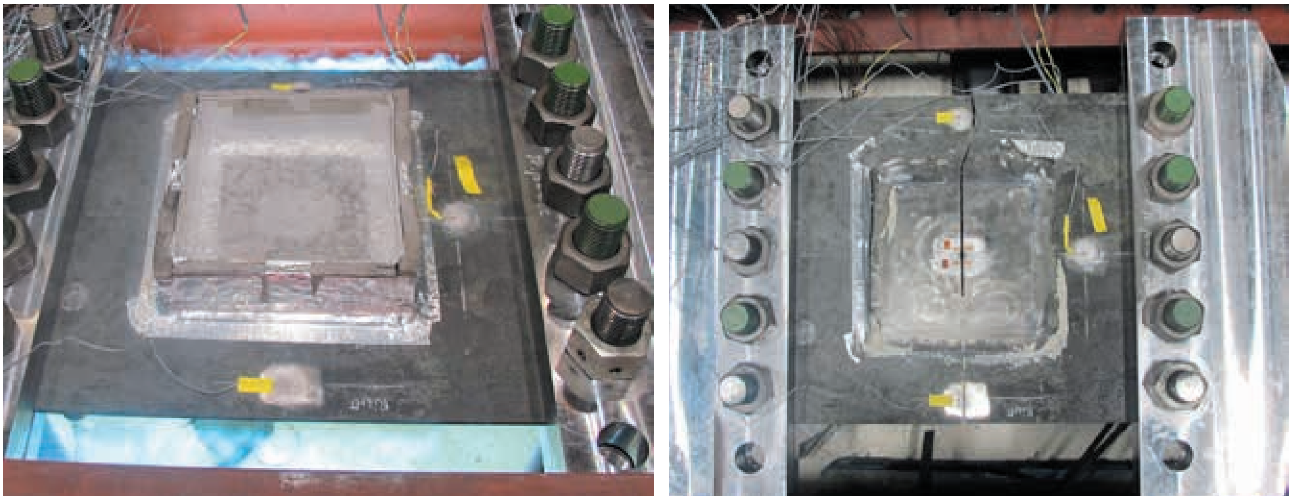


***Figure 26:*** *Left: pool boiling; right: fractured plate*

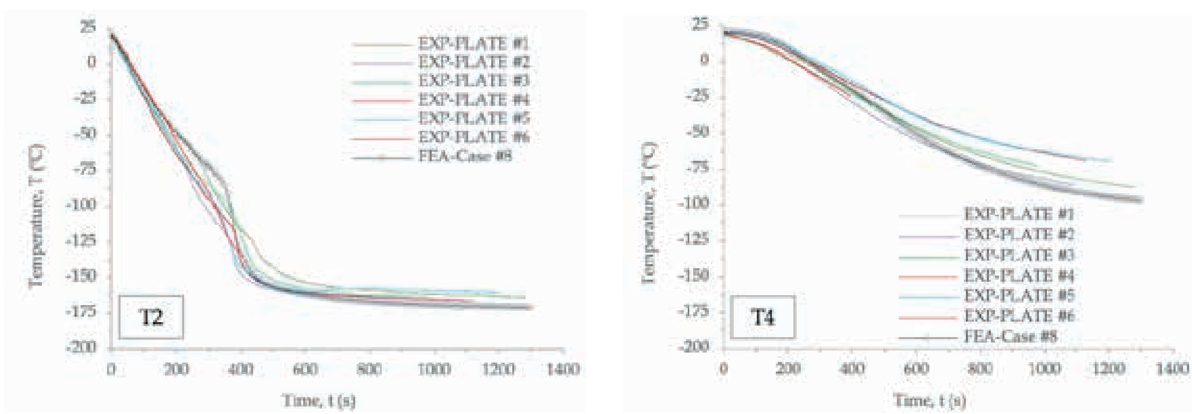



***Figure 27:*** *Experimental and calculated temperature histories Left; at pool border Right; 100 mm outside pool*

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# FIRST 6DOF WHITE-BOX COMBINED SHIP-AND-WAVE MODEL IDENTIFICATION

In marine operations, the performance of model-based automatic control design and decision support systems highly relies on the accuracy of the representative mathematical models. Model fidelity can be crucial for safe voyages and offshore operations.

Onboard 6DOF white-box ship model identification based on vessel motions is studied for the first time. Unlike earlier studies that use a limited number of unknown functions, a library of abundant candidate functions is applied to fully consider the coupling effects among all DOFs. Complex and high-order fluid-structure interaction effects are considered in the proposed method, such as the linear and nonlinear hydrodynamics, the influence of directional wave spectrum and thruster inputs. The features of the complex ship dynamics are extracted and expressed as a linear combination of several functions. Thruster inputs and environmental loads are considered and the hydrodynamic coefficients and wave-induced loads are simultaneously estimated.

The benefit of the proposed method is that it does not require the exact construction of the library functions. The selection of candidate functions can be more flexible. Sparse regression is firstly applied to ship model identification. The prediction of short-term wave loads is therefore achievable by using the identified model. The method can also be extended to other types of floating structures.

**Contacts:** Postdoc Zhengru Ren and Prof. Roger Skjetne (supervisor)

**Reference:**

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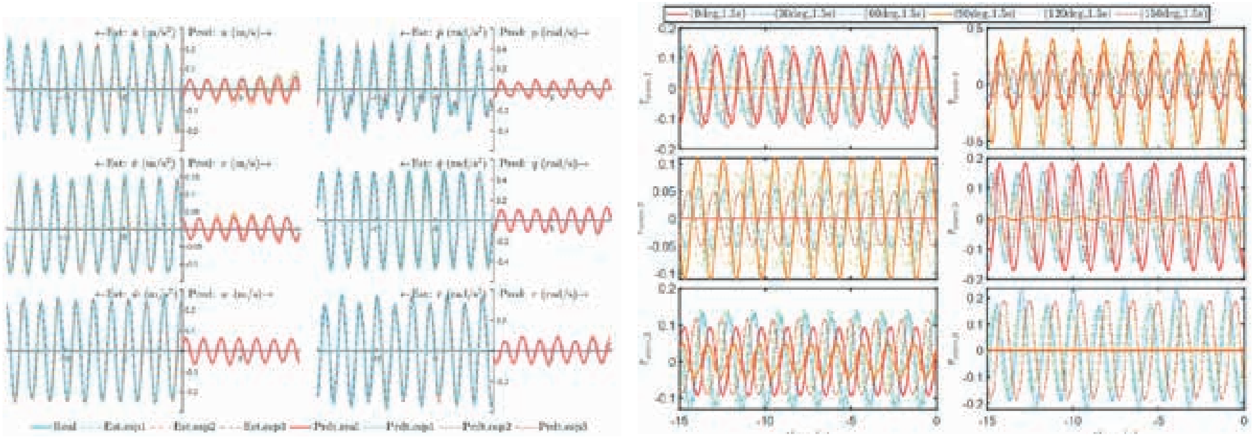


***Figure 1:*** *(Left) Fitting of acceleration and prediction of velocity; (right) Dimensionless wave-induced motion in 6 DOFs. The algorithm is verified through experiments.*

# MANEUVERING WITH SAFETY GUARANTEES USING CONTROL BARRIER FUNCTIONS

Many control problems may be separated into two objectives - a mission objective and a safety objective. For an autonomous vessel, the mission objective may be to reach a destination, whereas the safety objective is to avoid collisions. Designing an explicit control law that achieves both objectives simultaneously is often intractable. A preferred solution is then to solve the two objectives separately, and subsequently synthesize the two control strategies.

Control barrier functions (CBFs) is a novel feedback control strategy that ensures safety of controlled dynamical systems, by identifying a set of admissible control inputs that maintains the system in a safe state. An appealing feature of the CBF method is that the safety objective is defined and enforced independent of the underlying control objective. This enables the merging of CBF-based safety-critical control with any existing nominal control strategy, by solving a convex optimization problem that, at each time step, calculates the safe control input that is closest to the nominal input (by some appropriate measure).

Higher order CBF theory enables CBF design for systems of higher relative degree, following a procedure reminiscent of recursive construction of control Lyapunov functions, a process known as backstepping. At a kinematic level, first order CBFs for collision avoidance of autonomous ships identify a set of safe headings and linear velocities **[1]**, while second order CBFs identify a set of safe yaw velocities and linear accelerations. For the latter case, the commanded yaw acceleration becomes discontinuous. This may not be satisfactory for underactuated ships in transit, where turning is the preferred evasive maneuver. By backstepping one step further, to obtain a third order CBF, continuity of commanded yaw acceleration is achieved.

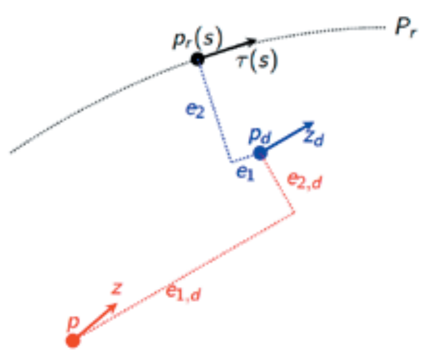



***Figure 1:*** *Illustration of the reactive maneuvering guidance design proposed in [2]. Black dashed line shows a reference path. A virtual vessel pd, shown in blue, follows the reference path when safety allows it, and deviates from the reference path when safety demands it. The ship, represented by the red circle, tracks the virtual vessel.*

A reactive guidance design for safe maneuvering of ships is presented in **[2]**, where the authors proposed implementing CBF constraints at a kinematic guidance level. The design, illustrated in **Figure 1**, uses a virtual vessel to reactively generate a safe trajectory for the ship to follow. The virtual vessel follows a reference path when safety allows it; otherwise, it deviates from the reference path when safety demands it, see **Figure 2**. Additionally, the virtual vessel provides reference signals for desired vessel motion as input to lower-level control layers, shown in **Figure 3**. The advantage of the proposed approach is that uncertainty in ship dynamics needs not be explicitly accounted for. Additionally, for ships with resilient and well-proven motion control systems, such as commercial DP control systems, this is an appropriate interface level. As an alternative, the ship dynamics, and even actuator dynamics, may be accounted for by constructing the CBF from a suitably selected reduced order model of the ship.

For any ship-obstacle scenario, there exists an approach angle where turning port or starboard is equally valid. An immediate consequence of this fact is that ordinary CBFs cannot ensure safety for ships with limited speed envelope since the control authority vanishes when approaching an obstacle at such critical angles. Resolving this issue by introducing discontinuities in

***Figure 2:*** *Illustration of safe trajectories reactively generated by virtual vessels. A reference path is shown as a dashed black curve, while black/grey circle indicates an obstacle. Two different CBF formulations are compared: blue curve shows the trajectory using a saturating CBF formulation, while red curve shows the trajectory resulting from a linear CBF formulation. Reprinted from [2].*

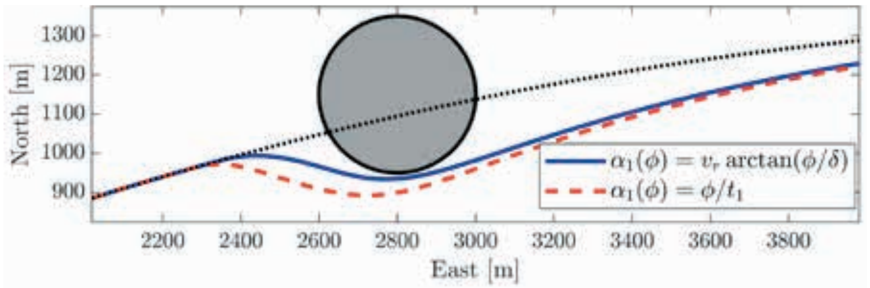
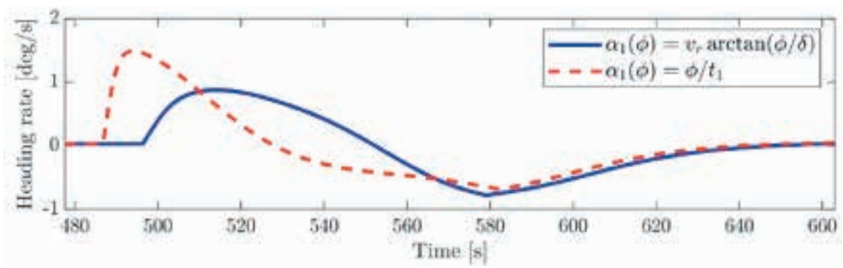



***Figure 3:*** *Heading rate of two virtual vessels, corresponding to the trajectories shown in Figure 2. The heading rate of the virtual vessels serve as reference signal for the guided ship. Reprinted from [2].*




the control law is deemed to fail in real life, since arbitrarily small disturbances can result in chattering and delayed evasive maneuver. A preferred solution is then to use a hybrid CBF formulation, as proposed in **[3]**. By augmenting the control system with logic variables, and properly switching between overlapping CBF-like functions, control authority is maintained in all situations.

**Contacts:** PhD cand. Mathias Marley and Prof. Roger Skjetne (supervisor)

## References

**[1] Marley, M., Skjetne, R., Breivik, M., and Fleischer, C.**, 2020, A hybrid kinematic controller for resilient obstacle avoidance of autonomous ships. IOP Conf. Ser.: Mater. Sci. Eng. 929 012022. DOI: 10.1088/1757-899X/929/1/012022

**[2] Marley, M., Skjetne, R., Basso, E.A., and Teel, A.R.**, 2021, Maneuvering with safety guarantees using control barrier functions. IFAC-PapersOnLine vol. 54(16). DOI: 10.1016/j.ifacol.2021.10.118

**[3] Marley, M., Skjetne, R., and Teel, A.R.**, 2021, Synergistic control barrier functions with application to obstacle avoidance for nonholonomic vehicles. Proc. American Control Conference, New Orleans, LA, USA. DOI: 10.23919/ACC50511.2021.9482979

# NTNU AMOS PARTICIPATION IN ASSOCIATED PROJECTS

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

## Awarded/Ongoing Projects

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

| Project Name | AMOS Coordinator | Budget | Time | Status | Partners | Comments |
|---|---|---|---|---|---|---|
| Center for Marine Operations in Virtual Environments (MOVE) | Zhen Gao<br>Roger Skjetne | 3 MNOK | 2015-2022 | SFI Centre | NTNU<br>SINTEF Ocean<br>Equinor<br>DNV-GL | 2 PhD<br>1 Postdoc |
| Coordinate aerial-underwater operations with gliders for large scale remote ocean monitoring | Tor Arne Johansen | 2 MNOK | 2017-2020 | MarTERA | Alex Alcocer, HIOA | 1 Postdoc |
| Reducing risk of autonomous marine systems and operations (UNLOCK) | Ingrid B. Utne<br>Asgeir J. Sørensen<br>Tor Arne Johansen | 12,5 MNOK | 2018-2022 | NFR FRINATEK | UCLA,<br>QUT | 3 PhD |
| Online risk management and risk control for autonomous ships (ORCAS) | Ingrid B. Utne<br>Asgeir J. Sørensen<br>Tor Arne Johansen | 15,4 MNOK | 2018-2022 | NFR<br>MAROFF<br>KPN | RRM,<br>DNV GL | 3 PhD<br>1 Postdoc |
| MarLander – Maritimt Landingssystem for UAS | Tor Arne Johansen | 3 MNOK | 2018-2021 | MAROFF IPN | Maritime Robotics AS | 2 yrs PhD |
| FlightSmart | Tor Arne Johansen | 2 MNOK | 2018-2021 | BIA IPN | Equator Aircraft SA | 1 Postdoc |
| ADRASSO – Autonomous Drone-based Surveys of Ships in Operation | Tor Arne Johansen<br>Thor I. Fossen | 2 MNOK | 2018-2021 | MAROFF IPN | DNV GL | 1 Postdoc |
| MASSIVE – Mission-oriented autonomous systems with small satellites for maritime sensing, surveillance and communication | Tor Arne Johansen<br>Kanna Rajan | 16 MNOK | 2018-2022 | IKTPLUSS | NTNU | 3 PhD<br>1 Postdoc |
| Legacy after Nansen – Arctic research project that provides integrated scien¬tific 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<br>Ingrid B. Utne<br>Geir Johnsen | 20 MNOK | 2017-2023 | NFR, KUD and partners | NTNU, UiT, UiO, UiB, UNIS, IMR. NPI, MET, Akvaplan NIVA, Nansen Centre Env Remote sensing | 5 PhD<br>2 Postdoc |
| Autoferry: Autonomous all-electric passenger ferries for urban water transport | Morten Breivik<br>Edmund Brekke<br>Egil Eide<br>++ | 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<br>Imperial College | |

