NTNU
Centre for Autonomos Marine Operations and Systems

NTNU AMOS
Centre for Autonomous Marine Operations and Systems

Annual Report 2022

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

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

The targeted research areas at NTNU AMOS are well aligned with national and international strategies, thus meeting the transformations for environmental, economic 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 (CoE's), FME and VISTA CAROS, in collaboration with national and international collaborators, enhance the societal and science impact of the research and innovation activities.

We are approaching the end of the 10-year-period of the Centre of Excellence scheme. This annual report also includes a summary of the entire period.

The main deliverables are:

- 230+ PhDs
- 50+ Postdocs
- 2000+ Scientific publications
- The observation pyramid consisting of a laboratory infrastructure of sensors and robotic platforms operating in space, air, sea surface and underwater
- 8 spin-off companies

The upscale through research-based education leaves lasting traces of research originating from the NTNU AMOS research environment. The candidates will 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 in place.

A major achievement in 2022 was the assembly and successful launch of the first research satellite from a Norwegian university! The mission is to detect changes in ocean colours, such as spring blooms, dangerous algal blooms and pollution in oceans and lakes with a hyperspectral camera. HYPSO-1 was launched on January 13, 2022 from a SpaceX Falcon-9 rocket from the Kennedy Space Center in Florida. It will orbit 500 kilometers above the earth for approximately five years. HYPSO stands for HYPer-spectral Smallsat for ocean Observation. The entire observation pyramid with sensor-carrying platforms operating in space, air, on the sea surface and underwater were successfully demonstrated on a field campaign in Ny-Ålesund, Svalbard in May 2022, in collaboration with UiT the Arctic University of Tromsø and UNIS.

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

Finally, I will also thank the Research Council of Norway for giving us the credentials and trust to become a Centre of Excellence having extended power of attorney with a license to create. Hopefully, the impact and outcome of NTNU AMOS gives a recognition of investments in long-term fundamental research and innovations.

Sincerely,

Asgeir J. Sørensen

Professor Asgeir J. Sørensen
Director NTNU AMOS

Asgeir J. Sørensen led the first trial of the observation pyramid in Ny-Ålesund in May 2022.

Photo: Eirik Sivertsen

BOARD OF DIRECTORS

AMOS has been run for almost 10 years since its inception in 2013. AMOS is mainly financed by the Research Council of Norway through the Norwegian Centres of Excellence scheme. AMOS has also been financed by Equinor, DNV, SINTEF Ocean, SINTEF Digital and NTNU.

AMOS has been a great success and has contributed to a significantly increased knowledge base and education of a large number of master's and PhD candidates. This provides a very large potential for future value creation within maritime industries.

AMOS has not only contributed results from basic research, but has managed to combine the development of basic knowledge with industrial applications and innovation. AMOS has shown that basic research can have a direct commercial value, through a working philosophy where an understanding of the development of basic knowledge, technological challenges and innovation has been combined.

AMOS fulfils the expectations as a Norwegian Centre of Excellence, and in addition a remarkable track record in creating associated research projects, innovations and spin-off companies.

The AMOS researcher groups are being recognized for their excellent research, innovation and outreach achievements. The interdisciplinary 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. AMOS has also contributed to developing a unique research infrastructure.

The knowledgebase created together with the research infrastructure provides an excellent research environment in the years to come.

Caption

Photo: Asgeir J. Sørensen

EQUINOR

Equinor is a proud partner of NTNU AMOS. Our interest in AMOS goes across all projects, and in support of advancing knowledge and solutions with higher levels of autonomy throughout the ocean space. We have been able to participate and set a strategic direction for AMOS that spurs unbiased basic research that can easily be implemented across industries.

While suppliers with market shares within segments covered by AMOS have been collaborating, we do see the unique position AMOS has kept throughout its existence, in which there is a genuine freedom to disrupt without concern for legacy products and technologies. It is believed that this freedom has been vital for the many innovations that have emerged from AMOS. We also see that suppliers and industry have stepped up to improve their own solutions based on the great work done in AMOS.

Bringing in end user perspectives to the research undertaken has proven to be a great virtue for activities in AMOS. End users set the bar on the quality and performance of systems, and hence spur AMOS researchers to rethink solutions – not at the cost of basic research, but rather fundamentally challenging the options provided by existing research and technology. AMOS has shown how basic research can grow from trying to radically improve given end-user objectives. Solution-agonistic approaches have the power to disrupt and fundamentally change industries.

The centre has consciously taken the approach of the rapid testing of ideas, technology and solutions. Such rapid testing of ideas with a high allowance for failure is essential for swift progress within the selected research areas. In this way, students get a chance to excel in their own research and theory, through corrective actions on hypothesis and models based on evidence. Such an approach increases the uptake of basic research from AMOS in research institutes and industry in general.

As industry partner to AMOS, it has been of the highest importance for us that AMOS became and stayed a daring research centre. Academia should have

PARTNER STATEMENT

that courage to test and fail in the quest for expanding the limits of what is, not humanly, but: scientifically or "robotically" possible. Fail in a safe way. This is a prerequisite for progress. If research does not fail in its early stages, it could indicate that the bar is set too low. Through 10 years of operation, AMOS personnel have been imprinted with this message, and need to aim high with their own research. The AMOS mantra has been: "Proud? Yes!, Satisfied? Never!" The constant quest for improvements, incremental as well as radical, has been the backbone of AMOS. Within the fast-moving research areas of AMOS, this is a prerequisite to stay as a world leader, which has served the centre well.

In academia, impact is often measured by the volume of scientific productions in high impact-rated journals. AMOS has shown great numbers in this respect, contributing to dissemination and awareness in a way that confirms NTNU and Norway as world leading on cutting-edge science and technology in the ocean space. This, however, offers only a limited view of the actual impact AMOS has had on academia, institutes, industry, and society as such.

AMOS provides great examples that interdisciplinary work is not in conflict with the scientific depth of single disciplines, but instead improves quality in such individual domains, as well as the collaboration across. Results are shown to be groundbreaking, in true honour of the intentions of the Centre of Excellence scheme. Profound impact is gained from the way AMOS has refined and educated its own students and employees to become polyvalent experts.

Even if the many new companies spun out from AMOS activities with the potential for a great impact on society, perhaps the greatest impact is still competence and mindset imprinted in the many MSc, PhD, postdocs and employees of AMOS. They are highly sought-after employees in industry, institutes, academia and with governing bodies. Fruits from their careers and future endeavors will last for many decades to come.

"As industry partner to AMOS, it has been of the highest importance for us that AMOS became and stayed a daring research centre. Academia should have that courage to test and fail in the quest for expanding the limits of what is, not humanly, but: scientifically or "robotically" possible. Fail in a safe way.

Equinor has throughout AMOS existence gained value from its production of insights, competence, solutions, and established spin-out companies. Our operations as well as rollout of robotic systems with increased level of autonomy in air, on sea surface, on the ground and subsea supporting petroleum as well as offshore wind business has been supported by AMOS competencies. As examples, this has aided environmental monitoring, inspection, maintenance, and repair as well as situation awareness for operators. Such systems and increased level of autonomy opens fundamentally new ways of operating. AMOS contributions have improved Equinor's ability to deliver according to the corporate strategy "Always safe, High value, Low carbon".

Dissemination into the public domain has also been in focus at AMOS. Over the last decade, a great number of TV broadcasts and news articles on AMOS activities have created curiosity, interest, pride, and enthusiasm to a wider audience. This increases the interest of youth to study and find a career within our industries.

AMOS has never been afraid of reinventing itself as a centre. Bringing in biology and archeology into AMOS, in addition to developing the observation pyramid concept, thereby proving its virtues and applicability, are just some. Conquering space with small satellites is another. Many more could have been mentioned, including robotic organizations. At the core of this is an ability to timely identify new and adjacent areas, white spaces on the map, as well as redefining and applying basic competencies to radically improve for high impact.

We would like to thank the Research Council of Norway, AMOS partners, the host institution and collaborators for an extraordinary and successful journey. The unwavering support from the host NTNU has been imperative for AMOS to succeed. We would like to thank the key scientists of AMOS, the administration, and the centre's director Asgeir J. Sørensen, who has created and maintained a sharp performing team.

Then finally: *"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."* (Quote: Sir Winston Churchill)

On behalf of Equinor
Kjetil Skaugset
Board member of AMOS for 10 years

DNV

The maritime and offshore segments have always been important areas for DNV and we have been a member of AMOS since the beginning. The focus of AMOS on autonomous systems, marine robot platforms, and risk management of ships and ocean structures are well aligned with the direction that DNV is taking.

The maritime and offshore segments have always been important areas for DNV and we have been a member of AMOS since the beginning. The focus of AMOS on autonomous systems, marine robot platforms, and risk management of ships and ocean structures are well aligned with the direction that DNV is taking.

We acquired Marine Cybernetics in 2014 as a means of providing new ways of testing and assuring software control systems. With digital twins of the sea states and the ships, we could now simulate the performance of the control system against these twins rather than test onboard the real ship. Such hardware-in-the-loop testing added additional capabilities to the conventional way of assuring control systems.

The collaboration with AMOS has strengthened our capabilities in this field beyond testing of control systems. Today, we see that cybernetics and simulation-based approaches is essential in assuring any kind of digital system, be it a full autonomous ship, a digital twin of the ship, a machine learning algorithm providing a function, etc. In our journey towards a digital class offering, we explore all these possibilities.

We test how ships can be assured based on standardised 3D models (digital twins) combined with simulations and use of operational data. The collaboration with AMOS has been important for DNV to advance these areas. To further harvest from the work in AMOS, DNV has also acquired a minority stake in the AMOS spin-off ScoutDI, who provides drone-based inspections.

DNV is a knowledge-based company. We therefore need to collaborate with academia to stay close to the scientific developments. One of our instruments to connect us to NTNU are the DNV-funded professors: We sponsor fulltime professors at NTNU that work on topics of special importance to DNV.

Three DNV-funded professors have been part of AMOS over the years: Edmund Brekke, Zhen Gao and Børge Rokseth.

These professors have been helping to advance the scientific work in AMOS, and also helped DNV in our harvesting of knowledge into our own work. Through AMOS and the professors, we have been able to shape and engage in scientific work, supervise students, recruit candidates, and deploy results from AMOS.

AMOS is important not only to DNV, but also to Norway as a maritime nation. Through this Centre of Excellence we have been able to take a leading role internationally in areas of special importance to Norway. This demonstrates that Norway has a competitive advantage on collaborations between government, academia, and industry.

Together one can have a fast cycle from development of regulations, development of concepts, testing on use cases, qualification of new technology and adaptions. This fast cycle from research to innovation is also the trademark of AMOS. In addition to doing cutting edge research, AMOS has created several spin-off companies. The ability of AMOS to make use of the whole value chain, from research to innovation through pilots and finally commercialization is truly impressive.

We would like to take this opportunity to thank AMOS and NTNU, the partners and everybody involved in AMOS for a project well done. AMOS is a success.

On behalf of DNV
Frank Børre Pedersen
Partner of AMOS for 10 years

"AMOS is important not only to DNV, but also to Norway as a maritime nation. Through this Centre of Excellence, we have been able to take a leading role internationally in areas of special importance to Norway."

PARTNER STATEMENT

SINTEF OCEAN

Norway is and has always been a nation relying on ocean industries. Fisheries, shipping, and petroleum has expanded to aquaculture, renewable ocean energy and other new industrial segments. The basis for this adventure has been the resources of the ocean and knowledge. In modern times NTNU and the entire Norwegian community of research organizations have contributed to the development of the ocean industries through education of students and world leading research.

SINTEF Ocean has been a partner of the Centre of Excellence NTNU AMOS since its start, and we have proudly participated in the research activities across all scientific areas in the centre. NTNU has taken strong leadership and challenged us and the other partners on experimenting with radical new ideas and solutions to support the future ocean industries. We cannot rely on the past to form the future, and we need to support the existing industry to perform significant shifts in their operations and value chains. The current climate crisis, biodiversity crisis and shifting positions in geopolitics underpins this.

The global ocean industries will need to renew their license to operate in the future. Many solutions to the climate crisis will be found in the ocean industries, and the new businesses will have to operate with minimal disturbance of the ocean ecosystems. The future scientists and employees in ocean industries will have to find new solutions with this in mind, and new technology is going to be developed and implemented in future value chains on new premises. AMOS has proved that new solutions can be found, and the students and researchers involved in AMOS will have the mindset and insight to take the development further in the future.

SINTEF Ocean has already recruited many of the students from AMOS, and they are doing industrial research supporting ocean-based businesses. They are a source of new ideas and solutions, and they are working in close collaboration with the industry. AMOS has been vital for establishing new research activity, and many new centers have been started based on results and proposals from AMOS. In addition, many industrial research projects have also been established from AMOS results, and we foresee that many solutions will have their industrial implementation in the near future.

AMOS has also been vital in building research infrastructure, as ideas from AMOS has been translated into future needs for education and industrial research. For example, The Norwegian Ocean Technology Centre has been developed with inspiration from AMOS, and the OceanLab infrastructure has been built on the needs to take AMOS' results into the future.

The collaboration between NTNU and SINTEF has been strong for more than 70 years. AMOS has been vital in strengthening this partnership, and new scientific areas have been developed to create values on future opportunities. SINTEF Ocean is grateful for the opportunity to work with NTNU and the other partners of AMOS. NTNU's strong leadership in the centre has been of particular value because "Excellent – generous – courageous" have been the real guideline for the work performed.

SINTEF Ocean would like to take this opportunity to thank AMOS and NTNU, the other partners and connected companies and researchers involved in AMOS for excellent cooperation. AMOS will stand out in history, and we are proud of the results.

On behalf of SINTEF Ocean
Vegar Johansen
Partner of AMOS for 10 years

> **"The global ocean industries will need to renew their license to operate in the future. Many solutions to the climate crisis will be found in the ocean industries, and the new businesses will have to operate with minimal disturbance of the ocean ecosystems. The future scientists and employees in ocean industries will have to find new solutions with this in mind"**

PARTNER STATEMENT

PERSPECTIVES **BEYOND** AMOS


Jørgen Amdahl
Thor I. Fossen

Marilena Greco
Geir Johnsen

Tor Arne Johansen
Kristin Y. Pettersen
Asgeir J. Sørensen





Norway plays an important international role as one of the main actors in the blue economy. More than ever, a holistic and sustainable approach is needed to address global challenges, value creation and knowledge-based management of the northern regions and oceans. We are in the United Nations Decade (2021-2030) of Ocean Science for Sustainable Development – The Science We need for the Ocean We Want (Intergovernmental Oceanographic Commission, 2019). Another important achievement was the UN Biodiversity Conference, COP15, in Montreal in December 2022, concluding with a “historic” deal to protect one-third of the world’s biodiversity to help strengthen the web of life, the protection and restoration of land and seas, and the launch of platforms for accelerating action.

A holistic and sustainable perspective of the blue economy (see Figure 1) that encompasses all stakeholders, including policymakers, is needed to achieve both the impact and implementation at the speed we require. The changes that take place in Arctic regions and ocean areas increase in speed and extent, and are strongly interconnected to activity on land and coastal areas around the globe. The oceans connect and belong to all of us (humans and other organisms), so we are in a hurry to understand and take proper actions. We must create incentives for *demand* and *deliver* across the entire value chain, stimulating the stakeholders from a think-tank to an executional do-tank to develop competence, knowledge and innovations subject to:

- *global challenges* related to habitat degradation, climate change, lack of energy, minerals and food, acidification and pollution of the oceans, a biodiversity crisis, natural disasters and a need for green logistics;
- *value creati*on (products, services, etc.) in terms of fisheries, aquaculture, maritime transport, oil and gas exploitation, offshore renewable energy, marine minerals, tourism, coastal and urbanization infrastructure;
- *governance and knowledge-based management* of the oceans, coastal areas, seabeds, and the Arctic; and
- *enabling technologies* such as information and communication technology (ICT), material technology, biotechnology, autonomy, big data cybernetics, nanotechnology, and interdisciplinarity.

When it comes to preserving and developing human health and well-being in the short- and long-term for the generations to come, we face a few dilemmas. Increasing occurrences of habitat degradation, extinction of species, extreme weather, accelerated melting of ice on land and sea, rising sea levels, pollution, and global diseases should indeed motivate us to develop more sound and sustainable human activities. The cost of overlooking this fact will simply be too high, both in economic and humanitarian terms.

Indeed, it is our belief that knowledge and competence can contribute to technology innovations and policy in two ways. To create changes fast enough in the desired direction, technology innovations may be implemented as a transformative process, while others may be more disruptive. Start-ups supported by academia, industrial and financial partners are often the most effective way to go, as no strings are attached to legacy products and services. Successful implementation relies on political leadership that enforces incentives and regulations. Fortunately, long-term responsible industry actors and investors that are looking beyond the next quarterly economic reporting also have similar interests. There does not need to be a contradiction between value creation and sound knowledge-based governance. For instance, for the fisheries and aquaculture industry, it is obvious that a healthy ocean is not only good for, but a precondition for business.

> **There does not need to be a contradiction between value creation and sound knowledge-based governance**

In being proactive, both for existing industry and start-ups, we may regard the 17 United Nations (UN) Sustainable Development Goals (SDG) as the largest and most systematic market study of the world, providing possibilities for economic growth and a better future. Knowledge and competence will be instrumental for the development of technology and services contributing to improved solutions.

Decades of systematic ocean science research using ships, landers and buoys, and lately advanced marine robotics and sensors, have told us how extensive and vulnerable the ecosystems are in the High North and Arctic Ocean. Even during the winter and polar night season, the marine ecosystems are fully functional and active. Threats to these ecosystems span from the discharge of toxic substances, the inflow of warm water and the intrusion of invasive species from the south.

During the polar night, we have also studied how sensitive the behavior of zooplankton and fish are to artificial light pollution (e.g. ships, settlements). The light climate influences the hunting and escape strategies for many species, such that they easily become disturbed by artificial light several kilometers away from the source, as well as ten folds of meter into the depth. The same behavior using large ships emitting light may also be an error source in the quantification of marine resources for research and management (fish stock surveys) purposes during the night and winter season (polar night).

We may claim that the advection pump of warm Atlantic water into the Arctic Ocean and the corresponding outflow of cold Arctic water, both taking place in the Fram Strait between Greenland and Svalbard, are of crucial importance for life in the northeastern Northern Atlantic and the Arctic Ocean. Any changes in these water fluxes not only directly affect the local climate, but have ramifications all over the Northern hemisphere. In simple terms, we can regard the Fram Strait as an oceanographic and biological

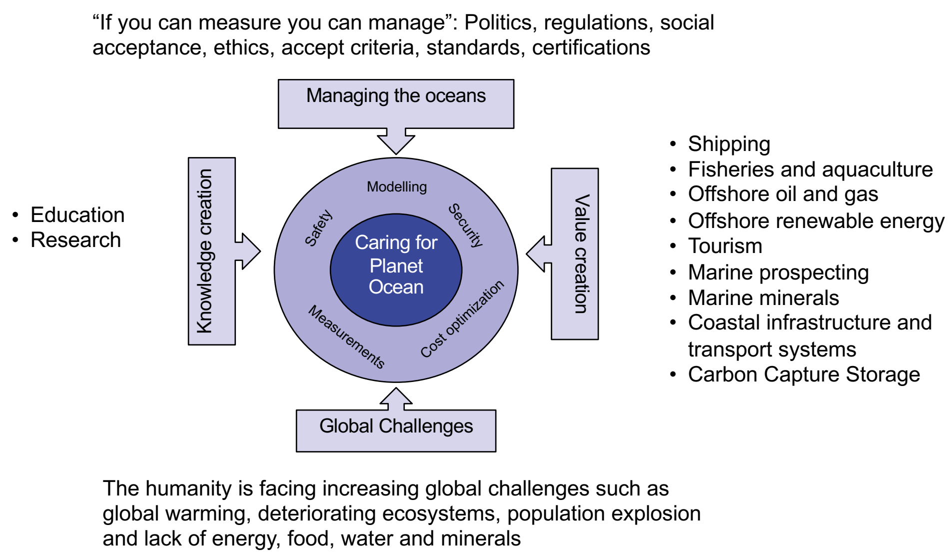


Figure 1: Sustainable value creation requires a holistic approach

"war zone" between the south and north. Today's climate change moves this war zone further north, with possible devastating effects on Arctic sea life, including sea birds.

As in the ancient times of the ice age, the pressure by the human exploitation of resources in the Arctic regions literally follows the ice edge. This also applies today for whaling, fisheries, shipping, tourism, mining, oil and gas, defined as the blue economy. In some few decades, we may experience that Arctic Ocean going from an iced covered white ocean to becoming a blue ocean during the summer, with little or no multi-year ice present.

The blue economy

The Norwegian economy is dominated by the blue economy (see Figure 2). Common factors for the blue economy are that the activities are taking place in the oceans, and that they are both local and global in their presence and trade. Concerning a more accessible new Arctic Ocean, we may foresee a global race for securing access to potential valuable fisheries, hydrocarbons and mineral resources. In addition, less multi-year sea ice will open new Arctic shipping routes. Hence, the level of human activities and possible environmental impact are expected to increase in a vulnerable environment, in which our knowledge is still rather limited. The sustainable exploration and exploitation of the ocean require hydrodynamically efficient, highly maneuverable, low intrusive, autonomous vehicles, so as to cope with long-distance missions, hostile environmental conditions (e.g. high pressure, low visibility) and fragile eco-systems; bio-inspired underwater vehicles can be crucial in the engineering implementation of these skills.

> **"We can regard the Fram Strait as an oceanographic and biological "war zone" between the south and north. Today's climate change moves this war zone further north**

Offshore oil and gas, the maritime industry, fishery and aquaculture are the three largest sectors of the Norwegian blue economy. They are all of great importance for Norwegian well-being, providing an important contribution to the world in the supply of energy, transportation and food. Emerging business areas are offshore renewables (primarily offshore wind), tourism and marine mining. Benefitting from ocean science and bioprospecting (the process of discovery and the commercialization of new products based on biological resources), we may also see huge potential in new marine species, bacteria, molecules, etc. to produce new pharmaceutical substances, such as antibiotics that kill antibiotic-resistant bacteria.

Reduced emission footprint in oil and gas

National oil and gas activities mostly take place in three areas - the Arctic region, the Norwegian Sea and the Barents Sea. Defining the border line for the sea ice edge in the Norwegian Arctic regions, restricting how far north oil and gas activities on the Norwegian continental shelf can take place, has been highly important. Oil and gas activities in the High North are not only of concern in Norway, as there are also large terrestrial and offshore activities in Russia, Canada and the US. The exploitation

> The exploitation of hydrocarbons is not sustainable. Carbon capture storage (CCS) may be methods to reduce the problem

of hydrocarbons is not sustainable. Carbon capture storage (CCS) in ground reservoirs and other capturing methods in the ocean (e.g. kelp and micro algae production) may be methods to reduce the problem. The work to replace polluting energy sources, such as coal and heavy oil, with cleaner sources using renewables has intensified. Regardless of how the energy transition will occur, the 50 years of experience and knowledge gained from designing and operating offshore oil and gas installations, and conducting marine operations in harsh environments, will be instrumental in developing offshore renewables and offshore aquaculture.

Toward zero carbon shipping
Maritime transport is probably the most environmentally friendly method to transport large amounts of goods and humans to secure primary logistics needs. However, in global terms, shipping is still a severe single source of greenhouse gases and black carbon, unintentionally causing the spread of invasive species with ballast waters and hull fouling. The UN International Maritime Organization (IMO) has therefore enforced a plan to reduce emissions in international shipping by a total of 50% in 2050 compared to the 2008 level. A reduction of up to 50% may not look ambitious. However, it will indeed create changes in the organization of logistic chains and motivate new ship concepts with hybrid power plants, using greener fuel mixtures, batteries, hydrogen, ammonia, etc. Green fuels are supposed to be produced by renewables, by limiting the capacity and speed of transition. An attractive substitution for some years is the production of blue hydrogen products based on hydrocarbons and CCS. Nevertheless, the cost of energy may rise on the order of 3-10 times, compared to today's use of conventional fuels.

> The cost of energy may rise on the order of 3-10 times, compared to today's use of conventional fuels

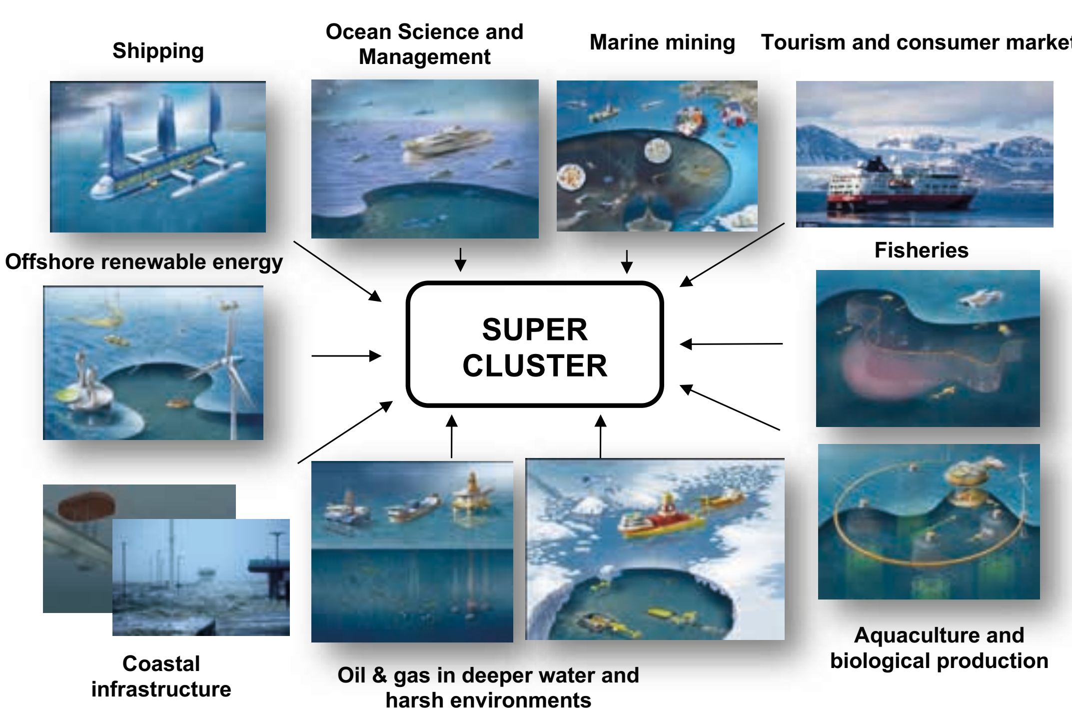


Figure 2: The blue economy (Courtesy: NTNU AMOS/Stenberg)

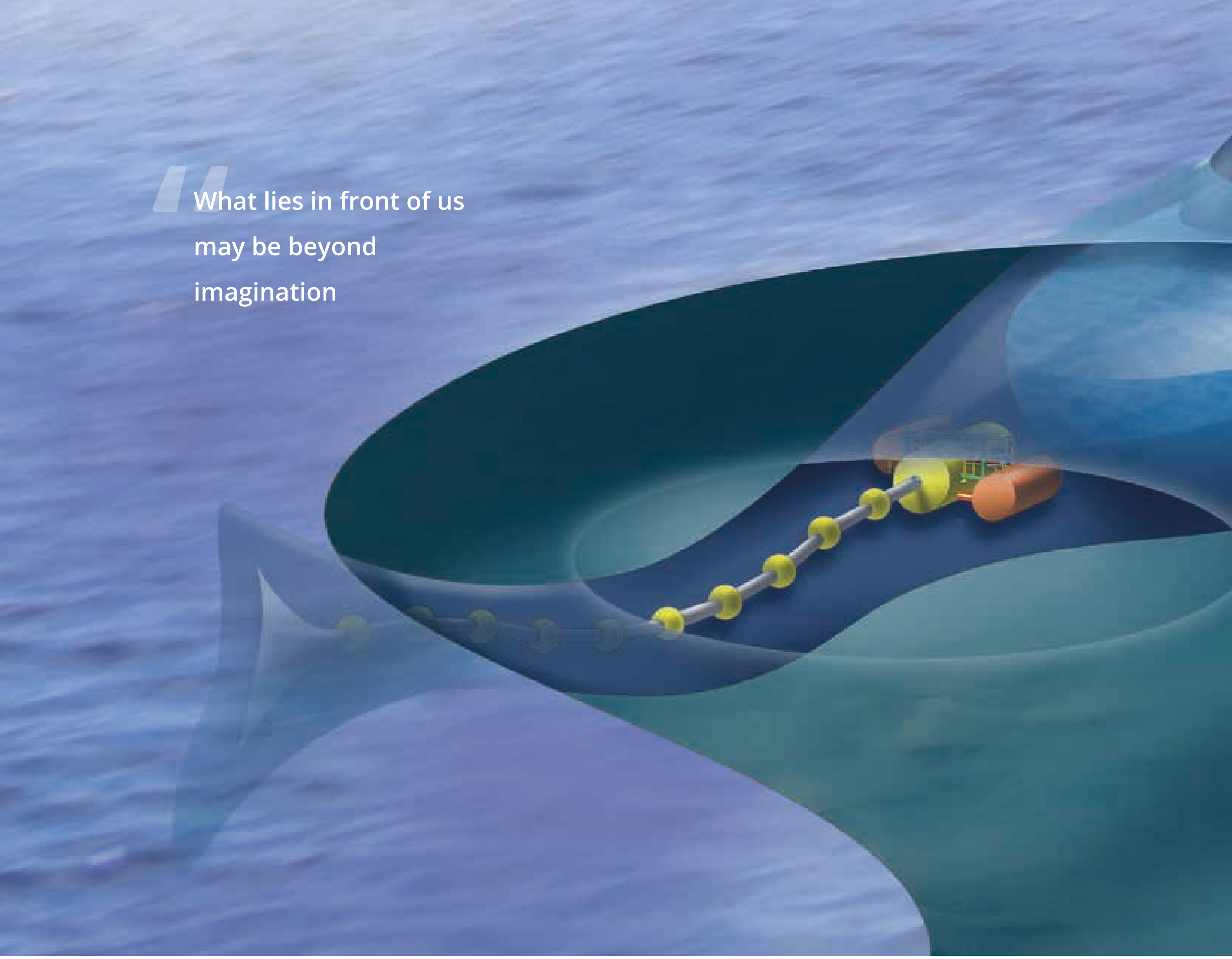


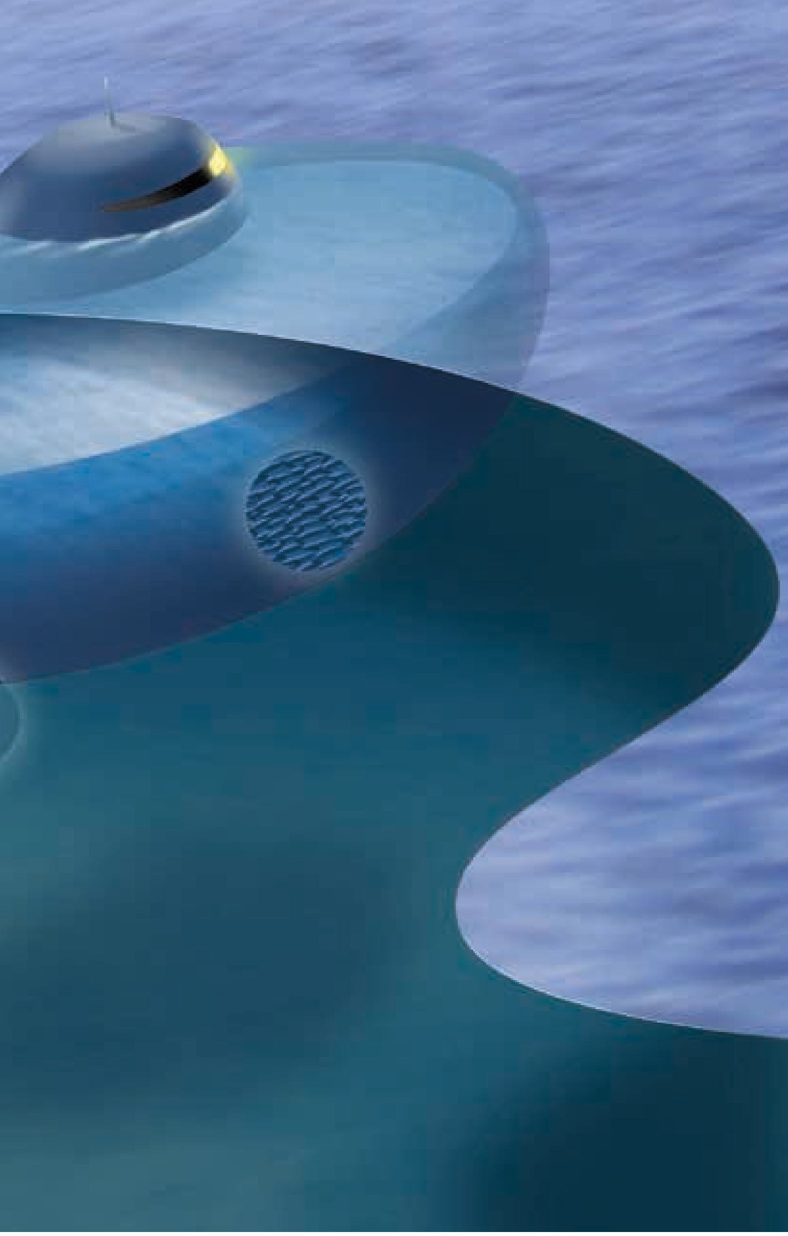
Figure 3: Disruptive innovations beyond imagination from micro to macro scales *Illustration: NTNU AMOS/Stenberg*

Reducing ship speed and selecting unmanned autonomous ships will represent possible solutions. A driver for a rapid transition towards zero carbon shipping may be to enforce even stricter requirements for reduced emissions in all maritime activity. This may be regulated by authorities using, e.g., a tax on emissions and creating a commercial *demand* and *delivery* mechanism from customer to producer through the entire supply chain. The combination of regulators and financial institutions is a significant driver for the transition. A license to operate and financial security are closely interconnected. For the various shipping segments, from deep sea shipping, regional shipping, domestic shipping, short sea shipping and urban transportation, it is evident that new commercial positions are to be taken, and we therefore see a race for innovations and investments in new technology, services and infrastructure. The response in the market is seen in, e.g., the form of innovation and spin offs, where:

- owners and logistic suppliers of goods to be transported commit to using zero-carbon shipping fuels (ref. Amazon and Ikea);
- partnerships between established and new actors develop a demand for knowledge, solutions, global infrastructure and distribution systems, thus supporting green fuel types on ships (e.g. the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping[1]);
- existing and new actors set up and develop production and distributions systems for green fuel types, batteries and charging systems; and
- novel logistics and ship concepts are developed for the various shipping segments.