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

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

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

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

| Project Name | AMOS Coordinator | Budget | Time | Status | Partners | Comments |
|---|---|---|---|---|---|---|
| Ship operational performance in following seas (ProfSea) | Tor Arne Johansen, Thor Fossen | 4 MNOK | 2021-2024 | NFR KPN | Kongsberg Maritime, SINTEF Ocean | 1 PhD |
| Science of resilient autonomy in perceptually-degraded environments (Sentient) | Kostas Alexis, Tor Arne Johansen | 12 MNOK | 2021-2024 | NFR IKTPLUSS | DNV GL, Equinor, Altera, Scout | 3 PhD |
| REmote Drone-based ship HUll Survey (REDHUS) | Kostas Alexis, Tor Arne Johansen | 4 MNOK | 2021-2024 | NFR IPN | DNV GL, Klaveness, Scout, Altera | 1 PhD |
| AUTOBarge - European training and research network on Autonomous Barges for Smart Inland Shipping. | Tor Arne Johansen, Edmund Brekke | 6 MNOK | 2021-2025 | EU – H2020 | Kongsberg Maritime, european partners | 2 PhD + 1 industry PhD with KM |
| AWAS - Autonomous water sampling with real-time in situ data analysis for ocean environmental monitoring. | Tor Arne Johansen, Geir Johnsen, Jo Arve Alfredsen, Muran van Ardelan | 12 MNOK | 2021-2024 | NFR IKTPLUSS | NIVA, Maritime Robotics, Moen Marin | 1 PhD + 2 Postdoc |
| SentiPro - Multi-Sensor Data Timing, Synchronization and Fusion for Intelligent Robots. | Tor Arne Johansen, Torleiv Bryne | 12 MNOK | 2021-2024 | NFR IKTPLUSS | SentiSystems, Zeabuz, Maritime Robotics | 1 PhD + 1 Postdoc |
| Lavutslippsverdikjede for havbruk til havs | Tor Arne Johansen | 1.5 MNOK | 2021-2024 | Grønn Plattform | Mange innen havbruk | Forsker |
| CRÈME | Kristin Y. Pettersen | 2.5 MEURO | 2021-2026 | ERC AdG | ERC | 4 PhD + 2 Post Doc |
| Light as a Cue for Life in Arctic and Northern Seas (LIGHTLIFE) | Geir Johnsen | 8.6 MNOK | 2021-2024 | NFR | Collab UiT, UNIS, Uni Helsinki. | Led by 2 researchers Sanna Majaneva & Martta |
| Autonomous underwater monitoring of kelp-farm biomass, growth, health and biofouling using optical sensors (MONITARE) | G. Johnsen G. Fragoso M. Ludvigsen | 8.5 MNOK | 2021-2024 | NFR | NTNU | 1 Postdoc |
| Observational Pyramid with Hyperspectral Nano-Satellites for Ocean Science (HYPSCI) | Tor Arne Johansen, Asgeir Sørensen, Geir Johnsen, Murat van Ardelan, Roger Birkeland, Morten Alver | 25 MNOK | 2022-2025 | NFR Tverrfaglig | REV Ocean (TBC) | 3 PhD + 3 Postdoc |

## New (submitted) proposals

| Project Name | AMOS Coordinator | Budget | Time | Status | Partners | Comments |
|---|---|---|---|---|---|---|
| Marine plankton community responses to fluctuations in fresh water run-off MAESTRO) | G. Johnsen<br>G. Fragoso | 12? MNOK | 2021-2023 | NFR | NTNU,<br>SINTEF Ocean,<br>U Southampton | 1 post doc |
| Ecology of bloom initiation and impact of toxic algae (NORHAB) | G. Johnsen | Total<br>12.3 MNOK,<br>NTNU<br>0.3 MNOK | 2021-23 | NFR | AkvaplanNIVA,<br>NTNU | 1 post doc |
| An Autonomous trace-metal-clean seawater Sampler to study iron and mercury transport in the Arctic (AtoMS) | G. Johnsen | Total 14.6 MNOK | 2021-24 | NFR | NIVA, NORCE Klima, NP, NTNU, Nanjing University, Naturhistoriska riksmuseet,<br>UC Santa Cruz | 1 post doc |
| Trophic Interactions between Primary and Secondary producers - climate change effects at the base of the Arctic marine food web (TRIPS) | G. Johnsen | Total 22.2 MNOK | 2021-23 | NFR | NP, UiB,<br>UiT, UNIS,<br>AkvaplanNIVA,<br>NTNU, SAMS,<br>Alfred Wegener Inst., Inst Oceanology i Polen, Aarhus universitet. | 2 PhD |
| GRAVITY – Cost-competitive gravity-based foundations for the offshore wind industry | Erin Bachynski | 21.5 MNOK | 2021-2024 | NFR KPN | NGI,<br>SINTEF Ocean,<br>NTNU | 1 PD NTNU |
| Gradient-based multidisciplinary design optimization of floating wind turbines | Erin Bachynski | 8.2 MNOK | 2021-2024 | NFR Forskerprosjekt | NTNU | 1 PhD + 1PD |
| ZEVS: enabling Zero Emission passenger Vessel Services | Sverre Steen and Roger Skjetne | 5.4 MNOK | 2021-2024 | NFR KPN | TØI, IFE, NTNU,<br>KU Leuven | 1 PhD<br>1 Researcher |
| A system-of-systems approach to real-time integrated ocean environmental monitoring | Tor Arne Johansen,<br>Geir Johnsen | 20 MNOK | 2022-2025 | NFR Teknologi-konvergens | Grieg Seafood,<br>Moen Marin,<br>NTNU TTO | 2 PhD +<br>2 Postdoc |
| Resilient Underwater Bit-rate Constrained Communication Networks (RUBICON) | Kristin Y. Pettersen<br>J. Tommy Gravdahl | 18.5 MNOK<br>NTNU:<br>3 MNOK | 2022-2026 | EU MSCA | Eindhoven Univ. Tech.<br>NTNU<br>Univ. Porto<br>Evologics<br>Eelume | 5 PhDs<br>(1PhD @ NTNU) |
| iSense<br>Centre for intelligent autonomous operations and sensing in marine ecosystem research<br>Host:<br>NTNU NV/IBI<br>5 years<br>UiT BF<br>5 years | **NTNU PIs:**<br>**Geir Johnsen**<br>Asgeir J. Sørensen<br>Martin Ludvigsen,<br>Ingrid B. Utne<br>**UiT PIs:**<br>**Jørgen Berge,**<br>Marit Reigstad,<br>Bodil Bluhm | 404 MNOK<br>-600 MNOK | 2023-2032 | SFF | Partners: NTNU, UiT, SINTEF Ocean, Akvaplan-Niva<br>International collaboration:<br>UH, UCB,(UCLA, NU, JHU, WHOI, MU, SAMS, US, UP | 30+PhD<br>10+Postdoc<br>40+Researcher man years<br>Field campaigns |

## 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<br>Tor Arne Johansen<br>Roger Skjetne<br>Ingrid B. Utne | 18,7 MNOK | 2011-2017 | NFR MAROFF | NTNU<br>Kongsberg Maritime<br>DNV GL | 6 PhD |
| Closed Flexible Cage (CFC) | Asgeir J. Sørensen | 4 MNOK | 2013-2017 | NFR | SINTEF Ocean | 1 PhD |
| Fault-Tolerant Inertial Sensor Fusion for Marine Vessels (MarineINS) | Thor I. Fossen<br>Tor Arne Johansen | 7 MNOK | 2012-2016 | NFR MAROFF | NTNU, RRM | 2 PhD |
| Low-Cost Integrated Navigation Systems using Nonlinear Observer Theory (LowCostNav) | Thor I. Fossen<br>Tor Arne Johansen | 9 MNOK | 2013-2016 | NFR FRINATEK | NTNU<br>FFI<br>UNIK | 3 PhD |
| Next Generation subsea inspection, maintenance and repair operations | Ingrid Schjølberg<br>Ingrid B. Utne<br>Thor I. Fossen | 20 MNOK | 2014-2017 | NFR KPN Awarded | NTNU<br>FMC<br>Statoil<br>SINTEF IKT | 4 PhD |
| Autonomous Unmanned Aerial System as a Mobile Wireless Sensor Network for Environmental and Ice Monitoring in Arctic Marine Operations | Tor Arne Johansen | 12 MNOK<br>0.9 MNOK for NTNU | 2014-2016 | NFR BIP Awarded | NTNU<br>Radionor<br>Maritime Robotics<br>KM Seatex<br>NTNU | Cover NTNU field trial cost, else company research |
| Power management on ships | Tor Arne Johansen | 3 MNOK | 2014-2017 | NRC Industry PhD Espen Skjong | NTNU<br>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<br>Geir Johnsen | 51,5 MNOK | 2016-2019 | Forsker-prosjekt NFR | UiT<br>NTNU<br>SAMS<br>APN<br>UiD<br>WHOI<br>UMA | 1 PhD<br>1 Postdoc for NTNU +<br>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<br>NTNU<br>FFI | Support field experiments |
| UAV ice detection | Tor Arne Johansen | NTNU | 2016-2017 | ERCIM / NTNU | | 1 Postdoc |
| Forprosjekt design og konstruksjon av nyttelaster til NORSat | Tor Arne Johansen | 250 kNOK | 2017 | Norsk Romsenter | Roger Birkeland, IET | |
| Snake Locomotion in Challenging Environments | Kristin Y. Pettersen | 13.9 MNOK | 2011-2015 | NRC | SINTEF IKT | 2 PhD<br>1 Postdoc |
| VISTA PhD-stipend Jørgen Sverdrup-Thygeson: Swimming Robot Manipulators for Subsea IMR. | Kristin Y. Pettersen | 3 MNOK | 2015-2018 | VISTA | NTNU | 1 PhD |
| VISTA Post doc –Eleni Kelasidi | Kristin Y. Pettersen | 3 MNOK | 2016-2018 | VISTA | NTNU | 1 Postdoc |
| Assessment of operational limits for installation of OWT monopile and transition piece and development of an alternative installation procedure | Torgeir Moan | 6 MNOK | 2013-2016 | NFR | | 2 PhD |

| Project Name | AMOS Coordinator | Budget | Time | Status | Partners | Comments |
|---|---|---|---|---|---|---|
| Experimental and numerical study of the combined wind/wave energy concept SFC in extreme and operational environmental conditions | Torgeir Moan<br>Zhen Gao | 3 MNOK | 2014-2016 | NFR | NTNU | 1 Postdoc |
| Numerical analysis of the dynamic response of an offshore wind turbine under wind and ice loads | Torgeir Moan | 3 MNOK | 2014-2016 | NFR | NTNU | 1 Postdoc |
| Numerical modelling and dynamic analysis of floating vertical axis wind turbines | Torgeir Moan | 3 MNOK | 2013-2016 | NFR | NTNU | 1 PHD |
| Dynamical analysis of anchor handling and trawling operations | Torgeir Moan | 3 MNOK | 2013-2016 | NFR | NTNU | 1 PHD |
| TerraDrone | Tor Arne Johansen | 15 MNOK | 2016-2018 | NFR BIA Innov prosjekt | Maritime Robotics<br>IDLETech<br>NTNU<br>NGU | 1 Postdoc |
| Multi-stage Global Sensor Fusion for Navigation using Nonlinear Observers and eXogenous Kalman Filter | Tor Arne Johansen<br>Thor I. Fossen | 10 MNOK | 2016-2019 | NFR FRINATEK | | 1 PHD<br>2 Postdoc |
| Integration of Manned, Autonomous and Remotely Controlled Systems for Coastal Operations | Tor Arne Johansen | 1.2 MNOK til NTNU | 2016-2018 | NFR MAROFF | Radionor,<br>Seatex,<br>Maritime Robotics | |
| D-ICE | Tor Arne Johansen | 6 MNOK | 2017-2018 | NFR FORNY | TTO | |
| SCOUT Inspection Drone | Tor Arne Johansen<br>Thor I. Fossen | 6 MNOK | 2017-2018 | NFR FORNY | TTO | |
| European Training Network funded by H2020 for 2015-2018<br>Marie Curie<br>Marine UAS | Tor Arne Johansen<br>Thor I. Fossen | 4 MEUR | 2015-2018 | EU | NTNU<br>IST<br>UiP<br>LiU<br>NORUT<br>Maritime Robotics<br>Honeywell<br>Catec<br>iTUBS | 15 PhD whereof 5 PhD at NTNU + project managem. |
| Drone air traffic control | Tor Arne Johansen | 0.9 MNOK til NTNU | 2017-2018 | JU SESAR | Internasjonalt konsortium ledet av Airbus | |
| Safe operation of CLOSED aquaculture CAGES in WAVES | Odd Faltinsen<br>Claudio Lugni | 2,2 MNOK til NTNU | Q4 2017-Q3 2019 | NFR MAROFF | SINTEF Ocean (P. Lader) | 1 Postdoc |
| Sensor Fusion and Collision Avoidance for Autonomous Surface Vehicles (Autosea) | Edmund Brekke<br>Morten Breivik<br>Tor Arne Johansen | 11,2 MNOK | 2017-2018 | RCN MAROFF | NTNU<br>DNV GL<br>Kongsberg Maritime<br>Maritime Robotics | 3 PHD<br>1 Postdoc |
| Enabling Technology providing knowledge of structure, function and production in a complex Coastal Ecosystem (ENTiCE) | Martin Ludvigsen<br>Geir Johnsen<br>Asgeir J. Sørensen | 6 MNOK | 2016-2019 | NFR, Marinforsk | SINTEF Ocean, NTNU IBI and IMT, SAMS | 1 PHD<br>1 Postdoc |
| Ice-algal and under-ice phytoplankton bloom dynamics in a changing Arctic icescape –"Boom or bust Boom or bust" | Geir Johnsen | 3 MNOK | 2016-2018 | NFR – Polprog | NP, NTNU, AWI | 1 PhD |

# HIGHLIGHTS OF THE APPLIED UNDERWATER VEHICLE LABORATORY (AURLAB)


*Figure 1: Jellyfish underneath the ice.*

*Figure 2: Ice station; making camp before deploying the mini-ROV with the hyperspectral imager.*

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

The AUR Lab runs and maintains a park of AUVs, ROVs, instruments, samplers and navigation equipment with support systems on behalf of partners from five different faculties. The lab represents an interdisciplinary scientific community, in which scientific questions are addressed by teams with specialists from many specialties. The resources are available for faculty, researchers, PhD- and MSc students to test and experiment to prove hypotheses and theoretical results. Some of the scientific questions for 2021 have been related to Arctic operations, archaeology and maritime heritage, pollution and oceanography. The Department of Marine Technology hosts the lab, and the University Museum, the Department of Engineering Cybernetics and the Department of Biology are partners. There are approximately 25 PhD and post-docs related to the lab through their research work.

## 1. Nansen seasonal cruise

Our L-AUV Harald was deployed in February in the Barents Sea from the Norwegian Icebreaker Kronprins Haakon, using adaptive sampling methods to measure the characteristics of the Polar front where the Arctic water body meets the Atlantic's water. Later in the season, we deployed a double Blueye mini-ROV to carry an underwater hyperspectral imager to document the blooming ice algae covering the underside of the Arctic ice cap, to help improve the understanding of this peak in primary production.

*Figure 3: The USV deployed in the Northern Barents Sea.*

The primary production is governed by light, and to support, complement and validate remote sensing measurements for phytoplankton estimations; both the AUV and USV were deployed with light sensors, providing both information about light intensity and spectral distribution. Running robotic operations in the Arctic is both challenging and rewarding – our operations from RV Kronprins Haakon were completed in collaboration with the Nansen Legacy, and provided valuable experience on how to combine science and technology to learn more about this fascinating environment.

## 2. OceanLab

The AUR Lab is ramping up our capacities in the Trondheim Fjord. We have established a control room to also help facilitate remote operations beyond the horizon. By adapting control room practices and protocols from the space industry, our control room does now allow an operator to connect to robots in the field from the control room. The subsea facilities will also be upgraded to two subsea stations to support testing and experiments with the inspection, intervention and docking of underwater vehicles. The potential of this capacity was demonstrated together with Equinor, which used the facility for the validation and verification of solutions for resident vehicles to be implemented on the Norwegian Continental Shelf.