The more capital-intensive innovations are often handled by the established enterprises, which may enter into joint ventures with

1 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping: https://www.zerocarbonshipping.com



other companies or investors by developing solutions for batteries and new fuel types (e.g., Aker[2], Yara[3]), while the smaller start-ups seek more disruptive and less capital-intensive opportunities, e.g., autonomous urban ferries (e.g. Zeabuz[4]) and energy-efficient high speed crafts using an air cavity to reduce resistance (e.g. SES-x Marine Technologies[5]).

Towards offshore aquaculture

Coastal aquaculture is currently struggling with ectoparasites and harmful algae blooms. In addition, the environmental impact of aquaculture is of concern in many fjords. Offshore aquaculture in more exposed areas has become the next step for growth in this business. It is likely that the activity level will move northwards, and to areas with better access to a natural supply of food for farmed fish, such as the dominant zooplankton species *Calanus finmarchicus*. Important research areas may be related to spatial and localization planning, a co-existence with other industries, environment monitoring, novel structures, fish welfare, extreme hydrodynamic loadings and response, precision farming, autonomy and marine operations.

Towards offshore wind

When it comes to climate, biodiversity and short-term profit, we obviously face several policy and economic dilemmas, and possible conflicts of interest. For instance, more costly offshore wind turbines may have a less negative impact on biodiversity than developing cheaper wind turbine parks on untouched land. Still, going offshore may potentially increase spatial area conflicts with fisheries. In economic terms, we may ask how to evaluate and price limited resources, such as land and terrestrial ecosystems, when setting up cost balance sheets for new energy projects. Similarly, unless we increase our mining activities, a shortage of minerals may challenge the further growth of green alternatives, such as solar energy and batteries, for energy storage in, e.g., cars and ships.

Electrifying remote settlements and ports

Today, the settlements on Svalbard are dependent on hydrocarbon-driven power plants for the production of electricity (local coal and transported diesel). It is really a contradiction that one of the most environmentally sensitive areas in Norway is not supplied with greener and more renewable energy. We may turn this contradiction to an opportunity, where Svalbard and other remote areas can be a destination for developing and testing hybrid power plants, combining solar and wind driven energy production with energy storage, and the possible production of green fuel types such as ammonia becoming a green port for ships as well. The use of hydrocarbons is hence limited to a minimum. Smart hybrid power plants that work autonomously off-grid without large transmission networks may be a natural next step powering societies and ships on a global scale with greener energy, with less of an impact on climate and biodiversity. Why not start at remote areas such as Svalbard, and then use this

"Offshore aquaculture in more exposed areas has become the next step for growth in this business

2 Aker: https://www.akerasa.com
3 Yara Marine Technologies: https://yaramarine.com
4 Zeabuz: https://zeabuz.com
5 SES-X Marine Technologies: https://sesxmarinetechnologies.com

> **Smart hybrid power plants that work autonomously off-grid without large transmission networks may be a natural next step powering societies and ships on a global scale with greener energy**

experience for the further export of knowledge, products and services on a global scale for remote areas.

Climate adaption of coastal infrastructure
Climate adaptation as well as novel concepts for the crossing of fjords and bays are increasingly important for the coastal economies. Most of the world population lives in urban settlements close to the sea. We can hardly comprehend the cost of adapting these cities and land areas to increasing sea level of only a few decimeters due to melting of land fast ice. Global and local infrastructure enterprises must look for innovative solutions for damage reduction.

Enabling technology

As we have seen, we face both challenges and enjoy opportunities where technology and its use play important roles for human activities and corresponding impact on life and environment. There are many drivers for technology developments such as market needs, exploration needs (and dreams) accessing new and maybe extreme environments, as well as policy-driven rules and regulations. Game-changing technology is often provided through so-called enabling technologies. Enabling technology may be defined in different manners. Here, it is technology that can be applied to drive radical and thorough changes of public and industry inventions and innovations. For instance, drivers for technology developments for improved mapping and monitoring of the oceans in the High North including the Arctic Ocean may be improved operability, access to remote and harsh environments (deep water, under ice, extreme coldness, etc.), long distance with limited ability to communicate, demand for improved coverage and higher resolution of data in spatial and temporal scales, reduced cost, improved safety, etc.

In this context we may categorize the following as enabling technologies with relevance for the ocean technology

- Information and communication technology.
- Nanotechnology.
- Biotechnology.
- Material technology.
- Big data cybernetics and data analytics.
- Autonomous systems.

Combined with fundamental knowledge fields such as mathematics, physics, chemistry, biology, computer science and engineering and by integrating disciplines and technologies we may become in the position to conduct research and innovations based on disruptive, game changing technology. What lies in front of us may be beyond imagination. Examples could be to develop technology inspired by nature that are far more efficient and effective than today's solutions, e.g. applying multi-scale and distributed systems for sensing and actuation: Micro-to-macro (see Figure 3).

We have so far only witnessed the early start of an era where digitalization, artificial intelligence (AI) and robotics substantially contribute to our society: The next opportunities and research challenges lie in embodied artificial intelligence. Embodied AI is AI that controls something physical, like a robot arm or an autonomous vehicle. It is able to move through the world and affect a physical environment with its actions. This opens a new era of opportunities. Such embodied AI needs to become resilient and field-hardened. We can then see embodied AI contribute on roads, tracks, waterways, and in the air transporting passengers and cargo. In precision farming and forestry. At industrial sites, performing inspection, maintenance, and repair. Flying above land and water as well as swimming under water.

> **We have so far only witnessed the early start of an era where digitalization, artificial intelligence (AI) and robotics substantially contribute to our society: The next opportunities and research challenges lie in embodied artificial intelligence**

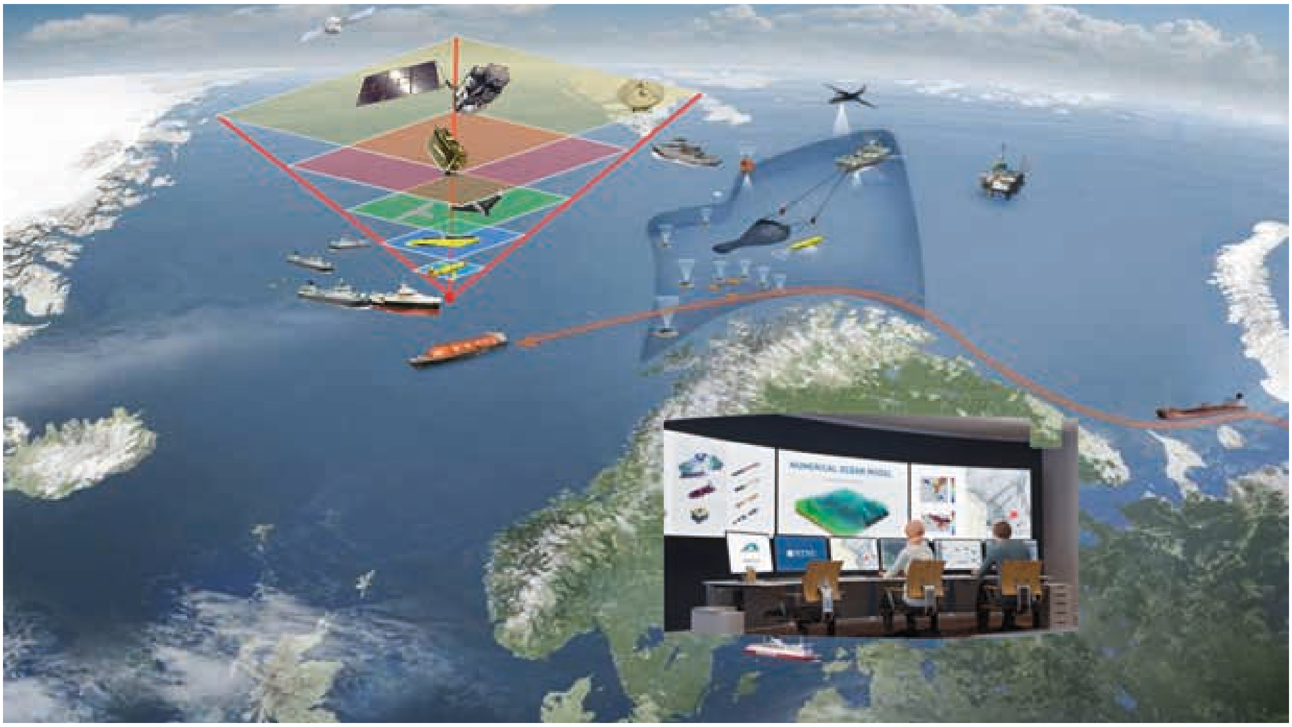


Figure 4: Observation pyramid

Enabling technologies such as information and communication technology, autonomy and microelectromechanical (MEMS) systems provide new possibilities for the development of sensors, sensor carrying platforms creating and observation pyramid (Figure 4), connectivity and big data analytics. The sensor carrying platforms operating from space to ocean space are:

- Underwater: Landers and buoys, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), gliders and profilers.
- Sea surface: Ships, and unmanned surface vehicles (USVs).
- Air and space: Satellites, unmanned aerial vehicles (UAVs) and airplanes.

Low-cost small satellites and in particular *nano* (1-10 kg) and *micro* satellites (10-100 kg) carrying customized payload sensors and communication devices have opened for a step change for remote sensing and communication in polar orbits at altitude of 450-500 km with about 3-6 hours for each passing. Constellations of satellites will provide a significantly improved spatial and temporal coverage. NTNU has decided to launch two small-satellites as a pilot: one for hyperspectral imaging of ocean color and one for supporting Arctic IoT communication.

Environmental mapping and monitoring may be carried out by single platforms, swarms of platforms or combination of several types denoted as *heterogeneous sensor carrying platforms*. Each platform and sensor have various capabilities in terms of spatial and temporal resolution and coverage. By combining them we face a paradigm shift in terms of capabilities that may be 100-1000 times higher than the state-of-the-art technology only some years ago. The entailed increase in data harvesting does also create new challenges in handling big data sets. To take full benefit of the data and develop efficient adaptive strategies for sampling and measurements for the sensor carrying platforms, refinement of models and co-simulation with numerical simulation models of the oceanography and ecosystems is essential.

References

Intergovernmental Oceanographic Commission (2019). The Science we need for the ocean we want: The United Nations Decade of Ocean Science for Sustainable Development (2021-2030) https://unesdoc.unesco.org/ark:/48223/pf0000265198

Wassman, P. (edited) with Auad, G., Babin, M., Balton, A.A., Carmack, E.C., Corell, R.W. et al. (2021). Whither the Arctic Ocean?: Research, Knowledge Needs and Development en Route to the New Arctic. Fundacion BBV, Spain

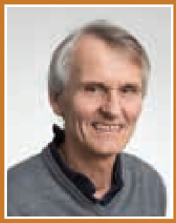
Berge, J., G. Johnsen, J., & Cohen, H. (2020). *Polar Night Marine Ecology - Life and Light in the Dead of Night. Advances in Polar Biology.* Springer Nature, Switzerland

PHOTO GALLERY

Key scientists


Prof.
Asgeir J. Sørensen


Prof.
Thor I. Fossen


Prof.
Jørgen Amdahl


Prof.
Marilena Greco


Prof.
Tor Arne Johansen

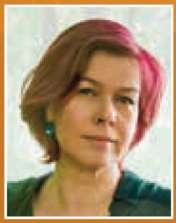

Prof.
Geir Johnsen

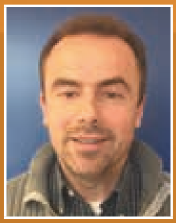

Prof.
Kristin Y. Pettersen

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

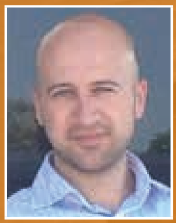

Adj. Prof.
Fred Sigernes

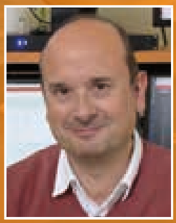

Adj. Ass. Prof.
Nadezda Sokolova


Adj. Ass. Prof.
Rune Storvold


Adj. Prof.
João Sousa


Adj. Prof.
Kjell Larsen

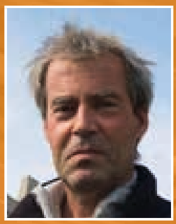

Adj. Ass. Prof.
Francesco Scibilia


Adj. Prof.
Fernando Aguado Ageleet

Technical staff


Pedro De La Torre


Trond Innset

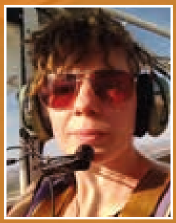

Pål Kvaløy


Christian Malmquist

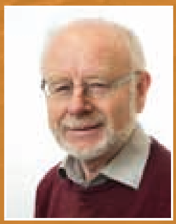

Terje Rosten

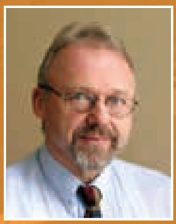

Kay Arne Skarpnes


Ole Erik Vinje


Ash Wells

Senior Scientific advisers


Prof.
Odd M. Faltinsen


Prof.
Torgeir Moan

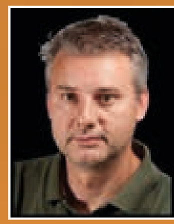
Management and administration


Renate Karoliussen

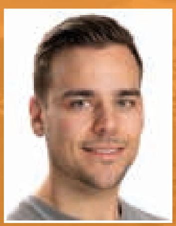

Knut Reklev


Live Oftedahl

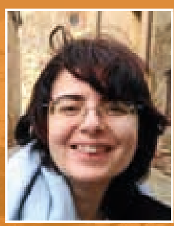

Eirik Siverten


Antonio Vasilijevic

Postdocs/researchers

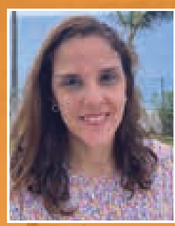

Dr. Erlend A. Basso

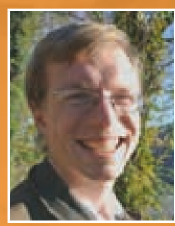

Dr. Roger Birkeland

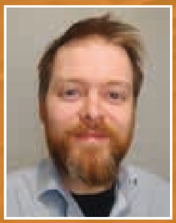

Dr. Giuseppina Colicchio

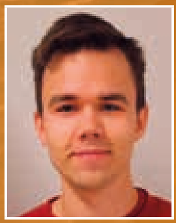

Dr. Katherine M. Crosman

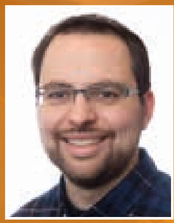

Dr. Bjørn-Olav Holtung Eriksen


Dr. Glaucia Moreira Fragoso

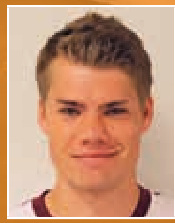

Dr. Joseph Garrett

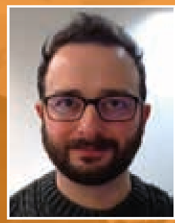

Dr. Stephen Grant

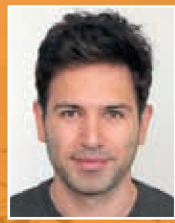

Dr. Kristoffer Gryte


Dr. Richard Hann


Dr. Finn-Christian W. Hanssen

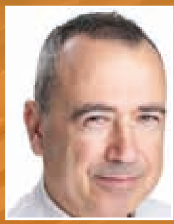

Dr. Håkon Hagen Helgesen


Dr. Alun Jones


Dr. Mojatba Mokhtari


Dr. Stein Melvær Nornes

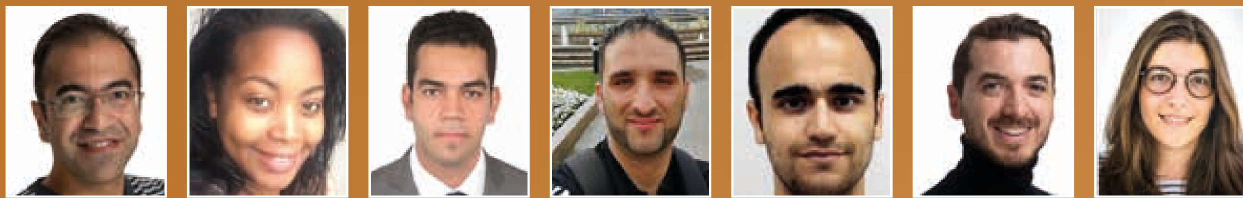

Dr. Yugao Shen


Dr. Kadir Atilla Toker

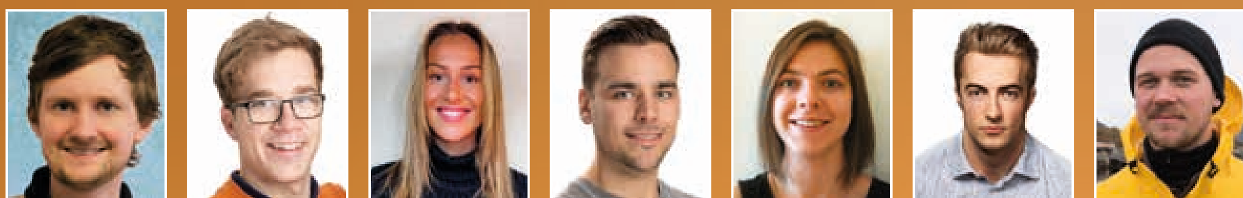

Dr. Artur Piotr Zolich


Dr. Øyvind Ødegård

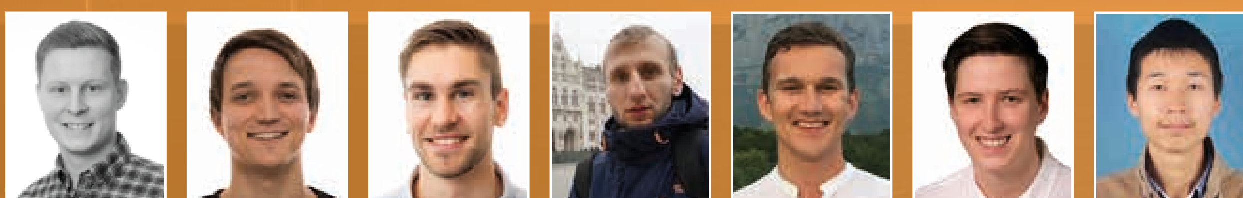
PhD candidates



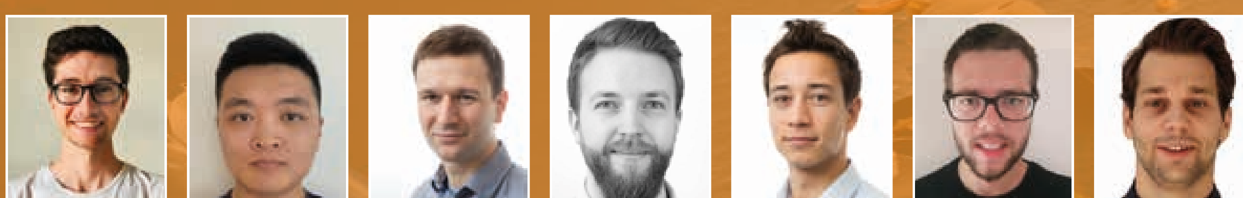
Behdad Aminian | Muram Abbadi | Serag-Eldin Abdelmoteleb | Ahmed W. Amro | Alireza Ahani | Melih Akdag | Irene Rivera Arreba



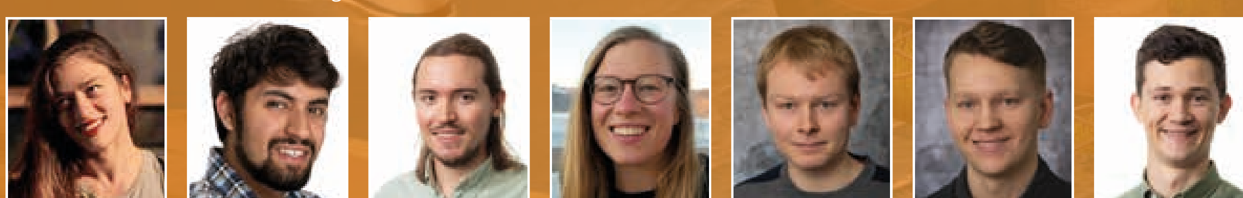
Martin Baerveldt | Sivert Bakken | Karoline Barstein | Erlend Andreas Basso | Gunhild Elisabeth Berget | Fredrik Hoel Bevreng | Tore Mo-Bjørklund



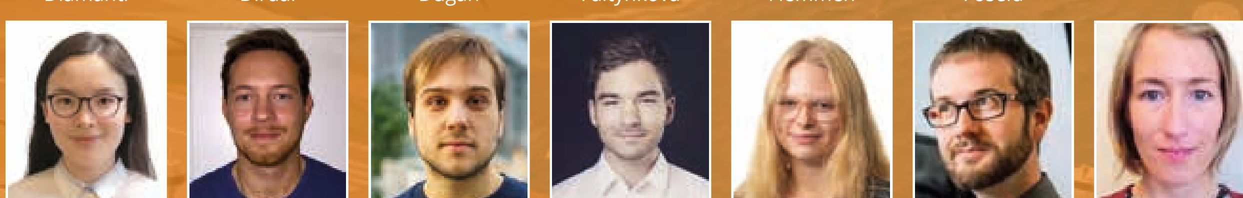
Jon Bjørnø | Simon Blindheim | Pål Tokle Bore | Vasileios Bosdelekidis | Jens Einar Bremnes | Eivind E. Bøhn | Chuanqui Guo



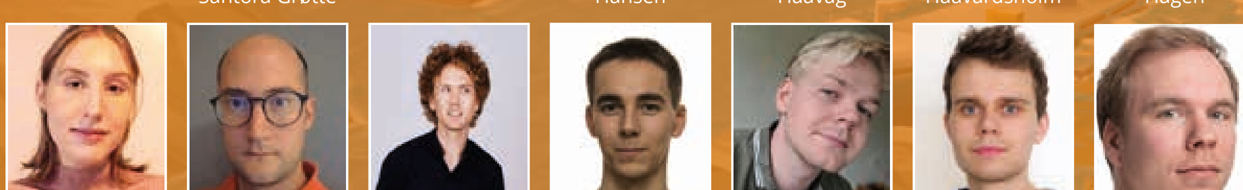
Alexandre Cardaillac | Man Ken Michael Cheung | Krzysztof Cisek | Erlend Magnus Lervik Coats | Andreas Reason Dahl | Albert Dallolio | Henrik Schmidt-Didlaukies



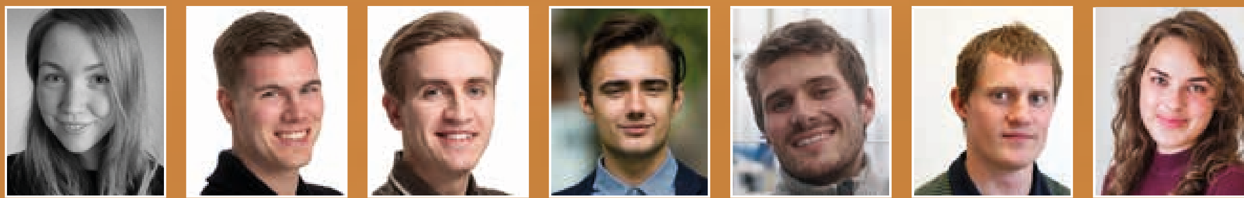
Eleni Diamanti | Johan Alexander Dirdal | Spencer August Dugan | Andrea Faltynkova | Henrik Dobbe Flemmen | Eirik Lothe Foseid | Markus Fossdal



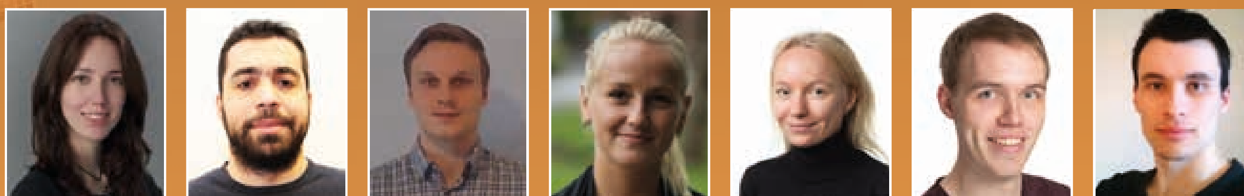
Fan Gao | Mariusz Eivind Santora Grøtte | Ivan Gushkov | Bogdan Løw Hansen | Aurora Skaare Haavag | Trym Vegard Haavardsholm | Inger Berge Hagen



Aurora Haraldsen | Oliver Kevin Hasler | Johan Hatleskog | Simen Haugo | Matias Haugum | Øystein Kaarstad Helgesen | Audun Gullikstad Hem

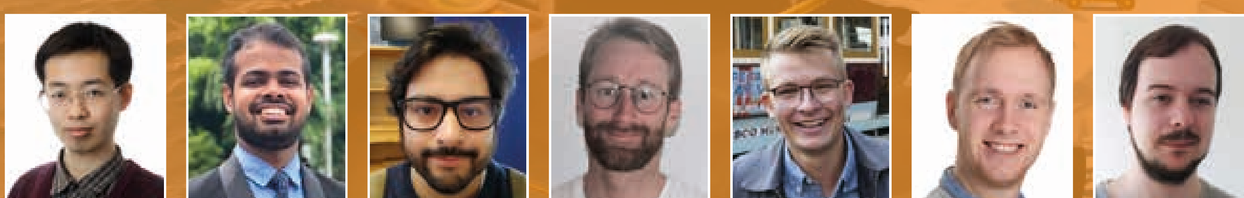


Marie Bøe Henriksen
Simon A. Hoff
Markus H. Iversflaten
Jan Henrik Jahren
Erling Rennemo Jellum
Thomas Johansen
Marianna Kaminska-Wrzos

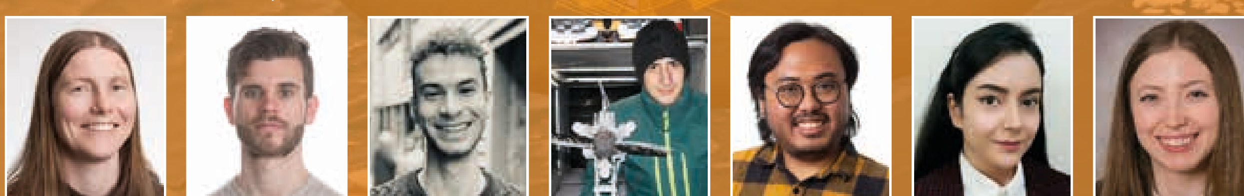


Gabriele Kasparaviciute
George Katsikogiannis
Toni Klausen
Veronica Liverud Krathe
Susanna Dybwad Kristensen
Bjørn Andreas Kristiansen
Dennis D. Langer

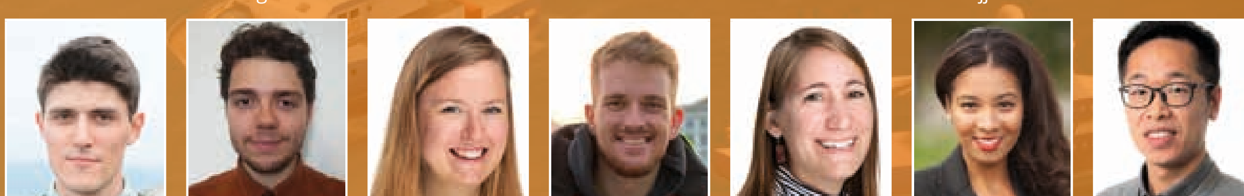
Martin Kvisvik Larsen
Marco Leonardi
Markus Lindner
Evelyn Livermor-Honoé
Ernesto Lopez
Ole Jacob Lorentzen
Håvard Snefjellå Løvås



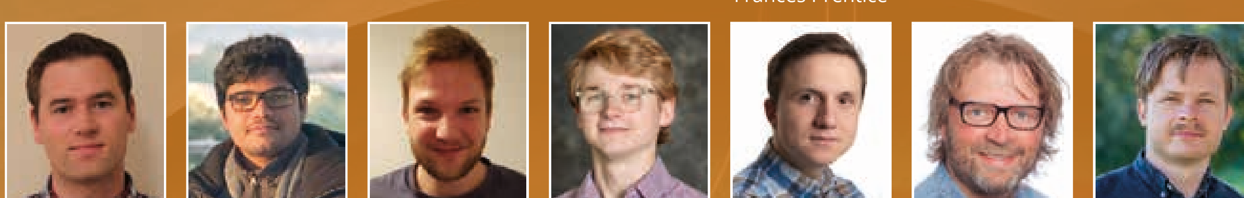
Shaojun Ma
Dhanika Mahipala
Renan Maidana
Mathias Marley
Emil Martens
Pål Holthe Mathisen
Josef Matous