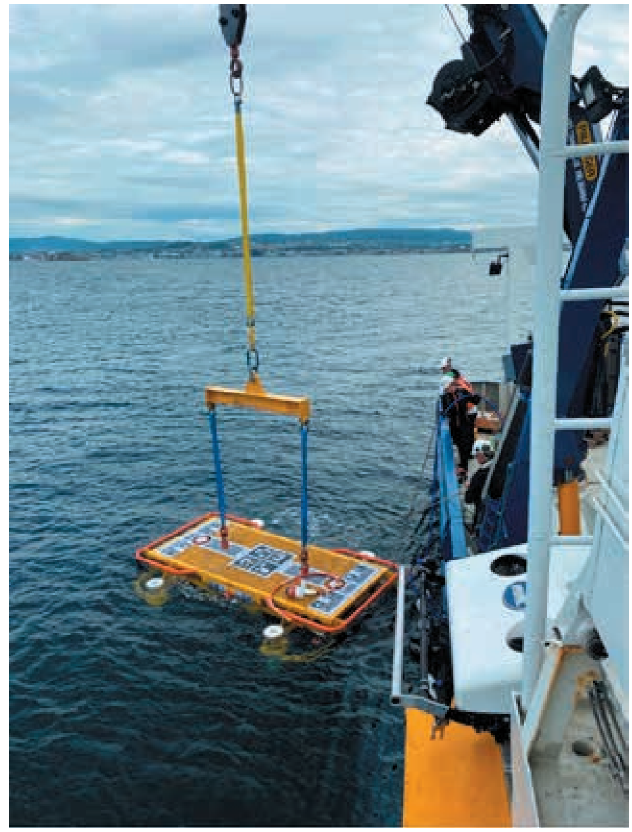


**Figure 5:** *Subsea docking plate entering the sea.*

2021 was an all-time high for activity in our lab. We had almost 50 days onboard the RV Gunnerus, in addition to a large number of other activities. Through the OceanLab and Fjordlab/Ocean Space Centre initiatives, AUR Lab is further developing its infrastructure, and also its operational capabilities supporting new and exciting research projects!

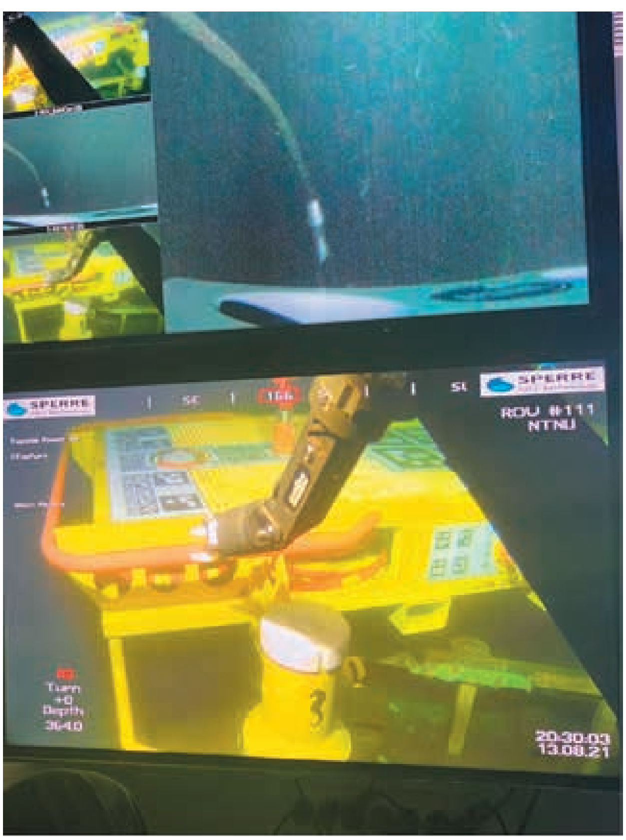



**Figure 4:** *Installation of subsea docking plate.*

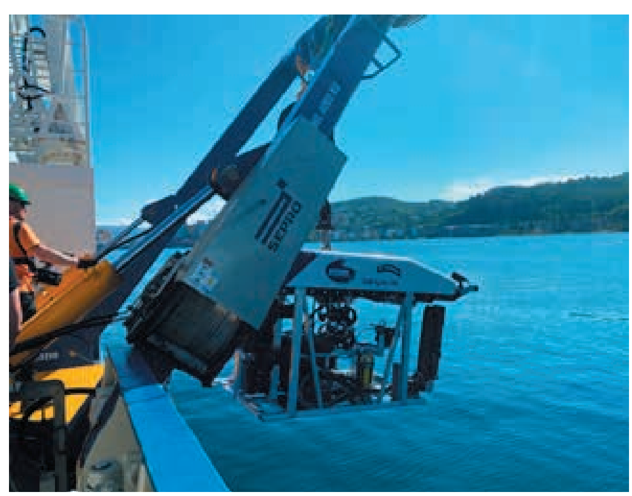


**Figure 6:** *ROV deployment from RV Gunnerus.*

# HIGHLIGHTS SMALLSAT LAB

## HYPSO-1 mission

HYPSO-1 (The HYPer-Spectral smallsat for Ocean observation) will observe oceanographic phenomena via a small satellite with a hyperspectral camera, intelligent on-board processing, and in collaboration with marine robots. Traditional Earth observation satellites are very expensive, and take several years to develop and launch. Dedicated small satellites can be used to provide images of selected areas of interest with shorter revisit times and better spectral resolution through hyperspectral imaging, see Figure 1. In the reference, **S1-R1**, the innovative operational concept of HYPSO-1 is described, and it is described how the high performance can be achieved with such a small satellite using accurate control and super-resolution image processing. The information can be downloaded to the ground, and used by both end-users and marine robots, which can investigate the areas of interest further, see reference **S1-R8**.

The HYPSO-1 spacecraft was finalized in 2021 in collaboration between NTNU, which developed the payload system and the mission, and the company NanoAvionics, which delivered the flight-ready satellite bus. Figure 2 shows the team finalizing the integration of the HYPSO-1 satellite.


***Figure 2.*** *The team finalizing the integration of the HYPSO-1 satellite (seen in the back) in NanoAvionics lab in Vilnius, Lithuania.*

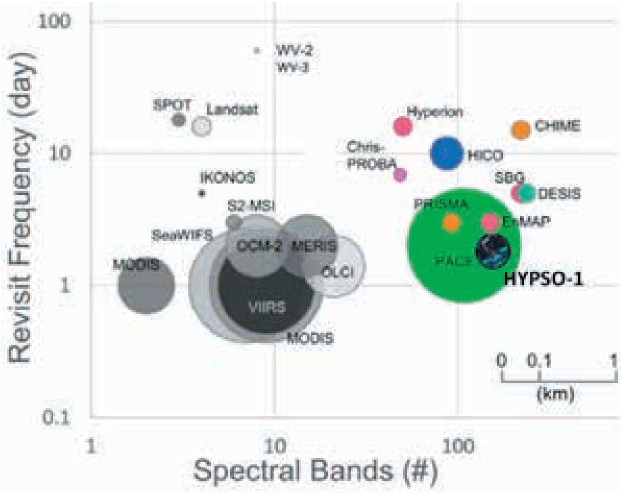



***Figure 1.*** *Classification of existing and planned multi- and hyperspectral earth observation satellites. HYPSO-1 is designed to achieve a high spectral resolution, a high spatial resolution (indicated by a small radius) and a short revisit time. The figure is adapted from the following recent article: Heidi M. Dierssen, Steven G. Ackleson, Karen E. Joyce, Erin L. Hestir, Alexandre Castagna,Samantha Lavender and Margaret A. McManus. Living up to the hype of hyperspectral aquatic remote sensing: Science, resources and outlook. Frontiers in Environmental Science,9:134, 2021.*

The developments at NTNU have been led by the Department of Electronic Systems and the Department of Engineering Cybernetics, with support from the Department of Marine Technology and the Department of Mechanical and Industrial Engineering. The HYPSO-1 project team in 2021 consisted of 10 PhD fellows (Evelyn Honoré-Livermore, Gara Quintana Diaz, Elizabeth Prentice, Dennis Langer, Mariusz Grøtte, Bjørn Kristiansen, Marie Henriksen, Mariusz Grøtte, Sivert Bakken, Jon Alvarez Justo), 2 postdocs (Roger Birkeland and Joseph Garrett), approximately 20 MSc and BSc students, technical staff (Terje Mathisen, Amund Gjersvik, and others) and professors Milica Orlandic, Fernando Aguado Agelet, Jan Tommy Gravdahl, Egil Eide, Fred Sigernes, Geir Johnsen, Asgeir Sørensen, Cecilia Haskins, Nils Torbjörn Ekman and Tor Arne Johansen, all working together in the NTNU SmallSatLab.

Several publications are documenting the hyperspectral instrument design **(S1-R2)**, pre-flight calibration and characterization **(S1-R3, S1-R4)** and software design, integration and test Satellite completion **(S1-R5, S1-R6, S1-R9)**.

HYPSO-1 was successfully launched at 10:25 am local time from Florida, and was deployed one hour later into a sun-synchronous polar orbit at an altitude of approximately 540 km, see Figure 3. On the next day, we established contact with HYPSO-1 on both UHF and S-band radio links to our local ground station at NTNU in Trondheim. During the following weeks, the satellite systems was carefully tested, and we successfully acquired images at first for validation and in-orbit re-calibration, in order to make it ready for scientific use.

HYPSO-1 is a research infrastructure that has an expected in-orbit lifetime of 5 years. It will therefore enable numerous research activities, both within and beyond AMOS. A key feature is the ability to upgrade software and firmware in-orbit, which means that it can be used for research questions that were not planned for in advance. The orbit of HYPSO-1 will continuously lose altitude, until it burns in the atmosphere after a few years. Planned research for the next couple of years include:

- In-orbit characterization and vicarious calibration of the instrument.
- Development of novel algorithms for the atmospheric correction of hyperspectral images, which is essential given that 80-90% of the incoming light is "noise" that has been scattered in the atmosphere.
- Development super-resolution image processing techniques for hyper-spectral images that can be embedded in the processing chain onboard the satellite.
- The development of algorithms for the detection and classification of targets (e.g. algae, or specific species of plankton) using spectral signatures.
- The development of custom data products that enable a rapid response to the detection of harmful algal blooms for environmental monitoring, and the protection of fish health in aquaculture facilities.
- The integration of HYPSO-1 into a system-of-systems with drones, autonomous surface vehicles, conventional satellites (Copernicus) and ocean models (digital twins) to help support adaptive sampling and intelligent monitoring of the oceans.

## HYPSO-2 and beyond

The development and construction of the successor satellite, HYPSO-2, is progressing well. It will be based on HYPSO-1, with the following enhancements:

- An upgraded hyper-spectral imager with several incremental improvements in optics, electronics and mechanical design, such as temperature compensation (see also reference S1-R4).
- A highly increased onboard processing power, enabling a more powerful image analysis algorithms and artificial intelligence to be executed onboard.
- A secondary software defined radio (SDR) payload for radio communication research, especially for the internet-of-things in the ocean/Arctic, and direct communication with robotic agents (reference S1-R8).
- Deployable solar panels, with an increased electric power capacity compared to HYPSO-1.
- Upgraded software.


***Figure 3:*** *Successful launch of HYPSO-1 with the Transporter-3 rideshare mission with a SpaceX Falcon-9 rocket from Kennedy Space Center in Cape Canaveral, Florida, on 13 January 2022.*

The plans and funding for HYPSO-3 and beyond do not yet exist. Some current ideas are to go beyond the visible and near-infrared (NIR) wavelength into short-wave-infrared (SWIR), using InGaAs image sensors for improved material classification capabilities (e.g. methane and gas emissions) and atmospheric correction, as well as a larger telescope to achieve a much higher spatial resolution for coastal and freshwater applications.

**Contact** Professor Tor Arne Johansen

**Media** SpaceX Transporter-3 Mission - YouTube
NRK Satellitten HYPSO-1, utviklet ved NTNU i Trondheim, skytes opp med SpaceX fra Florida – NRK Trøndelag
NTNU Norges første forskningssatellitt fra et universitet er i bane rundt jorda | NTNU Nyheter

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**S1-R2.** Prentice, E., Grøtte, M., Sigernes, F., and Johansen, T. A. Design of hyperspectral imager using COTS optics for small satellite applications, Int. Conf. Space Optics (ICSO), 2021

**S1-R3.** Henriksen, M. B., Prentice, E. F., Sigernes, F., and Johansen, T. A. Pre-Launch Calibration of the HYPSO-1 Cubesat Hyperspectral Payload, IEEE Aerospace Conference, 2022

**S1-R4.** Prentice, E. F., Henriksen, M. B., Johansen, T. A., Navarro Medina, F., and Gómez San Juan, A. Characterizing Spectral Response in Thermal Environments, the HYPSO-1 Hyperspectral Imager, IEEE Aerospace Conference, 2022

**S1-R5.** Bakken, S., Birkeland, R., Garrett, J. L., Marton, P. A. R., Orlandic, M., Honore-Livermore, E., Langer, D. D., Haskins, C., and Johansen, T. A. Testing of Software-Intensive Hyperspectral Imaging Payload for the HYPSO-1 CubeSat, IEEE/SICE International Symposium on System Integration (SII), 2022

**S1-R6.** Bakken, S., Honore-Livermore, E., Birkeland, R., Orlandic, M., Prentice, E. F., Garrett, J. L. Langer, D. D., Haskins, C., and Johansen, T. A. Software Development and Integration of a Hyperspectral Imaging Payload for HYPSO-1, IEEE/SICE International Symposium on System Integration (SII), 2022

**S1-R7.** Birkeland, R., Quintana-Diaz, G., Honore-Livermore, E., Ekman, T., Aguado Agelet, F., and Johansen, T. A. Development of a multi-purpose SDR payload for the HYPSO-2 Satellite, IEEE Aerospace Conference, 2022

**S1-R8.** Dallolio, A., Quintana-Diaz, G., Honoré-Livermore, E., Garrett, J., Birkeland, R., and Johansen, T. A. A Satellite-USV System for Persistent Observation of Mesoscale Oceanographic Phenomena, Remote Sensing, Vol. 13, 3229, 2021

**S1-R9.** Garrett, J., Bakken, S., Prentice, E., Langer, D., Leira, F., Honoré-Livermore, E. Birkeland, R., Grøtte, M., Johansen, T. A., and Orlandić, M. Hyperspectral Image Processing Pipelines on Multiple Platforms for Coordinated Oceanographic Observation, 11th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS), 2021

# HIGHLIGHTS OF THE UNMANNED AERIAL VEHICLE LABORATORY

## Starting the NTNU UAV Icing Lab

A new research group at NTNU AMOS is focusing on the challenges of in-flight icing on unmanned aircraft.

Atmospheric in-flight icing is a major weather risk, and a severe threat to UAVs. During flight in icing conditions, ice accumulates on critical aircraft surfaces such as wings and propellers. These ice accretions generate flow disturbances, which reduce the aerodynamic performance. The adverse effects lead to an increase in drag, a reduction in lift and thrust, as thrust substantially increases the risk of the aircraft crashing. Today, UAVs cannot fly in icing conditions, and are grounded when icing conditions are prevalent. This is a major limitation of the flight envelope and operational availability of UAVs – especially in marine or Arctic environments.

NTNU | UAV Icing Lab
Department of Engineering Cybernetics

During the past year, the research on UAV icing was taken to the next level by starting the UAV Icing Lab at the Department of Engineering Cybernetics at NTNU. The research group is backed by three grants that have been awarded by the Research Council of Norway with a total volume of 27 Million NOK. Six PhD candidates and several master students are currently working in the lab. The UAV Icing Lab will provide knowledge and solutions for UAVs in icing conditions under the leadership of Dr. Richard Hann and Prof. Tor Arne Johansen. Their contributions will be essential to unlock regular and safe UAVS operations in cold climate environments all around the globe.

Their research focuses on a wide range of practical applications and challenges related to icing on unmanned aircraft. The main research goals of the UAV Icing Lab are:

- Icing at low Reynolds numbers on 2D and 3D UAV geometries;
- Icing on UAV rotors and propellers;
- Optimization of ice protection systems;
- Ice detection with sensors and flight performance monitoring;
- Path planning of UAV missions in adverse weather conditions; and
- System identification of iced UAVs.


***Figure 1:*** *Icing on a propeller during a test campaign in an icing wind tunnel.*

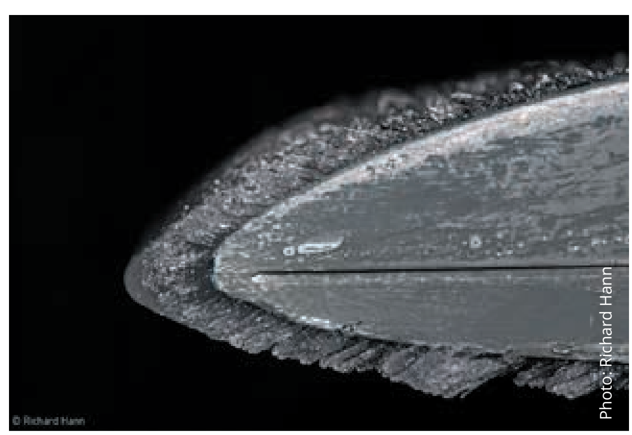


***Figure 2:*** *Ice accretion on the leading-edge of a wing.*

The UAV Icing Lab works in close collaboration with UBIQ Aerospace, a spin-off company founded in 2017 with its origins in NTNU AMOS, as well as Andøya Space, Maritime Robotics, DLR, NASA, ANSYS, the Von Karman Institute, VTT Finland and other companies and research organizations.