Mariann Merz
Aksel Alstad Mogstad
Raphael Mounet
Nicolas C. Müller
Muhammad Mukhlas
Samieh Najjaran
Carina Norvik



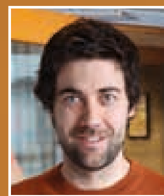
Torje Nysæther
Amer Orucevic
Esmée Oudijk
Casper Potter
Elizabeth Frances Prentice
Nathalie Ramos
Xiaoming Ran

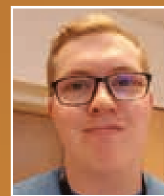


Øyvind Rabilås
Namireddy Praveen Reddy
Dirk Peter Reinhardt
Peter Rohrer
Sverre Velten Rothmund
Dag Rutledal
Simen Troye Røang


Dag Rutledal


Simen Troye Røang

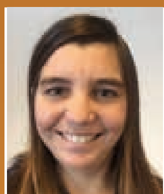

Martin Slagstad


Martin Lysvand Sollie


Petter Solnør

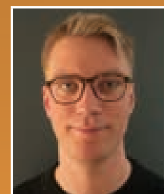

Carlos Eduardo Silva de Souza

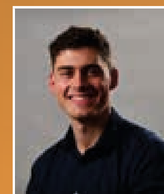

Øystein Sture


Natalie Summers

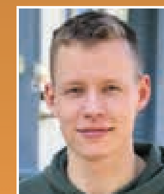

Eirik Svendsen

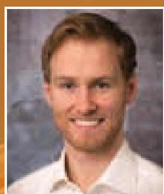

Stian Høegh Sørum


Johan Bakken Sørensen

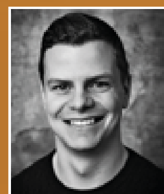

Bjørn Kåre Sæbø


Bálint Zoltán Téglasy


Emil Hjelseth Thyri


Lars-Christian Ness Tokle


Tobias Rye Torben

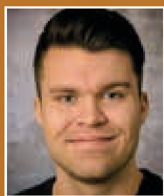

Trym Tengesdal

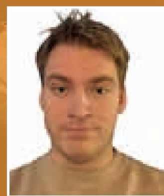

Hoang Ahn Tran

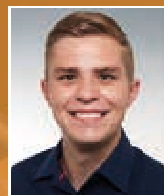

Erling Tveter


Anete Vagale

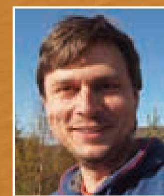
Kjetil Vasstein


Øystein Volden


Ambjørn Waldum


Joachim Wallisch

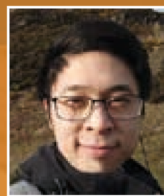

David Williamson


Adrian Winter


Xintong Wang

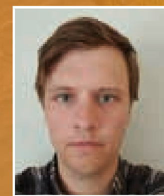

Hui-Li Xu


Ruochen Yang

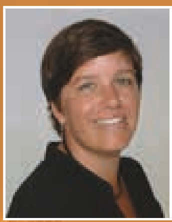

Mauhing Yip


Young Rong Kim

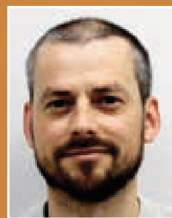

Wai Yen Chan


Henning Øvreaas

Affiliated scientists

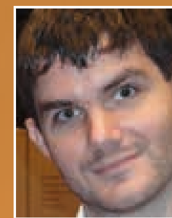

Ass. Prof. Nicole Aberle-Malzahn


Ass. Prof. Jo Arve Alfredsen

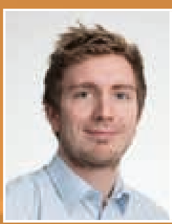

Ass. Prof. Morten Omholt Alver


Prof. Erin E. Bachynski


Ass. Prof. Morten Breivik


Ass. Prof. Edmund Brekke


Ass. Prof. Astrid Helene Brodtkorb

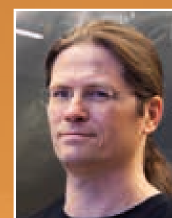

Ass Prof. Torleiv Håland Bryne


Ass. Prof. Robin T. Bye


Ass. Prof. Egil Eide


Ass. Prof. Martin Føre

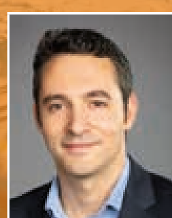

Prof. Zhen Gao


Prof. Jan Tommy Gravdahl

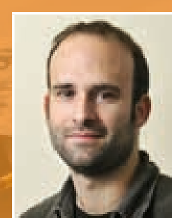

Prof. Lars S. Imsland


Ass. Prof. Ekaterina Kim


Prof. Trygve Kristiansen

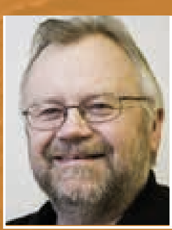

Prof. Alexis Konstantinos


Prof. Pål Lader


Ass. Prof. Anastasios Lekkas


Prof. Martin Ludvigsen


Prof. Nguyen Trong Dong


Prof. Yngvar Olsen


Prof. Eilif Pedersen


Prof. Slobodan Petrovic


Ass. Prof. Børge Rokseth


Prof. Roger Skjetne


Ass. Prof. Annette Stahl


Prof. Oleksandr Tymokha


Prof. Ingrid B. Utne


Prof. Houxiang Zhang


Ass. Prof. Yu Zhaolong

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:

- Thor I. Fossen, Co-director
- Renate Karoliussen, Senior Executive Officer
- Live Oftedahl, Senior Executive Officer
- Knut Reklev, Senior Engineer
- Eirik S. Sivertsen, Project Manager

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
- Equinor
- SINTEF Digital
- SINTEF Ocean
- 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 Arcak, 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 2022

•	7	Keypersons
•	13	Adjunct prof/associated prof
•	31	Affiliated scientists
•	2	Scientific advisers
•	6	postdoc/researchers
•	15	Affiliated postdocs/resarchers
•	24	PhD Candidates
•	105	Affiliated PhD candidates
•	6	Administrative staff
•	2	Management
•	2	Technical staff
•	3	graduated PhD candidates financed by NTNU AMOS
•	9	graduated PhD candidates associated to NTNU AMOS

Revenues (NOK 1000)

Actual:	
• Income	38 713
• Costs	44 254
• Year end allocation	- 5 541
In Kind:	
• Income	14 377
• Costs	14 377
Total:	
• Income	53 090
• Costs	58 631
• Year end allocation	- 5 541
• AMOS 1 end allocation	5 497

Publications

•	81	Refereed journal articles
•	78	Refereed conference papers
•	3	Book chapters
•	9	Keynote lectures

Observation pyramid trial Kongsfjorden, Svalbard May 22: Emily Venables (right) and Tomasz Piotr Kopec from the University of Tromsø participated by operating an unmanned surface vehicle (USV) which did CTD-scanning.

© Live Oftedahl

MAIN RESEARCH AREAS AND PROJECTS

Pål Kvaløy, technical staff in the UAV-Lab during observation pyramid trial in Kongsfjorden May 22.

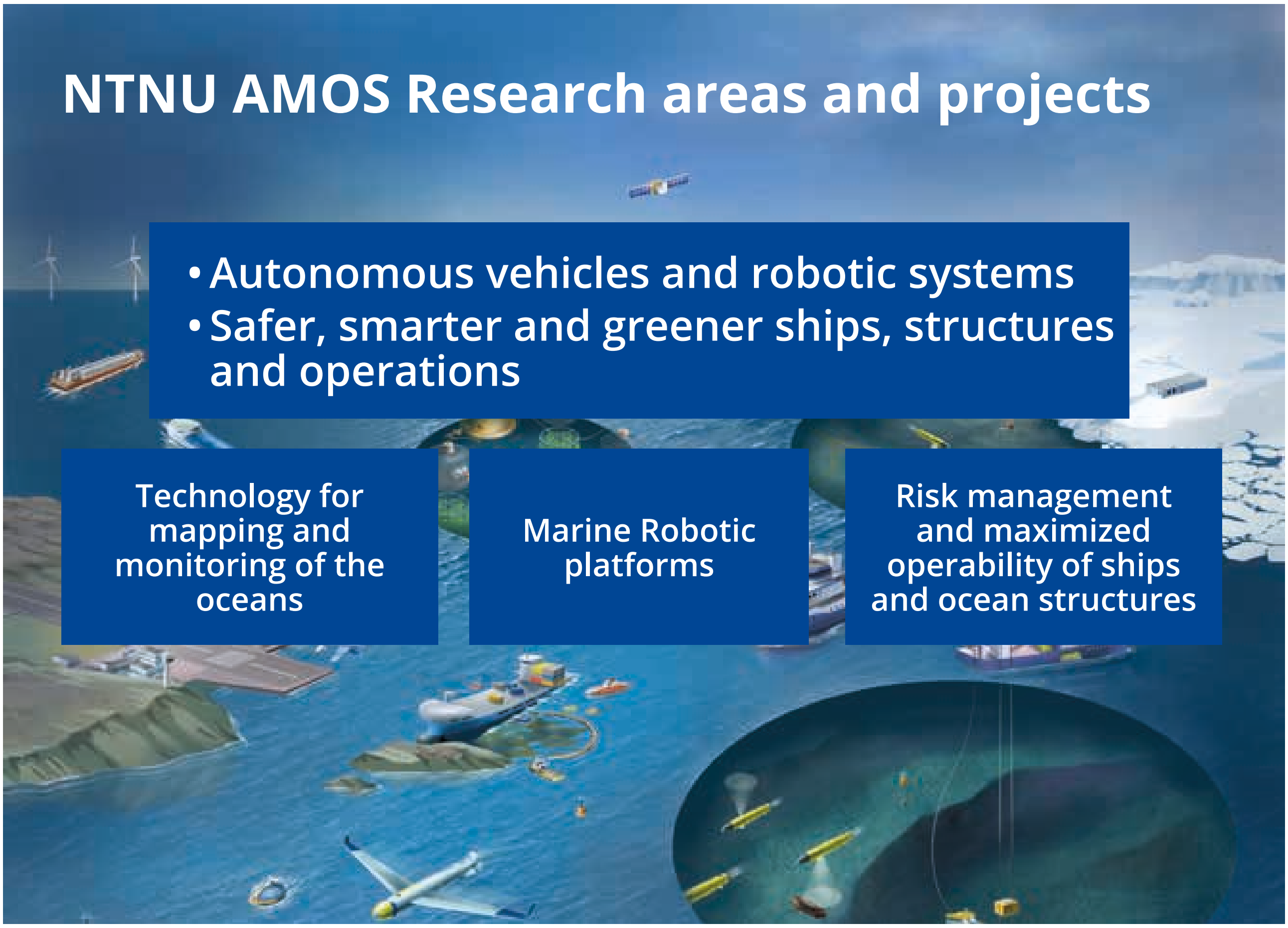
Photo: Asgeir J. Sørensen

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.



ASGEIR J. SØRENSEN
THE WIZARD OF AMOS

By Live Oftedahl

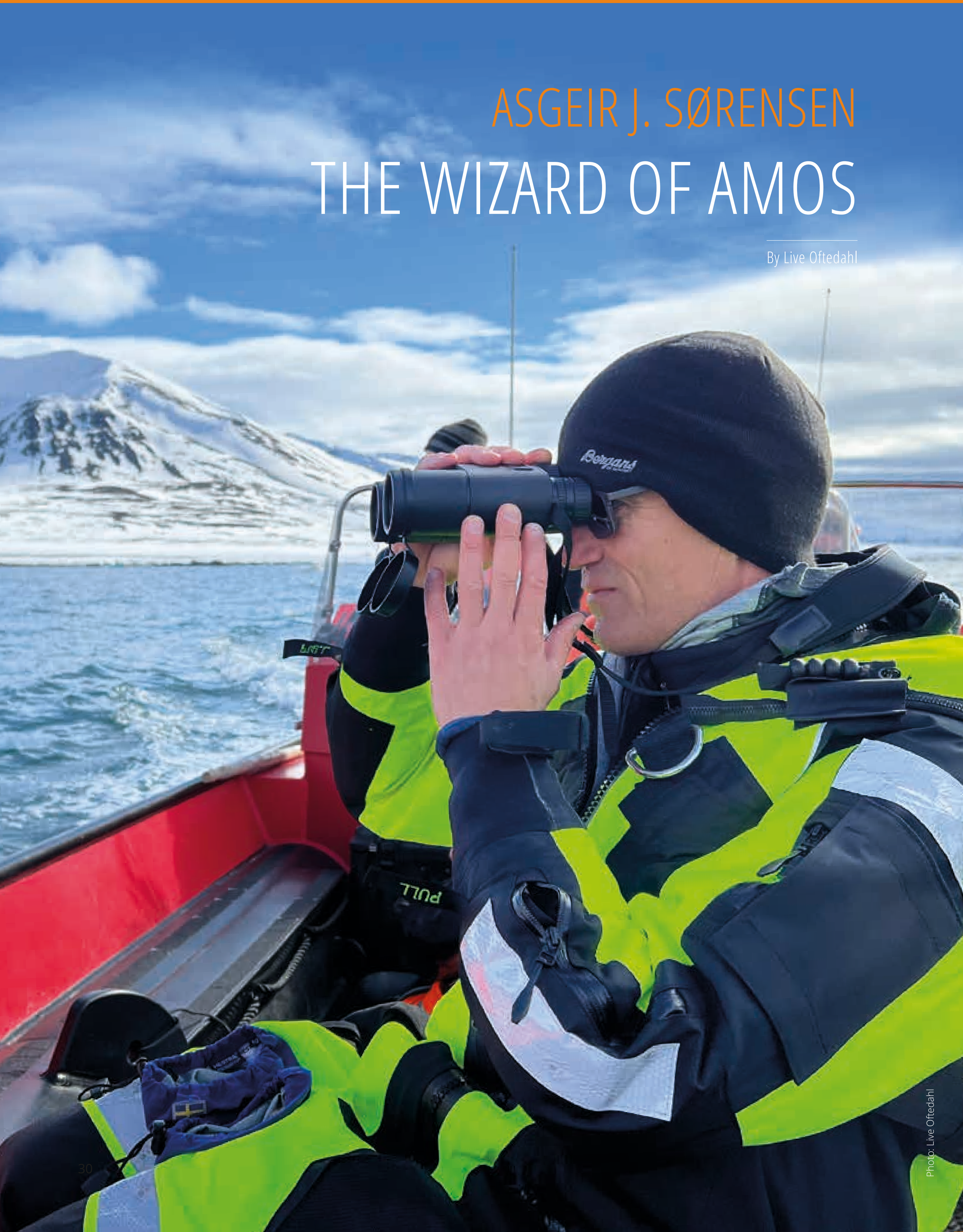


Photo: Live Oftedahl

He could have earned four times more in industry instead of being a professor. But, according to Asgeir J. Sørensen, life is not only about money or happiness. It is about going as far as you can in making a positive impact in this world.

"None of the key researchers in AMOS are necessarily the happiest nor most comfortable. We always have this restlessness that keeps you in motion. NTNU AMOS is most of all about teamwork creating a culture for excellent performance," Asgeir J. Sørensen says.

He has the air of a superhero. If he threw away the glasses and ripped of his shirt, it would most probably reveal a blue tight suit with a red A in front, and nobody would be amazed if he flew away in this suit.

A Centre of Excellence (CoE) gives a kind of superpower.

His superpower is spreading enthusiasm and joy in marine technological research and chasing impact. Together with his AMOS team, he has led hundreds of PhD- and master students to finish their degrees and have strong visions and ambitions on how far the research can go.

If someone is in doubt in as to what they are doing or need a pep-talk to continue the hardships of their research or their studies, send them to Asgeir!

The lack of Norwegian politicians' ambitions when it comes to financing basic engineering research is this superpower's kryptonite.

But let's not get all too dark here.

Happiness is still a part of life. And when are those moments of happiness in a director of a CoE, a lecturer and professors' life? According to Asgeir J. Sørensen, one of the most memorable moments, and a moment of bliss during these years of running NTNU AMOS, was in Svalbard a few years ago.

Strong bond

The sun was shining, and the fieldwork had gone well. He was standing on an ice-flake in Kobbefjorden with one of his former PhD students, Øyvind Ødegård, now a researcher in marine archeology. Geir Johnsen, key researcher in AMOS and professor in marine biology, took their photo.

At the top of the world, where the ice meets the sea, doing fieldwork, is where you find happiness and a bigger skyline.

Fun science

It is important to have fun doing research. The enthusiasm in doing this research reaches far beyond the footprints. It provides knowledge to a larger audience than merely the research world, it recruits students and certainly gives purpose, and leads to new understanding, ways of working and innovation.

The respect between the key researchers, and his ability to see their imprints and capacities, has also been a factor in the collaboration climate in AMOS.

"Geir is vibrantly full of positive energy, and has the deep understanding of how ecosystems, nature, technology, and humans are connected. Listen to Geir! He uses technology to get to remote areas that before were inaccessible, making us able to answer the bigger questions about life on earth. Marilena understands the significance of fundamentals in hydrodynamic loads and structural responses but has also moved towards bio-cyber-hydrodynamics. She is brilliant. Jørgen's force is understanding what you do when everything goes to hell – if so, collisions, grounding and so one. Kristin is the queen of basic theory in cybernetics, equations that have led to groundbreaking new technology. She is a true role model for all of us believing in long-term high-quality research, finally bridging theory and practice. Tor Arne has an astonishing width – from the deepest theories to entrepreneurship, and he operates in the air, on land, in space, and the ocean. Thor Inge is the artist. He is extremely focused and has an extreme capacity. I am just orchestrating all these extraordinary researchers; I am playing conductor doing my best not to mess up."

> We wanted to take chances and push the limits, be groundbreaking, cross barriers and go to places we have never been before, into the unknown, and foster innovations beyond imagination.

Asgeir with collegaue Øyvind Ødegård on an ice floe in Kobbefjorden, Danskøya, Spitsbergen, June 2019.

20 years of excellence

Asgeir J. Sørensen has spent two decades as a researcher at a Centre of Excellence (CoE) and had hoped to retire after the third decade of being part of a CoE, with Geir Johnsen and Jørgen Berge as the new director team. The Norwegian Research Council thought otherwise.

Before he took his PhD-degree, he took a master in both marine technology and engineering cybernetics, and worked for eight years in ABB. Their financial muscles in research are two or three times bigger than the Norwegian Research Council's muscles, but of course mostly directed towards applied research. The world was the playground during the years in ABB, being formative for the international mindset and ambitions driving him.

In his second master and PhD he met Kristin Y. Pettersen and Thor I. Fossen, who later became two of the key researchers in AMOS.

In the first steps as a researcher in the previous Centre of Excellence – Centre for Ships and Ocean Structures (CeSOS), he was led by Torgeir Moan and Odd Faltinsen; two of the most renowned researchers in marine technology, Moan in the field of marine structures and Faltinsen in the field of hydrodynamics, Thor I. Fossen was leading the control group at CeSOS.

When CeSOS' time was up, Sørensen, Fossen, and their team of key scientists, succeeded in obtaining funding from the Norwegian Research Council for a new CoE: NTNU AMOS, so the work could continue in a new direction. After a few years, AMOS included Geir Johnsen, and the purpose of saving the marine environment with generous, excellent and courageous research was set.

"CeSOS was a success, but we had to move on. It is the excellent researchers that should set the new directions in working methodology as well. In AMOS, we also wanted to have the innovation element more predominantly, to do systematic development to get new results, and don't see basic, slow science as an opposition to disruptive innovation, to be in a flow outside of the comfort zone. We wanted to take chances and push the limits, be groundbreaking, cross barriers and go to places we have never been before, into the unknown. It is a fact that enabling technology is one of the key elements together with the people, market understanding and financial capabilities that are fostering innovations beyond imagination."

The disappointment

They really wanted to continue this work in a third Centre of Excellence, but only got to the second round in the "competition". If they did not get it this time, they would be too old for the next round, which will be in five years. But with the rejection from the part of NFR, a CoE in marine technology, control engineering and marine science, seems to be a closed chapter for now, and the work done so far has to continue with other types of resources.

This is of course a huge disappointment.

The license to create, and the financial muscles of a CoE, would have given them the opportunity to continue developing the observation pyramid, which had the first real trial last spring - among many other things.

"One of the stories in the Old Testament that really made an impression on me when I was younger, was the story about

Joseph and his brothers. He was his father's favourite son, and his brothers were jealous. They sold him as a slave, but he ended up being the advisor of the pharaoh. A life of ups and downs! The point is, when they had experienced seven good years, and built up a lot of values in the old Egypt, they experienced seven bad years. Joseph made the pharaoh prepare for this. And he listened. I am afraid that today's pharaohs don't listen. They think of this year's harvest, not the next seven years. We must continue using knowledge and research for value creation, and position Norway for the changes that soon will come after years of super profitable offshore oil and gas production."

He realizes that it is a form of vanity, this urges to make a difference.

"In Norway we have built up an enormous amount of welfare, and I got the trust to lead one of Norway's biggest investments in technology. I am grateful for the trust and the power it gave. More than ever, we must position Norway to have new types of knowledge-based workplaces, sustainable workplaces in the biggest shift we have faced in many, many years. I am worried about Norway's role. We should lead the way in innovation processes, both incrementally and disruptively."

The next 10 years

Instead of flying high, he prefers cross-country skiing and mountain biking.

Every year, he goes with one or two of his grown-up kids to the cross-country ski race Birkebeinerrennet. Last year, his wife also joined, a 54-kilometer race from Rena to Lillehammer, over the mountains from Østerdalen to Gudbrandsdalen, two valleys in the middle of Norway. According to Norwegian history, the race is a kind of a memoir of how two of the Birkebeiners' (Birchbarkleggers) in the Viking age had to flee with the newly born king's son, Håkon Håkonsson, to escape the enemy.

According to the Canadian Birkie, a Birkebeiner has come to mean a person strong in adversity, never daunted by trial and hardships.

As a former top athlete, Asgeir J. Sørensen is trained to not look back in regret or anger, but always to evolve and look ahead. This will be his strategy after the NTNU AMOS adventure chapter closes as well.

"The next 10 years will be about saving the ocean, the health of the ocean, the climate, and the environment. We have pushed the earths limits further than we should, the margins are smaller now."

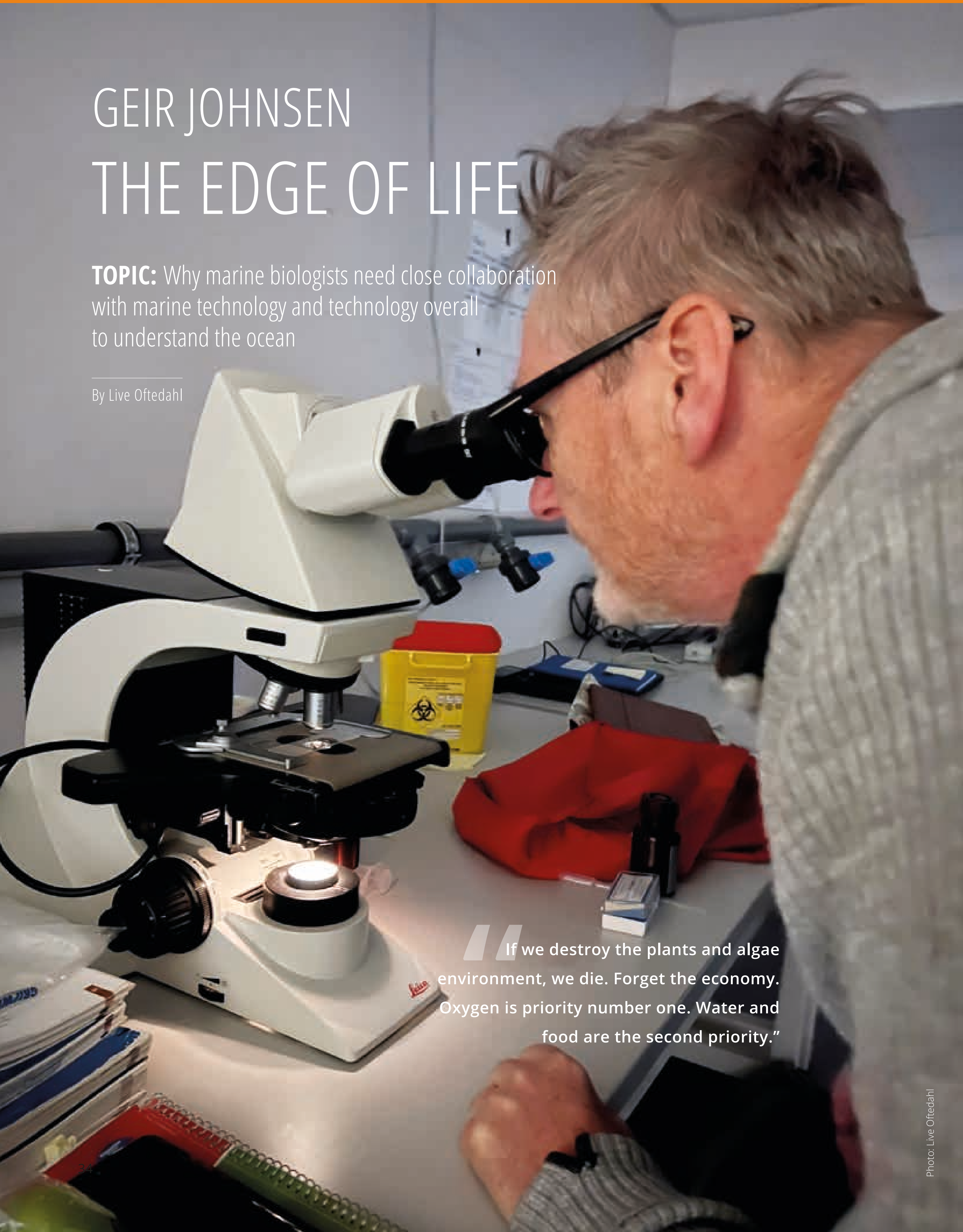

"The next 10 years will be about saving the ocean, the health of the ocean, the climate, and the environment. We have pushed the earths limits further than we should, the margins are smaller now."

Photo: Live Oftedahl

GEIR JOHNSEN
THE EDGE OF LIFE

TOPIC: Why marine biologists need close collaboration with marine technology and technology overall to understand the ocean

By Live Oftedahl



"If we destroy the plants and algae environment, we die. Forget the economy. Oxygen is priority number one. Water and food are the second priority."

Photo: Live Oftedahl

2022 has been an annus horribilis. NTNU AMOS' own ringed seal, Geir Johnsen, almost died due to acute necrotizing pancreatitis.

He was hospitalized 10 weeks in the autumn, with 5% functional kidneys, the lungs 80% full of water, multiorgan failure, more than 20 kilos lost, and then seven operations after two months when his condition became more stable. He escaped death's backyard, and got out of the hospital just in time to celebrate Christmas at home with his lifetime wife Hilde, and his two grown-up sons. This is possibly because nothing can put him out of the mood for a good laugh, being curious about new experiences – including what suddenly happened to his body.

"I'm not constructed with fear, I just accepted the situation and did the best out of it. It is a mindset. I have never been ill or away from work since 1989, so this was totally new. I learned a lot, and I understand more now."

Now he is back to his own energetic and vibrant self, with a constant need for conversations and new adventures. He just came back from a round trip in the US, including Hawaii, Florida, Boston and Connecticut, where some of the key AMOS researchers are establishing a network to continue to work on the observation pyramid and big data.

"We have integrated thoughts of providing detailed information of organisms at the surface, water column and seafloor in the Arctic, Mid-Norway, the USA, Australia and other regions. During meetings in the USA, we coordinated a diverse use of the operation pyramid to gain knowledge of ecosystem dynamics, and to map and monitor the biodiversity and health state of harmful algal blooms and tropical coral reefs."

The need for oxygen

Like Johnsen's lungs were filled with water, we fear a catastrophe that will push the Earth towards the apocalypse – a life-threatening lack of oxygen - if the ecosystem functionality gets totally out of balance due to human degradation.

"We are a part of nature, and we take for granted that there is enough oxygen, but all the oxygen is produced by plants and algae. If we destroy their environment, we die. Forget the economy. Oxygen is priority number one. Water and food are the second priority."

In Johnsen's work as a marine biologist, one of the domains in NTNU AMOS has been to work on the planet's marine "edges", where nobody has explored before – under the ice of the North Pole and in the deep. In places where mankind, until a few years ago, thought where not very crowded with species in the wintertime, marine biologists have discovered more life than they could imagine. Life that is essential to the big cycles, such as oxygen production and carbon dioxide uptake during photosynthesis from marine algae, providing food for the world's food web.

"As a part of AMOS, our master students, PhDs and post docs have had the possibility to go and examine habitats where we have never been before, in remote and extreme areas. These places had been impossible to reach without the collaboration with marine technologists and engineering cybernetic technologists. We have obtained information that is totally new to science at nighttime, in the polar night, under the sea-ice, and at greater depths (4200 m)."

With the mobile platforms with sensors, they got to places where humans have never been before.

"We have shown habitats filled with life during the Polar Night and at greater depths where the common belief was that there is 'no life'. We have also done several new discoveries that 'Light is the Cue of Life' everywhere in the oceans – the major 'sensor' for this is a colour-sensitive photoreceptor in all living organisms – from bacteria to blue whales - including humans."

You never swim alone

"When you jump into the ocean, imagine the "Matrix". There are billions of viruses and bacteria in one litre of water; there are millions of phytoplankton cells and thousands of zooplankton. It is not just water. Water is just a medium. You are swimming in a biochemical soup of organisms. Imagine if they all could talk!"

He talks about bioluminescence, like swimming in a starlit sky.

"It is so beautiful, and all of this is connected. It is fantastic beyond our imagination."

As a marine biologist for 34 years, with a biology course about light climate and primary productivity in the Arctic every year since 1996 (except for two Covid years), he has seen the changes in the Artic Sea with his own eyes. The sea-ice diminishing drastically, the introduction to new species in the Arctic that used to live further south, far less polar bears, ringed seals and other typical Arctic species.

He still chooses to be an optimist.

"When we discovered there were holes in the ozone layer in early 1990´s, we changed our ways to avoid being 'fried from UV radiation. Today the holes are gone. There is still hope, but we must react quickly and not work against the environment. If you destroy habitats for species, you destroy the climate and water balance."

He continues:

"The tropical rain forests are storage places for water, they are rain generators. You can't start with the climate. Yes, we burn fossil fuels and greenhouse gases, but we also destroy habitats. If the rainforests are cut down, they become deserts instead and the surface will absorb heat from the sun. People, and especially politicians, need to understand this. My hope is that a lot of young people seem to get 'the grand environmental overview', that we are in a hurry."

Young understanding

He is amazed by how fast nature adapts to changes.

"During Covid there were a lot more migratory bird activity in mid Norway. Humans influences the environment a lot more than we are aware of. Nature responds faster than we think. One example is the Great Barrier Reef where 60 percent of the corals has bleached and died the last decade. Now it seems to come back to life again faster than we thought. We don't know why. The nature is extremely complex; therefore, we need biologists, chemists, mathematicians, and technologists to understand."

So, what is the most important?

"We must take care of the ecosystems. We must see the big picture, like young people do. I am extremely happy that the technologists in AMOS see this. They are a part of making tools to see, identify, map and monitor. What do we have? How can we take care of this in the best possible way? The observation pyramid can make us do wise choices. This is highly motivating."