The lab conducted two major icing wind tunnel test campaigns in 2021. The tests were conducted at the Technical Research Centre of Finland (VTT) in Helsinki. The objective of the campaign was to test new ice protection systems on wings and propellers for UAVs. The findings from these tests are currently being processed, and will be published during the next year, see also Figures 1 and 2.

## Highlights of the Autofly Project

### Methods

Fixed-wing UAVs can be an essential part of robotic networks deployed in ocean monitoring, search and rescue, crop monitoring in agriculture and logistic infrastructure, to name a few. There exists open-source software for the guidance, navigation and control of the vehicle based on linear theory for the control algorithm design on the lowest level, i.e., control of the vehicle's attitude and speed based on PID loops. The flight performance is usually satisfactory for non-aggressive maneuvers under normal conditions, but can increasingly deteriorate for more aggressive flight trajectories in which the nonlinear effects of the aerodynamics become more significant. A practical approach to this problem is to limit the range of flight conditions the UAV is operated in, referred to as the flight envelope. Our goal in the Autofly project is to extend this envelope by applying state-of-the-art nonlinear control theory, and demonstrating these methods' performance in practical experiments. We went deeper into three different types of nonlinear control methods, and will give a brief outline for each before touching on the results.

One approach is Model Predictive Control (MPC), which allows us to explicitly encode the flight envelope in the controller design as nonlinear constraints in an Optimal Control Problem that can be periodically solved to obtain an optimal control input trajectory, see reference **U1-R1**. Optimal performance with respect to a defined cost function and prediction, in addition to constraint satisfaction by use of the actuation system in an integrated Multiple-Input-Multiple-Output fashion, are traits that are hard to achieve with the existing autopilot used at the UAV Lab (ArduPlane). However, the drawback is its increased computational complexity and requirement for a dynamic model of the UAV, which demands powerful embedded computing platforms and a considerable engineering effort in system identification. In order to be able to test the controller onboard one of the UAVs at our lab, we developed a payload architecture that can be run in parallel with the existing flight stack of the UAV. The field of MPC is quite mature and conditions for performance and stability guarantees exist on a theoretical level, but are hard to give for a specific system.

In addition to MPC, we looked at deep reinforcement learning (DRL), a set of data-driven methods for approximate optimal control, in which the controller is implemented as a neural network, see reference **U1-R3**. These methods can operate on- and optimize control performance for the full nonlinear dynamics in a model-free manner (at least in theory), as their online operation is generally highly computationally efficient, and can exhibit (nearly) arbitrarily complex behaviour. A downside of the DRL methods is the lack of interpretability of the deep neural network; stability, robustness and constraint satisfaction properties are not guaranteed. Moreover, DRL requires a lot of training data, a challenge that is further complicated for flight control applications by the high inherent risk associated with data collection using a suboptimal controller.

A third approach we considered is to apply nonlinear control methods based on Lyapunov stability theory, in particular geometric attitude control (GAC), see reference **U1-R2**. Such methods require only a fraction of the computational resources required by MPC, and stability and robustness guarantees can be given for the particular system under study, even with limited knowledge of the system model. Even so, constraint handling is difficult to address, and optimality is not addressed. Traditionally, the orientation/attitude of aircraft in 3D space is parametrized using Euler angles, which have singularities for certain orientations, which in themselves contribute to a more limited flight envelope. In our work, we employ global, nonsingular attitude representations. In addition to avoiding singularities, this enables more efficient, shortest path (geodesic) rotation maneuvers.

***Figure 3:*** *Ready for take-off.*

***Figure 4:*** *Pushed the limits a bit too far. Luckily, we recovered the UAV and found the bug that caused the crash.*

## Results

We extensively tested our experimental platform and the implemented controllers in campaigns at the Breivika airfield, see Figures 3 & 4. A lot of work in the literature has been done on nonlinear control of UAVs, although there are few experimental results on the published control algorithms. The experimental verification of our algorithms was a primary goal of the overall project. We have obtained preliminary experimental results with GAC, which are very promising for different UAVs, with a different actuator configuration. Further experiments will gauge how the performance compares to the baseline ArduPlane controller. We will now proceed with the results for MPC and DRL.

In a nominal waypoint tracking operation with a guidance controller commanding slowly varying attitude and speed references, the MPC was able to achieve comparable tracking performance to the existing PID controller, while making more effective use of the actuators. In more aggressive maneuvers in which the nonlinearities become more dominant, we showed that the MPC gives a better tracking performance, while satisfying the constraints at all times. With the established results, we aim at more challenging maneuvers that are closer to the limits of the flight envelope.

The DRL approach was first verified to exhibit superior performance compared to the existing PID-based autopilot in the simulation environment. We then targeted control of the real UAV in the field, and to this end developed a new architecture and method for the DRL controller with a focus on data efficiency, achieving comparable control performance to the established autopilot in the field. The development of these learning controllers was a highly iterative process of generating ideas in the simulation environment and verifying the most promising ones in the field. Ultimately, we determined that the robustness of the controller and a high-phase margin was vital for success, achieved through a combination of carefully designing the simulation environment (notably with a high actuation delay) and incentivizing a low gain through the learning objective. Next steps include tackling more complex flight control challenges such as recovery from a loss of control, possibly through developing a new method to learn online on the real UAV in the field.

Experimental Platform and Simulator for Machine Learning
To test our controllers in practice, we needed to extend the existing flight stack available onboard the fixed-wing UAVs at the lab, with additional embedded computing hardware that can be run in parallel to safety-critical autopilot systems, see Figure 5. Keeping in mind that the scope of the project is control, we used a serial communication link (MAVLink/UART) to the autopilot to feed estimates from the navigation system to the companion computer, in which we can implement our control methods in DUNE. Both the experimental and established control algorithms generate PWM signals in parallel, and the pilot has control over which one is being propagated to the actuators.

As previously discussed, the data-intensive nature and data collection risk for flight control constitute a significant challenge for DRL. To help remedy this challenge, we took the approach of training the DRL controller in a simulator environment before deploying the controller on the real UAV in the physical world. To this end, we developed an open-source simulator (https://github.com/eivindeb/pyfly) that has since seen wide adoption in the community. To ensure a smooth transfer of the control performance from the simulator to the field, the simulation environment is designed in order to robustify the DRL controller. To run the DRL controller onboard the UAV, we interface TensorFlow as a DUNE task to evaluate the neural network, and then translate its outputs to PWM signals as described above.

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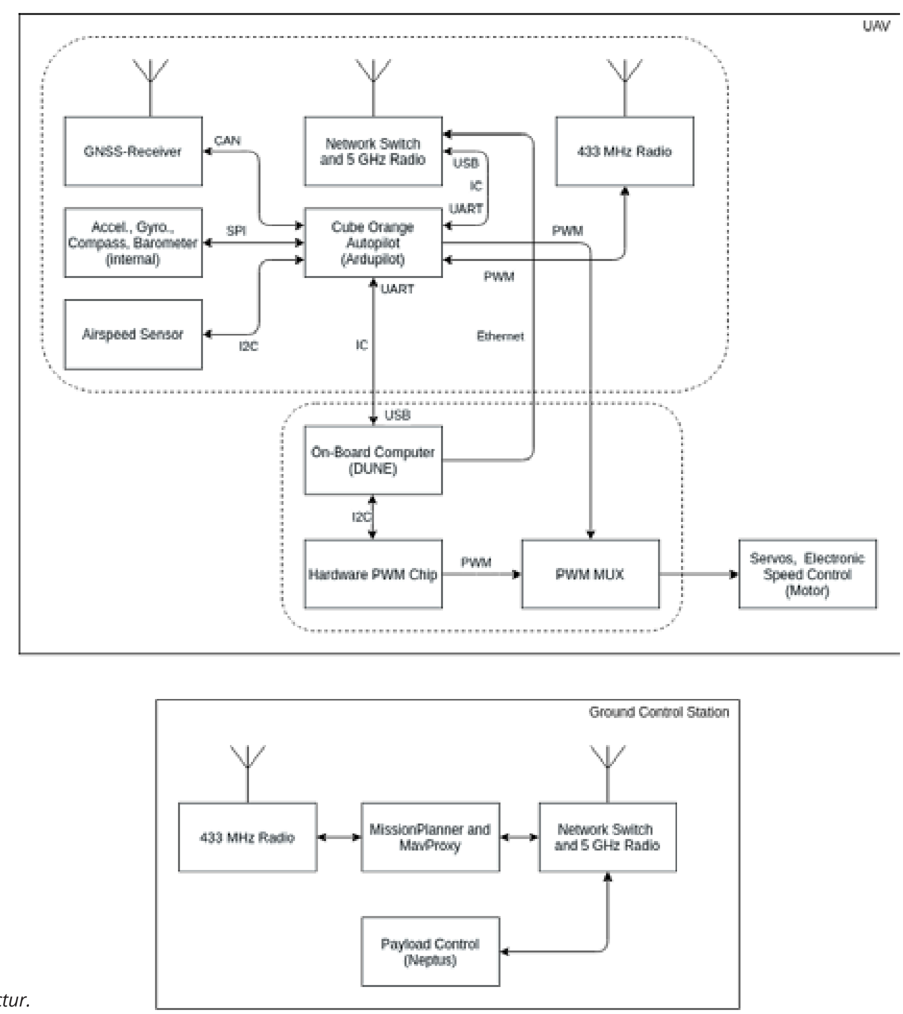


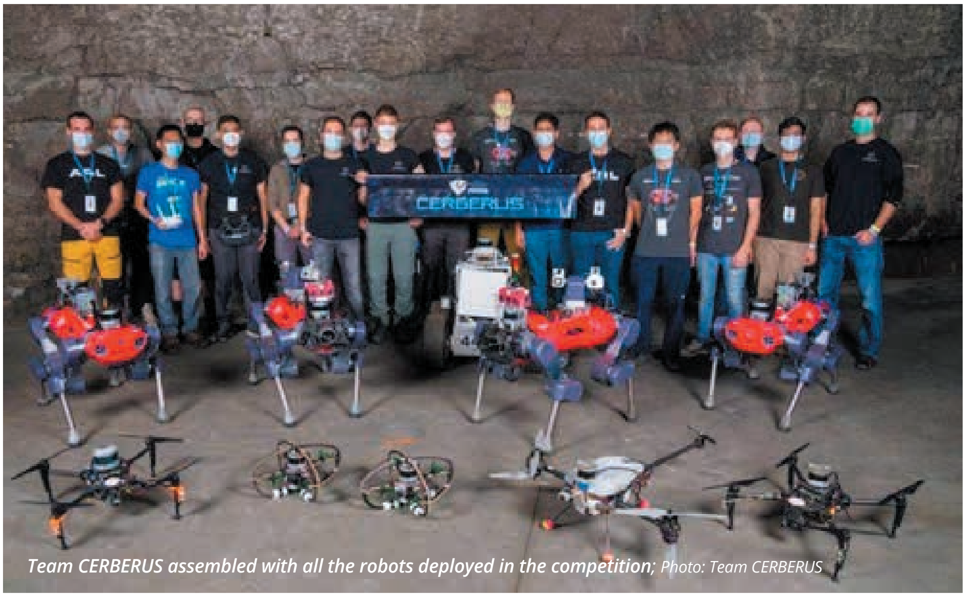

***Figure 5:*** *System architectur.*

Photo: Asgeir J. Sørensen

# AWARDS AND HONOURS 2021

## A $2 million prize for subterranean robots

Team Cerberus has won a highly prestigious international competition with their subterranean robots, competing against top-ranked challengers. The group is headed by the NTNU AMOS Affiliated Professor Kostas Alexis.



*Team CERBERUS assembled with all the robots deployed in the competition; Photo: Team CERBERUS*

The DARPA Subterranean Challenge calls on teams to develop innovative robots that can explore diverse subterranean environments. This competition challenges and pushes previous technological boundaries. The prize for the winning team is $2,000,000.

Professor Alexis received support from the US Defense Advanced Research Projects Agency (DARPA) to work on the project while he was still affiliated with the University of Nevada, Reno.

## Professor Marilena Greco becomes Specially Appointed Professor (honorary position) at Osaka University, Japan

Professor Marilena Greco, Centre for Autonomous Marine Operations and Systems, Department of Marine Technology covers from 1st April 2021 to 31st March 2022, the position of Specially Appointed Professor (honorary position) at the Division of Global Architecture, Graduate School of Engineering at of Osaka University, Japan.

This type of position targets researchers/scientists with advanced specialized knowledge or with considerable experience in a specific field to join the host university for a certain period, and perform research and/or provide a series of lectures. In this case, it was her valued expertise in marine hydrodynamics that provided an opportunity to enlarge the footprint of female scientists in Osaka University's engineering academia, and to provide an international female role model to the next generation of engineers.

## Professor Kristin Y. Pettersen wins prize for her research from NTNU, becomes a Distinguished Lecturer of the IEEE Control Systems Society and receives ERC Advanced Grants

Professor Kristin Ytterstad Pettersen, Centre for Autonomous Marine Operations and Systems, Department of Engineering Cybernetics, wins NTNU employee prize for her groundbreaking research.

The outstanding research work done by Kristin consists of the motion control of mechanical systems, with a primary emphasis on autonomous ships, subsea crafts and snake robots. In particular, the main results of the last few years have been achieved by research on subsea snake robots.

Before her efforts, this field has been dominated by mechatronic trial and error studies, while Pettersen has contributed with new theoretical results by a model-based analysis and control of these robots.

## From innovation to commercial products

She has been leading the work of designing new control systems with performance and stability in a way that highly surpasses previous efforts in this field.

She has also urged the confirmation of new theoretical knowledge, which has resulted in several prototype robots that have been tested, both in terrestrial and subsea.

Kristin has also contributed to innovation. The result is a spin-off company Eelume, which shows that Kristin's research can go all the way from advanced theoretical results to a commercial product.

Under her leadership, the state-of-the-art research done by the research group has moved the field of snake robots significantly forward.

## International visibility

Her work has resulted in several prizes and awards. The most prestigious was in 2020, when she received the Hendrik W. Bode Prize, the most honourable prize in the field of control engineering. In the past, only one woman and one from Scandinavia have won this prize.

In 2018 she was chosen as a member of The Royal Norwegian Science Academy. Through her publications, conference speeches and honours, she has contributed to NTNU's international visibility.

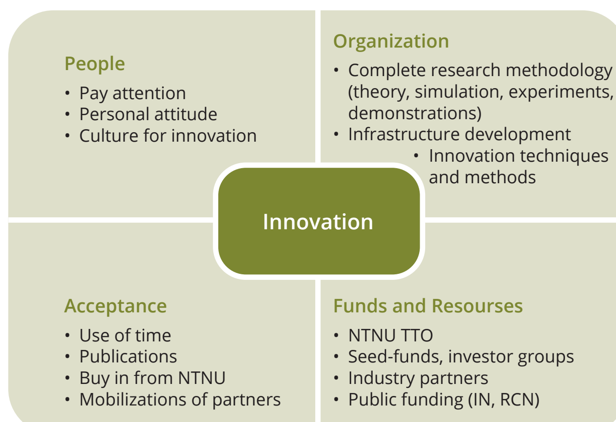
Another award for Professor Kristin Y. Pettersen. She currently holds several pronounced trusted positions in the IEEE, IFAC and EUCA. She is also a Distinguished Lecturer of the IEEE Control Systems Society. She was also awarded the European Research Council (ERC) Advanced Grant in 2021.

# WITH A LICENSE TO CREATE,
## 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, with NTNU AMOS preparing to become a leading international player in heterogeneous robotic systems for marine mapping and monitoring. These efforts are strongly supported by NTNU AMOS' partners – NTNU, Equinor, DNV, SINTEF and the Norwegian Research Council, in collaboration with industry and governmental agencies.

Key scientists hypothesized the importance of these as early as in 2010 before they became "hot¨ in Norway and elsewhere. This is also one of the reasons 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, as 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 entrepreneurship were then systematically explored, and PhD and postdoc candidates were offered training on innovation processes. To date, **eight** spinoff companies represent a direct measurable outcome of this, in addition to several filed patents.