Nansen ancestor

Geir Johnsen studied biology at the University of Trondheim – now NTNU, and finished his MSc in 1989 and PhD in 1994. His mentor and supervisor, Egil Sakshaug, had Trygve Braarud as his supervisor and mentor. Braarud was again a student of Haaken H. Gran, and they had several joint new phytoplankton species publications. Gran worked with Johan Hjort, the father of modern fisheries science, and Fridtjof Nansen, the famous scientist, explorer, diplomat and humanitarian. As a professor and researcher, you have "kids" in more than biological ways, and direct research ancestors inherit a certain way of understanding and working in their field.

"Egil is proud of this heritage. He was a strict and solid as a supervisor, no shortcuts. He advised me to be an active part of the world, not passive, and to contribute without being asked. He said he could open doors for me, and it was my choice if I wanted to enter. Often, I did. These doors gave me opportunities that have been very important, both professionally and as a human being. I am forever thankful for Egil's advice."

During the last year of his PhD, Sakshaug advised him to go to the University of California, Santa Barbara to work under Barbara Prezelin, which he did. Johnsen describes her as a fantastic wise lady in every way, both professionally and as a person.

She picked six PhD students to work in her lab.

"She used a long time to select us because she wanted us to fit together workwise. The six of us are still friends for life, and we work all over the world, in the US, in Australia and in Europe."

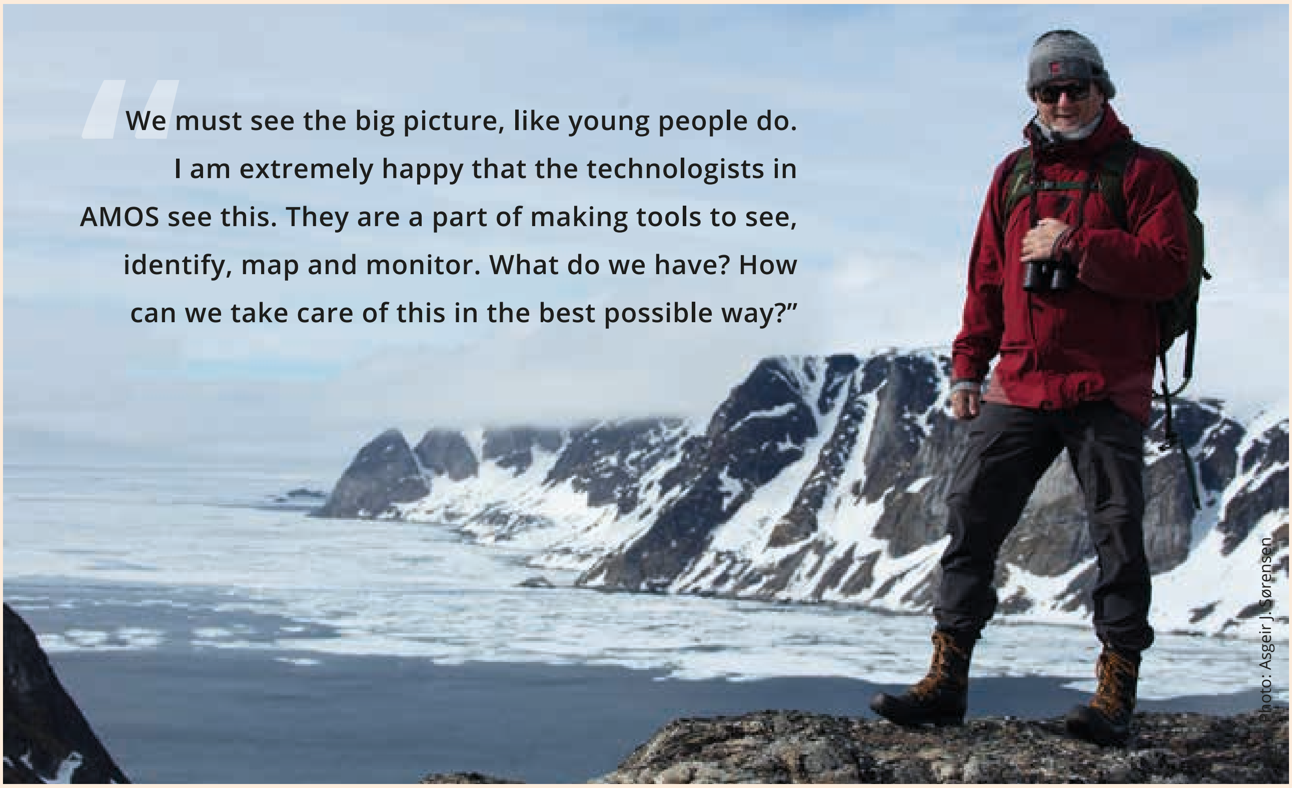
From affiliated to key scientist

Geir Johnsen was an affiliated scientist in AMOS from the beginning, but after his mid-term evaluation, Asgeir J. Sørensen, director of NTNU AMOS, asked him to become a key scientist. Johnsen's passion for using marine technology in marine biological research

> **"As a part of AMOS our master students, PhDs and post docs have had the possibility to go and examine habitats where we have never been before, in remote and extreme areas. We have obtained information that is totally new to science at nighttime, in the polar night, under the sea-ice, and at greater depths."**

Geir with MSc student Malin Nevstad, now PhD candidate and Fulbright student Amy Li in Karihavet, Nordmøre using ROV for mapping of seafloor.

Photo: Geir Johnsen selfie with students



Geir Johnsen in Danskegattet.

brought them together. When Johnsen was included as a key scientist, one of the main purposes with AMOS was reinforced: We need to know more about what is going on in the oceans and lakes.

Five years ago, they increased the activity using underwater hyperspectral imaging (UHI) in extreme environments (cold, deep and icy) to identify, map and monitor bio-geo-chemical objects of interest, to help provide information for knowledge, education and nature management. They started to use UHI on mid- to-large size remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs) and autonomous surface vehicle (ASVs). Johnsen started the NTNU spin-off company Ecotone with Sørensen to produce UHI, which is patented in the USA, Canada and Europe.

"From 2020, we are using smaller platforms to lower the threshold of use. We have mapped the seafloor with hyperspectral cameras from 0-4200 m depth at different areas in the world, such as under the sea-ice of the North Pole, in Norway and Peru."

What has changed

The methods have developed, the proof-of-concept, and pilot studies have been converted into further operative mapping and monitoring through infrastructure programs such as the SeaBee program.

"We have lowered the user threshold. This technology can also be used by different end-users like biologists, archaeologists and chemists. Without the interdisciplinary team in AMOS – none of this could have been done. We have had in-house expertise in building buoys, data transfer - broad band radios, sensors - cameras with fish lenses as light sensors, underwater hyperspectral imaging (UHI) and PlanktonScope, SilCam, also used in observatories and different mobile platforms."

The biggest inspiration has been the teamwork, in which different skills and personalities have pursued common goals.

"We have worked so closely together in the field for extended periods that we have gotten this 'Fellowship of the Ring' feeling. And it has been highly motivating to be with students doing research to provide better nature understanding and management."

The last five years have shown that we can go to places where humans did not have access before.

"We can obtain information that is important for knowledge, education and for decision-makers, and can also do risk assessments. The threshold to provide robots and sensors is lowered – with less need for large vessels, big teams and heavy equipment. Everything is faster-cheaper-smaller-more handy- and easier to use for marine scientists."

TOR ARNE JOHANSEN
CROSS-DISCIPLINARY COLLABORATION CATALYST

TOPIC: Reflections about interdisciplinary team spirit from down under.

The AMOS legacy: The UAV lab. SeaBee. SmallSatLab. HYPSO. The observation pyramid. UBIQ Aerospace. ScoutDI. Zeabuz. SentiSystems.

Tor Arne Johansen, professor at the Department of Engineering Cybernetics, is hunting high and low for research impact, and sees AMOS as a key to the disruptive development his field has gone through during the last decade. This has been accomplished from research satellites, via flying drones, to autonomous surface vessels being independently operated, to a coordinated system-of-systems.

“NTNU AMOS has been a catalyst for cross-disciplinary collaboration, and given us the long-term support needed to build an advanced research infrastructure” he says.

This has led to brand new research directions and laboratories at NTNU. But where did it all start?

Identifying research gaps of national importance

The Unmanned Aerial Vehicle (UAV) Laboratory was established immediately after the start of AMOS. Research on UAVs was emerging at the time as a hot international research topic.

“We created a research strategy focused on the gaps that were identified to be of national importance.”

These included technology for the operation of UAVs from ships and offshore platforms, how to deal with adverse arctic weather such as icing, and how to reduce cost and complexity by making UAVs smart and autonomous.

“Moreover, our research strategy focused on applications such as maritime surveillance, inspection of ships and offshore assets, and mapping of the marine environment.”

Research breakthroughs

Through these applications, AMOS exploited cross-disciplinary collaborations with researchers in marine biology, in addition to stakeholders in the offshore and maritime industries, as well as security.

“Breakthroughs were made in several areas such as landing and recovery systems for confined spaces, low-cost hyperspectral imaging systems, localization without satellite navigation, inflight icing protection systems and machine vision systems for ocean surface surveillance.”

These developments were timely and well aligned with the increasing interest in drones in the industry and government, as well as the democratization of the airspace that is now increasingly accepting of UAVs co-existing with traditional aircrafts.

“This AMOS legacy is now an essential part of the NIVA-lead Norwegian Infrastructure for Drone-based Research, Mapping and Monitoring in the Coastal Zone (SeaBee).”

Spin offs

Moreover, three spin off companies were a direct result of AMOS research on UAVs: UBIQ Aerospace, ScoutDI and SentiSystems.

“The UAV-lab at NTNU has provided a unique and professional field test capability with advanced operations beyond-line-of-sight, that has been impossible to do at most other universities in the world.”

But with this, why not go even further?

It was recognized from the start that satellites are essential components in autonomous systems, not only for data communication and satellite navigation in autonomous robots, but also as complementary platforms for earth observation.

“Half-way into AMOS, we concluded that although the global earth observation satellites from NASA and ESA deliver a steady stream of high-quality images, there were some gaps.”

Pursuing new opportunities

He sums up the gaps as follows:

- low spectral and spatial resolution makes it difficult to study, e.g., biodiversity;
- low temporal resolution with infrequent revisit makes it hard to track dynamic phenomena such as phytoplankton blooms; and
- the delivery of data with significant delays from capture makes them hard to use in real-time decision and control loops for adaptive sampling.

"The idea of an agile small satellite with hyperspectral imaging, intelligent onboard data processing and a dedicated radio communication solution for autonomous systems then came up as a way to bridge these gaps."

It was then decided to pursue this opportunity, which was not envisioned at all in the original AMOS plans.

"Establishing NTNU's SmallSatLab and developing the HYPSO-1 and HYPSO-2 satellites suddenly became a large part of AMOS, and close collaborations with the Department of Electronic Systems, Professor Fernando Aguado at the University of Vigo, and others, were established to facilitate this development."

The unique hyperspectral imaging payload of HYPSO-1 was developed and built in-house, based on a design by Professor Fred Sigernes at the University Centre at Svalbard.

"HYPSO-1 now delivers hyperspectral images with the expected quality, and is by now the main data source for a wide range of projects both inside and outside of AMOS."

Coordinating system-of-systems

Consequently, NTNU is now providing data for scientific projects on oceanography and marine biology, and continue to develop remote sensing algorithms and systems for fresh-water quality monitoring, and harmful algal bloom warning for the aquaculture industry.

Establishing the SmallSatLab at NTNU was supported by NTNU at all levels, and by now is a research infrastructure independent of AMOS. NTNU is exploiting this research success through a stronger educational profile on space systems.

"It was soon recognized that NTNU's field robotic capabilities (in air, water surface and underwater), as well as small satellites and conventional assets such as buoys and research vessels, could be operated together and coordinated as one system-of-systems."

Building upon the visions of Professor Kanna Rajan that brought to AMOS his experience from NASA and MBARI, this led to the realization of the concept of the operational pyramid for ocean monitoring. It realizes AMOS's high level vision of disrupting how to collect ocean data with an order of magnitude of lower costs, and an order of magnitude of a higher impact by using autonomous systems.

"The idea is to be able to 'zoom in' from wide-area low-resolution remote sensing from space, via low-altitude UAVs under the clouds that gives medium-resolution remote sensing, to marine robots providing high-resolution in-situ data from the water column."

Implementation of the observation pyramid

In this way, the less mobile but more accurate in-situ robotic agents can be guided in real time to collect the most important data, which again can be used in real time to enhance the data products delivered by UAVs and satellites.

"This concept could not have been developed and implemented successfully without the deep cross-disciplinary collaboration among scientists in chemistry, biology and physics, and the engineering disciplines such as automatic control, electronics and marine technology, which AMOS facilitated."

The deep collaboration with Professor João Sousa's lab at the University of Porto has enabled AMOS to build upon their software toolchain and extensive competence in designing and operating such systems-of-systems.

"I believe one of the prime outcomes of AMOS is the demonstration of the observation pyramid in several science missions. It is exciting to see that the AMOS legacy is already being taken further in several new projects and missions, also outside NTNU," says Tor Arne Johansen.

By Live Oftedahl

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

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

Research activities:

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

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

The first year in the life of HYPSO-1

This note is based on **P1-R1**.

The HYPSO-1 satellite is a 6U CubeSat that was launched on January 13, 2022, to image ocean color for marine research using hyperspectral imaging.

CubeSats are a type of miniaturized satellite for space research. These satellites are comprised of multiples of 10x10x10 cm (about the length of the long edge of a credit card) cubic units known as U´s, and are often used for educational and research purposes. As the satellites are small compared to conventional satellite systems, they can be launched as secondary payloads on rockets, making them a cost-effective alternative. In addition, the standardization of components makes more vendors of both rocket launchers and various satellite components available. This standardization makes satellite research accessible to companies and institutions.

On the other hand, hyperspectral imaging is an advanced and emerging technology that makes it possible to capture and analyze the light reflected from the Earth´s surface across a wide range of distinct wavelengths of the electromagnetic spectrum. These measurements allow for identifying specific materials and chemicals, making it useful for applications such as ocean color and other types of environmental monitoring.

During the first year of operations, the HYPSO-1 satellites have been all over the world quite literarily, and this deserves review. Through tenacious efforts from the students and employees at the NTNU SmallSat Lab during 2022, it came together. At the beginning of January, just after the launch, much was still unknown. Luckily the HYPSO-1 satellite announced itself to the

Figure 1 *shows a screenshot of the webapp dubbed SOUIES for Satellite User Interface Enhancement Suite. This is a tool we use to help simplify the planning of different captures, and communication between the ground and the satellite.*

__Figure 2__ shows selected RGB renders of some of the captures that HYPSO-1 has acquired during its first year. The different images show a wide range of targets that HYPSO-1 can focus on.

world just the day after, and the commissioning could commence. This initial period passed without any reason for concern, and the time to turn on the hyperspectral payload came at the end of January. The first attempt at operating the payload was successful, and the team rejoiced. Suddenly, the relevancy of operations planning became apparent. Even though HYPSO-1 is the first satellite launched by NTNU, the team was able to utilize the payload soon after launch. The first campaign came in Frohavet in April. Subsequently, HYPSO-1 focused on Svalbard in May, capturing up to four images daily at good elevation angles. In addition, the HYPSO-1 satellite, with its hyperspectral imager, has been used to monitor other areas of environmental interest, such as the Florida areas stricken by Hurricane Ian, as well as various forest fires and volcanic eruptions. As time progressed, more tools and routines were developed, with 2022 seeing the dawn of an easy-to-use satellite planner dubbed SOUIES (Satellite Operation User Interface Enhancement Suite). This tool significantly simplified the utilization of the payload, and helped plan other activities, such as ground station contact for multiple other satellites. With significant momentum, the development of all activities related to HYPSO-1 is ushering forward new and novel approaches to the Earth Observation of targeted areas. This development and work are effectively demonstrating a disruptive approach to the environmental management of marine interests.

HYPSO-1 represents a highly capable CubeSat, which allows agile planning and captures with low revisit time. The in-orbit performance of the hyperspectral instrument is characterized, including the usable spectral range of 430 nm to 800 nm over 120 bands. Having this spectral range means that the HYPSO-1 can deliver similar data products as existing satellite infrastructure, such as the Sentinels and PRISMA, at a higher spectral resolution and at a fraction of the cost. The native spatial resolvability, before any processing, is already at least 142 meters (about half the height of the Empire State Building) across-track. The swath width of the hyperspectral imager is 40 km for nominal captures, and can easily be extended to 70 km (about half the distance from Washington, D.C. to New York City) for specific targets if desired. The spectral resolution is estimated to be approximately 5 nm across the valid spectral range, which makes HYPSO-1 able to acquire data at the frontiers of ocean color research. The high spectral resolution with a Signal-to-Noise Ratio (SNR) was measured to be greater than 300 at instrumental spectrum

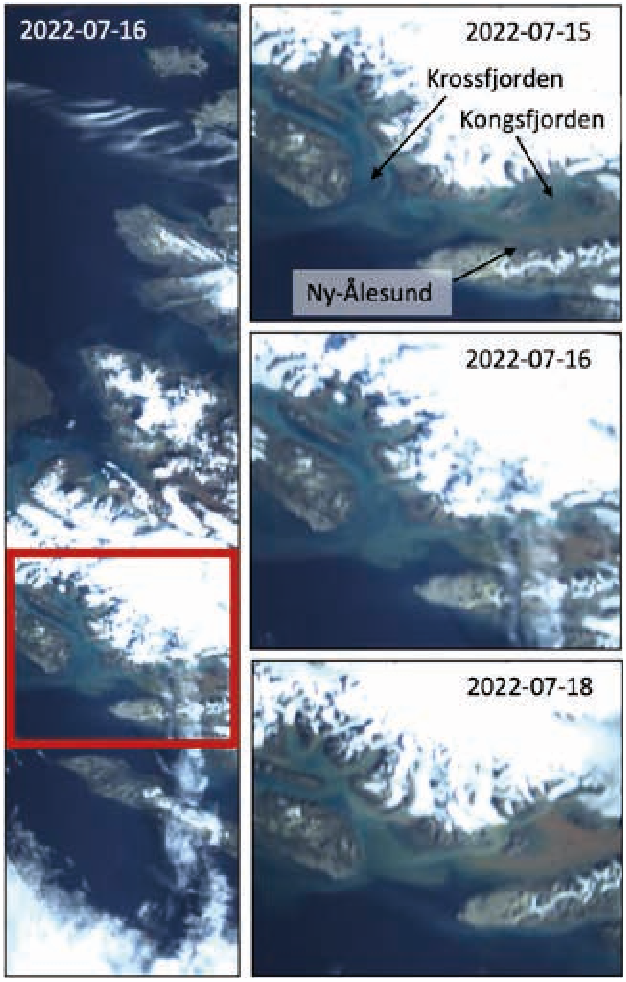
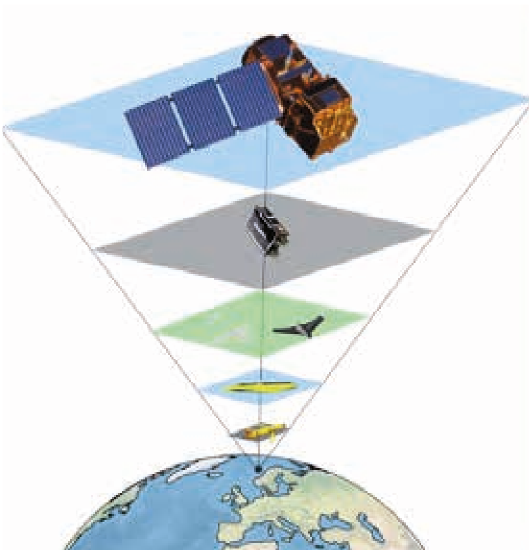


***Figure 3:** A series of captures over the fjords near Ny-Ålesund in Svalbard, showing the capacity of capturing with a high revisit time to monitor changes*

ranges for ocean color research. During its first year, the HYPSO-1 satellite captured nearly 1,000 unique data sets of various parts of the Earth. During nominal operations, HYPSO-1 has captured up to six amazing images daily, and more if the data latency could



Other Remote Sensing Satellites Optical remote sensing and more Area: < ~300 km×300 km Speed: Dependent on orbit
LEO Small Satellites Optical remote sensing Area: <100 km×100 km Speed: 7.7 km/s
Unmanned Aerial Vehicle (UAV) Optical remote sensing Area: <50 km×50 km Speed: 2-50 m/s
Autonomous Surface Vehicle (ASV) In-situ measurements Area: <10 km×10 km Speed: < 5 m/s
Autonomous Underwater Vehicle (AUV) In-situ measurements Area: <5 km×5 km Speed: 2 m/s

Figure 4: *The HYPSO-1 plays a crucial role in a bigger vision at SFF AMOS. We are working to bring together an array of multi-modal measurements, both in time, coverage and type, from various autonomous assets, including everything from underwater vehicles to existing satellite infrastructure, to create a truly comprehensive picture.*

be ignored. This achievement is made possible by the generous offer by KSAT for the University CubeSats of Norway. Using hyperspectral remote sensing, scientists at SFF AMOS can observe dynamic oceanographic events, and acquire new and valuable insight for marine management, aquaculture, and water quality monitoring.

The development of a second hyperspectral CubeSat, the HYPSO-2, is well underway. This satellite will benefit extensively from the experiences gained through operating HYPSO-1. The next generation will be equipped with a more refined hyperspectral imager and an extensive improvement to the communication subsystems. These improvements will allow for the collection of up to 10x as much data, as well as the possibility to do radio interference measurements and communicate with the other autonomous assets in the observational pyramid.

Hyperspectral remote sensing of ocean color and water quality is a valuable tool for understanding the health and productivity of our waters. Using satellites, such as the HYPSO CubeSats, allows us to gather vital information from space, helping us to better understand and protect our waters, an essential resource. We are excited to see what the future will bring!

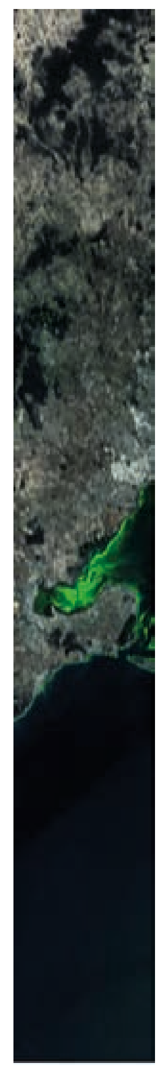


Figure 5 (left) *shows an image from HYPSO-1 near Melbourne, Australia on the 6th of January 2023. The colors that we perceive as red, green and blue have been used to make a regular image composite.*

Figure 6 (right) *shows an overlay of the same figure where the water pixels have been filtered and analyzed. The pixels correlated with an elevated level of chlorophyll are colored green with an intensity proportional to the estimated intensity*

Mission Mjøsa

The goal of Mission Mjøsa is to contribute to value creation through a sustainable use of Mjøsa's resources and ecosystem services, while at the same time maintaining the ecosystem's structure, functions, productivity, socially critical infrastructure and biological diversity. Mission Mjøsa will therefore be a tool for both facilitating value creation, water quality and food safety, and for maintaining the environmental values in Mjøsa.

By using a mission approach to the project, we believe we can trigger synergies that would not be possible in other ways. As a fundament in all projects connected to Mission Mjøsa, interdisciplinarity, sustainability and synergies will be made visible.

Mission Mjøsa will also be more than a research program. By involving municipalities, industry, regional authorities and national agencies, we also will be looking for better planning, management innovations and new opportunities for industry, inside a frame of sustainable management.

Background

Lake Mjøsa has been an important resource for the people living in the area for thousands of years. It has been a source for drinking water, and the water has been used for agriculture, industry and hydro power. The lake has a rich and diverse biology, and is used for leisure activities and fishing. But it also has been used as for transport – both with boats and ice roads during winter –, with the dumping of sewage and the dumping of ammunition from the ammunition factory. Runoff from agriculture creates problems, and time after time it results in algae blooms in the lake. High concentrations of mercury and PCB have resulted in restrictions of the consumption of fish from Mjøsa.

In the 1960s, Mjøsa had a very bad environmental development. The danger of reaching a critical tipping point was met with a large rescue operation called "Mjøs-aksjonen". It was a costly operation, but it succeeded. Since then, quite a bit of monitoring has been established in the lake.

Based on the development over recent years and new technology, there has been a broad agreement for the need of a reinforced effort to manage the lake and the surroundings even better.

Observational Pyramid

AMOS' goal is to revolutionize how we can collect data from the ocean. A result of this work, there is an observational pyramid. With small satellites, 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 analyzed, gives researchers a more exact knowledge on what is really taking place.

We are now moving these resources into Mjøsa to map and monitor the lake in an even better way than has been possible before.

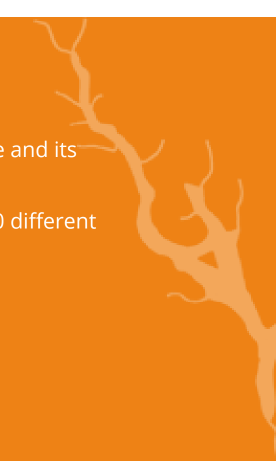
Projects

Already, there have been three campaigns to map dumped ammunitions in Mjøsa. This is a follow-up on the order from Miljødirektoratet (Norwegian Environment Agency) given to the Ministry of Defense, as findings from these campaigns show more ammunition than expected. In addition, we found two new shipwrecks at the bottom. One of them – the steamship DS Lillehammer - was known from before, but with a unknown position. The other one is the wreck of a ship or large boat measuring 10 by 2.4 meters, and for the year is estimated to be between 130,050 and 185,000. Further investigations with ROVs are now planned in March 2023.

During the summer of 2022, together with NIVA, we established a monitoring of the lake by using the research satellite HYPSO-1. Daily pictures were taken with the hyperspectral imager, trying to identify blooms of algae bacteria. NIVA was responsible for the analysis of water samples as the ground truth. These blooms can potentially be harmful for humans, so we also had an agreement

About Mjøsa

- 369 square kilometers
- Greateast measured depth 453 meters, real depth unknown
- Catchment area of rain ~ 17000 km^2
- Source of drinking water for approximately 100,000 people
- Dumping area of ammunition
- Rich cultural heritage, both in the lake and its surroundings
- Great biological diversity, including 20 different species of fish
- More than 40 inlet rivers
- Outlet to Oslofjorden



with the municipalities to warn if we found any indications. During the summer of 2022, there were no significant blooms. We will continue this project in 2023.

NTNU has now allocated eight Ph.D. positions, along with several other positions to this mission. Innlandet County and the seven municipalities have granted funds. During 2023, NTNU will define more research projects connected to Mission Mjøsa, and invite other partners to join us in this effort. The goal is to define this as a nationally funded mission during 2023.

Outcome/impact

Mission Mjøsa is growing organically. Due to this bottom-up perspective, it is difficult to describe all the activities that will take place. But as a starting point, we have defined these outcomes:

- Mapping cultural underwater cultural heritage monuments, such as shipwrecks of Viking ships, pilot vessels, etc.
- Ensuring water quality
- Mapping and monitoring environmental toxins
- Mapping and monitoring ecosystems
- Mapping and monitoring environmental toxins
- Identifying dangerous objects (ammunition waste, among other things) and emissions, and creating systems to monitor them
- Creating a terrain model and developing a digital twin of Mjøsa, including deciding on Mjøsa's greatest depth

Deployment of the observational pyramid at Frohavet

This note is based on **P1-R2**.

Climate change and other human impacts are severely increasing the intensity and occurrences of algae blooms in coastal regions **P1-R3**. Ocean warming, marine heatwaves and eutrophication promote suitable conditions for rapid phytoplankton growth and biomass accumulation. An increase in such primary producers provides food for marine organisms, with phytoplankton playing an important global role in fixing atmospheric carbon dioxide, and producing much of the oxygen we breathe. But they can also form harmful algal blooms (HABs) that may adversely affect the ecosystem by reducing oxygen availability in the water, releasing toxic substances, clogging fish gills and diminishing biodiversity. An understanding of the exact conditions that trigger a harmful bloom remains elusive. Understanding, forecasting, and ultimately mitigating HAB events, could reduce the impact on wild fish populations, help aquaculture producers avoid losses and facilitate a healthy ocean.

Phytoplankton responds rapidly to changes in the environment, and measuring the distribution of a bloom and its species' composition and abundance, is essential for determining its ecological impact and potential for harm. Satellite remote sensing of chlorophyll concentrations has been extensively used to observe the development of algal blooms. Although this tool has wide spatial and temporal (nearly daily) coverage, it is limited to surface ocean waters and cloud-free days. Microscopic analyses of water and net samples allow a much closer examination of the species present in a bloom and their abundance, but this is a time-consuming process that only collects discrete point samples, sparsely distributed in space and time. Neither of these methods alone captures the rapid evolution of algal blooms, the spatial and temporal patchiness of their distributions, or their high local variability. In situ optical devices and imaging sensors mounted on mobile platforms, such as autonomous underwater vehicles (AUVs) and uncrewed surface vehicles (USVs), capture fine-scale temporal trends in plankton communities, while uncrewed aerial vehicles (UAVs) complement satellite remote sensing. Such autonomous platforms have the flexibility to react to local conditions, and can use adaptive sampling techniques to respond to the marine environment in real time.

This motivates the integrated approach of a group of scientists at NTNU AMOS — an "observational pyramid" that includes both classical and newer complementary observation methods (see Figure 1). We aim to identify trends in phytoplankton blooms in a region with a strong aquaculture activity on the Atlantic coast of mid-Norway. Field campaigns were carried out in consecutive springs (2021 and 2022) in Frohavet, an area of the sea sheltered by the Froan archipelago. The region is a shallow, highly productive basin with abundant fishing and a growing aquaculture industry. Typically, there are one or more large algal blooms here during the spring months. We use multi-instrumentation from a macro- to a micro-scale perspective, combined with oceanographic modelling and ground truthing, to help provide tools for early algal bloom detection.

At the very largest scale, in 2021 we used multispectral images from the Sentinel-2 and PRISMA satellites, and in 2022 from NTNU's Hypso-1 hyperspectral imaging satellite [**P1-R4**, **P1-R5**] to monitor ocean color in the area of interest over several weeks surrounding the main fieldwork (see Figure 3). A long-endurance USV, equipped with a payload of ocean sensors including a CTD, an acoustic Doppler current profiler, oxygen optode and a fluorometer also monitored the area before, during and after the missions. SINMOD, a coupled physical-chemical-biological ocean model, was used to simulate environmental conditions in the area of interest (Figure 4). During the field work, the satellite imagery was supplemented by hyperspectral data from cameras mounted on a plane [P1-R6] (in 2021) and on a UAV, covering smaller areas at higher resolution, and less affected by cloud cover. At the same time, we launched an AUV [P1-R7] that covered hundreds of cubic meters of ocean, while taking high-magnification underwater images (Figure 5) and collecting CTD and chlorophyll data. Finally, monitoring the smallest area, but producing the most detailed measurements, we deployed a Niskin water sampler at a number of locations within the AUV and UAV observation area, and at several depth layers, for microscopy (Figure 6) and eDNA analysis. These water measurements provide a basis for estimates from the other instruments. Details of the instruments' coverage and resolution are shown in Table 1.

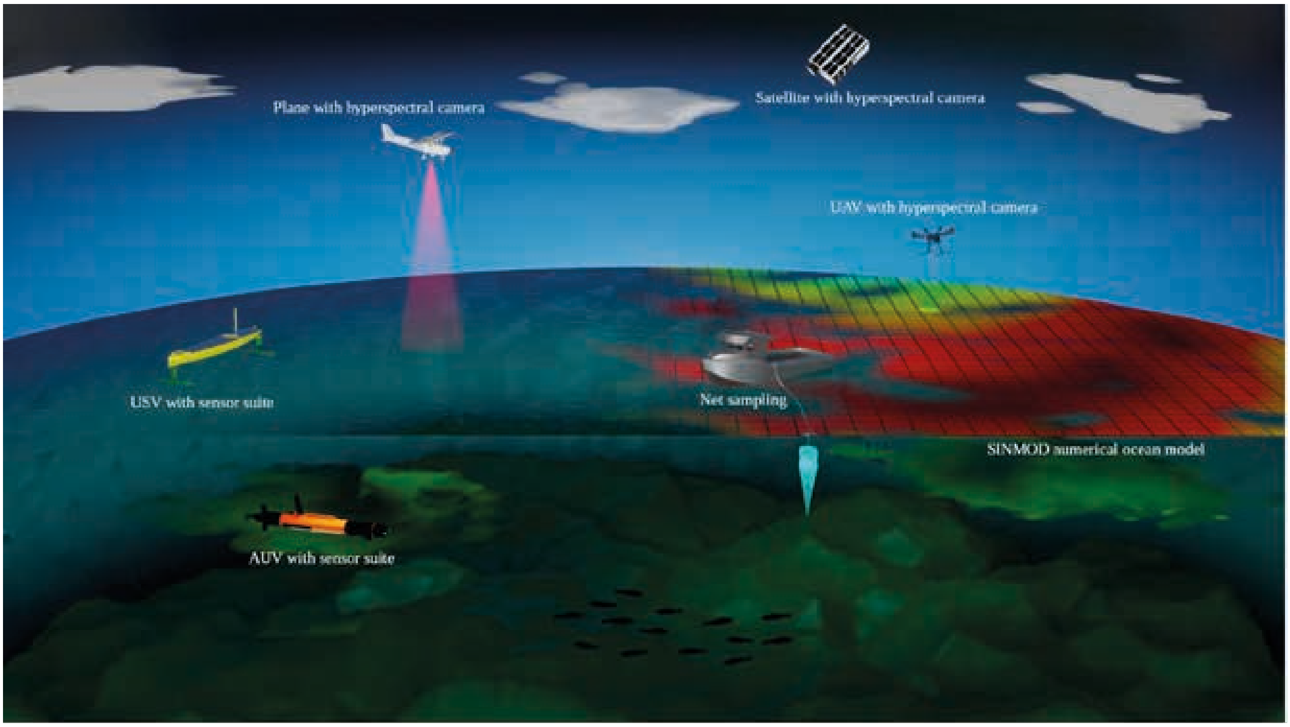


Figure 1a: *Conceptual view of a multi-platform, multi-scale field experiment involving net sampling, satellite and aerial monitoring, AUV, USV, and ocean modelling*

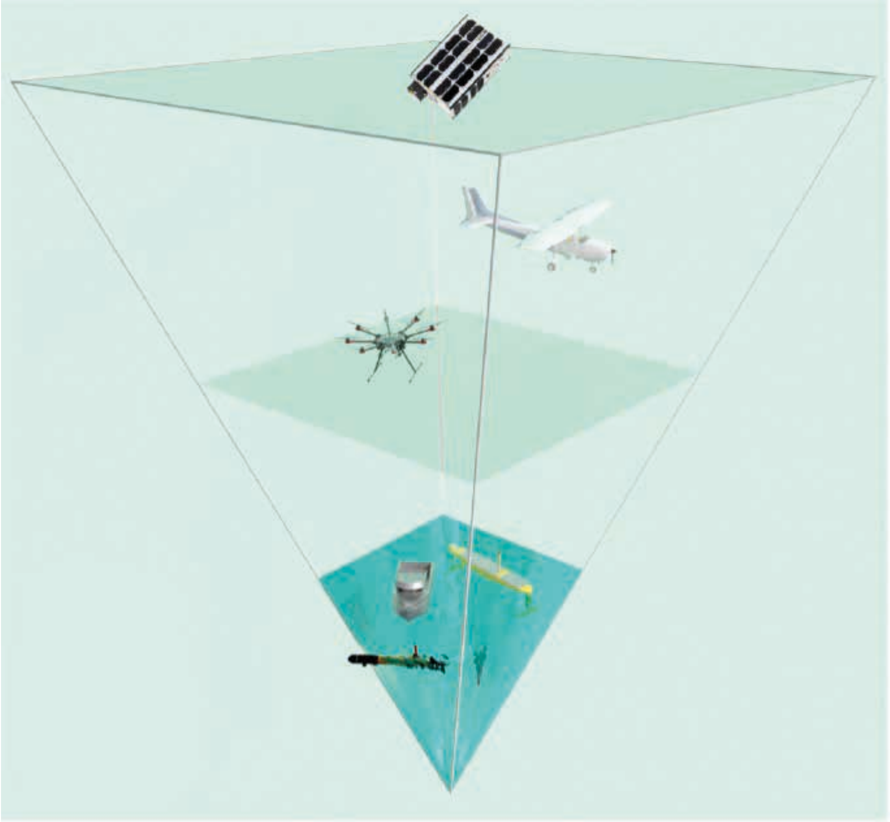


Figure 1b: *The observational pyramid concept: simultaneous, integrated monitoring of the marine environment from space to seabed, from the scale of hundreds of square kilometers to the microscopic. channels. The spatial resolutions of the hyperspectral mosaic and photomosaic are 1 cm and ~4 mm, respectively. The mosaics in (c) and (d) are made up from 12 transects in the North-East direction.*

Platform	Total spatial coverage	Sample coverage	Image spatial resolution	Temporal coverage	Sampling frequency	Data types used
Hypso-1 Satellite	Global	50 x 300 km	30-100 m/pixel	Years	Every 3-72 hours	Hyperspectral imaging
SINMOD	1000s of km^2	123 x 92 km	160 m/ pixel	Several months	Every 30 seconds	CTD, species abundance, nutrients (model data)
Plane	100s of km^2	10s of km x				
10s of meters	meters/pixel (varies with altitude)	Several hours	50 Hz	Hyperspectral imaging		
USV	10s of km^2	10s of km	n/a	Several weeks	1 Hz	CTD, chlorophyll
UAV	Several km^2	Several km x several meters	cm/pixel (varies with altitude)	Several hours	50 Hz	Hyperspectral imaging
AUV	Several km^2	Several km^2	30 μm/ pixel	Up to 8 hours	4 Hz imaging, 1 Hz other	Imaging, CTD, chlorophyll
Net sampling	< 1 km^2	10s of km^2	< 200 nm / pixel	Several hours	Several times an hour	Microscopy images, DNA
Water sampling	< 1 km^2	< 0.1 m^3	< 200 nm / pixel	Several hours	Several times an hour	Microscopy images, eDNA

Table 1: Comparison of the multiple spatial and temporal scales of the data collection platforms used in our approach. Total spatial coverage: the area in which the platform operates. Sample coverage: the actual area or volume of water in which data is collected during a mission. Image spatial resolution: for image data, the size of a single pixel in the image. Temporal coverage: timeframe over which the platform typically operates. Sampling frequency: how often the platform collects data; for example an image, sensor reading or water sample.

These multisensor, multiscale operations will allow us to assess phytoplankton health, and divide their population growth into stages: pre-bloom (cells begin to grow), bloom phase (exponential growth) and post-bloom (grazing and decay). The data from all of the overlapping instruments will be integrated into a single, more complete view of the conditions in the ocean. While remote sensing provides a broad view of such growth, through ocean color, net and water sampling, provides us with insight into the changing species composition within a bloom. Simultaneous AUV imaging provides information on grazers that feed on the phytoplankton - thought to be an important factor in the evolution of algal blooms. Multisensor operations also provide a ground truth for remote sensing, and help us link hyperspectral observations from novel aerial and satellite sensors with conditions in the water. All of these data sources will be used to validate and improve the SINMOD model of the ocean, thereby allowing it to better predict the occurrence and composition of HABs and other algal blooms. Reliable prediction and automated observation also improve monitoring by telling us where and when expensive fieldwork with small-scale, high-resolution sensors can be most effective.

Observational efforts that combine state-of-the-art technology for monitoring, such as autonomous sensor platforms, multi- and hyperspectral remote sensing, ecosystem modelling, traditional water sampling and integrated taxonomy via microscopic and molecular (eDNA) species identification, are paramount for a holistic understanding of bloom formation, as well as marine primary production overall. Our project demonstrates the advantages of this approach, and enables more effective ocean monitoring in the future.

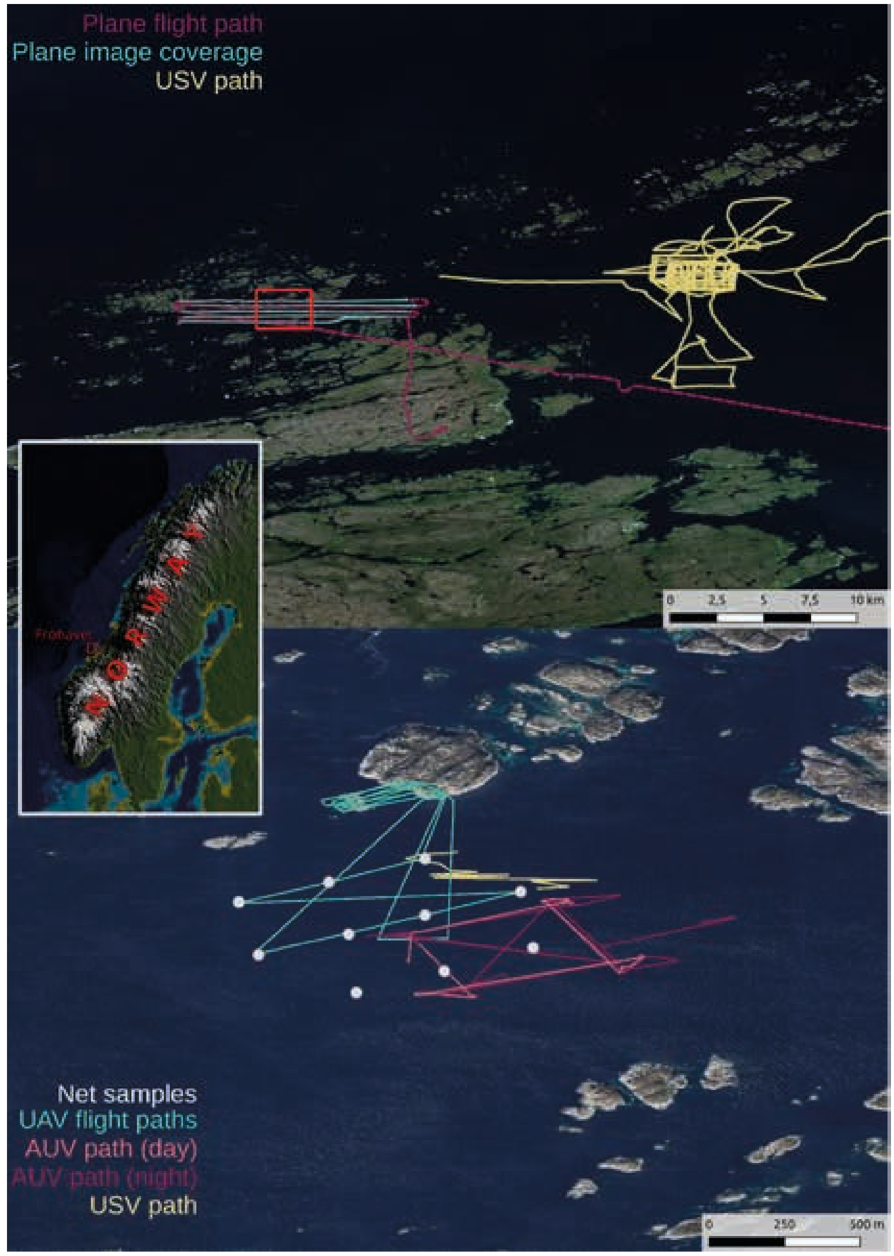


Figure 2: *The location of the fieldwork in relation to Norway (inset); the larger Frohavet region with the path and coverage of the plane equipped with a hyperspectral camera during fieldwork in 2021, and the path of the long-endurance USV in the weeks around fieldwork in 2022 (top); and the locations of water samples and the paths of the UAV, AUV and USV missions in the main sampling area in 2022 (bottom). Red rectangles show the locations of zoomed-in areas. Elevation data from Kartverket, satellite images from Norge i bilder/ Kartverket, and CNES/Airbus, Landsat/ Copernicus, Maxar Technologies via Google Maps3.*

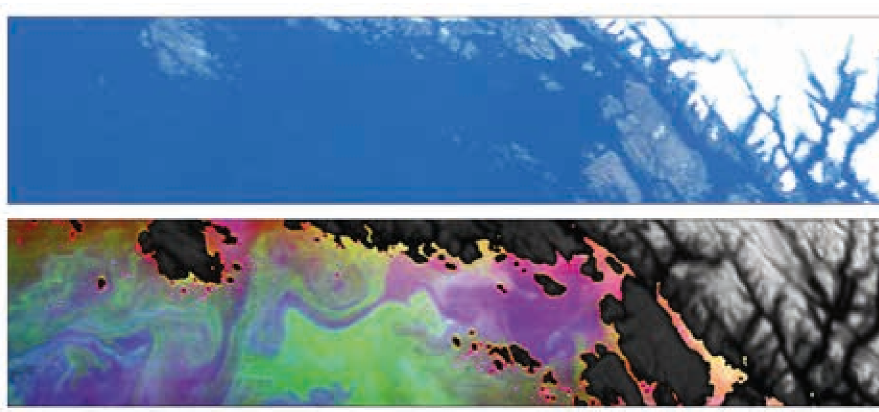


Figure 3: *An image of the Frohavet region on April 19, 2022 recorded by the Hypso-1 satellite. The images covers an area of approximately 300 × 50 km. Shown are RGB color bands only (top), and the 1st, 3rd, and 4th principal components (bottom). These show features in the image which may be related to thin clouds (red), chlorophyll (green) or colored dissolved organic matter (blue).*

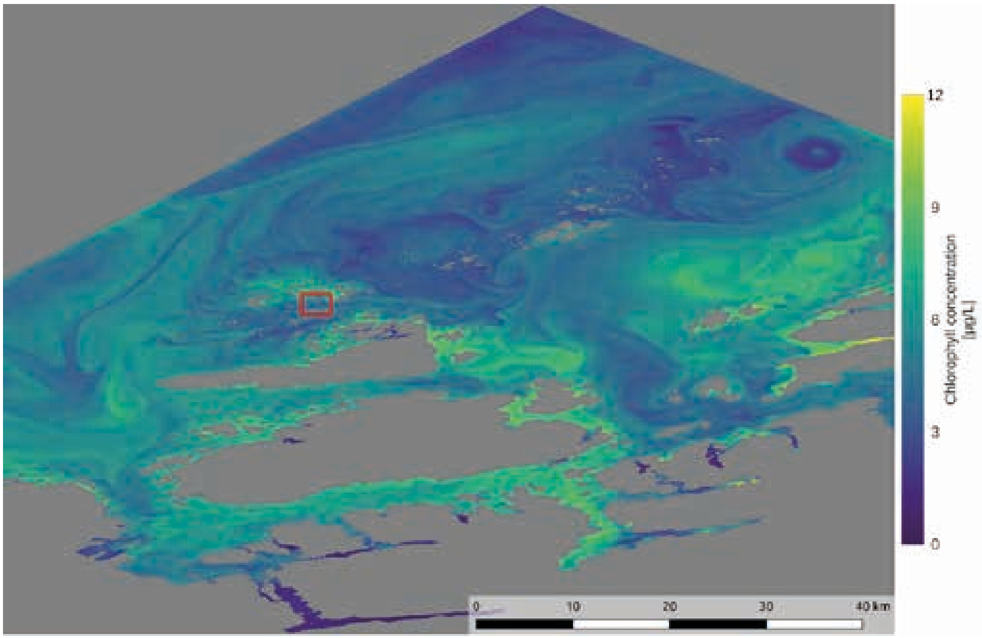


Figure 4: *A chlorophyll forecast made for fieldwork on April 19 2022 using SINMOD, and a coupled physical-chemical-biological ocean model (spatial resolution 160 m). The red box shows the fieldwork area.*

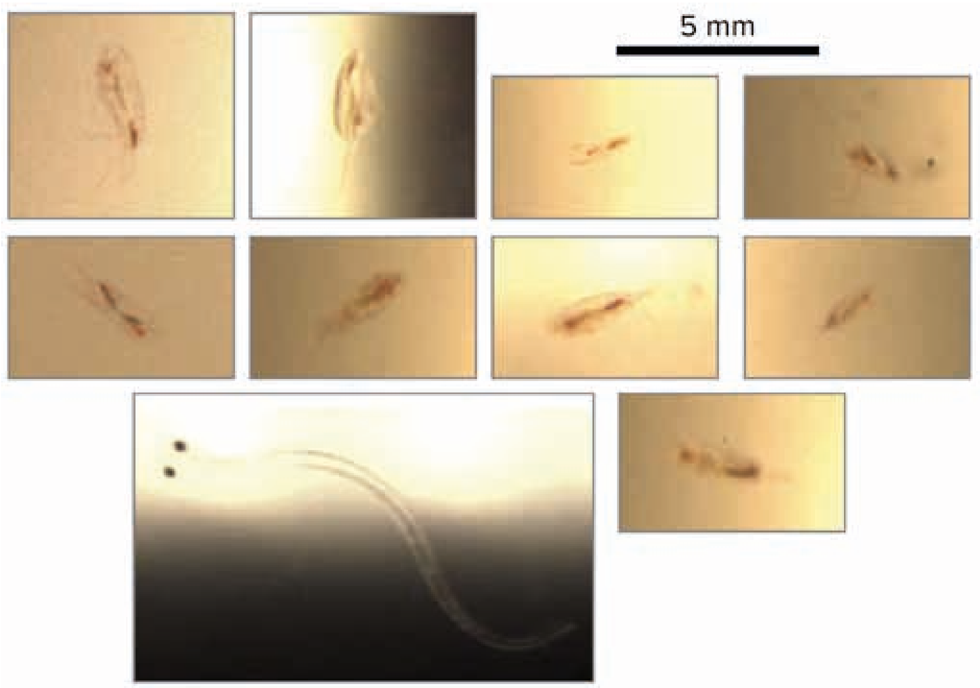


Figure 5: *A collage of cropped images from the AUV-mounted silhouette camera (SilCam), showing copepods and a fish larva found during fieldwork. The abundance of such grazers may impact the timing and size of algal blooms. Image resolution is approximately 30 µm per pixel.*

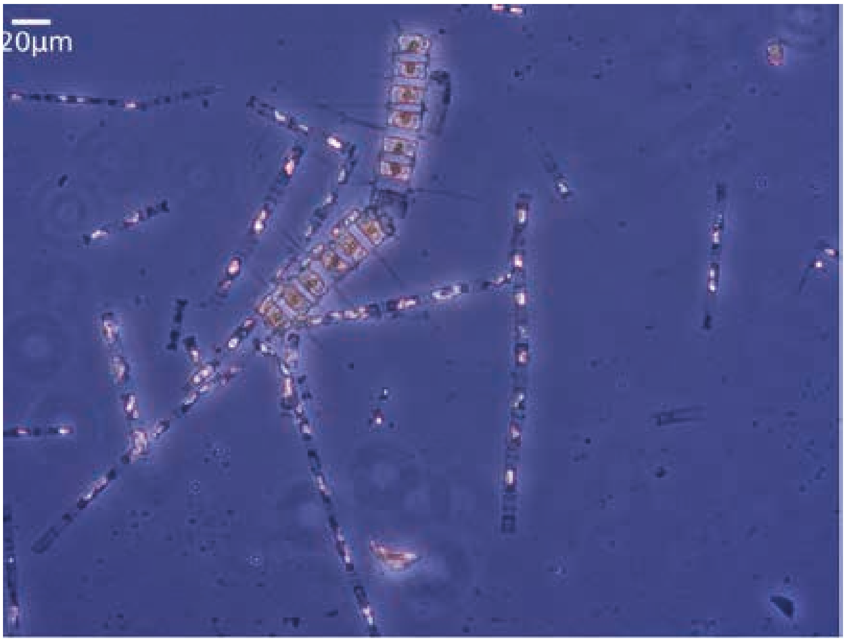


Figure 6: *Microscopy image of phytoplankton from a water sample taken during fieldwork, showing the diatoms Skeletonema sp. and Chaeotoceros sp. — typical species found in the spring blooms.*

References

P1-R1. S. Bakken, M. B. Henriksen, R. Birkeland, D. D. Langer, A. Oudijk, S. Berg, F. Gran-Jansen, Y. Pursley, J. Garrett, E. Honoré-Livermore, M. E. Grøtte, B. A. Kristiansen, M. Orlandic, P. Gader, A. J. Sørensen, F. Sigernes, G. Johnsen, T. A. Johansen, HYPSO-1 CubeSat: First Images and In-Orbit Results, Remote Sensing, 2023; https://doi.org/10.3390/rs15030755

P1-R2. D. R. Williamson, G.M. Fragoso, S. Majaneva, A. Dallolio, D.Ø. Halvorsen, O. Hasler, A.E. Oudijk, D.D. Langer, T.A. Johansen, G. Johnsen, A. Stahl, M. Ludvigsen, and J.L. Garrett. 2023. Monitoring algal blooms with complementary sensors on multiple spatial and temporal scales. In Frontiers in Ocean Observing: Emerging Technologies for Understanding and Managing a Changing Ocean, Oceanography, Vol. 36, 2023. https://doi.org/10.5670/oceanog.2023.s1.11

P1-R3. IPCC, Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2022.

P1-R4. M. E. Grøtte, R. Birkeland, E. Honoŕ e-Livermore, S. Bakken, J. Garrett, E. F. Prentice, F. Sigernes, M. Orlandi ́c, J. T. Gravdahl, and T. A. Johansen, "Ocean color hyperspectral remote sensing with high resolution and low latency — the HYPSO-1 CubeSat mission," IEEE Transactions on Geoscience and Remote Sensing, pp. 1–19, 2021.

P1-R5. A. Oudijk, O. Hasler, H. Øveraas, S. Marty, D. R. Williamson, T. Svendsen, S. Berg, R. Birkeland, D. Ø. Halvorsen, S. Bakken, M. Henriksen, M. O. Alver, G. Johnsen, T. A. Johansen, A. Stahl, P. Kvaløy, A. Dallolio, S. Majaneva, G. Fragoso, and J. L. Garrett, "Campaign for hyperspectral data validation in North Atlantic coastal waters," IEEE Whispers, Rome, Italy, 2022.

P1-R6. D. D. Langer, E. F. Prentice, T. A. Johansen, and A. J. Sørensen, "Validation of hyperspectral camera operation with an experimental aircraft," IGARSS, Kuala Lumpur, Malaysia, 2022.

P1-R7. A. Saad, A. Stahl, A. Vaage, E. Davies, T. Nordam, N. Aberle, M. Ludvigsen, G. Johnsen, J. Sousa, and K. Rajan, "Advancing ocean observation with an AI-driven mobile robotic explorer," Oceanography, vol. 33 (3), pp. 50–59, 2020.

THOR INGE FOSSEN
RISE OF THE ROBOTS

By Live Oftedahl

All the PhD candidates he has supervised have thus far finished their degrees. He does what must be done to get them through. "You must be a motivator, coach and hobby psychologist for diamonds in the rough."

Thor I. Fossen has been a professor for 32 years at the Department of Engineering Cybernetics and has supervised more than 45 PhD candidates. For the last 10 years, the research and supervising have been done under the NTNU AMOS Centre of Excellence (CoE) umbrella.

He grew up in Ørland watching fighter aircrafts before he moved to Trondheim to study. Today, he enjoys visiting his cabin in Oppdal, a winter paradise south of Trondheim, where he enjoys off-piste skiing, cross-country skiing, and hiking. He has been on a sabbatical in 2022/2023, which he spent at the Université Côte d'Azur in France and the University of Porto in Portugal.

Fossen finished his PhD in 1991 and became a professor two years later. In addition to his employment as a professor, he has been involved in several start-up companies, among them Marine Cybernetics, which DNV acquired in 2012.

"The short version is that we made a method and technology to find programming errors in software without reading it."

The goal was set early

That he would become a researcher was not clear to his family and friends, but he had the goal as early as the age of 12.

"I was going to take the highest form of education – a PhD – and develop new methods and gadgets. I didn't even know about engineering cybernetics back then."

It is a shame that of the approximately 60 Centres of Excellence that the Norwegian Research Council has funded so far, only three include engineering science. It seems politically decided that the Norwegian Research Council no longer grants money for Centres of Excellence with engineering sciences in the lead.

Photo: Asgeir J.

Although he has dyslexia, he is one of the most quoted researchers at NTNU with a sky-high H-index, which establishes that he is internationally recognized for his research.

“I have published a lot. My work week was 70 hours for 10 years. That boosted my carrier, but it was tough for the family life.”

His work week now has an average of 40 hours.

“I manage the time better now, and the kids are grown up.”

CoEs versus Centres of innovation

Twenty years ago, he researched ship modeling and control. For the last 20 years, the research has focused on guidance, navigation and control systems for unmanned drones in the air, water and subsea.

“The biggest advantage of being part of a Centre of Excellence is getting funding for basic research, experimental testing and fieldwork. You can make theory into practice.”

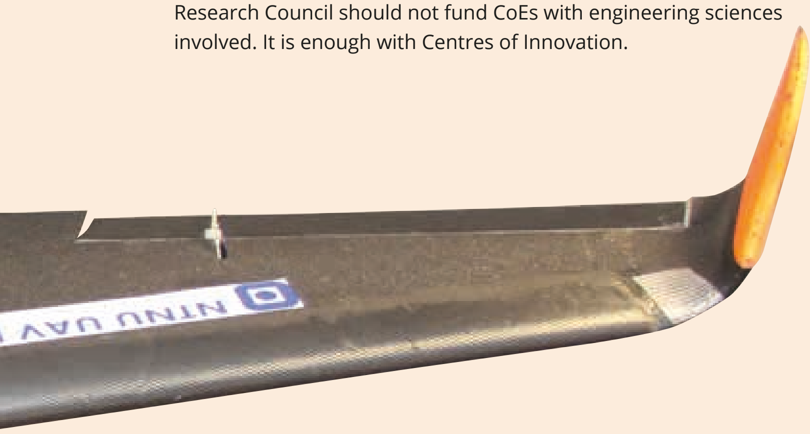
Another significant advantage he sees is that in a CoE you can put groups of PhD candidates with different subject areas together.

“They will also be supervised horizontally. When they are many, they can talk about everything. Science gets more impact when biologists, marine technology and engineering cybernetics work close together.”

There is a difference between establishing things with or without funding. The strategic research areas at NTNU are not well funded, though a CoE is.

“The Centres of Excellence is a powerful management instrument. It educates highly skilled engineers that will give ten times back to the business world and make Norway more than a raw material supplier. It is about educating the best for the future Norwegian businesses.”

He thinks it is a shame that among the 60 CoEs financed by the Norwegian Research Council so far, only three have had engineering sciences included. He has worked in two of them, CeSOS and AMOS. It seems politically decided that the Norwegian Research Council should not fund CoEs with engineering sciences involved. It is enough with Centres of Innovation.



“An SFI is a totally different concept, involving external companies, research institutes and universities, where applied science and applications are the goal. An SFI has a shorter time span and more concrete goals. The obvious problem is that many industrial partners look at each other with poker faces. No one wants to disclose their intentions.”

CoE gives continuity

A CoE has different basic requirements.

“In AMOS, we have researched and developed a lot of drone technology and intelligent autonomous systems. We have developed and tested methods for unmanned aerial vehicles (UAV’s), unmanned surface vessels (USV’s) and autonomous underwater vehicles (AUV’s).”

There is a media buzz about the race in artificial intelligence and autonomous systems in Silicon Valley, a possible new Klondike in the tech world.

This race is also on in the domain of cybernetic systems, in which you extend the possibilities for what the robots can do, understand and fix without taking orders.

“These robots are your best friend in dirty, dull and dangerous work.”

AMOS has also given the possibility to finance lab engineers, which assures continuity. The UAV lab would not have existed without AMOS.

“Ten years of funding has been fantastic. Now we have to get funding through other NFR-projects, EU projects and assignment research projects. This is a time-consuming process”.

Eternal education

Fossen is a professor, but he still educates himself by following the subjects of his colleagues at the various departments, but without taking any exams. As a former NTNU student, you have access to the digital materiel used in the courses.

It is essential to stay tuned and in front if you want to be an outstanding professor. Fossen is more concerned about the time professors must use on applications to get PhDs.

“A professor should get a certain amount of PhDs to supervise in ten years, and cease to use a lot of time and effort on writing applications and doing management.”

He wants to use his time in the core business of research and education, not applications.

Therefore, it is a shame that long-term strategic projects such as Centres of Excellence no longer seem available to engineering science-oriented research adventures.

KRISTIN Y. PETTERSEN
THE IMPORTANCE OF ACADEMIC FREEDOM

TOPIC: Why basic science is so important for the development of cutting-edge technology

By Live Oftedahl

> "It is from basic research that the most innovative solutions can arise."

Photo: NTNU

"It was a wonderful day when we learned that the NTNU AMOS application was accepted: The research opportunities that unfolded, and the research freedom we were given."

Kristin Ytterstad Pettersen just had her first winter holiday since she went to high school and arrived back from Paris yesterday, where the family met close relatives.

Now she really needs to catch up on a lot of work in the last months at NTNU AMOS, which is in its 10th and final year. She is famous for her snake robot research, and even got to see a blockbuster movie, in which one of the main characters was inspired by her last year.

Last year, she also received a five-year grant for her research from the European Research Council's ERC Advanced Grant. This was a needle's eye for researchers at the forefront of their field, which means that she can fund basic and researcher-driven research for a few more years.

Long lines

She is happy about the recognition and funding this gives to her research, but has no doubt that even longer time horizons than five years offer more opportunities to take bigger leaps.

"NTNU AMOS gave resources to gain proper momentum in the research. It gave us the opportunity to have more professors who worked interdisciplinarily, and enabled us to plan long-term," says Pettersen.

A time horizon of three to five years in academia means you are in a hurry. You must hire PhD students straight away to get the work done before time runs out.

"A longer time horizon means that highly skilled master's students can continue, both as a doctoral candidates and postdocs."

The recruitment can also be done with an overlap, so that there are no gaps and discontinuities in the research projects, so you get the necessary transfer of experience along the way.

"Continuity gives momentum, and it is from basic research that the most innovative solutions can arise."

The research frontier

So, what is the plan going forward? The aim of her current and planned research is to develop the brains of field robots, making them sufficiently intelligent.

Major opportunities and research challenges lie in embodied artificial intelligence (AI). Embodied AI is an AI that controls something physical, like a robot arm or an autonomous vehicle, robots that are able to move through the world and affect a physical environment with its actions. Currently, this research area is in its infancy.

"Robots still have surprisingly little autonomy. The aim is to take a significant step forward in the development of robots that can not only monitor, but also interact physically with their environment, like picking up objects and doing maintenance and repair."

Both environmental monitoring and the monitoring of infrastructure that need regular maintenance, and not least monitoring for security reasons - in a Europe with an unstable security situation, is also a goal.

Academic freedom depends on funding.

"If you don't have the financial resources, you won't get the momentum."

Previously, there were regular announcements of free funds in the form of PhD scholarships that were not allocated to a particular thematic area. If you had a good project and a good student, there was a high likelihood of obtaining such funding for projects with researcher-driven thematics.

"The result was good and exciting projects. We got to test out new ideas. The snake robot research was started with these free funds. I miss it."

Energy and enthusiasm

She cannot fully praise the team enough that has been at NTNU AMOS.