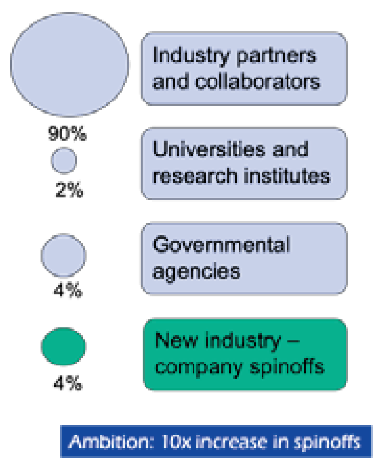

*NTNU AMOS has systematically develc ped a culture for innovation in collaboration with the partners and NTNU TTO*


*Since 2003 NTNU has hosted two Centres of Excellence – CeSOS and NTNU AMOS. Since then, 10 companies have been founded. In 2021, SentiSystems was founded.*

In 2021, the eighth AMOS spinoff company, SentiSystems, was founded. SentiSystems offers a novel platform solution for real-time sensor data processing. SentiSystems started with sensor integration for autonomous operations, though the versatility of the platform also makes it suitable for a variety of other intelligent applications, such as mapping, monitoring and surveillance systems. SentiSystems was recently selected as this year's newcomer in technology in the Trondheim region by the Norwegian bank DNB.

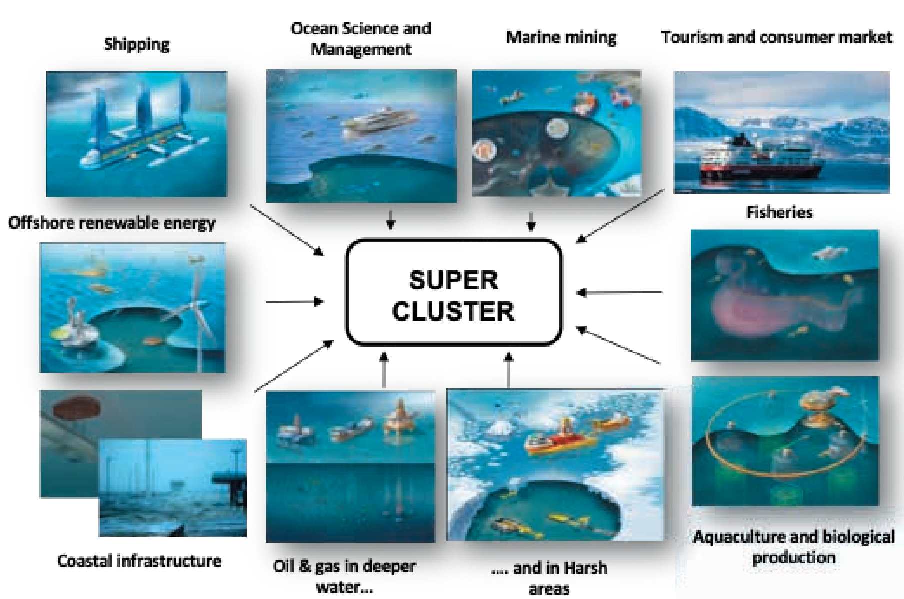
In the immediate future, we foresee the need to develop autonomous instrumental carrying platforms due to human impact, for improved knowledge-based mapping and monitoring of the marine environment; this will lead to better natural resource management and decision-making, which will help to integrate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

NTNU AMOS has several innovation areas, the most important of which is established industry. However, we see an increasing trend in innovation that we directly attribute to the public sector. For instance, we strongly believe that a 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 all over Norway.





*The most important innovation areana for NTNU AMOS is primarly established industry. Nevertheless, per December 2021 eight start-up companies have been spun off from the AMOS research environment.*




*The blue economy is a super cluster in which Norway plays a leading role – also in transitions toward the green shift and digitaization.*

# SENTISYSTEMS

Sensor timing, synchronization and fusion: From technical problem to commercialization.

## The problem

When AMOS started almost 10 years ago, one of the main research topics was sensor fusion for navigation and mapping. Raw data from cameras, satellite navigation, inertial measurement units and other sensors have to be combined to obtain highly accurate estimates of the variables of interest, typically position, velocity and orientation with respect to given coordinate references. Sensor fusion is necessary to achieve an accurate navigation of autonomous vehicles and robots, and to achieve accurate maps and surveillance.

Operating agile robotic vehicles, such as drones that can fly at 20 m/s and turn at 180 deg/s, means 2 m or 18 deg motions during 100 milliseconds. Unknown or uncompensated latencies in data acquisition, serial communication, software and synchronization therefore cause much bigger errors than the individual sensors themselves. This means that having accurate sensors does not provide accurate results in sensor fusion, navigation and mapping unless the sensor data are synchronized and latencies are known. It hence came as a surprise to us that there were no open commercial solutions that would help us to solve this problem, which is by no way unique to our research. Clearly, researchers and engineers have been solving this problem in-house by various proprietary, and more or less ad hoc electronic circuits and software solutions. This led us to the conclusion that we needed to develop our own solution.

## The prototype

PhD student Sigurd Albrektsen took on this task in 2013 since he needed it for his research on the camera-based navigation of UAVs. At the time, we estimated that this work would take a couple of months, and would only serve the selfish needs of this particular project. However, there were three reasons why things took a different turn:

- A notorious series of bad luck events led to the SyncBoard – which was the name of the first prototype – being onboard several UAVs that made hard crashes. While it survived out of a total wreck in a forest near Eggemoen, it did not survive after

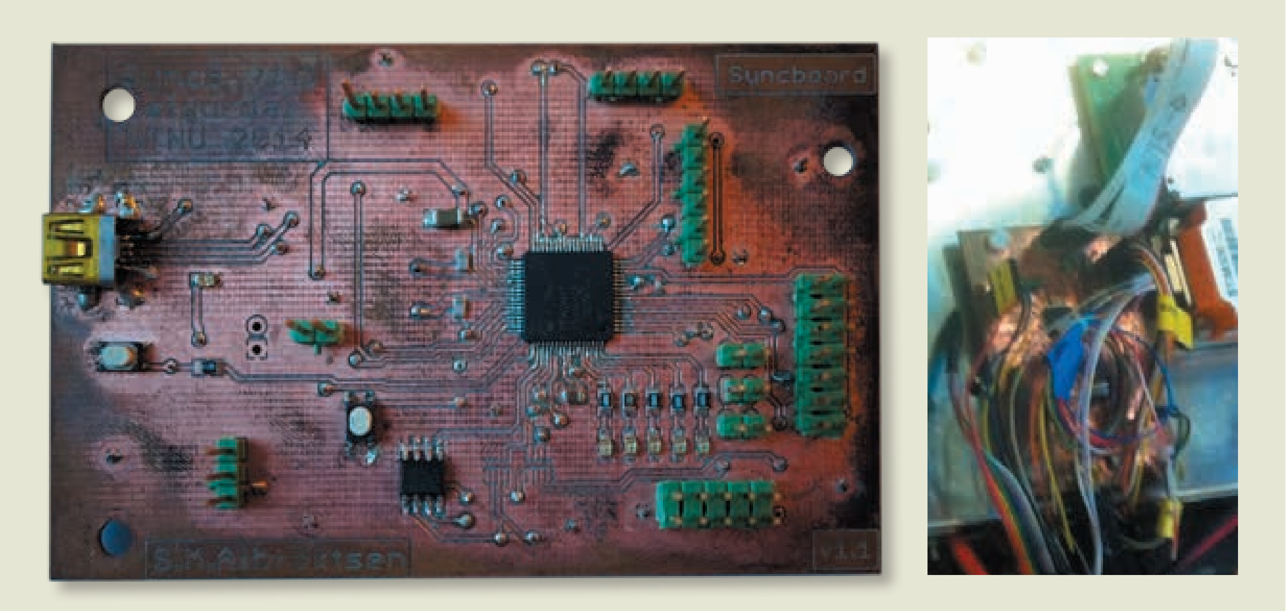



***Figure 1:*** *SyncBoard 1.2. The circuit board on the left was made in-house and shown after recovery from some hours in salt water. The picture to the right shows an early integration in a UAV.*

hours in salt water outside Ørland. Sigurd was forced to make a new board, and like most engineers, he could not resist the temptation to make (many) upgrades and improvements.

- Rumours about this useful piece of technology quickly spread around the UAV lab, and we quickly had to order 50 copies of the circuit board due to the popular demand among other researchers and students. Approximately 10 PhD candidates at AMOS working on sensor fusion used the SentiBoard - which is its current name - as an essential component in their experimental setups, and the number is increasing.
- We realized that the SentiBoard was not only a research tool, but actually a research result of its own that had potentially wider interest. It was therefore presented at conferences, and mentioned to other researchers in our network. They usually had two questions: Can we get one? And how much does it cost? One of these was Airbus, which needed one for their Lidar-based prototype for the European Space Agency's moon lander system, and had at the time extensively searched the industry and web for a solution.

Sigurd's research and PhD now focused primarily on the SentiBoard, with various applications to UAV navigation and sensor fusion. Due to the demands from many different applications and users, it evolved into a powerful and configurable component that could synchronize data from many different sensors simultaneously. "Everybody" in the lab started using the SentiBoard, and after Sigurd left NTNU we invested in software, testing and documentation, which made it into something more than the usual lab equipment that would depend on the extensive knowledge of the developer himself. The SentiBoard was no longer a prototype, but instead an internal "product" under continuous development, in which Frederik Leira and Erling Jellum were key developers taking over after Sigurd.

Meanwhile, Torleiv Bryne, who was a postdoc at the time, and now an Associate Professor, started developing a powerful software package for Kalman filter-based navigation and sensor fusion that could exploit the accurate timing information of the SentiBoard to achieve a maximum performance out of the sensors. While the Kalman filter has been around for 60 years, including numerous textbooks and research articles written on Kalman filtering, there is a lot of know-how and magic about inertial navigation, calibration, system integration, timing and tuning that is not openly available. With the SentiBoard solution and the sensor fusion software hand-in-hand, we have a unique and powerful research tool in our lab.

***Figure 2:*** *A recent version of the SentiBoard, where various sensors are connected through the various connectors on the top, left and bottom sides; the output goes through the USB connector on the top right, and the functionality is implemented in firmware on the Microchip PIC32 microcontroller.*

## Commercialization

The "marked pull", as well as the gap in the market, made the idea of commercialization emerge quickly. AMOS has always encouraged commercialization, and we contacted NTNU's Technology Transfer Office (TTO) to evaluate potential exploitation strategies. After two years, the company SentiSystems was established in January 2021 to licence, enhance and commercialize this technology. During that period, the product ideas and market understanding matured. SentiSystems aims to empower autonomy by delivering high integrity, scalable and synchronized sensor agnostic systems and technology. Sensor fusion and real-time data analysis, using tightly synchronized sensors, are key components that will improve the decision making and control of autonomous platforms. Moreover, the SentiBoard and related technology continue to be improved and used internally at NTNU, and in research projects together with industrial collaborators. Applications in various industries are being pursued, including manufacturing, agriculture, maritime, aerospace, road vehicles and railways.

**Contact:** Tor Arne Johansen

# FLYING HIGH INTO THE DEPTHS OF MARINE TECHNOLOGY

Marilena Greco, the first female professor at the Department of Marine Technology at NTNU, and one of the key scientists in AMOS, accepted an honorary position at OSAKA University last year.

> **"A lot must be done to bridge across disciplines. The needs from society and the environmental issues pose challenges, yet bring opportunities for the next generations of marine engineers."**

Greco never gave it a thought before another professor pointed out to her that she was the first female professor at the Department of Marine Technology of NTNU. Since 2010, she has been a full-time professor in Marine Hydrodynamics at NTNU, while keeping a part-time affiliation as a senior researcher at the Institute of Marine Engineering, CNR-INM, Rome.

For her, it is very important to have earned her positions due to hard work and efforts, and because she was judged as the best candidate, not just because she was a woman. Yet, she considers it to be of primary importance to ensure that women can have the same opportunities as men in all fields, including in engineering, where men still play a major role.

In 2021, Greco accepted to be a Specially Appointed Professor, an honorary position, at the Division of Global Architecture, Graduate School of Engineering - OSAKA University, Japan, for a year.

In this appointment, the Japanese wanted to enlarge the footprint of female scientists in the Osaka University engineer academia, and to provide an international female role model to the next generation of engineers. This type of position targets researchers

*Marilena Greco grew up in a family living among vineyards, olive trees and cattle, with six siblings in the south of Italy.*

*Photo: iGreco*


*Greco and her siblings, Greco in the blue dress in the middle. One of here nephews in the front.*

with advanced specialized knowledge, or with considerable experience in a specific field, to join the host university for a certain period, and perform research and/or provide a series of lectures. In this case, her expertise in marine hydrodynamics was valued.

Unluckily, due to the COVID pandemic, her physical stay at Osaka University was not possible last year.

## Research: footprint and perspective

Greco's scientific work and achievements are in marine hydrodynamics. She likes to consider her contribution as one of the key scientists in conceiving the vision and research at NTNU AMOS, and making this Centre of Excellence a reality, as one of her most important footprints.

"To me, such an award is a lifetime achievement, and I am honoured and proud to have given my contribution, together with such brilliant and inspiring minds! For this, I will thank Asgeir Sørensen for having believed in me", Greco said.

At NTNU AMOS, she is collaborating in bio-inspired studies aimed at identifying the mechanisms governing marine animal skills as swimmers, and to transfer them to engineered vehicles. This overall target requires interdisciplinary efforts involving hydrodynamics, marine biology and control theory.

In her opinion, NTNU AMOS has recognized the crucial importance of multi- and interdisciplinary research to enable a proper knowledge and use of the ocean's resources.

"A lot must be done to bridge across disciplines. The needs from society and the environmental issues pose challenges, yet bring opportunities for the next generations of marine engineers. They will need to cover the technological gaps and identify feasible, cost-efficient and sustainable solutions. My discipline of hydrodynamics is expected to play a crucial role to ensure proper behaviour at sea in the marine/ocean scenarios to come, but multi- and interdisciplinary approaches will be increasingly needed. This might also require new features in the role of the engineer."

## Top-notch

She grew up in a family living among vineyards, olive trees and cattle, with six siblings in the south of Italy. So how do you go from a childhood with agriculture roots, to become a recognized Professor?

As the sixth child in a family with seven siblings, five boys and two girls, she had to find her own voice but also felt lucky, as she was strongly encouraged and supported in her Life choices by all of them, as well as her parents. She never wanted to be competitive with others at school; she just followed her own path, worked


*Greco has collaborated closely with Odd Faltinsen since she became a PhD at the Department of Marine Technology at NTNU, here with Faltinsen and his wife.*

hard and conscientiously, as she considers this always pays off with good results. At the university, a more competition-oriented student pointed out that they would have to compete for the same work positions. Her answer was clear: "If you choose to go in one direction I will go in the other!"

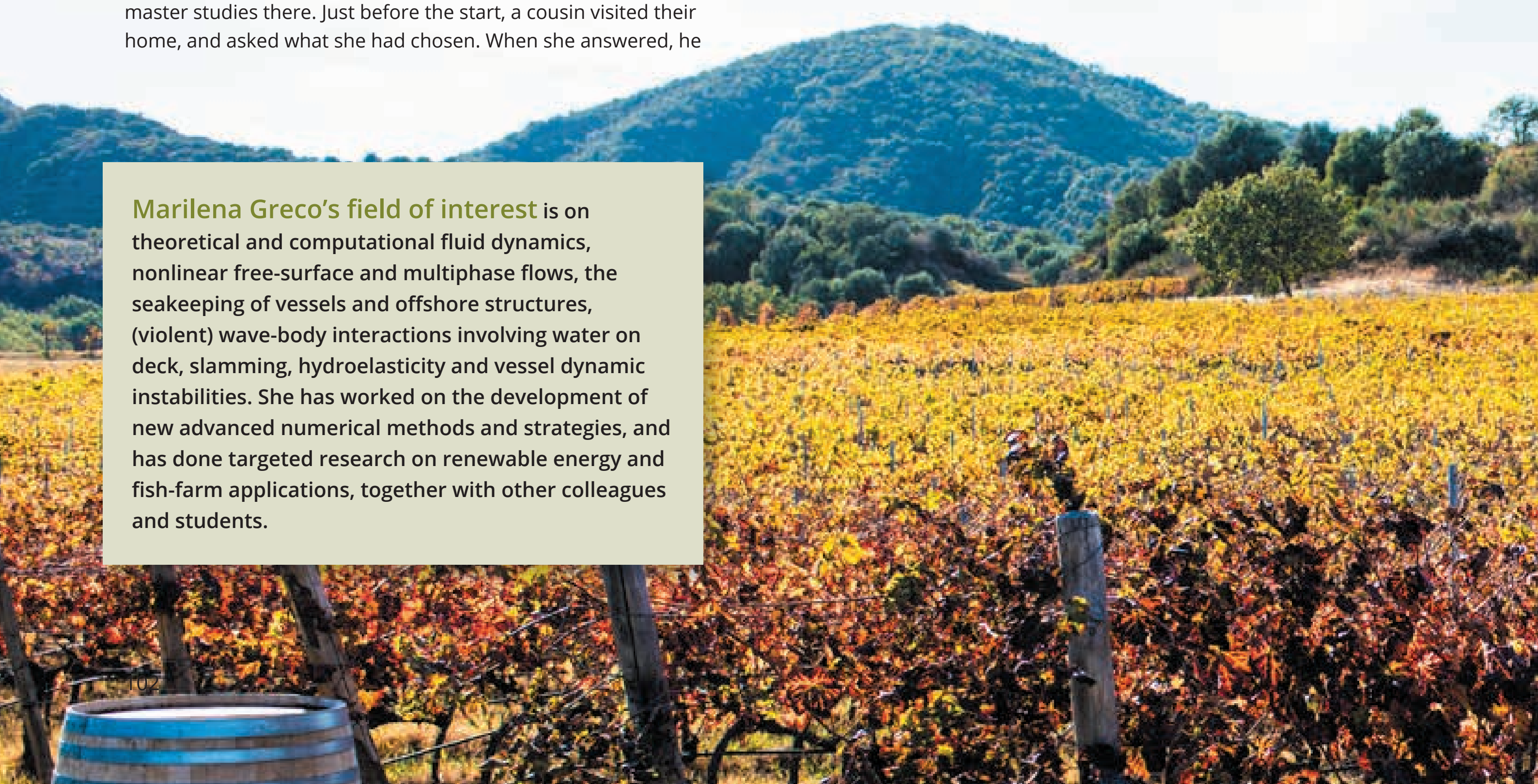
Why she ended up as a merited Professor in marine hydrodynamics is a tale about choosing a path, and coincidences that just lead you in other directions.

Her secret dream was to become an aeronautical engineer. But she feared her father's objection because this would have brought her far away from home, so she first chose to study electronic engineering in Bologna. All her siblings had done their master studies there. Just before the start, a cousin visited their home, and asked what she had chosen. When she answered, he exclaimed: "Why don't you study to be a naval engineer?" Then, she replied with "Well, I choose aeronautical engineering". Her father, lying on the couch, suddenly approved. The day after, she applied for her secret wish: Aeronautical Engineering.

In 1997, she graduated with honors and a master's in Aeronautical Engineering after some great years in Rome.

## From aeronautical to naval

But her cousin eventually got his suggestion sustained a few years later. After waiting for an aeronautical topic for the master's thesis, a professor offered to let her work on "hydrodynamic loads



**Marilena Greco's field of interest is on theoretical and computational fluid dynamics, nonlinear free-surface and multiphase flows, the seakeeping of vessels and offshore structures, (violent) wave-body interactions involving water on deck, slamming, hydroelasticity and vessel dynamic instabilities. She has worked on the development of new advanced numerical methods and strategies, and has done targeted research on renewable energy and fish-farm applications, together with other colleagues and students.**

and wave generation during the motion of marine vehicles" at the Italian Ship Model Basin, INSEAN (now CNR-INM). She did so well that she was offered a fellowship at INSEAN. In the meantime, her immediate boss started a research collaboration with Professor Odd Magnus Faltinsen at the Department of Marine Technology, NTNU. She was told that there was a call for a PhD position there. She applied and got it shortly thereafter. She barely knew where Norway was, and did not imagine this would be the start of the most important adventure of her Life.

Photo: iGreco

She arrived on January 18, 1998. It was dark and cold as she recalls: Norway in the worst condition. It could only go upwards from there. She describes the years as a researcher and PhD as a wonderful experience. She had the privilege to be one of Professor Faltinsen's students. Faltinsen is known world-wide, and recognized for his research and books in marine hydrodynamics. Her experience was that he was inspiring and humble at the same time.

"I always thought that if I could have 10% of his skills, then I would consider myself accomplished as researcher", she said.

After finishing her PhD, she went back to Italy, and worked with her colleagues at INSEAN in Rome, and continued to cooperate with Faltinsen. Subsequently, CeSOS, the Centre for Ships and Ocean Structures, the first Centre of Excellence at the Department of Marine Technology, started up in 2002. She got a position as a visiting researcher, and spent six months a year in Trondheim since 2004. In 2008, she was offered and obtained the position as an Adjunct Professor. In 2010, she became a full professor in the same year as Faltinsen's retirement.

## Close connections

Professor Greco has now been researching marine hydrodynamics for more than 20 years. She is responsible for three courses in marine hydrodynamics and sea loads, among them one of the most important courses in marine engineering studies, supervising several PhDs along the years, and two post-docs at the Department of Marine Technology. Greco has published more than 100 research articles and conference papers. There has been a lot of co-publishing with Faltinsen over all these years. She has also kept a close collaboration with her Italian colleagues in Rome, strengthened by the long-lasting research agreement between NTNU AMOS and CNR-INM.

Photo: iGreco

# WINNING THE WORLD'S MOST CHALLENGING ROBOT COMPETITION

The most recent DARPA Subterranean Challenge has been compared with the Olympic Games – in robotics. This is both precise and unprecise, but it is a competition for razor-sharp minds.

The Olympics is a celebration of the participating nations' athletic heroes, and through that a celebration of the nations themselves. On the other hand, DARPA is sponsoring teams independently of their nationality so they can participate in the competition. The teams are extremely international, which would have been impossible in the Olympic Games.

The goal with this competition? To revolutionize the way robots operate, to inspire technological breakthroughs and to speed up the development and innovation force through the format of a competition.

In the beginning of this millennium, DARPA started with a kind of rally for robots driving autonomously in the Mojave Desert. It continued with a competition on humanoid robots. DARPA then started a challenge that took place under the surface of the earth – with robots that can move in both natural and human made space: tunnel systems, urban underground, and cave networks. Three rounds were planned before the finals.

## Team leader from NTNU

Kostas Alexis, Professor at the Department of Engineering Cybernetics at NTNU, led the CERBERUS team to a victory in the DARPA Subterranean Challenge (SubT) in the autumn of 2021.

The robots were tested in difficult subterranean environments: In light, in the dark, in places that were wet and dripping, filled with smoke, without the possibility to navigate with a GPS, and in various terrains. The competition had both physical and virtual rounds, with CERBERUS focusing on the "systems" track - the physical competition with real robots and real environments.

*Four legged robot, resembling a dog.*

*Photo: Team Cerberus*

The tasks of the robots were to map, navigate and search for objects of interest under these conditions, which had to be done autonomously.

The prize was two million dollars, alongside a total of 4.5 million dollars of grant support to aid the research activities of the team (distributed over three years).

"The prize money of course goes to new development and research," Alexis says. He is proud of the victory, but at the same time very clear that there are a lot of complex factors in a competition like this. Many of the teams had the same high level, and the victory depended on the most challenging details.

## 60-member team

The CERBERUS team consisted of 60 top notch scientists.

The team used three years of preparation, and had years and years of research before this. Several teams participated through the three years of the competition, with only eight making it to the finals of the "systems" competition. In total, DARPA funded six "systems" teams, with all of those in the finals having received DARPA funding support.

"We struggled to pass from the first challenge to the second. On the second challenge we did much better, but were not among the top performing teams," Alexis says.

He thinks this was because they focused on fundamental research and new approaches to the problem.

> **We are proud for our result, especially because we know the quality of our competitors, being teams from NASA JPL/MIT, Carnegie Mellon University, CSIRO, the University of Colorado and more"**

## What is DARPA?

DARPA stands for the **Defense Advanced Research Projects Agency**, and is a part of the US Army and Pentagon. It was previously called ARPA, and was launched when the Soviet Union managed to launch Sputnik, the first satellite, in 1957. A technological race was on.

### DARPA Subterranean Challenge

**A three-year competition in both:**

- **a physical systems competition,**
- **and a virtual competition.**

1 Challenge
2 Competitions
3 Subdomains – tunnel, urban underground and cave networks

In the Systems Competition: 1st prize: $2M, 2nd prize $1M, 3rd prize $500k

"However, making it to the finals this approach paid off. We won the Final Event of the DARPA Subterranean Challenge by mapping the environment with a team of our robots and finding 23 objects of 40 in a complex environment that presented parts of an underground mine, an urban subterranean infrastructure and cave networks."

The second team had the same score, but CERBERUS used a shorter amount of time, which was the tiebreaker in their favor. The third team found 18 objects.

"We are proud for our result, especially because we know the quality of our competitors, being teams from NASA JPL/MIT, Carnegie Mellon University, CSIRO, the University of Colorado and more," Alexis says.

DARPA Subterranean Challenge was supposed to have three rounds before the finals, but one of them was cancelled because of Covid. They were tested in a tunnel, and an empty nuclear plant, while the "Cave Circuit" was cancelled. In the final event during this last September, they had elements of all three types of areas.

**Kostas Alexis** obtained his PhD in the field of aerial robotics control and collaboration from the University of Patras, Greece in 2011. His PhD research was supported by the Greek National European Commission Excellence scholarship.

After successfully defending his PhD thesis, he was awarded a Swiss Government fellowship and moved to Switzerland and ETH Zurich. From 2012 to June 2015, he held the position of Senior Researcher at the Autonomous Systems Lab of ETH Zurich, leading the lab efforts in the fields of control and path planning for advanced navigational and operational autonomy.

During the summer of 2015, he moved to the Computer Science and Engineering Department of the University of Nevada, Reno, where he was tenured in 2020.

Since the fall of 2020, he moved to the Department of Engineering Cybernetics at the Norwegian University of Science and Technology as a Full Professor. He is the founder and director of the Autonomous Robots Lab (https://www.autonomousrobotslab.com/), involving more than 15 researchers, and conducting research in the domain of autonomy, perception, planning and control.

Dr. Alexis' research has received multiple awards, including the world record in unmanned aircraft endurance, and has been funded by a variety of sources, including DARPA, NSF, DOE, USDA, NASA, the European Commission, the Research Council of Norway, the private sector and other sources. Notable achievements include the winning performance of Team CERBERUS (with Prof. Alexis being the PI) at the DARPA Subterranean Challenge Finals (September 2021), and the world endurance record in the below 50kg UAV-class with the 81.5h of the solar-powered AtlantikSolar co-developed by Dr. Alexis and colleagues at ETH

The comparison with the Olympics can fit when it comes to the prestige of winning DARPA, the level that is needed and the frequency of the competition – it is not every year.

## Research leaps

As previously mentioned, the beginning was in the 2000s. Since then, different competitions with various types of challenges have been arranged.

In 2004, in the DARPA Grand Challenge, the mission was to cross the Mojave Desert on a 240-kilometre route with robot cars. The year after, 23 finalists from the year before had to go through a curved and hilly 212-kilometre route.

In 2007, DARPA gave an urban challenge. The teams had to cross 96 kilometres that simulated an urban area, where they had to follow traffic rules, get around obstacles and relate to other traffic. These three competitions led to a leap in the development of driverless cars.

In 2012, a new DARPA Robotics Challenge started. It went for three years with humanoid robots. Their mission was to do different kinds of complex tasks in dangerous environments.

In 2017, the DARPA Subterranean Challenge started, where robots had to cope with both natural and manmade subterranean spaces, like caves, tunnels, mines and metro stations.

## Why join such a competition?

"There is a lot of activity underneath the surface of the earth. Mining and transport. These environments are a lot more dangerous than above the surface of the earth. If robots can be first responders, improve operations in the industry, perform different tasks and be a resource, it can be both safer and more economical," Alexis says.

He believes that one of the most interesting reasons relates to the exploration of Mars, with the NASA JPL team having relevant research.

"It is the human nature to explore. In NTNU AMOS, we build technology for autonomous operations, robots that can follow patterns, explore, inspect, map, monitor and search."

## Flying and four-legged

At Alexis' Autonomous Robots Lab at NTNU, they primarily make flying robots. He does not like to call them drones, as he thinks the word has bad connotations.

"In the competition, we used both flying robots and robots with legs. After a while, all the teams used the same robot concepts, but we were among the first who proposed the combination and – importantly – all our systems were made by us or by spin-offs with which we have tight relevance," he says.

> "It is the human nature to explore. In NTNU AMOS, we build technology for autonomous operations, robots that can follow patterns, explore, inspect, map, monitor and search."

*Flying robot.*

*Photo: Team Cerberus*

They had several types of the same flying and four-legged robots that resembled dogs. They were equipped with different types of sensors, and therefore functioned as teams under the different challenges. The legged robots used by Team CERBERUS were the ANYmal C systems by ANYbotics and ETH Zurich.

They were programmed to do searches and come back and report maps and object detections within a certain timeframe.

## Future dream target

What does Alexis want to achieve with his research? What is the ultimate goal?

"I want to make resilient autonomous robots capable of long-term operation in complex and degraded environments. Robots that will function well, and can be used as a resource for diverse tasks.

## CERBERUS team

**Acronym for CollaborativE walking and flying RoBots for autonomous ExploRation in Underground Settings**

CERBERUS is an international partnership that involved NTNU, the University of Nevada Reno, ETH Zurich, University of California Berkeley, University of Oxford, Flyability and Sierra Nevada Corporation. Alexis is the team Lead and got the project when he was still a professor at the University of Nevada.

> **There is a lot of activity underneath the surface of the earth. Mining and transport. These environments are a lot more dangerous than above the surface of the earth. If robots can be first responders, improve operations in the industry, perform different tasks and be a resource, it can be both safer and more economical"**

This is a persistent problem across autonomy systems. Look at the domain of autonomous driving, for example: Today, a robot that will do well in San Francisco will not make it in Mumbai, because the cities are so different from one another."

The week before the interview a five-year-old boy in Morocco fell down a 32-metre well. He survived the fall, but the responders were unable to get to him because the well was too narrow. They had to dig a new tunnel. They used five days. Unfortunately, they could not save Rayan in time.

Alexis is uncertain whether robots could have helped in that situation, but he believes this is the goal, and highlights that it will take significant research to reach that level.

He also mentions an incident in Thailand, where twelve boys in a soccer team were trapped several kilometres inside the Tham Luang cave system, and a complex and dangerous rescue operation was carried out. One of the rescuers died during this mission.

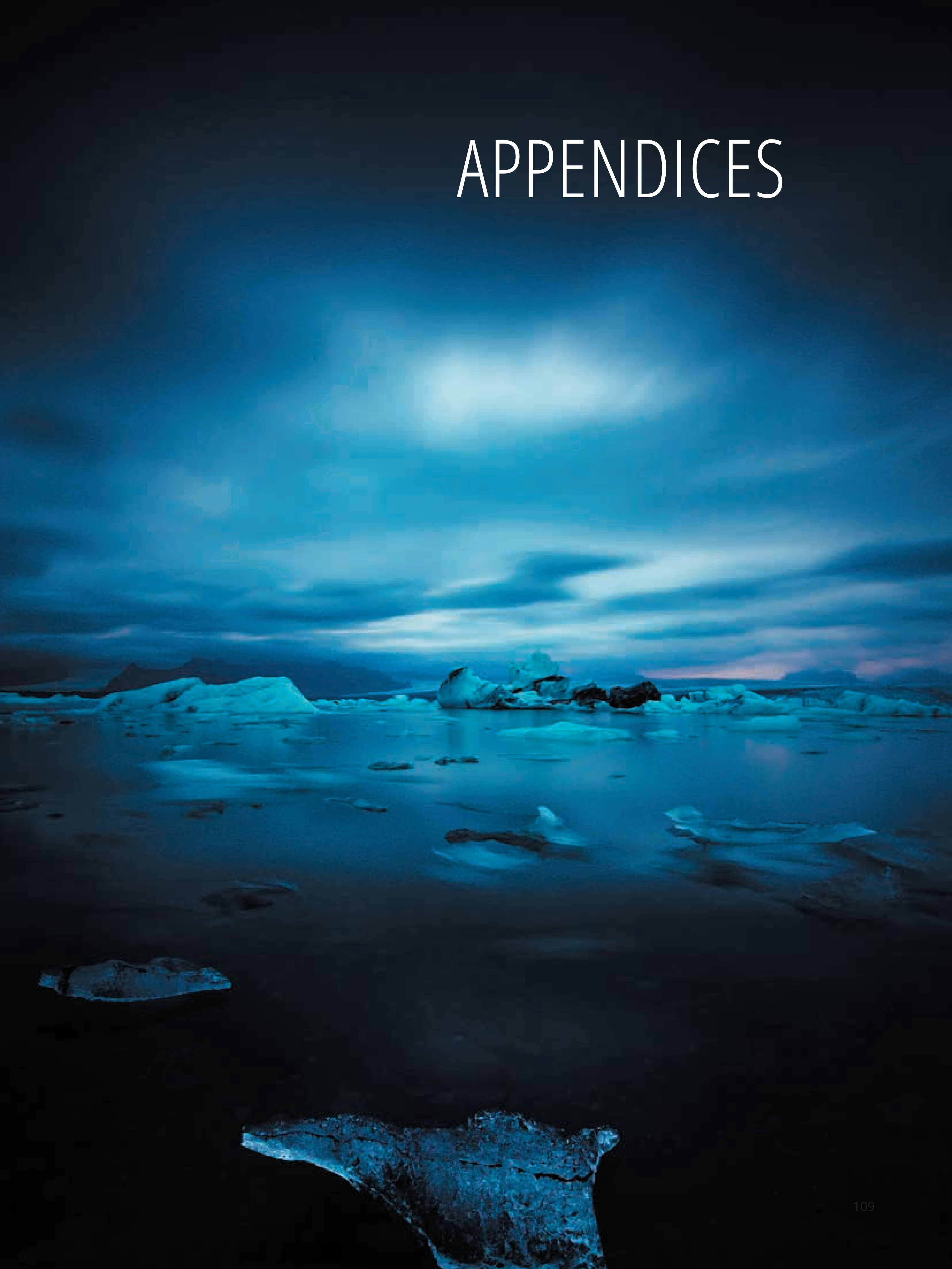
"Robots are not yet able to undertake similar missions with robustness," Alexis says.