"I think we have all been made better by AMOS. It gives a lot of energy to work with people who are really good at something you are not, and where we complete each other. The collaboration in AMOS has been uniquely inspiring and effective."

She says that some international PhD candidates have been surprised by how open and trust-based the culture in AMOS has been. The energy and enthusiasm that director Asgeir J. Sørensen has radiated has been infectious.

"We get a lot more done together instead of sitting alone in our offices. AMOS has provided the opportunity to build on each other's thoughts and expertise. The work that has been done in AMOS has been important, both for the cross-disciplinary research environment at NTNU and for Norway."

"If you don't have the financial resources, you won't get the momentum."

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

Other involved scientists: Prof. Jørgen Berge (UiT, The Arctic University of Norway/UNIS), Prof. Roy E. Hansen (University of Oslo), Kjetil Bergh Ånonsen (Norwegian Defence Research Establishment (FFI), Assoc. Prof. David Johan Christensen (Technical University of Denmark), Prof. Thijs J. Maarleveld (University of Southern Denmark), Prof. Gianluca Antonelli (University of Cassino, Italy), Prof. Tim W. Nattkemper (Bielefeld University, Germany), Dr. Francesco Scibilia, Dr. Vidar Hepsø (Equinor), Dr. Ståle Johnsen (SINTEF), Prof. Mark Moline, Prof. Jon Cohen, Dr. Ian Robbins (University of Delaware, USA), Dr. Finlo Cottier (Scottish Association for Marine Science, Scotland), Emlyn Davies (SINTEF Ocean), Dr. Maxime Geoffroy (Memorial University of Newfoundland, Canada), Prof. Hanumanth Singh (Northeastern University, USA), Dr. Malin Daase (University of Tromsø) and Prof. Murat Arcak, UCB

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 Shipwrecks in the High Arctic Using Underwater Sensor-Carrying Robots
- Advancing ocean observation with an AI-driven mobile robotic explorer (AUV)

Main results

Global Asymptotic Tracking for Marine Vehicles using Adaptive Hybrid Feedback

It is well known that continuous-time systems whose state space can be identified with a vector bundle on a compact manifold have no point that can be globally asymptotically stabilized by continuous-time state feedback. Such systems include all mechanical systems that have orientation as a state variable. This limitation is referred to as a topological obstruction to global asymptotic stability and follows from the fact that no compact manifold is contractible. The obstruction can be overcome by employing hybrid feedback, and in this work we present an adaptive hybrid feedback control law, and prove that it provides global asymptotic tracking for marine vehicles [P2-R1].

Employing hybrid feedback to overcome topological obstructions on compact manifolds has been extensively studied in previous literature through simulations in the idealized case where the model structure and the model parameters are assumed to be known. However, little attention has been paid to the more practical case in which there is parametric modelling uncertainties.

To handle parametric modeling uncertainties, adaptive control laws have previously been proposed for underwater vehicles where Euler angle representations were utilized for the vehicle orientation. The Euler angles inherently introduce a singularity in the state space representation, obstructing global results. To overcome this, adaptive quaternion-based control laws for underwater vehicles have also been proposed. Nonetheless, global asymptotic stability results cannot be achieved by continuous-time quaternion-based control approaches either. This is due to the inevitable existence of an undesired and unstable equilibrium point.

Specifically, two things may occur. The control action may vanish at an undesired equilibrium point that does not correspond to the desired physical orientation, or the control law induces an unnecessary full rotation of the rigid body when it is close to an undesired equilibrium point.

The primary contribution of our work, as reported in [P2-R1], is the development of an adaptive hybrid feedback controller for marine vehicles subject to parametric modelling uncertainties. We prove that the proposed controller provides global asymptotic tracking. The results hold for both surface vehicles and underwater vehicles. Moreover, as our approach is based on traditional Euler-Lagrange system models on SE(2) and SE(3), the proposed adaptive hybrid control law is also applicable also to other mechanical systems. For instance, it can easily be extended to robot manipulators or, more generally, vehicle-manipulator systems.

The theoretical results are validated for surface and underwater vehicles through both numerical simulations and experiments.

Contact: Kristin Y. Pettersen

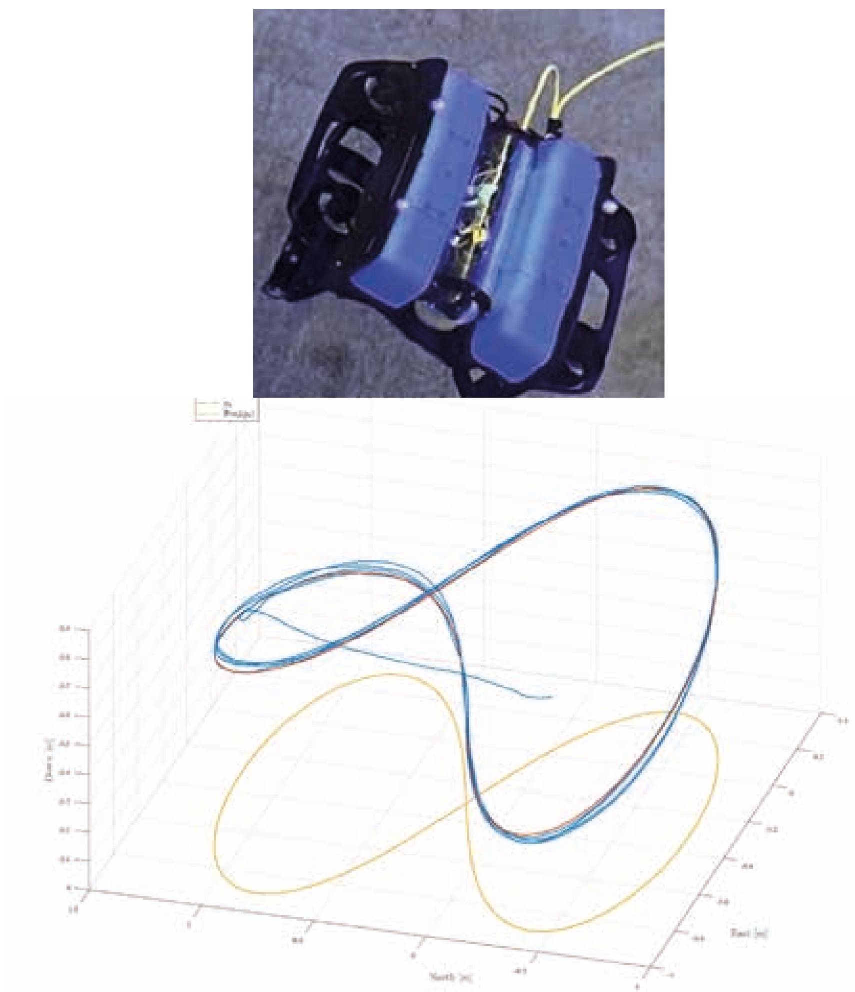


Figure 1: *Experiments with the BlueROV2 in MC-lab (Top). North-East-Down plot showing the position p, the desired position pd and the projection of* p_d *onto the North-East plane*

Bio-inspired studies relevant for underwater robots

Most fish and cetaceans generate propulsion force for cruising, fast-starting and maneuvering by bending their bodies into a backward-traveling wave that extends to the caudal fin; this type of swimming is often classified as body and/or caudal fin (BCF) locomotion. The basic source of their propulsion forces is the control of vortices produced by their oscillating bodies and fins. Inspired by fish, three geometries of two-dimensional (2D) foils, a NACA 0012 foil, a NACA 0021 foil and a foil with the same trailing edge as the former and maximum thickness as the latter, were studied under harmonic oscillations to characterize the influence of body profiles on the hydrodynamic loads and performance. The simulations are performed as 2D within a stepwise research strategy and using a thoroughly validated finite-volume-based code in the OpenFOAM platform based on a collocated grid and documented in [P2-R2].

The results of the rigid flapping foils at frequency f=2.244s^{-1}, amplitude θ_0=0.153rad and chord-based Reynolds number R=1173 showed that the NACA 0012 foil is associated with the largest thrust but experiences the largest hydrodynamic torque, which might pose possible issues for robustness, while the NACA 0021 foil was associated with worse propulsive conditions, experiencing a drag force, but suffered the smallest torque. This leads to the following research question: *Can we identify a morphing-foil strategy so as to generate a thrust similar to that of the NACA 0012 foil while reducing the hydrodynamic torque to a level comparable to that of the NACA 0021 foil?*

A first attempt to combine these advantages within a foil morphing strategy is to enforce that the foil becomes thicker when close to the mean position and thinner when close to the extreme positions. To pursue our scope, the foil profile is morphed between the NACA 0012 and NACA 0021 foils, as illustrated in Fig. 2.

This deformable NACA foil is studied under the same pitching condition as for the rigid cases. Fig. 3 compares the non-dimensional horizontal force (C_x) and power (C_p) from the rigid and deformable NACA foils.

From the plots of C_x, the deformable NACA foil generates a time-averaged thrust force, which is slightly smaller than that of the NACA 0012 foil. The time histories of C_p prove that the deformable NACA foil requires as less power as the NACA 0021 foil to perform the prescribed pitching motion. This attempt proved that a morphing strategy could serve to the scope, and a systematic study was carried out to identify the features for an optimized morphing strategy.

A large number of real-fish tests have been carried out by biologists in swim tunnels with the focus on accurately estimating the fish metabolic rate. The space between the fish and boundary walls of the tunnel is often limited, leading to possible wall effects on swimming performance from a hydrodynamic perspective. They were investigated numerically assuming a streamlined symmetric fish-like shape, i.e. a NACA 0012 foil, as the profile of a swimming foil (see Fig. 4) at an equilibrium position [P2-R3].

The fish kinematics can be resembled in the form of a wave traveling in the streamwise direction. The numerical simulations were performed for the self-propelled NACA 0012 fish swimming at frequency f=1.0s^{-1} in a uniform current, with inflow velocity U_c=0.5m/s, while the swim tunnel size is systematically varied from h_t=6m (i.e., h_t/D=50) to ht=0.72m (h_t/D=6, which is a normal ratio

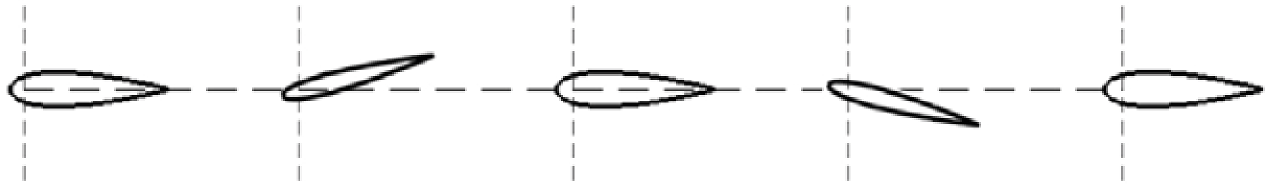


Figure 2: *Schematic showing foil morphing between NACA 0012 and 0021 during one oscillation period.*

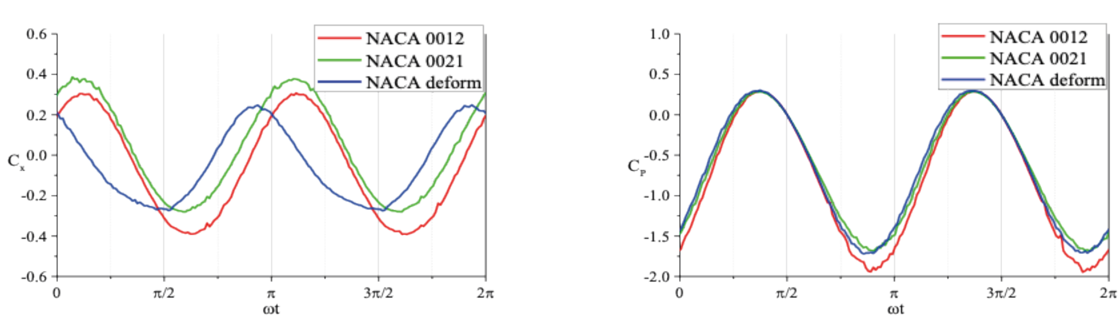


Figure 3: *Steady-state horizontal force and input power coefficients for rigid and deformable NACA foils.*

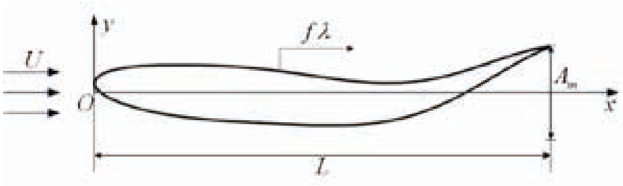


Figure 4: *Schematic view of the fish model with the leading edge of the body located at x=0 at rest. An elongated body of length L undulates in an inflow of speed U with a wave traveling backward at speed fλ and amplitude A_m at the trailing edge.*

for swim tunnel real-fish tests) to investigate the wall effect of the swim tunnel on fish behavior.

Table 1 documents the time-averaged results of the total swimming speed in the narrowest examined swim tunnel and in an infinite fluid domain (labelled h_t/D=∞). Their comparison shows that a sufficiently small tunnel width results in a significant reduction of the fish swimming speed.

Table 1: Time-averaged steady-state swimming speed of the NACA 0012 fish oscillates at f=1.0s^{-1}.

h_t (m)	∞	0.72
h_t/D	∞	6
U_t	-0.586	-0.432
Reduction	–	26.25%

The aquatic motion of fish is characterized by paths of long-term cruising swimming and by very fast maneuvers during prey–predator encounters, either for escaping or for foraging needs. For instance, the so-called C-start gives rise to a sudden change of the swimming direction together with a huge acceleration (up to several times the gravity) leading the fish to follow a proper path to survive or to capture the desired pray. Such impressive performances, still poorly understood, are not common to other living beings and are clearly related to the interaction with the aquatic environment. To enable these features in engineered vehicles systematic studies are needed. In this framework, a numerical study was carried out to investigate to role plaid by added mass and its time variability in this maneuver's performance [P2-R4].

For the analysis, the full system of the evolution equations for the kinetic variables pertaining to the body center of mass has been studied. A simple two-dimensional impulse model with concentrated vorticity was used for the self-propulsion of a deformable body in an unbounded fluid domain, to quantify the potential-flow and the vortical contribution to the impulse experienced by the body and to highlight their interplay induced by recoil motions. This decomposition is crucial for a proper physical interpretation of the results.

Fig. 5 outlines the main phases of a C-like fast start. The fish willing to suddenly accelerate and change its swimming direction initiates a preparatory phase via a rotation of its tail, which induces a simultaneous opposite rotation of the body fixed frame. The successive propulsive phase, corresponding to the rapid return of the tail to the position aligned with the forward axis, gives rise to a substantial velocity boost in the same direction while the whole motion is accompanied by a significant release of vorticity.

The kinematic performance of the C-start maneuver for a neutrally buoyant fish may be furtherly appreciated by the velocity components reported in Fig. 6 where we see that during the preparatory phase, i.e. for 0 ≤ t/T < 0.5 when the tail is raised towards the head (see Fig. 5), the body fixed frame starts to counter-rotate with an angular velocity whose maximum occurs approximately for t/T = 0.5. A relatively small forward velocity U from right to left (i.e. negative in sign) is also obtained halfway, but a much larger forward speed is finally achieved at the end of the propulsive phase when the tail is pushed back.

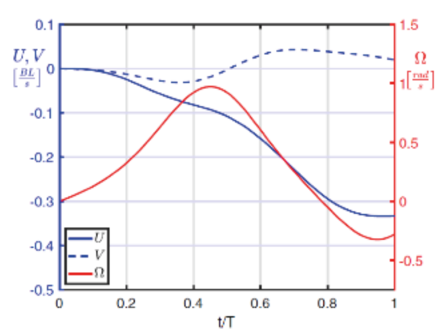


Figure 6: *Velocity components for the C-start maneuver of a neutrally buoyant fish.*

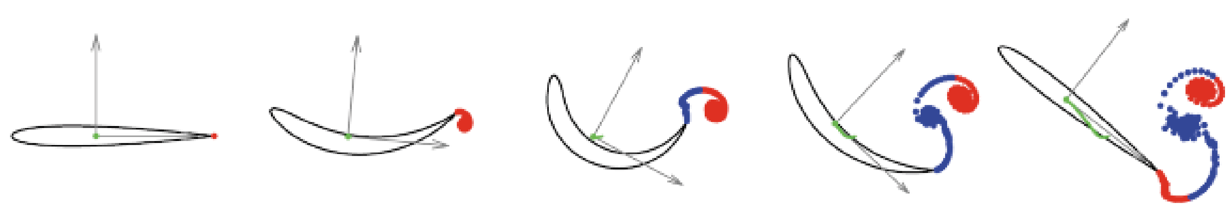


Figure 5: *Snapshots of the C-start maneuver of a neutrally buoyant fish from the numerical simulation.*

Obstacle Intention Awareness in Automatic Collision Avoidance: Full-Scale Experiments in Confined Waters

Even though numerous algorithms for automatic collision avoidance have been developed, there is only a handful of these that consider the uncertainties associated with the kinematics and intentions of nearby ships/dynamic obstacles. In this work, we present full-scale experiments with a dynamic obstacle intention-aware collision avoidance (COLAV) system. It consists of the Probabilistic Scenario-based Model Predictive Control (PSB-MPC) COLAV algorithm with a Dynamic Bayesian Network (DBN) for inferring obstacle intentions online. The experiments put an emphasis on hazardous situations, in which intention information is both useful and necessary to avoid high collision risk. Experimental results demonstrates the validity of the proposed COLAV system, with adherence to the traffic rules (COLREGS) 7-8 and 13-17 in a diverse set of situations [P2-R6].

A key part of achieving autonomy for maritime surface vessels are robust and deliberate collision avoidance (COLAV) systems. These systems are responsible for providing both a safe and efficient avoidance solution in situations where there is a risk of collision with nearby dynamic and static obstacles. To ensure safety, the COLAV system must provide maneuvers that ensure a low risk of collision with static and dynamic obstacles, in addition to adherence to the traffic rules of the sea (COLREGS).

Previous work on automatic maritime COLAV has most often neglected or simplified the situational awareness part of COLAV, assuming constant behavior in speed and course for nearby obstacle ships without uncertainty. This assumption of constant course and speed for vessels involved in encounters will not hold in practice, and limits the own-ship decision-making, possibly leading to more reactive avoidance maneuvers being made.

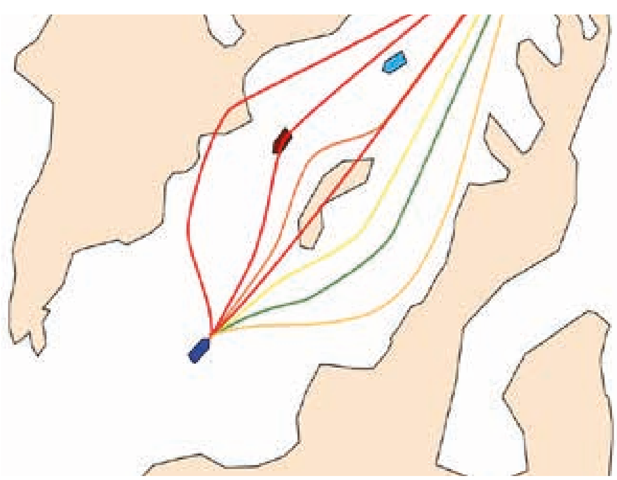


__Figure 1:__ PSB-MPC illustration, with the own-ship running the algorithm in blue. The algorithm considers a finite set of possible avoidance trajectories for the ship to follow and calculates the cost of each. The one giving minimal cost (green one) is chosen as the optimal solution.

This work develops a COLAV algorithm with improved situation awareness capabilities with respect to the future behavior of other vessels, and experimentally tests the resulting system. The COLAV algorithm considers a set of possible own-ship trajectories (shown in Fig. 1) and a set of obstacle-ship trajectories (shown in Fig. 3). The algorithm evaluates the cost of each combination of own-ship obstacle-ship scenarios, considering among other things the likelihood of the obstacle ship following that scenario, the risk of collision considering kinematic uncertainty, the fulfillment of rules specified in COLREGS, and grounding risk.

The probability of the obstacle ship following a particular scenario is evaluated with the intention inference module presented in Fig. 2. This module uses a Dynamic Bayesian network (DBN) to infer the intentions of the other ships based on the observed behavior. Some of the key intentions that are inferred are whether the obstacle ship acts as if it has a higher priority, in which case it will not give way, whether the obstacle ship will disregard the specifications outlined in COLREGS on how it should give way, and inferring which of the situations outlined in COLREGS the obstacle ship thinks it is in if the current situation is unclear. The intention information, together with the intention model (Fig. 2) is used to evaluate the probability of the obstacle ship following the different predefined scenarios. Additionally, the intentions are directly used by the PSB-MPC to, for example, neglect costs related to performing compliant avoidance actions if the obstacle ship intends to not comply with the rules.

The system is validated in experimental trials using the Milliamper 2 prototyping ferry owned by NTNU in the Dora basin in Nyhavna, Trondheim. The Mannhullet Havfruen vessel and NTNU ITKs Cyber-Otter were used as dynamic obstacles. GNSS information was broadcast from each of the dynamic obstacles for tracking purposes. A video of the experiments can be found at https://youtu.be/9cmDqQDgBDc.

Results from one of the stand-on situations are shown in Fig. 3. Here, the intention model first believes that the obstacle ship (shown in green) will perform an avoidance action in accordance with the rules. The PSB-MPC then chooses to fulfill its obligations by keeping its course and speed. As the ships come closer and the obstacle ship does not perform any avoidance actions, the belief that it acts as if it has a higher priority increases. As a ship acting with a higher priority will keep its course and speed the PSB-MPC, it evaluates that it has to reduce its speed to avoid collision.

The experiments demonstrate that the resulting system has increased situational awareness in hazardous encounters, and an improved ability to make decisions based on uncertain information on the kinematics and intents of nearby dynamic obstacles. The system is compliant with all the behavioral rules specified in COLREGS for power-driven vessels operating outside of traffic separation schemes, more specifically rules 8 and 13-17. Also, the system has a better adherence to rule 7 on collision risk assessment, as more situational information is considered.

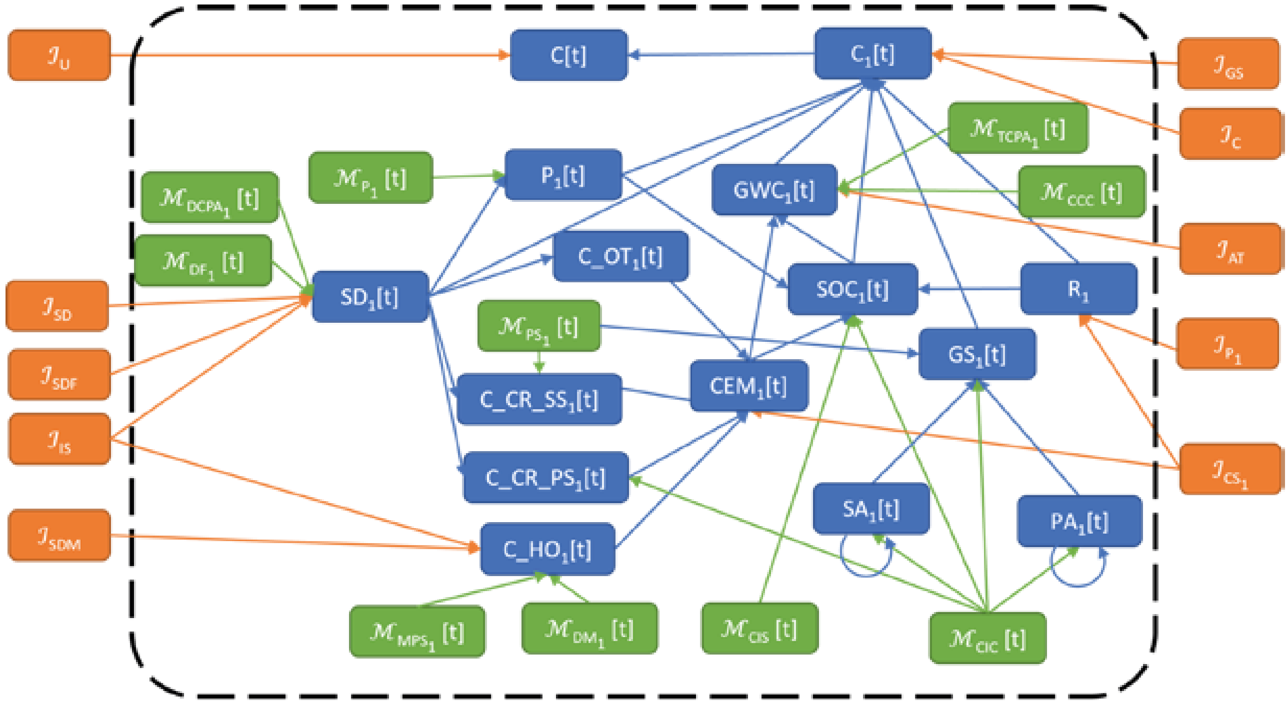
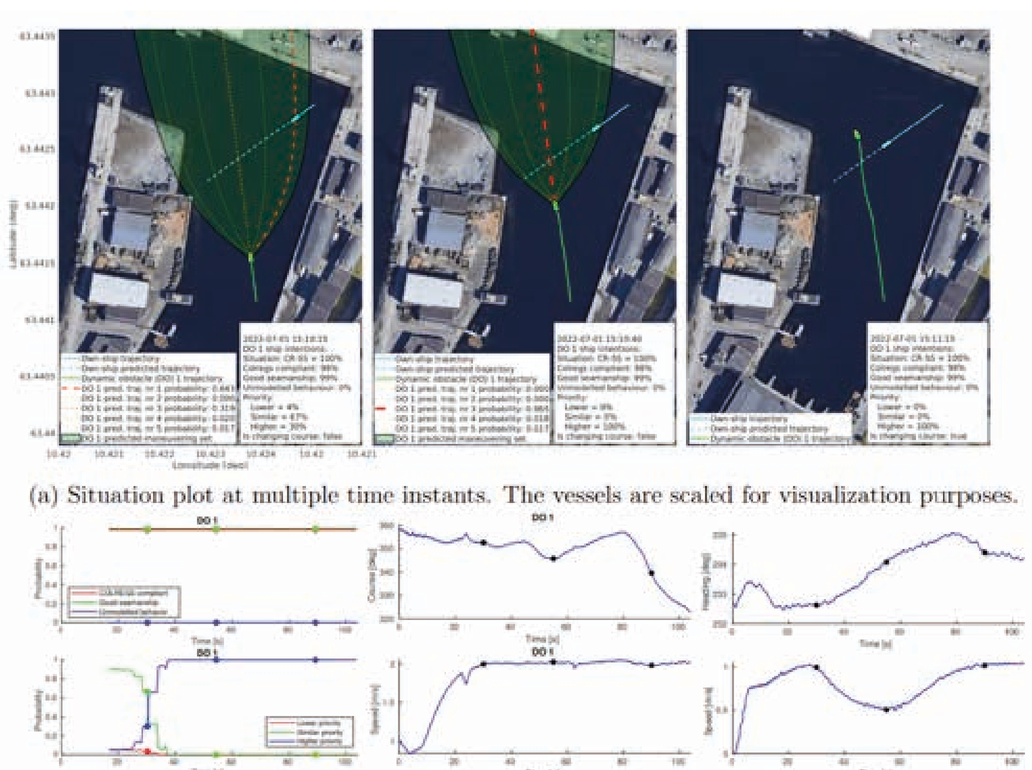


Figure 2: *The intention module, represented as a Dynamic Bayesian Network.*

Figure 3: *Crossing with an obstacle (green) on the port side of the Milliampere 2 ferry (teal), near Dora, Trondheim. The different prediction scenarios for the obstacle are shown through dashed lines from its heading, with the corresponding prediction uncertainty. The prediction scenarios have probabilities proportional to the color and linewidth of the plots.*



(a) Situation plot at multiple time instants. The vessels are scaled for visualization purposes.

(b) Dynamic obstacle intention states.

(c) Dynamic obstacle course and speed.

(d) Own-ship heading and speed.

Design and validation of autonomy system for a long-endurance unmanned surface vehicle: From engineering to science

The lack of autonomous mobile platforms recording data continuously over long periods of time, and in different areas of the globe, suggests the necessity to develop technologies that allow a persistent and sustainable monitoring at sea. Unlike common marine vehicles, surface or underwater gliders are designed to operate at sea for extended periods of time (i.e. weeks and months). However, the control of such robotic systems is a challenging task due to the unpredictability of the environment that most of the time governs their behavior.

The AutoNaut (see Fig. 7) is a wave-propelled surface vehicle whose heading, course-over-ground (COG) and speed, are influenced by the environmental forces due to winds, waves and surface currents. The first challenge faced when designing an autonomous vehicle dedicated to scientific campaigns is autonomous navigation and control. This was initially addressed [P2-R7], where a nonlinear model of the USV's COG was derived and analyzed through simulations in the Laplace domains. The theoretical investigation supported extensive field testing (see Fig. 8), which confirmed the assumptions and paved the way for a more sophisticated navigation system, as described in [P2-R8]. In the refined approach, an acoustic doppler current profiler (ADCP) was used to provide surface sea current measurements relative to the vehicle, and allows automatic scheduling of the course controller gains. As a result, course oscillations are damped, and navigation becomes more efficient (see Fig. 9).