So far, humans surpass robots in being adaptable and flexible in the movements, and "intelligent" enough to fulfill missions like this. But someday, probably soon, robots might help first responders assess danger zones before risking human lives. Alexis and his colleagues are working on the matter.

*The teams were tested in three different harch subterranean environments.*

*Photo: Team Cerberus*

# APPENDICES



# ANNUAL ACCOUNTS AND MAN-YEAR EFFORTS

## Annual accounts and man-year efforts

| REVENUES IN 2021 (amount in NOK 1000) | |
|---|---|
| **Actual:** | |
| Income | 68 993 |
| Costs | 55 733 |
| Year end allocation | 13 260 |
| | |
| **In Kind** | |
| Income | 4 979 |
| Costs | 4 979 |
| | |
| **Total** | |
| Income | 73 972 |
| Costs | 60 712 |
| Year end allocation | 13 260 |
| AMOS 1 end allocation | 5 497 |

| PERSONNEL 2021 | |
|---|---|
| Keypersons | 7 |
| Adjunct prof/associated prof | 14 |
| Affiliated scientists | 29 |
| Scientific advisers | 2 |
| Postdoc/researchers | 8 |
| Affiliated postdocs/resarchers | 18 |
| PhD Candidates | 27 |
| Affiliated PhD candidates | 103 |
| Administrative staff | 5 |
| Management | 2 |
| Technical staff | 2 |
| Graduated PhD candidates financed by NTNU AMOS | 2 |
| Graduated PhD candidates associated to NTNU AMOS | 910 |

## Annual accounts and man-year efforts

| ANNUAL ACCOUNTS | |
|---|---|
| **Operating income** | **Accountes income and costs** |
| The research council of Norway | 24,788 |
| NTNU | 40,783 |
| Others | 3,421 |
| in kind | 3,179 |
| **Sum operating income** | **72,172** |
| | |
| **Operating costs** | **Accountes income and costs** |
| Salary and social costs | 46,394 |
| Equipment investments | 5,591 |
| Procurement of R&D servises | 525 |
| Other operating costs | 3,222 |
| in kind | 3,179 |
| **Sum operating costs** | **58,912** |
| | |
| Year end allocation | 13,260 |
| | |
| Opening balance 20180101 | 5,497 |
| Closing balance 20181231 | 6,382 |

| Total man-years efforts | |
|---|---|
| Man-years | 2021 |
| Centre director | 0.30 |
| Co-director | 0.20 |
| Adm.personnel | 1.20 |
| Technical staff | 1.00 |
| **Summary** | **2.70** |

| | |
|---|---|
| Key professor | 3.50 |
| Adjunct prof/ass.prof | 2.70 |
| Affiliated prof/scientists | 6.07 |
| Scientific advisor | 0.50 |
| Postdocs | 3.83 |
| Postdoc (affiliated) | 11.81 |
| Visiting researchers | - |
| PhD candidates | 15.5 |
| PhD candidates (affiliated) | 62.76 |
| **Total research man-years** | **109.37** |

## 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 | 8 | 20 | 2 | 10 | - | 18 | 60 | 7 | |
| Other nationalities | 1 | 6 | 9 | - | 16 | - | 9 | 44 | - | |
| **Sum** | **7** | **14** | **29** | **2** | **26** | **-** | **27** | **104** | **7** | **-** |
| Man-years | 3.50 | 2.70 | 6.07 | 0.50 | 15.64 | - | 15.50 | 62.76 | 2.20 | 108.87 |

The sum above does not include centre director and co-director

# AMOS PERSONNEL 2021

## Management and administration

| NAME | TITLE | ACRONYM |
|---|---|---|
| Bolme, Sigmund | Higher executive officer - communications | SB |
| Oftedahl, Live | Senior executive officer - communications | LO |
| Prof. Fossen, Thor I | Co-director | TIF |
| Karoliussen, Renate | Senior executive officer | RK |
| Reklev, Knut | Senior engineer | KR |
| Sivertsen, Eirik S. | Project Manager | ESS |
| Prof. Sørensen, Asgeir J | Director | AJS |

## Key scientists

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

## Senior Scientific advisers

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

## Adjunct professors and adjunct associate professors

| NAME | INSTITUTION, DEPARTMENT | MAIN FIELD OF RESEARCH | ACRONYM |
|---|---|---|---|
| Adj. Prof. Berge, Jørgen | UiT, The Artic University of Norway | Marine biology | JB |
| Adj. Prof. Fredheim, Arne | SINTEF Ocean | Fisheries and aquaculture | AF |
| Adj. Prof. Kruusmaa, Maarja | Talin University of Technology | Marine robotics | MK |
| Adj. Prof. Lugni, Claudio | CNR - INM | Marine hydrodynamics | CL |
| Adj. Ass. Prof Nielsen, Ulrik Dam | DTU | Wave-ship interactions | UDN |
| Adj. Prof. Skaugset, Kjetil | Equinor | Marine operations and structures | KS |
| Adj. Prof. Sigernes, Fred | UNIS | Remote sensing | FS |
| Adj. Ass. Prof. Sokolova, Nadezda | SINTEF Digital | Integrated navigation systems | NS |
| Adj. Ass. Prof. Storvold, Rune | NORUT | Aircraft and remote sensing | RS |
| Adj. Prof. Sousa, Joao | Porto University | Autonomous systems | JS |
| Adj. Prof. Johansson, Karl Henrik | KTH | Automation and control | KHJ |
| Adj. Prof. Larsen, Kjell | Equinor | Marine operations and structures | KL |
| Adj. Ass. Prof. Nguyen, Trong Dong | DNV GL | Marine control systems | TDN |
| Adj. Ass. Prof. Scibilia, Francesco | Dept. of Engineering Cybernetics | Remote sensing and autonomy | FS |
| Adj. Prof Agelet, Fernando Aguado | UiVIGO - University of Vigo | Systems engineering for small satellite systems | FAA |

## Affiliated scientists

| NAME | INSTITUTION, DEPARTMENT | MAIN FIELD OF RESEARCH | ACRONYM |
|---|---|---|---|
| Ass. Prof. Aberle-Malzahn, Nicole | NTNU, Dept. of Biology | Marine biology | NAM |
| Ass. Prof. Alfredsen, Jo Arve | NTNU, Dept. of Engineering Cybernetics | Automation in fisheries and aquaculture | JAA |
| Ass. Prof. Alver, Morten Omholt | NTNU, Dept. of Engineering Cybernetics | Automation in fisheries and aquaculture | MOA |
| Ass. Prof. Brekke, Edmund F. | NTNU, Dept. of Engineering Cybernetics | Sensor fusion | EB |
| Prof. Bachynski, Erin E. | NTNU, Dept. of Marine Technology | Wind energy/offshore renewable energy systems | EEB |
| Ass. Prof. Brodtkorb, Astrid Helene | NTNU, Dept. of Marine Technology | Marine Cybernetics | AB |
| Adj. Prof. Bryne, Torleiv Håland | NTNU, Dept. of Engineering Cybernetics | Navigation systems | THB |
| Dr. Breivik, Morten | NTNU, Dept. of Engineering Cybernetics | Nonlinear and adaptive motion control | MB |
| Ass. Prof. Bye, Robin T. | NTNU, Dept. of ICT and Natural Sciences | Cyber-physical systems and AI | RTB |
| Ass. Prof. Eide, Egil | NTNU, Department of Electronic Systems | Nagvigation of autonomnous ships | EE |
| Ass. Prof. Føre, Martin | NTNU, Dept. of Engineering Cybernetics | Fisheries and aquaculture | MF |
| Prof. Gao, Zhen | NTNU, Dept. of Marine Technology | Wind energy/offshore renewable energy systems | ZG |
| Prof. Imsland, Lars S. | NTNU, Dept. of Engineering Cybernetics | Automatic control, optimization | LI |
| Prof. Kristiansen, Trygve | NTNU, Dept. of Marine Technology | Marine hydrodynamics | TK |
| Ass. Prof. Kim, Ekaterina | NTNU, Dept. of Marine Technology | Marine structures | EK |
| Prof. Lader, Pål | NTNU, Dept. of Marine Technology | Aquaculture structures and Experimental hydrodynamics | PL |
| Ass. Prof. Lekkas, Anastasios | NTNU, Dept. of Engineering Cybernetics | Fusing artificial intelligence with control engineering to develop cyber-physical systems of increased autonomy | AL |
| Prof. Ludvigsen, Martin | NTNU, Dept. of Marine Technology | Underwater technology and operations | ML |
| Prof. Pedersen, Eilif | NTNU, Dept. of Marine Technology | Mathematical modeling of marine physical systems and operations. | EP |

| NAME | INSTITUTION, DEPARTMENT | MAIN FIELD OF RESEARCH | ACRONYM |
|---|---|---|---|
| Prof. Olsen, Yngvar | NTNU, Dept. of Biology | Marine biology | YO |
| Prof. Skjetne, Roger | NTNU, Dept. of Marine Technology | Marine control systems | RS |
| Ass. Prof. Stahl, Annette | NTNU, Dept. of Engineering Cybernetics | Robotic vision | AS |
| Researcher Tymokha, Oleksandr | NTNU, Dept. of Marine Technology | Marine hydrodynamics | OT |
| Prof. Utne, Ingrid B. | NTNU, Dept. of 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. of Engineering Cybernetics | Control Engineering | JTG |
| Prof. Konstantinos Alexis | NTNU, Dept. of Engineering Cybernetics | Autonomous systems | KA |
| Prof. Nguyen, Trong Dong | NTNU, Dept. of Marine Technology | Marine control systems | TDN |

## Technical staff, directly funded by NTNU AMOS

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

Photo: Adressa Brand Studio

## Postdocs/researchers

| NAME | INSTITUTION | MAIN FIELD OF RESEARCH | ACRONYM |
|---|---|---|---|
| Dr. Zhaolong, Yu | NTNU, Dept. of Marine Technology | Marine Structures | UZ |
| Dr. Grant, Stephen | NTNU, Dept. of Biology | Light climate measurements in the Arctic | SG |
| Dr. Mokhtari, Mojatba | NTNU, Dept. of Marine Technology | Assessment of marine structures in Arctic and Cryogenic conditions | MM |
| Dr. Shen, Yugao | NTNU, Dept. of Marine Technology | Limits for fish-farm operations | YS |
| Dr. Fragoso, Glaucia Moreira | NTNU, Dept. of Biology | Marine primary production: Bio-diversity, bio-geography, enabling technology for marine ecology | GMF |
| Dr. Mogstad, Aksel Alstad | NTNU, Dept. of Marine Technology | Underwater hyperspectral imaging as a tool for benthic habitat mapping" | AAM |
| Dr. Ødegård, Øyvind | NTNU, Dept. of Marine Technology | Use of underwater robots and sensors in marine archaeology, including the integration of autonomy in scientific knowledge production | ØØ |
| Dr. Colicchio, Giuseppina | CNR - INM | Mesh generation and analysis for acomputational fluid mechanics | GC |
| Dr. Toker, Kadir Atilla | NTNU, Dept. Engineering Cybernetics | Airborne GNSS/GBAS receiver experimental platform for UAVs | TA |
| Dr. Crosman, Katherine m, | NTNU, Dept. of Marine Technology | Digital and Cultural Approaches to Building Trust in Ocean Data | KC |
| Dr. Garrett, Joseph | NTNU, Dept. Engineering Cybernetics | Superresolution techniques for hyperspectral remote sensing | JG |
| Gomola, Alojz | NTNU, Dept. of Marine Technology | Development of methodology for software risk assessment and modeling | IBU |
| Gryte, Kristoffer | NTNU, Dept. Engineering Cybernetics | Autonomous systems software | KG |
| Dr. Helgesen, Håkon Hagen | NTNU, Dept. Engineering Cybernetics | Autonomous ships | HHH |
| Dr. Jones, Alun | NTNU, Dept. of Marine Technology | Ecosystem indicators for the Barents Sea | IU |
| Dr. Rokseth, Børge | NTNU, Dept. of Marine Technology | Online risk control of automatic sailing and power and propulsion systems. | BR |
| Dr. Wenz, Andreas Wolfgang | NTNU, Dept. Engineering Cybernetics | Flight performance, optimization and fault tolerance with hybrid power and propulsion | AW |
| Dr. Thieme, Christoph Alexander | NTNU, Dept. of Marine Technology | Online risk modelling for autonomous systems | CAT |
| Dr. Birkeland, Roger | NTNU, Dept. of Electronic Systems | Mission-oriented autonomous systems – with small satellites for maritime sensing, surveillance and communication | RB |
| Dr. Fossum, Trygve | NTNU, Dept. of Marine Technology | Intelligent autonomy, data-driven sampling, and planning for marine robotics | TF |
| Dr. Eriksen, Bjørn-Olav Holtung | NTNU, Dept. Engineering Cybernetics | Robustifying control and collision avoidance systems for autonomous ferries | TOF |
| Dr. Jain, Ravinder Praveen Kumar | NTNU, Dept. Engineering Cybernetics | Machine learning methods for adaptive sampling and control | EB |
| Dr. Wilthil, Erik F. | NTNU, Dept. Engineering Cybernetics | Situational awareness for autonomous urban ferries | EW |
| Dr. Ren, Zhengru | NTNU, Dept. of Marine Technology | Control methods for more efficient offshore wind installation | ZR |
| Dr. Zolich, Artur Piotr | NTNU, Dept. Engineering Cybernetics | Coordination of unmanned vehicles in marine environment | APZ |
| Dr. Hann, Richard | NTNU, Dept. of Cybernetics | Icing and icing mitigation in UAV rotors and propellers | RH |

## PhD candidates associated with NTNU AMOS with other financial support

| NAVN | SUPERVISOR | TOPIC |
|---|---|---|
| Aminian, Behdad | DV | Channel-aware adaptive numerical optimization algorithms for distributed underwater systems’ |
| Abbadi, Muram | TAJ | Flight dynamics of UAVs in icing conditions |
| Abdelmoteleb, Serageldin | EB | Design of Large Floating Substructures for Supporting Future Generation Offshore Wind Turbines |
| Amro, Ahmed W. | SK | Communication and cybersecurity  for autonomous passenger ferry |
| Ahani, Alireza | MG | Local structural response due to wave slamming |
| Akdag, Melih | TAJ | Protocols and algorithms for collaborative collision avoidance in autonomous ships |
| Arreba, Irene Rivera | EB | Effect of atmospheric stability and wake meandering on floating wind turbines |
| Barstein, Karoline | ML | Mesopelagic resource estimation in adaptive mission planning with heterogeneous platforms |
| Bitar, Glenn Ivan | MBR | Energy-optimal and autonomous control for car ferries |
| Berget, Gunhild | TAJ | Intelligent monitoring of drilling operations in sensitive environments |
| Bjørkelund, Tore-Mo | ML | Adaptive and collaborative vehicle behaviour for mission management for autonomous underwater vehicles |
| Bjørnø, Jon | RS | Icebreaker guidance and coordination for effective ice management tactics |
| Blindheim, Simon | TAJ | Risk-based optimization of control system behavior |
| Bosdelekidis, Vasileios | TAJ | Navigation System Integrity Assurance for Safety-Critical Autonomous Operations, |
| Bremnes, Jens Einar | AJS | Risk-based planning and control of AUVs |
| Bøhn, Eivind | TAJ | Machine learning in control and estimation |
| Guo, Chuanqui | SH | Risk analysis and management for autonomous passenger ferry |
| Cardaillac, Alexandre | ML | Autonomous Robotic Inspection and Maintenance on Ship Hulls and Storage Tanks |
| Cheung, Man Ken Michael | TAJ | Adverse weather mission planning for unmanned aerial vehicles (UAVs) |
| Coates, Erlend Magnus Lervik | TIF | Nonlinear Autopilot Design for Operation of UAVs in Extreme Conditions |
| Dahl, Andreas reason | RS | Nonlinear and fault-tolerant control of electric power production in Artic DP vessels |
| Dallolio, Albert | TAJ | Autonomous wave powered surface vessel for oceanography |
| Dugan, Spencer August | IBU | Reliable and robust design and operation of propulsion system for autonomous ships |
| Diaz, Gara Quintana | TE | Small satellite system communication |
| Diamanti, Eleni | ØØ | underwater robotics and sensors in marine archaeology |
| Faltynkova, Andrea | GJ | Detection of microplast using new optical tools |
| Flåten, Andreas L. | EB | Multisensor tracking for collision avoidance |
| Flemmen, Henrik Dobbe | EB | |
| Foseid, Eirik Lothe | KYP | Robust motion planning and control of AIAUVs |
| Fossdal, Markus | AJS | Formal and informal methods for robust design,testing and verification of autonomus control systems of subsea resident AUV |
| Gao, Fan | AB | Hybrid combinator curves for autonomous ships |
| Grøtte, Mariusz Eivind Santora | TG | Attitude Determination and Control for Hyperspectral Imaging Small Satelite in Multi-Agent Observation System |
| Hansen, Bogdan Løw | TAJ | Detection of icing on UAVs |
| Haavag, Aurora - Skare | TK | |
| Haavardsholm, Trym Vegard | AST | Collaborative visual mapping and exploration for teams of unmanned systems |
| Hagen, Inger Berge | EB | Collision Avoidance for Autonomous Ferry |
| Haraldsen, Aurora | KYP | Autonomous Collision Avoidance |

| NAVN | SUPERVISOR | TOPIC |
|---|---|---|
| Hassan, Waseem | MF | Real-time acoustic telemetry for fish behaviour monitoring in aquaculture |
| Hasler, Oliver Kevin | THB | Multi-sensor fusion for increased UAV resilience and safety, |
| Hatleskog, Johan | TAJ | Autonomous Industrial Inspection in a Contextualized Environment |
| Haugo, Simen | AST | Computer vision methods for assisted teleoperation of unmanned air vehicles |
| Helgesen, Øystein Kaarstad | EB | Sensor fusion for autonomous ferry |
| Hem, Audun Gullikstad | EB | |
| Hoff, Simon A. | KYP | Distributed communication-aware path planning for autonomous underwater fleets |
| Iversflaten, Markus H. | KYP | Cooperative control for joint observation and intervention tasks |
| Jahren, Jan Henrik | AST | Aquaculture technology - Artificial intelligence and computer vision for applications in Fish Welfare monitoring |
| Jellum, Erling Rennemo | THB | Next generation hardware for multi-sensor timing, data processing and fusion |
| Johansen, Thomas | IU | Risk Modeling for Supervisory Risk Control |
| Jónsdóttir, Kristbjõrg Edda | JAA | Dynamics of waterflow and turbulence in large-scale aquaculture sea cages |
| Kasparaviciute, Gabriele | ML | Mission planning |
| Katsikogiannis, George | EB | Loads and Responses of Large-Diameter Monopile Wind Turbines |
| Krathe, Veronica Liverud | EB | Multiscale/-fidelity wind turbine dynamics models for structural design and control |
| Kristensen, Susanna Dybwad | IBU | Online risk modeling of autonomous ships |
| Larsen, Martin Kvisvik | ML | Visual Navigation Systems for Improved Seabed Mapping and Monitoring |
| Leonardi, Marco | AST | Visual odometry and servoing for 3D reconstruction |
| Livermor-Honoé, Evelyn | EE | Rapid systems engineering |
| Lorentzen, Ole Jacob | | Synthetic Aperture Sonar Interferometry in Rough Seafloor Bathymetry |
| Lopez, Michael Ernesto | AST | Pose estimation and extended object tracking for situational awareness in autonomous maritime vessels |
| Martens, Emil | AST | Multi-sensor object detection and classification |
| Martinsen, Andreas Bell | AL | Reinforcement learning methods for guidance, navigation and control |
| Matous, Josef | KYP | Distributed cooperative control of marine multi-vehicle systems |
| Müller, Nicolas C. | TAJ | Ice accretion, icing penalties, and ice protection systems on unmanned aerial vehicle rotors |
| Mukhlas, Muhammad | PL | Closed flexible bags in waves |
| Najjaran, Samieh | RS | Enabling zero-emission high speed ferries along the coast of Norway |
| Orucevic, Amer | JTG | Energy harvesting for underwater snake robots |
| Potter, Casper | MG | Bio-inspired flow sensing for articulated intervention autonomous underwater vehicles |
| Ran, Xiaoming | EB | High-fidelity determination of wave loads and load effects for floating wind turbine hulls subjected to severe wave conditions |
| Rabliås, Øyvind | TK | maneuvering in waves |
| Reddy, Namireddy Praveen | MZ | Intelligent power & energy management system for autonomous ferry |
| Reinhardt, Dirk | TAJ | Nonlinear Autopilot Design for Extended Flight Envelopes and Operation of Fixed-Wing UAVs in Extreme Conditions |
| Rohrer, Peter | EB | Generic Techniques for Multidisciplinary Design Optimization of Floating 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 |
| Røang, Simen Troye | TAJ | Optimal control of ships in following sea |
| Prentice, Elizabeth | TAJ | Onboard data processing for planning and operation of SmallSat mission |

| NAVN | SUPERVISOR | TOPIC |
|---|---|---|
| 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 | EB | 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 |
| Sæbø, Bjørn Kåre | KYP | Motion planning and control of light-UVMS. |
| Téglasy, Bálint Zoltán | MAL | safety and security of next generation industrial control systems |
| Thorat, Laxminarayan | RS | Control Methods for Highly Redundant and Energy Efficient Shipboard Electric Power Production Systems |
| Thoresen, Marius | KYP | Motion planning in rough terrain for unmanned ground vehicles |
| Thyri, Emil Hjelseth | MBR | Mission planning and collision avoidance for autonomous passenger ferry |
| Tokle, Lars-Christian Ness | EB | Sensor fusion for autonomous ferry |
| Torben, Tobias Rye | AJS | Verification and Control Design for Safe Autonomous Ships |
| Ueland, Einar S. | RS | Study of Fundamental Constraints in the Hybrid Test Loop, and Optimal Control and Estimation Strategies for Actuation of Effort on the Physical System |
| Vagale, Anete | RB | Intelligent Collision Avoidance and Path Planning for Autonomou Surface Vessels in Opertaing in Confined Waters |
| Vasstein, Kjetil | EB | |
| Volden, Øystein | TIF | Real-Time Encryption of Computer Vision Feedback Control Systems for Autonomous Ships |
| Waldum, Ambjørn | ML | Situation aareness |
| Wallisch, Joachim | TAJ | Icing models for adverse weather mission planning for unmanned aerial vehicles (UAVs) |
| Winter, Adrian | TAJ | Multi-sensor fusion for increased resilience of UAVs with respect to satellite navigation cyber-security |
| Wang, Xintong | JAM | |
| 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 |
| Yip, Mauhing | AST | Underwater Visual Perception: Next-best-view prediction and 3D scene reconstruction for exploration and situational awareness in unknown environments for articulated intervention autonomous underwater vehicles |
| Chan, Wai Yen | ML | Underwater Vehicle-Manipulator System (UVMS) for Autonomous Intervention Operations in  fish farms |
| Øvreaas, Henning | THB | Autonomous navigation and mission planning of wave propelled unmanned surface vehicle (USV |

## PhD candidates with financial support from NTNU AMOS

| NAME | SUPERVISOR | TOPIC |
|---|---|---|
| Bakken, Sivert | TAJ | Coordinated oceanographic observation system with autonomous aerial/surface robots and hyper-spectral imaging in SmallSat |
| Basso, Erlend, Andreas | KYP | Motion Planning and Control of Articulated Intervention-AUVs |
| Bore, Pål Tokle | JAM | Structural design of reliable offshore aquaculture structures |
| Cisek ,Krzysztof | TAJ | Multi-body unmannes aerial systems |
| Didlaukies- Schmidt Henrik | AJS | Modeling and Control of Hyper-Redundant Underwater Manipulators |
| Dirdal, Johan | TIF | Sea-State and Ship Response Estimation |
| Fortuna, Joao | TIF | Processing and analysis of Hyperspectral Images from unmanned systems |
| Henriksen, Marie Bøe | TAJ | Hyperspectral imaging in drones and small satellites |
| Klausen, Toni | TAJ | Prediction of aircraft icing based on the microphysical properties of condensed water vapour outside mixed-phased clouds, using models and empirical data |
| Kaminska-Wrzos, Marianna | KYP | Free-floating intervention operations using AIAUVs |
| Kristiansen, Bjørn Andreas | JTG | Energy optimality for spacecraft attitude manoeuvres |
| Langer, Dennis | AJS | Hierarchical Control of Heterogenous Robotic Systems from Satellites. |
| Løvås, Håvard Snefjellå | AJS | Classification and Detection of Microorganism Including Plastics in the Oceans Using Optical Methods |
| Marley, Mathias | RS | Resilient hybrid motion control of autonomous vessels |
| Mathisen, Pål | TIF | Sea-State and Ship Response Estimation |
| Ma, Shaojun | MG | Manoeuvring of a ship in waves |
| Merz, Mariann | TAJ | Deplyment, search and recovery of marine sensors using a fixed- wing UAV |
| Mounet, Raphael | AB | Sea state estimation based on measurements from multiple observation platforms |
| Maidana, Renan | IU | Risk Assessment for Decision-support in Automated Planning and Resource Management in Autonomous Marine Vehicles |
| Mogstad, Aksel Alstad | GJ | Marine biological applications for underwater hyperspectral imaging (UHI) |
| Norvik, Carina | MG | Bio-inspired fins for highly performant articulated autonomous underwater vehicles |
| Ramos, Nathalie | KJ | 4D printing of intelligent marine structures |
| Slagstad, Martin | JAM | Advanced and rational analysis of steel fish farms in exposed waters |
| Sørum, Stian Hoegh | JAM | Offshore Wind Turbines |
| Tengesdal, Trym | TAJ | Risk-based COLREGS compliant collision avoidance for autonomous ships |
| Williamson, David | ML | Autonomous approaches to in-situ monitoring of early fish life stages |
| Xu, Hui-Li | MG | Fish-hydrodynamic study finalized to the bio-cyber-hydrodynamics |

## PhD degrees 2021

### Supervised by Key Scientists at AMOS

| NAME | DATE | TOPIC | SUPERVISOR |
|---|---|---|---|
| Aksel Alstad Mogstad | September 2. | Underwater Hyperspectral Imaging as a Tool for Benthic Habitat Mapping | GJ |
| João Fortuna | June 18 | Hyperspectral remote sensing, Hardware Development, field campaigns and data analysis | TIF |

### Supervised by Affiliated Scientists at AMOS

| NAME | DATE | TOPIC | SUPERVISOR |
|---|---|---|---|
| Eske Nørgaard Sørensen, Mikkel | Decmeber 9 | Topics in Nonlinear and Model-based Control of Ships | MBR |
| Wu, Mengning | October 21 | Uncertainty of Machine Learning-Based Methods for Wave Forecast and its Effect on Installation of Offshore Wind Turbines | ZG |
| Skulstad, Robert | September 21. | Data-Based Modelling of Ships for Motion Prediction and Control Allocation | HZ |
| Bell Martinsen, Andreas | September 8. | Optimization-based Planning and Control for Autonomous Surface Vehicles | AL |
| Hassan, Waseem | September 9. | Fish on the net – acoustic doppler telemetry and remote monitoring of individual fish in aquaculture | MF |
| Skiftestad Ueland, Einar | September 9. | Load Control for Real-Time Hybrid Model Testing using Cable-Driven Parallel Robots | RS |
| Jónsdóttir, Kristbjörg Edda | April 27. | Current flow processes at full-scale Atlantic salmon farm sites | JAA |
| Bitar, Glenn Ivan | March 21 | Optimization-based Trajectory Planning and Automatic Docking for Autonomous Ferries | MBR |

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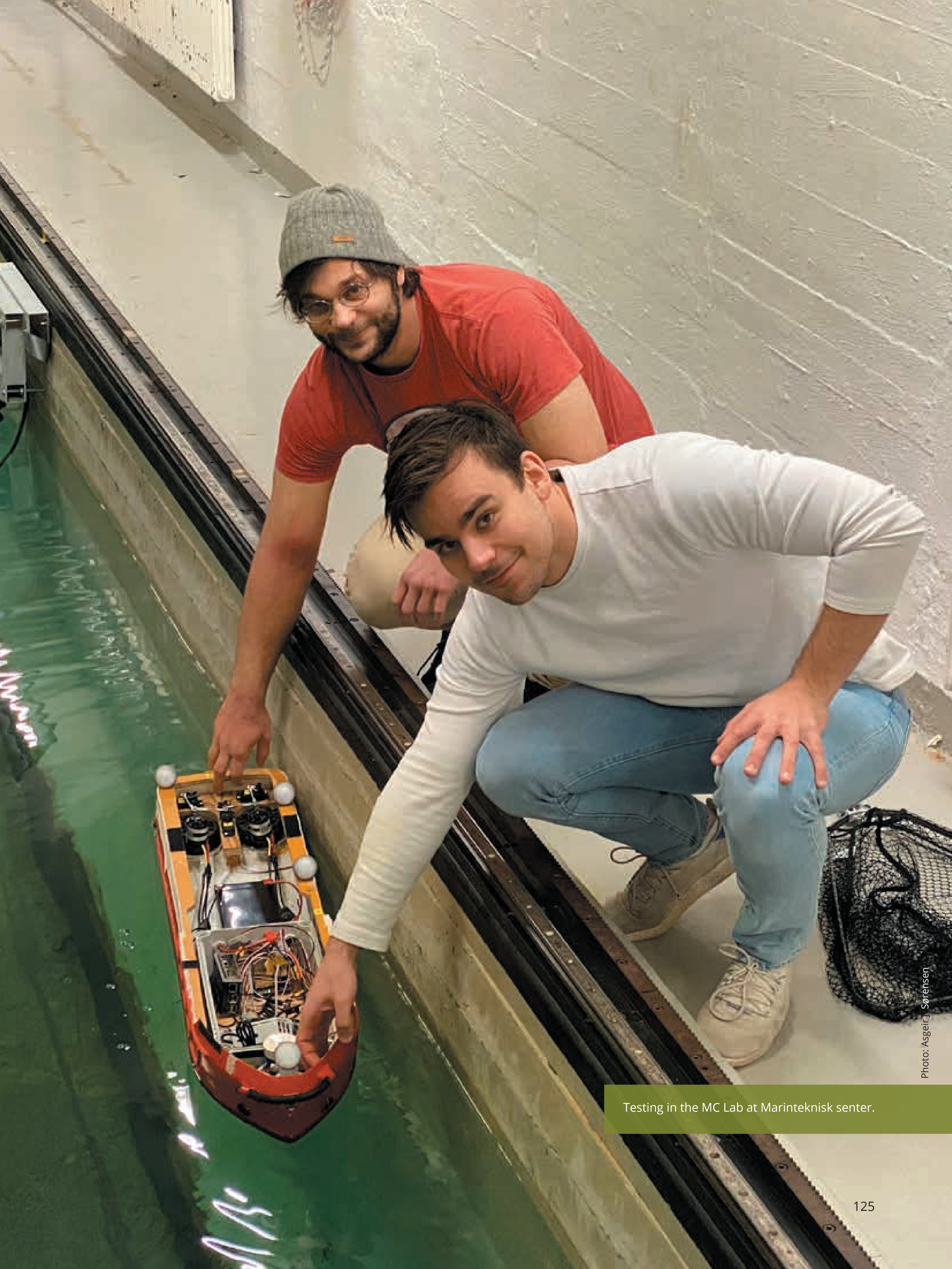

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The king and queen of the Netherlands, and our own crown prince and princess visited Trondheim to hear more about ocean research. Here a researcher and a master student talk about their work in AMOS.

Photo: Live Oftedahl

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