A harmful algal bloom (HAB) is a rapid increase in the density of algae in an aquatic system. Due to the increased anthropomorphic activity, the dynamics of the ocean are

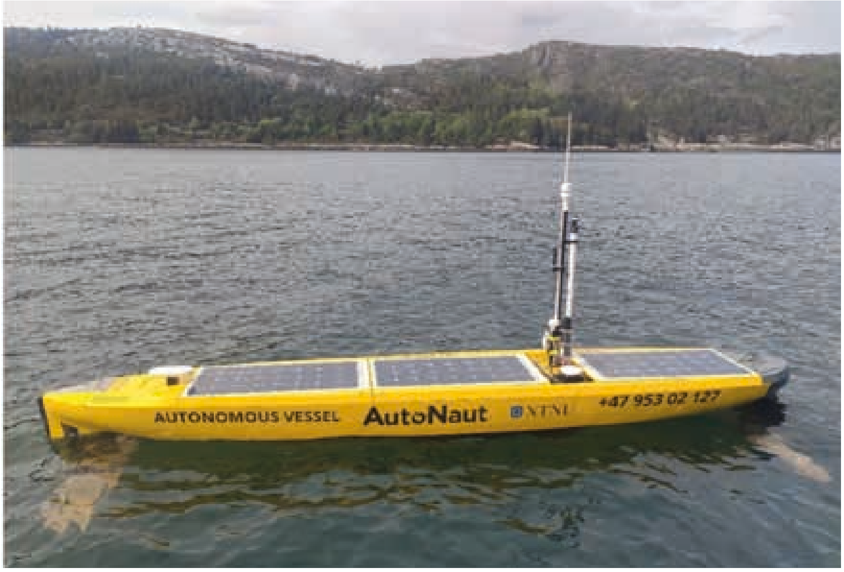


Figure 7: *The AutoNaut: a wave-propelled surface vehicle.*

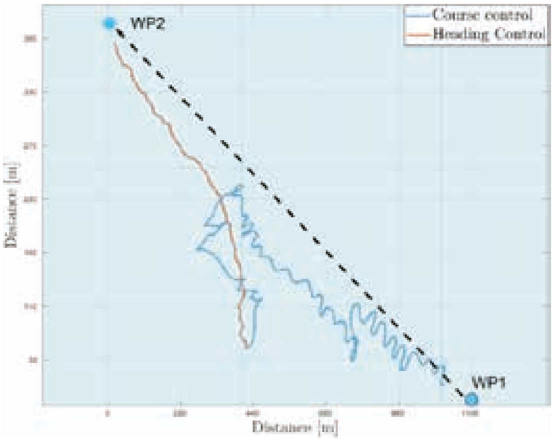


Figure 8: *Course and heading controller performances in Frohavet (mid-Norway) [P4-R1].*

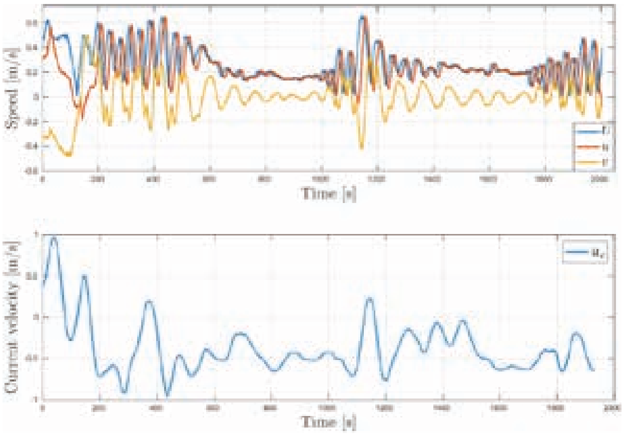


Figure 9: *Gain-scheduled steering controller performances in Trondheimsfjorden [P4-R2].*

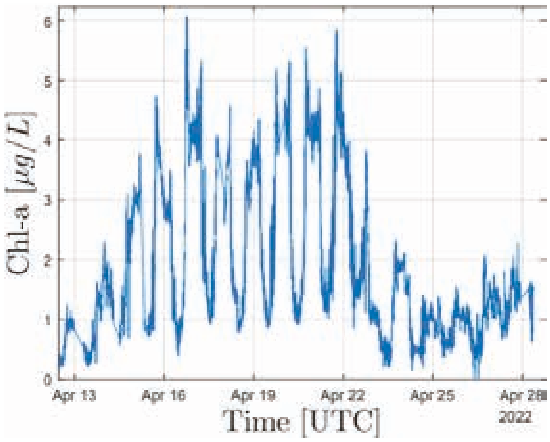


Figure 10: *Chl-a measurements from AutoNaut (Frohavet,mid-Norway).*

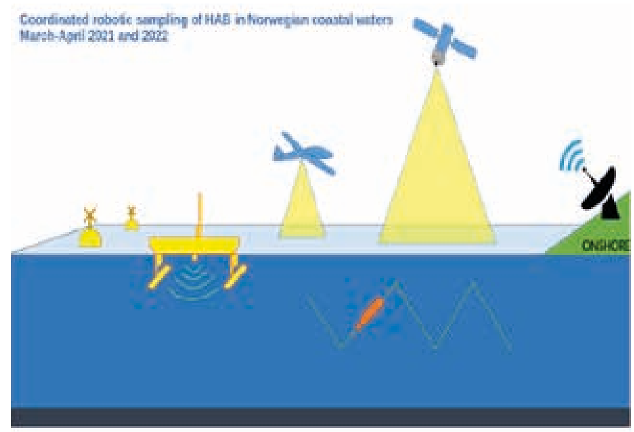


Figure 11: *Coordinated robotic sampling of HAB (2021, 2022 and planned in 2023).*

changing, hence potentially increasing the frequency of HABs. HABs can be toxic to aquatic life, causing a depletion of oxygen and eventually increasing fish mortality. This has severe consequences, for example, in the fish farming industry, where large economic losses are observed as a result of HABs.

The dynamics of a bloom is highly complex, and is regulated by some key environmental variables, such as ocean currents, light, temperature and ocean mixing. A bloom appears as peaks in the phytoplankton biomass, often with chlorophyll-a (chl-a) fluorescence exceeding 5 μgL^{-1}. Naturally, a way to detect if a HAB is growing is to monitor the levels of chl-a fluorescence in the water column. According to traditional ocean observation methodologies, in-situ measurements of this kind are collected from research vessels using manual techniques such as vertical profiling. With the advent of robotic platforms, the human presence at sea, and therefore the employment of large vessels, has been replaced by autonomous assets capable of operating remotely and continuously, thereby making data collection economically more affordable, reducing the human risks and limiting CO_2 emissions. Fig. 10 shows chl-a measurements collected over a total of 16 days in Norwegian coastal waters, where the AutoNaut operated autonomously in April 2022, as described in **[P2-R9]** and **[P2-R10]**. The data collected in that occasion are the fundamental basis of a larger field campaign dedicated to HAB monitoring in Norwegian coastal waters. This extensive field exercise involves several other autonomous robots of NTNU (AUVs, UAVs, drones and fixed-wings), as depicted in Fig. 11.

Fish migrations regularly manifest themselves as remarkable natural phenomena, which have probably intrigued humans at all times. In a time of unprecedented anthropogenic pressures on the oceans, knowledge on how fish move and distribute over different scales of space and time, how they interact with their biophysical environment, and how this affects their reproduction and survival, is of crucial interest, and plays an essential role in developing and implementing well-advised ocean management and conservation strategies.

Successive detections of a tagged fish at different receiver locations make it possible to establish a chronological account of a fish's movement pattern. The advent of cost-effective automatic monitoring receivers has made it feasible to deploy entire systems of moored receivers (often referred to as passive acoustic telemetry), which enable continuous year-round monitoring of aquatic habitats. Such stationary receiver systems are typically organized as clusters of transects or arrays, or in less regular structures. The number of receivers that can be deployed in a passive telemetry system is usually subject to practical and economic constraints, and cannot scale cost-effectively with the size of the target area to make complete coverage a realistic option in many studies. Optimal placement and configuration of receiver transects and arrays with respect to detection probability have been investigated and established. Nevertheless, the risk

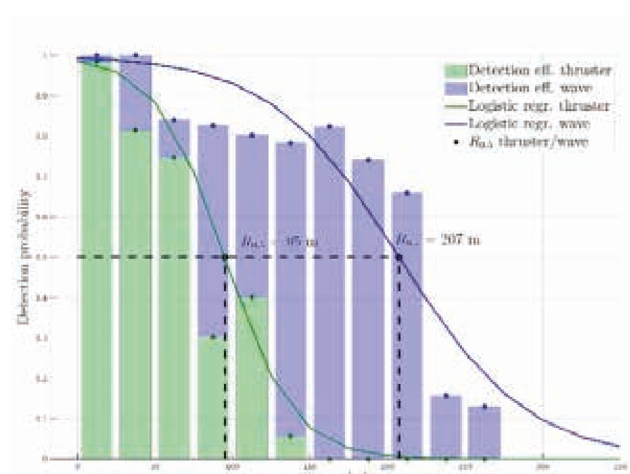


Figure 12: *Statistical analysis of the USV acousting range.*

of low detection rates and location biases in movement data will necessarily increase with a decreasing ratio of receivers to the size of the sample area. Being equipped with an acoustic hydrophone, the AutoNaut has been employed since 2020 in field campaigns in Nordfjord, with the objective of extending the passive acoustic grid, and provides further useful information about salmon smolt migration in the fjord, as described in **[P2-R11]**. After a statistical investigation of the effects of the thruster and wave-propulsion system on the acoustic capabilities of the USV, it was concluded that the thruster had to be turned off while scanning the area, as the "listening" range would deteriorate significantly (see Fig. 12). Based on this investigation, the thruster was kept idle during the field campaign. The detection of a fish individual outside the grid of passive receivers, at the brink of the ocean (see Fig. 13), proved the concept and allowed scientists to expand the migration history of the individual. This study demonstrated that the USV can be used as mobile acoustic telemetry receiver, given its silent propulsion and its capability to operate continuously for several days and weeks.

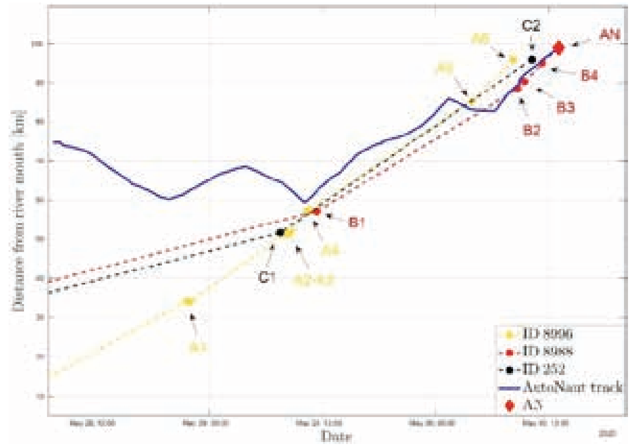


Figure 13: *Acoustic detection of ID8988 outside the grid of passive receivers.*

Autonomous Robots for Ocean Sustainability (AROS) – Improving the robustness of underwater visual perception systems

Due to the presence of marine snow, underwater environments can present a challenge for conventional visual Simultaneous Localization and Mapping (SLAM) methods. Marine snow are small particles of organic matter that float in the water column and can cause keypoint detectors, which are essential for most visual SLAM methods, to fail. To address this problem, researchers at NTNU have developed a solution to classify keypoints into "marine snow" or "clean" [P2-R12]. This classification is based on image patches obtained from keypoint detectors or descriptors computed from these patches. By protecting the SLAM pipeline against unusable keypoints, the marine snow classification scheme improves the performance of visual SLAM in underwater environments.

The effectiveness of the marine snow classifier has been evaluated on both real underwater video scenes, and on simulated underwater footage that includes marine snow. The

Figure 14: *Superimposing marine snow. Top left: Underwater sequence with marine snow. Bottom left: Extracted marine snow. Top right: Image scene superimposed with marine snow. Bottom right: Another sequence superimposed with the extracted marine snow.*

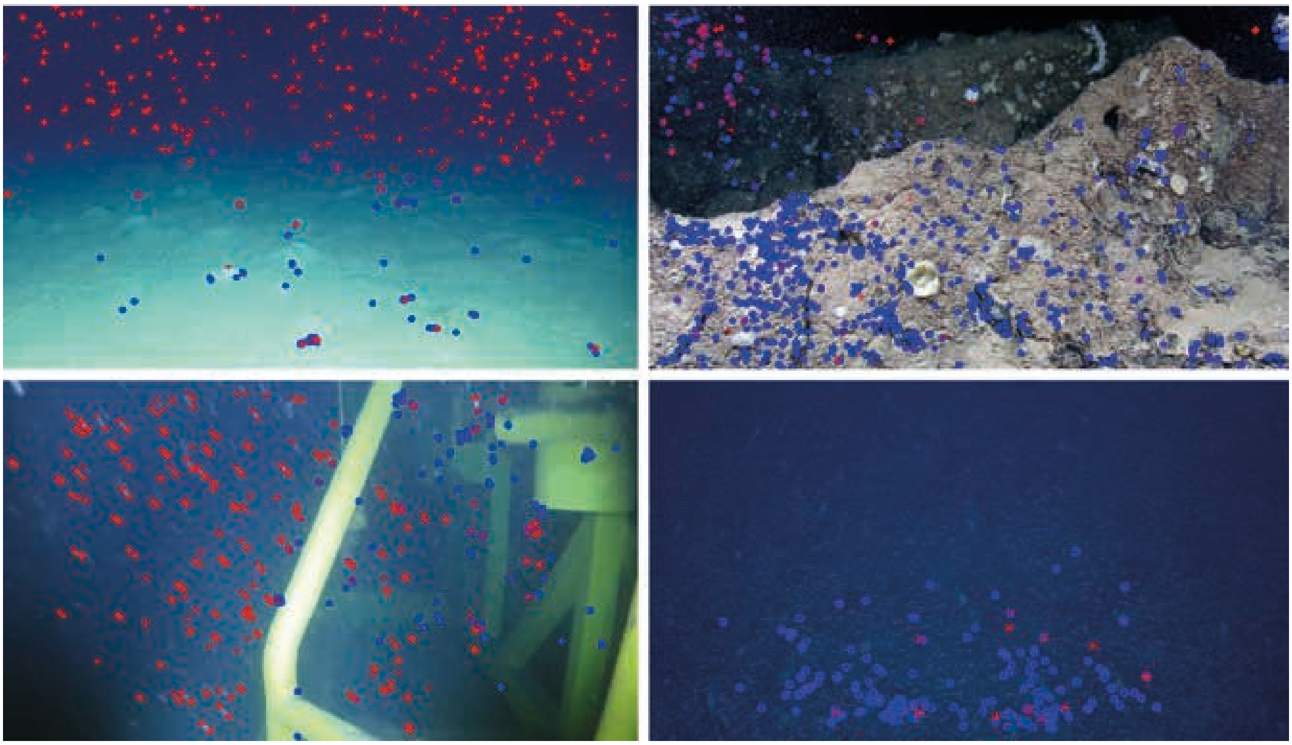


Figure 15: *Frames from four videos used for visualization of keypoint classification. Red crosses indicate a snow classification, while blue circles indicate a clean keypoint classification. A total of 2,000 keypoints were detected per frame.*

results show that the marine snow classifier can significantly improve the performance of SLAM. The classifier's performance has also been evaluated in a full SLAM pipeline integrated with the pySLAM system, demonstrating its applicability in autonomous systems. Additionally, the marine snow detection and suppression has been qualitatively evaluated on a night-time road sequence with snowfall to demonstrate its potential for use in other areas **[P2-R12]**.

Figure 14 shows a typical marine snow extraction and suppression case, in which marine snow is first extracted from a real underwater image and superimposed onto a synthetic underwater scene (two examples are shown). Such sequences are then used for keypoint classification (cf. Figure 15) within a classical SLAM system (cf. Figure 16).

Contact: Annette Stahl

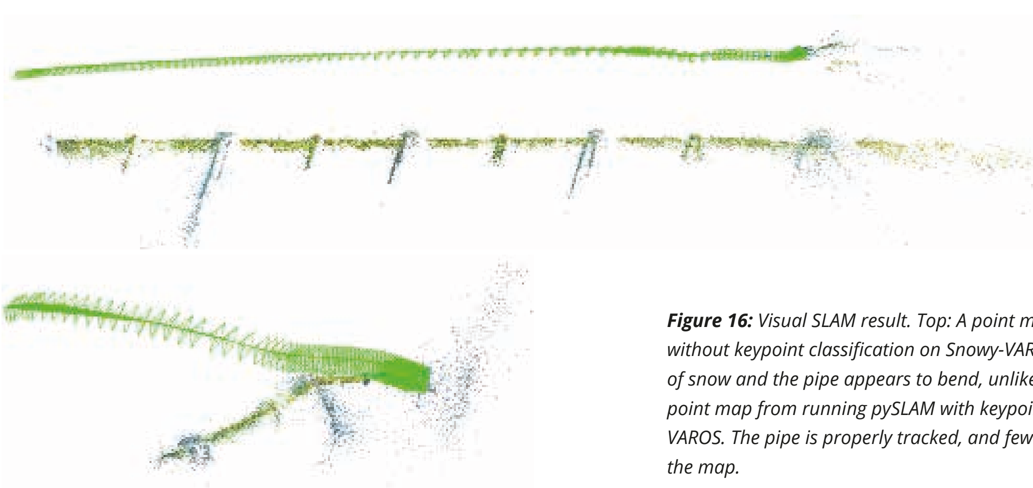


Figure 16: *Visual SLAM result. Top: A point map from running pySLAM without keypoint classification on Snowy-VAROS. The path stops in a wall of snow and the pipe appears to bend, unlike the source video. Bottom: A point map from running pySLAM with keypoint classification on Snowy-VAROS. The pipe is properly tracked, and few snow keypoints are added to the map.*

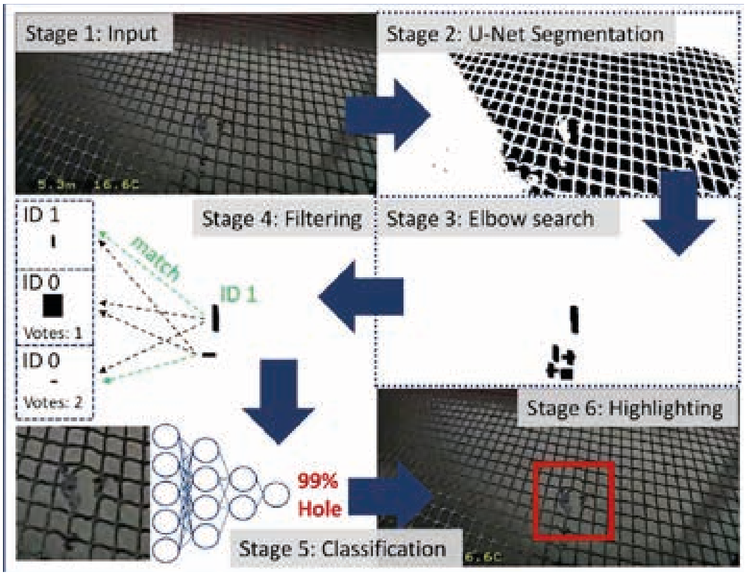


Figure 17: *Automated hole-detection framework.*

Robotic Vision for Aquaculture Monitoring of Structural Integrity and Fish Behavior

In aquaculture, it is crucial to keep farmed salmon secure within their cages. Any escape from these facilities could have a negative impact on wild salmon populations. To detect and prevent such escapes, frequent inspections of the integrity of the salmon cages are essential. Traditionally, these inspections were performed manually, but with advancements in computer vision and machine learning, a more automated approach is now possible. A novel framework for detecting potential damages in salmon cage nets using video recordings captured by cleaner robots is presented in **[P2-R13]**. The framework uses a combination of deep learning and computer vision techniques to analyze the video footage. In addition, a traditional computer vision technique for irregularity detections in fish cages is proposed in **[P2-R14]**. Both approaches were tested on real-world video recordings from commercial fish-cage operations, showing that these systems can effectively detect potential holes, even in difficult lighting conditions typical in aquaculture environments (cf. Figure 17).

Health and welfare assessment in aquaculture fish farms is another very important topic. In order to understand the behavior and stress levels of these fish, a new computer vision and machine learning system [P2-R15] was developed for tracking their movements at aquaculture sites. In the study, an advanced deep learning technique was used to identify and track fish. With this information, the fish's 3D position and their movement trajectories were estimated (cf. Figure 18). The new approach was tested in a real-world aquaculture setting, thus allowing a qualitative observation about fish behavior.

Contact: Annette Stahl

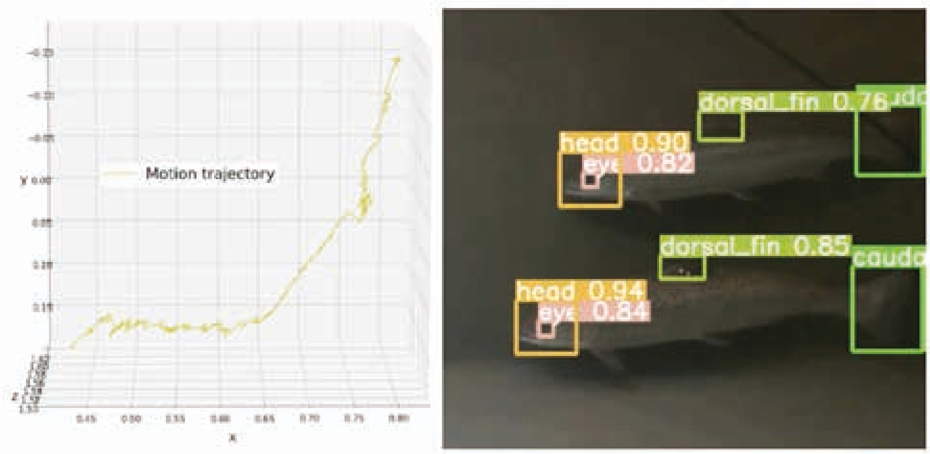


Figure 18: *Estimated fish motion trajectory based on detected fish features.*

Selected references:

P2-R1. **E.A. Basso, H.M. Schmidt-Didlaukies, K.Y. Pettersen, A.J. Sørensen**, "Global Asymptotic Tracking for Marine Vehicles using Adaptive Hybrid Feedback", *IEEE Transactions on Automatic Control*, 2022. DOI: 10.1109/TAC.2022.3161372

P2-R2. **Xu H., Greco M., Lugni C., 2022**, "Influence of Rigid/ Deformable Foil Shape on the Hydrodynamic Loads and Performance", 37th Int. Workshop on Water Waves and Floating Bodies, Giardini Naxos, Italy.

P2-R3. **Xu H., Greco M., Lugni C.**, 2022, "Numerical Study Relevant for Proper Design of Experiments on Swimming-fish Hydrodynamics", 14th International Conference on Hydrodynamics ICHD2022, Wuxi, China.

P2-R4. **Paniccia D., Graziani G., Lugni C., Piva R.**, 2022, "The fish ability to accelerate and suddenly turn in fast maneuvers", Scientific Reports, Vol. 12(1).

P2-R5. **Rothmund, S. V., Tengesdal, T., Brekke, E. F., Johansen, T. A.**, "Intention modelling and inference for autonomous collision avoidance at sea", Ocean Engineering, Volume 266, Part 4, Article 113080, 2022.

P2-R6. **Tengesdal, T., Rothmund, S. V., Basso, E. A., Johansen, T. A., Schmidt-Didlaukies, H.**, "Obstacle Intention Awareness in Automatic Collision Avoidance: Full Scale Experiments in Confined Waters", Field Robotics, 2022, Submitted.

P2-R7. **A. Dallolio, H. Øveraas, J. A. Alfredsen, T. I. Fossen, T. A. Johansen**, *Design and Validation of a Course Control System for a Wave-Propelled Unmanned Surface Vehicle*, Field Robotics, Vol. 2, pp. 748-773, 2022; https://doi.org/10.55417/fr.2022025.

P2-R8. **A. Dallolio, H. Øveraas, T. A. Johansen**, *Gain-Scheduled Steering Control for a Wave-Propelled Unmanned Surface Vehicle*, Ocean Engineering, Volume 257, paper 111618, 2022.

P2-R9. **Williamson, et al.**, "Monitoring algal blooms with complementary sensors on multiple spatial and temporal scales". *Frontiers in Ocean Observing: Emerging Technologies for Understanding and Managing a Changing Ocean*. Oceanography 36 (Supplement 1), https://doi.org/10.5670/oceanog.2023.s1.11.

P2-R10. **A.E. Oudijk et al.**, "Campaign For Hyperspectral Data Validation In North Atlantic Coastal Waters," *2022 12th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing (WHISPERS)*, Rome, Italy, 2022, pp. 1-5, doi: 10.1109/WHISPERS56178.2022.9955134.

P2-R11. **A. Dallolio, H. B. Bjerck, H. A. Urke, J. A. Alfredsen**, "A persistent sea-going platform for robotic fish telemetry using a wave-propelled USV: Technical solution and proof-of-concept", Frontiers in Marine Science, 2022.

P2-R12. **Hodne, L.M., Leikvoll, E., Teigen, A.L., Yip, M., Stahl, A., Mester, R.**, "Detecting and Suppressing Marine Snow for Underwater Visual SLAM," IEEE/CVF Proceedings - Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), pp. 5097-5105, 2022, doi:10.1109/CVPRW56347.2022.00558.

P2-R13. **Madshaven, A., Schellewald, C., Stahl, A.**, "Hole detection in aquaculture net cages from video footage" SPIE Proceedings, Vol. 12084, pp. 258-267, 2022, https://doi.org/10.1117/12.2622681. Fourteenth International Conference on Machine Vision (ICMV 2021) 12084,

P2-R14. **Schellewald, C., Stahl, A.**, "Irregularity detection in net pens exploiting Computer Vision» IFAC-PapersOnLine 55 (31), pp. 415-420, 2022, https://doi.org/10.1016/j.ifacol.2022.10.463.

P2-R15. TA Nygård, JH Jahren, C Schellewald, A Stahl, Motion trajectory estimation of salmon using stereo vision. IFAC-PapersOnLine 55 (31), pp. 363-368, 2022, https://doi.org/10.1016/j.ifacol.2022.10.455.

Selected media coverage

- **Snakes and Ladders - What The Duck?!**, By Dr. Ann Jones, ABC Radio National, March 5, 2022.

Plenary lectures

- **Pettersen, Kristin Ytterstad.** Snake robots and the power of nonlinear control. Plenary lecture at NOLCOS 2022+, Canberra, Australia.

- **Pettersen, Kristin Ytterstad.** Snake robots – and how snake robots research led to a new class of marine robots. IEEE WIE@25 "Extraordinary Science, Extraordinary Women Seminar Serie", September 2022.

JØRGEN AMDAHL
DO THE MATHS!

TOPIC: A popular and well-respected lecturer and researcher soon retires (he says). What is the sum up?

By Live Oftedahl

Jørgen Amdahl in front at Nordenskiöldsloppet in Sweden after 60 kilometers. It is the world's longest ski race: 220 kilometers long.

Photo: Private

Jørgen Amdahl (72) bikes every day with nearly the speed of light from his house at Byåsen to the Department of Marine Technology.

Either way he starts downhill and then work his way up. Electrical bike? No way! If you are a former ultra-ski race and mountain bike race competitor, you continue to push the limits and enjoy the muscle force and hardships that the hills will give you.

In his work as a professor at IMT and key researcher in NTNU AMOS, he has worked predominantly with the loads and forces that structures endure in the extreme environment of the ocean. He has an appetite for understanding the deformation and energy dissipation of structures under extreme actions, and not least the limits of the loads before you get fatigue, cracks, and failures.

What happens when everything goes to hell? When the oil platform Alexander Kielland flipped in stormy weather in 1980, and 123 people died, he could have been one of the experts to tell what went wrong, and how to prevent this from ever happening again.

Legendary lecturer

Amdahl is a legendary lecturer. He strictly judges his students. Every year a certain percentage end up failing their exams, but they worship him anyway. If he thinks they need to go up that hill again, he makes them do it. No mercy, but it is meant for the student's own good – and not least the industry. You cannot turn out candidates who can't do the maths. Ultimately, it can lead to death and destruction to not understand the calculations behind statistics, theoretical models and algorithms.

He started as a student at the department – at the time called the Department of Naval Architecture - in the early 70s. With his sharp mind and urge to teach, he ended up being a research assistant for a couple of years. The plan was to take a PhD, but at first, he did not find a subject that really captured his attention. Instead, he decided to work in DNV (Det norske veritas), and did so for three years.

> "Do we have to change the rules and regulations because of the climate changes? I am worried about the decades that are coming."

"When the former rector Dag Kavli asked me if I wanted to complete a PhD on ship collisions, I went back. The PhD comprised both of crushing of models in the laboratory and developing analytical models."

After finishing his PhD, he worked with structures in SINTEF's Department of Structural Engineering, later Marintek, and then as an associate professor at the department. In 1988 he became an associate professor and in 1994 he became a full professor.

Hereditary education

Altogether, he has spent 35 years at the department doing research and giving lectures and exams.

So why ship technology in the first place? He reveals that he also considered technical physics at the Norwegian Technical University – now NTNU. His father was a naval architect. He finished the same study program right after the second World War, and worked in Det Bergenske Damskibsselskab, which was founded in 1851, where he designed several coastal steamers. Thus, it was a kind of hereditary education profile.

He describes a very happy childhood at Persaunet, near Tyholt, and close to the laboratories at the Marine Tech Centre. But the way he pronounces the letter r, reveals that he might have had another dialect than the one from Trøndelag early on. The first three years he grew up in Bergen. It was there that he acquired the alveolar trill, the same as French people and Norwegians from the south-west coast are famous for.

He built a house with his wife at Byåsen in 1993 close to the best recreational areas in Trondheim and raised two boys there. He can walk out the door with his skis on, but to work, biking is the best option. Almost every day since the 90s, he has taken his bike to work, including in the winter.

Ultra

So, what does a professor and expert in collisions and extreme loads of structures do in his spare time?

In the summer: Some MTB races, and once he did UltraBirken – a 120 km challenging mountain bike race. In the winter: the Troll Ski Marathon in Lillehammer. The main distance is 95 kilometres, a classic cross-country ski race adventure. Amdahl has participated 17 times.

But it is not enough with just one ultralong ski race. The 90-kilometre Grenaderløpet in the Oslo area has also been one of his favourite races. He has participated 11 times, with the last time being four years ago when he was 68.

In 2017 he went to Sweden to participate in Nordenskjoldsloppet, which is 220 kilometres.

Amdahl seems to be a fan of finding the limits, not only of the structures in the ocean environment, but also within his own body.

Early wind turbine development

Since the 90s, he has seen a shift in the offshore industry and the research. At that time, the research was about extreme loads, accidental loads, ship collisions, fires and explosions.

He has been part of a team that has developed the software "Usfos" for the verification of structure robustness to accidental and abnormal environmental actions.

"Among other things this software has contributed to keeping oil platforms in business longer. We use it on other types of structures as well, for example, wind turbines."

Along with a group of colleagues at NTNU, DTU and engineering companies, they formed a company called Virtual Prototyping which assisted the Sway company in developing tension leg wind turbines around 2012.

"We may have been a bit ahead of time. We worked for three to four years with testing and development, and software for bottom-fixed structures, but in the end the Sway company got no investors, so the work stopped."

In the past decade he has seen a shift where assessment of the residual strength of structures with moderate damages from ship impacts and wave slamming becomes important. Can they still be used, or must they be repaired? Lighter and more marginally designed structures emphasize the needs for improved assessment of hydrodynamics-structure interactions.

At the same time, he sees a trend where the standards have to be modified. For example the 10,000-year waves are coming more often or should be increased, and design needs to be sufficiently robust.

"Do we have to change the rules and regulations because of the climate changes? I am worried about the decades that are coming."

The sunset of oil and gas

He also sees the sunset of the oil and gas industry ahead - but reassures that the department will still educate candidates who can do design and assessments of the platforms during operation.

"The trend is that we have a lot of master students on wind turbines, aquaculture structure, solar islands, floating bridges,

Photo: Private

On the top of the Smørstabbertind near Storebjørn in 2019.

From Markathrillern in Trondheim. A 30 km bike race in the mountains.

and fewer on oil and gas. The theory is the same, so I don't need to change all my teaching, but new issues are emerging, which is interesting. And in the end, we need to do research related to new and novel structures."

His motivation is that his field of interest never ceases to provide him with new learning.

"I think my field is fun and interesting, and I still think that I know too little, which is inspiring," he says.

He really enjoys teaching.

"I go straight to the point. They will learn to do estimations, and hopefully they learn a lot."

His advice to students is that they really should use time on the maths, and at least aim for a C or better.

Simple applied mathematics

"In the first year, the students should really take the math seriously. Good knowledge in mechanics, dynamics and fluids are extremely important, and is also important if you want to get at job after your studies. And you will certainly use it in the first parts of your career, before you move into leadership positions."

His primary worry now is that he thinks that there are currently far too few graduates in hydrodynamics and marine structures. He used to have classes of more than 80, now they count 25.

"I am worried that the industry will get a desperate lack of people with the competencies of understanding hydrodynamics, ocean structures and loads in the years to come."

"I am worried that the industry will get a desperate lack of people with the competencies of understanding hydrodynamics, ocean structures and loads in the years to come. More and more people can push buttons, but fewer know the estimations behind them. There are some really good senior engineers that must be replaced when they retire. I hope the ones that will take over are able to take the baton."

He also thinks the math he teaches is simple applied mathematics. (But he probably sees a marathon as a walk in the park as well?)

"The theoretical level as such is not that high. Everybody who studies here should do the maths, and like the maths. It is not that advanced."

These are always his famous last words. When the students do not understand at all, he exclaims:

"This is trivial!"

MARILENA GRECO

WAVE TO THE FUTURE:
FUTURE MARINE SCENARIOS WILL NEED BASIC RESEARCH

By Live Oftedahl

"AMOS wanted to be a live heart attracting people from all around the world to collaborate on complex topics as a multidisciplinary centre."

Photo: Live Oftedahl, NTNU

NTNU AMOS' research goal was to make the courageous choices to do leaps and progress.

Marilena Greco came to Norway from Italy to do a PhD in hydrodynamics with Professor Odd Faltinsen, recognized worldwide in his field as the primary supervisor. More than 20 years later, she is still here at the Department of Marine Technology.

She has been part of a Centre of Excellence (CoE) all these years, first in CeSOS run by Torgeir Moan and Odd Faltinsen, and then at NTNU AMOS.

"It is a unique situation to have two CoEs. I never forget the moment where we were presented as the new CoE after CeSOS decade was finished," she tells.

Another event Greco remembers well was the 70th year celebration of Odd Faltinsen and Torgeir Moan, the two leaders of CeSOS and scientific advisors of NTNU AMOS. It was a unique event. All their graduated PhD students were gathered, and there were presentations, discussions and outlines on new directions.

Among them was the societal need for greener, safer, and smarter marine and maritime solutions.

Complex and novel topics

"NTNU AMOS was our new research adventure. I remember the process when we formed the ideas into a vision. AMOS wanted to be a live heart attracting people from all around the world to collaborate on complex topics as a multidisciplinary centre."

She is certain that what was formed and achieved has an incredible footprint and opened to novel patterns of future research.

"There is no magical recipe, but part of the game is to try to do our very best. CeSOS had opened a path, now we needed to attempt to be even more interdisciplinary. In NTNU AMOS, this was a core effort."

She notes that they were a team of people from different disciplines, with different languages, different perspectives, and with different approaches to science and technology. For them it has been a challenging target; they did their best, and more will be needed in this direction because strong inter-and multi-disciplinary research paradigms will be more and more crucial for future scenarios in the marine field.

"Within NTNU AMOS, I had the opportunity to work on topics I never studied before, among them, on bioinspired studies involving fish hydrodynamics."

Bio-cyber-hydrodynamics

"Marine and maritime technology can directly and indirectly contribute to many of the 17 UN sustainable developments goals and play a primary role for energy and food production," says Greco.

In terms of research and development strategies, combining hydrodynamics and structural mechanics will be needed even more for a correct knowledge creation, while in certain contexts, other disciplines must be considered.

"For example, there will be an increasing effort to identify effective bio-inspired solutions that can overcome the limits in present marine operations and systems."

This will require a proper understanding of the physical mechanisms and their proper translation into robust and effective algorithms, and therefore an interdisciplinary coordinated effort, including biology, hydrodynamics, structural mechanics, material science and control theory.

"Marine engineered solutions have not achieved yet the same performance and skills observed in some aquatic animals. By learning from their biological features, we can develop greener and more sustainable solutions in several marine scenarios, with the potential of a game changer."

At the same time as new areas arise, Greco emphasizes that we should not be disrespectful to oil and gas technology. Several lessons can be learned from the classical marine and maritime technology and transferred to the novel applications, although the peculiarities of the latter must be recognized for which research, also of a fundamental type, is required.

CoEs and future research fundings

Greco thinks it will be hard to set new Centres of Excellence with the same footprint in the marine field as that of NTNU AMOS, because future CoEs will not involve industrial partners. Only Centres of Innovations (SFIs) can be used for this purpose.

"Collaborating with industries can be an important added value for CoEs in our research field. They can inspire on the challenges they face on a longer run, leading to research questions that require fundamental type of research to achieve disruptive, instead of incremental, changes," she states.

She continues: "The hope is that the changes that we might face in terms of research-funding availability and other trends will not endanger the important and independent role of our university in providing high quality education, supervision and research."

A unique journey

For Greco, NTNU AMOS has been a lifetime achievement and a unique research opportunity.

"Asgeir has been the main strategist of NTNU AMOS. To me he is a big shining star, a generous and honest researcher and person. His ability of inspiring people gathered us as a team, making this 10-year research adventure a reality. I am honoured and thankful to have been part of such brilliant group of scientists."

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:

- Experimental and theoretical, comparative analysis of semi-closed and closed fish cages in waves
- Experimental and numerical analysis of a local hydroelastic response of concrete shells during impact and challenges in connection with proper scaling laws
- Experimental and numerical analysis of local hydroelastic effects induced by wave impacts relevant for offshore structures in steel
- Experimental, numerical and analytical analysis of the filling-flow phenomenon occurring in confined spaces of offshore and coastal structures
- Development of a fully nonlinear 3D numerical wave tank using HPC for accurate and efficient modelling of large-scale waves
- Hydrodynamic studies relevant for floaters of floating offshore wind turbines
- Simplified method for the calculation of net and rope forces, and fatigue prediction of aquaculture nets subjected to waves and current
- Numerical analysis of wind turbine structures subjected to ship collision
- Design, structural modelling, control and performance of very large wind turbines
- Fatigue sensitivities of large monopile offshore wind turbines to design parameters and engineering models
- Experimental and numerical analysis of structures subjected to cryogenic temperatures
- Development and verification of material models for integrated ice-structure analysis with the nonlinear finite element method
- Verification of nonlinear finite element modelling of aluminum structures considering residual stresses and strength reduction in the heat affected zone

Highlights

Closed and semi-closed fish cage systems have been proposed, as cage designs prevent salmon lice, which nowadays represents an important challenge for the Norwegian aquaculture industry. A comparative analysis between a closed cage (CC) and a semi-closed/open-bottom cage (OC) in regular, white-noise and irregular waves has been performed [R3-P1]. A primary target is to experimentally and theoretically examine the similarities and differences of the hydrodynamic behavior between the two cages.

Each of the examined cages consists of a vertical, circular, free surface-piercing cylinder with an external toroidal floater (see Fig. 1).

Transfer functions obtained from regular and white-noise waves test show that the two cages have a similar performance in surge motion, ovalizing deformations, interior wave elevation and mean drift loads in shorter waves (wavelength-to-cage diameter ratio $\lambda/D < 1$). This is not the case for heave, with OC experiencing a much larger heave. A clear sinkage (minus average heave) is also observed for OC, which is almost proportional to the square of the incident wave amplitude. The linear potential flow solver WAMIT can provide a reasonable prediction of surge and pitch motions, as well as mean drift loads for OC in shorter waves ($\lambda/D < 1.5$), but is unsatisfactory in longer waves and, in general, for heave motion.

From the analysis of irregular wave tests, there is a small difference in the standard deviations of the surge motion (wave-frequency component) and interior waves for the semi-closed and closed cages. The slow-drift component is dominant in surge

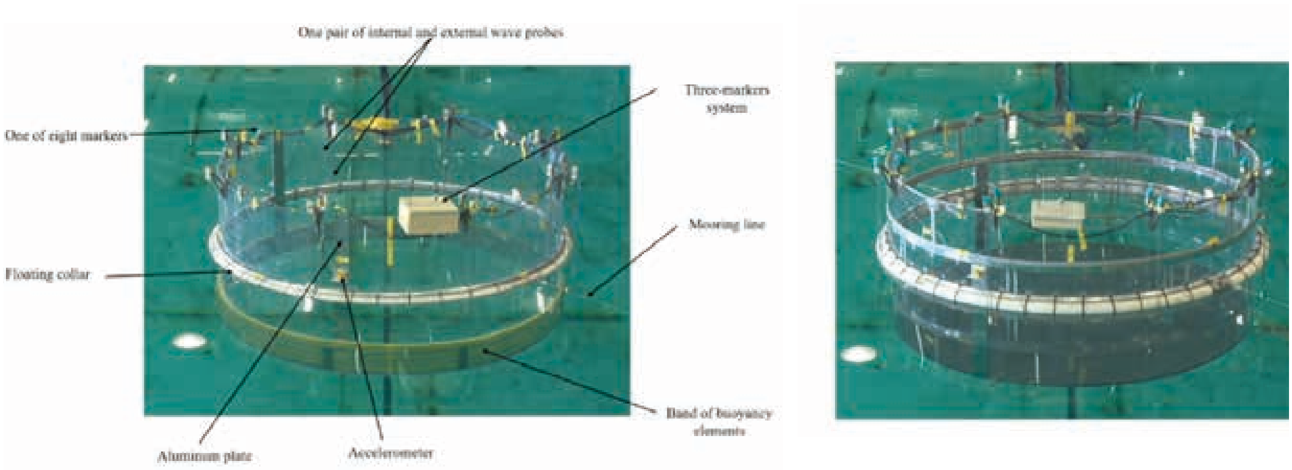
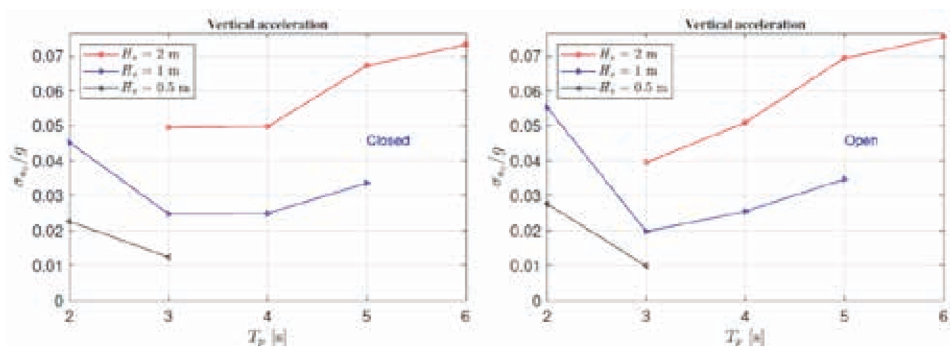


Figure 1: *Front-camera photo of the physical model for the open-bottom cage (left) and closed cage (right)*

Figure 2: *Standard deviation of interior vertical acceleration at the back side of the closed (left) and semi-closed (right) cages at a fixed wave heading and different significant wave height Hs and peak wave period T_p*



for both cages, with OC having a smaller value due to a larger viscous damping associated with flow separation at the bottom. Theoretical evaluations of standard deviations based on transfer functions from a white-noise test and from WAMIT are performed, assuming that the linear superposition principle applies.

A reasonable agreement against results from experiments in irregular waves is achieved, with the exception of response variables with strong nonlinear effects. Survival conditions for both cages are determined through systematic evaluations, with the platform freeboard identified as the most critical parameter. The minimum freeboard for the closed and semi-closed cage should be at least 1.05 and 1.3 m, respectively, to operate at moderate exposure sea states. Due to rigid body motions and interior waves, the standard deviation of vertical acceleration could reach 0.72 m/s^2 for both cages at high exposure sea states (see Fig. 2), which might be of concern for the fish inside.

Slamming implies a water-structure impact, and is of concern for the structural design of ships, offshore platforms, the lowering of subsea structures through the splash zone, accidentally dropped objects and the launching of free-fall lifeboats from offshore platforms. Relevant scenarios, important parameters and phenomena, in addition to related challenges, have all been documented by Prof. Faltinsen within a plenary keynote lecture [P3-R2].

One must note that slamming on ships and sea structures causes both a local and global structural response, and ought to be coupled with structural mechanics to find important time scales of the many physical effects associated with slamming. Hydroelastic slamming has an analogy to the transient response of a mass-spring system. Important factors are the ratio between slamming duration and important structural natural periods, the time history of loading, added mass and slam damping. If the time scale of a fluid mechanic effect, such as liquid compressibility or gas cavity oscillations, is very small relative to the structural natural periods associated with maximum structural stress, the details of the fluid mechanic effect does not matter. Hydroelasticity of concrete shells, horizontal plates and wedge-shaped cross-sections during drop tests are theoretically discussed, and partly compared with experiments. Both the water-entry and water-exit phase matter in describing the global load effect due to wet deck slamming on catamarans and offshore platforms. Bow slamming

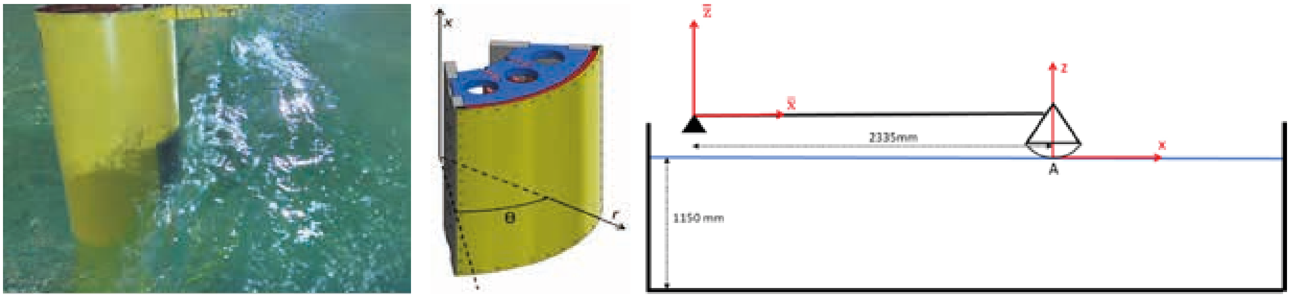


Figure 3: *Left: Wave hitting a monopile during a scaled ocean basin model test at 1:55. Center: A local approximate Froude-scaled model shell representing concrete covering a section of the column with a local elastic section. Right: Idealized drop-test set up showing the hinged arm and the frame holding the elastic model shells.*

and the whipping of ships are discussed with an emphasis on the modelling of slamming in an engineering context. Sloshing-induced slamming in prismatic LNG tanks is perhaps the most complicated slamming problem, because many fluid-mechanic and thermodynamic parameters, as well as hydroelasticity, may matter. Furthermore, complicated in-flow scenarios of slamming may appear due to violent sloshing. The consequence is that both computational tools and model test scaling are limited.

Many ocean structures located offshore are supported by large vertical concrete columns. High and steep storm waves – in the process of breaking – may induce large local slamming loads on these columns (see the example on the left of Fig. 3, from model tests). The fundamental physics of the local hydroelastic shell response due to slamming has been examined both experimentally and numerically [R3-P3].

The concrete columns supporting typical offshore structures are large; the size means that full-scale tests of a segment of the column are impractical and expensive. Model-scale testing in a wave tank is also challenging. Firstly, the scaling of structural properties needs to adhere to the scaling laws of hydrodynamics. Secondly, the manufacturing of realistic Froude-scaled elastic shell models is hard since curved shells carries loads by a combination of bending and membrane action (see example in the center of Fig. 3, from model tests). The challenge is to scale both the bending and membrane action properly. The present study examined how realistic Froude-scaled elastic shells representing concrete shells can be designed, along with the experimental and numerical analysis of drop tests (see sketch in the right side of Fig. 3). The results show that even large and thick concrete shells experience significant hydroelastic effects during slamming. The hydroelastic response of the concrete shells is dominated by only a few structural eigenmodes. This means that the calculated dynamic amplification factors, DAF, resemble those of one-degree-of-freedom mass–spring systems exposed to loads of finite duration.

Fig. 4 shows the DAFs of the shell displacement, hoop bending moment and hoop membrane force near the shell center (see left sketch in the figure) as a function of the ratio between the load duration T_d and the dry natural period, T_n, of the governing structural mode. The DAFs are plotted for thin and thick experimental concrete shells, and for their corresponding models.

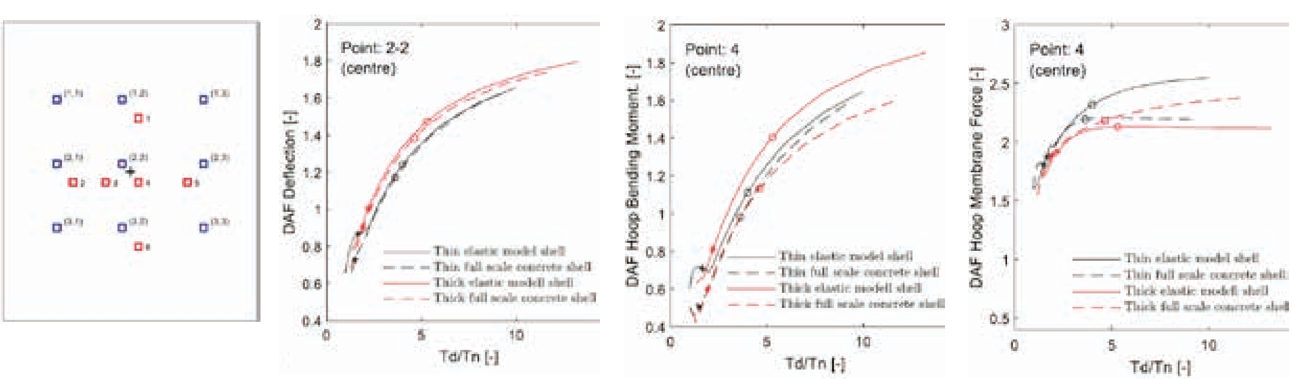


Figure 4: *Left: Location of accelerometers (blue) and strain measurement points (red) and related numbering; the shell is seen from the outside (wet side). a-b-c panels: Dynamic amplification factors versus load duration-to-governing natural period ratio Td/Tn for (a) the deflection at the centre (pt. 2–2), (b) the hoop bending moment at the centre (pt. 4) and (c) the membrane force at the centre (pt. 4). The impact velocity of 10 m/s and 24 m/s are indicated by circles (o) and stars (*), respectively.*

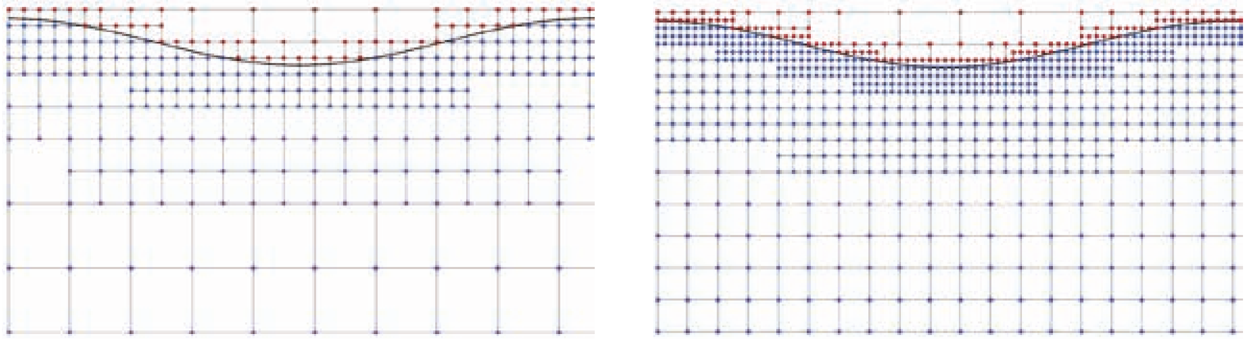


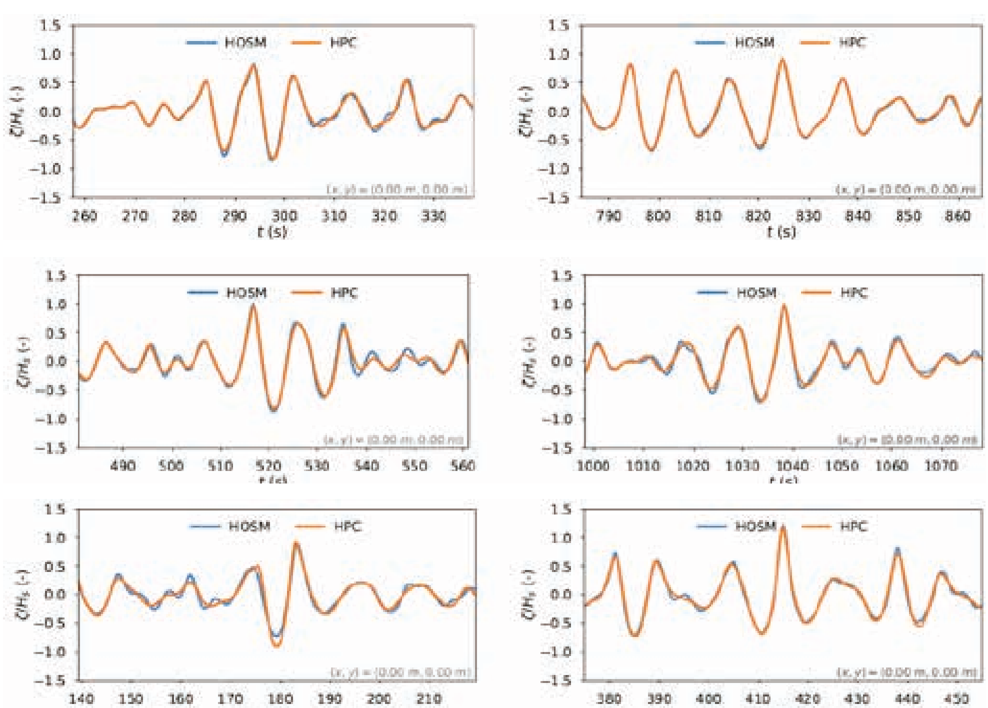
Figure 6: *Example of numerical wave tank with AGR. The blue nodes are below the free surface and the red nodes are free-surface ghost nodes used to enforce free-surface boundary conditions within the HPC solution strategy.*

None of the DAFs for the concrete shell approached 1 for large T_d/T_n, differently from steel/aluminium wedges impacting a flat free surface (see, e.g., Faltinsen, 1999, J. of Ship Res.). The analysis also indicates that structural responses significantly modify the hydrodynamic loads, both in terms of added-mass effects and in terms of a time-dependent slam damping term, which reduce the structural response when properly accounted for. Both terms are necessary to accurately calculate the concrete shell response.

A thorough understanding of ocean-wave processes is needed to explain extreme observations such as rogue waves. The transfer of energy between different wave components due to nonlinear dispersion effects may play an important role in the formation of high wave crests in a stochastic sea state leading to rogue waves. Moreover, nonlinear wave effects can be important to predict accurate loads on a structure, for example, slamming loads related to the height of- and kinematics under an approaching wave crest, or the slowly varying excitation of a moored floater in a stochastic sea state. With this perspective, a three-dimensional (3D) fully nonlinear potential flow (FNPF) numerical wave tank (NWT), able to study large-scale free-surface wave scenarios efficiently, has been developed [R3-P4].

The governing Laplace equation for the velocity potential is solved using the harmonic polynomial cell (HPC) field method, which is a field method giving a high-order accuracy, provided that the cells used to describe the water domain have no stretching or distortion. This can only be achieved in a grid with cubic cells, which leads to a poor numerical efficiency unless measures are introduced to refine the grid locally. Here, to improve the

Figure 7: *Time-series excerpts showing deepest troughs (left) and highest crests (right) in the middle of the numerical tank for deep-water long-crested irregular sea conditions from present (HPC) and reference (HOSM) simulations. From to bottom: Significant wave height Hs = 5, 7 and 9 m and spectral peak period T_p=10 s.*



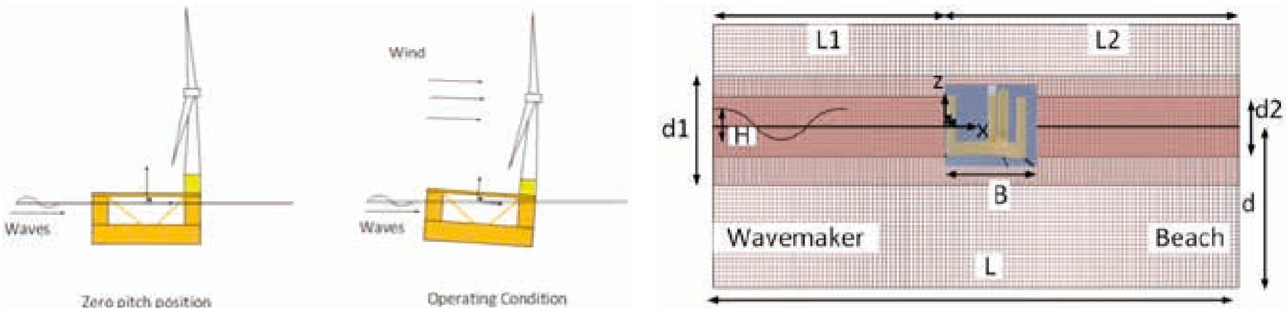


***Figure 8:** Left: typical mean pitch angle in parked vs. operating condition for a FOWT. Right: Computational domain for the diffraction CFD simulations of the floater in waves.*

efficiency using strictly cubic cells, an adaptive grid refinement (AGR) technique is introduced (see Fig. 6).

This can improve the computational speed with a factor of up to 20 without sacrificing accuracy. Numerical results are shown to be in a good agreement with highly accurate nonlinear reference solutions for regular and irregular waves of various steepness up to the limit of theoretical wave breaking (see examples in Fig. 7).

For long-crested irregular waves, significant discrepancies with a second-order theory for the crest-height distribution are identified, while the second-order theory appears to provide a better description of the crest height for the single short-crested irregular sea state simulated. Having demonstrated that the proposed numerical method accurately models nonlinear wave phenomena up to the limit of wave breaking, future work should seek to implement wave-body interaction capabilities. The adaptive grid refinement technique, which refines the grid dynamically depending on the position of boundaries of interest, is developed with this application in mind. Except from providing a robust way of dealing with wave-body intersection points, extending the method to account for wave-body interactions should therefore involve a limited difficulty.

The development of floating offshore wind turbines (FOWTs) has picked up a great pace in the last 5-10 years. Commercial projects in planning and development demonstrate a shift of industry perception, thereby making it relevant to, understand the behavior of these complex systems. A numerical investigation has been carried out on the hydrodynamic behavior of the floating substructure (floater) for FOWTs [R3-P5] also examining the mean pitch angle experienced by them in operational conditions (see the left side of Fig. 8).

Generally speaking, potential-Flow (PF) methods are used to calculate the hydrodynamic loads on the floater with a Morison Element (ME) model to empirically approximate the drag (viscous) forces. On the other hand, Computational Fluid Dynamics (CFD) methods inherently account for viscous effects. In the present research, a diffraction analysis for a semi-sub FOWT (UMaine Volturn US-S) was performed using the open-source CFD platform OpenFOAM (OF) in regular waves (see computational setup in the right of Fig. 8), with the results compared against the PF method. The effect of a varying wave height and wave heading for the floater is examined. The influence of a non-zero pitch angle in the operating condition for FOWTs on wave-drift loads is investigated, using CFD and compared against PF results with empirical viscous-flow corrections. The effect of static pitch appears slightly larger in CFD results, though the underlying physics need to be investigated further.

As fish farms move to more exposed locations, engineers need quick and accurate tools for both initial design proposals and analysis verification. A simplified method to estimate the axial force in the ropes supporting the fish net is proposed [P3-R6].

As shown in Fig. 9, the problem is simplified from a complete panel to a single rope analogous to representing a stiffened panel by a single stiffener. The axial force in the rope is estimated based on the principle of virtual displacements, assuming a triangular displacement shape. Loads from both waves and current are considered. The results for most of the ropes agree well with simulations using a RIFLEX fish net element, which is based

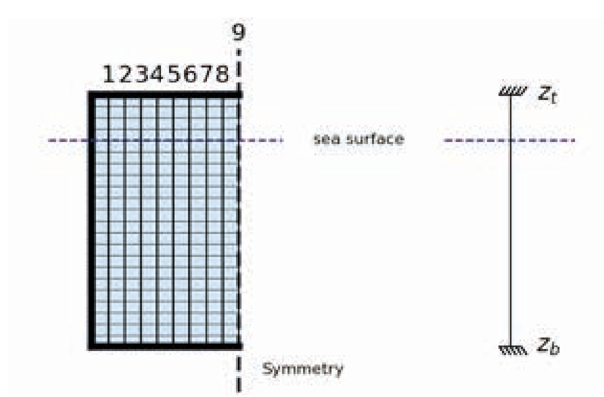


***Figure 9:** Left: Half of a complete panel analysis model. Vertical ropes shown with numbers, fish net elements with thin horizontal black lines. Thick black lines are beams supporting the net panel. The shaded area represents the net. Right: Simplified model of one rope.*

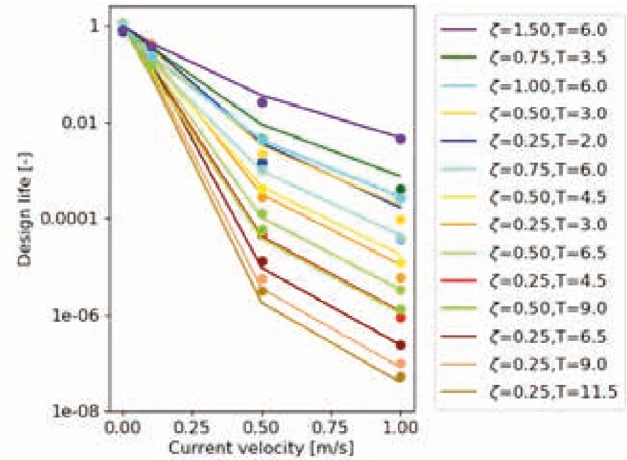


Figure 10: *Change in fatigue life as a function of current velocity for different wave periods and wave heights. Solid lines are numerical analyses, while the dotted lines are simple hand calculations based on PVD. Fatigue for steel detail with m = 3.0.*

on Løland's screen model. The fatigue in the steel supporting beam due to axial force oscillations as estimated for different wave and current combinations, as the fatigue estimates by the simplified model were generally in a good agreement with numerical simulations, as shown in Fig. 10. The simplified method is approximately 300 times faster than ordinary calculations, and is therefore suitable for engineering use.

The fatigue limit state (FLS) design of offshore wind turbines (OWTs) is based on design load cases according to relevant design standards, which account for the uncertainty in resistance and loads by applying safety factors to achieve a specified reliability level. The safety factors give little information on how the uncertainty in specific parameters influences the total uncertainty of the support structure capacity of an OWT. Such knowledge is essential, notably in the design of larger OWTs and foundations in deeper water or harsher conditions

Previous sensitivity studies have typically focused on uncertainties from specific engineering disciplines, hence making it hard to grasp which parameters are important for the predicted capacity in a design process. The influence of these uncertainties on the fatigue capacity for monopile-supported wind turbines, with a rated capacity of 5 MW, 10 MW and 15 MW (Fig. 11), were investigated (P3-R7) focusing on the tower and pile itself. First, the uncertainties in site conditions, production and material properties, and turbine operational parameters were considered. Second, the uncertainties related to various engineering models were considered.

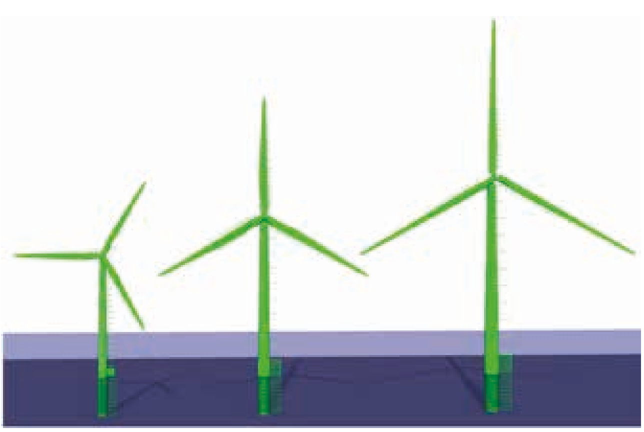
In the first stage, uncertainty in the fatigue capacity of steel was found to have the largest effect on the lifetime fatigue damage, followed by uncertainties in the environmental conditions and soil parameters (Fig. 12). Wind loads become increasingly important when the turbine size increases.

Alternative models for wind coherence, wave spreading, wave spectrum, and soil and scour protection were considered relative to baseline models (Fig. 13). All models were found to be important in some locations of the support structure. Wind models had the largest influence on the tower top utilization, while the soil model and selection of wave spectrum in general had the highest effect on the predicted utilization in the tower base. Wave spreading, soil model and scour protection models were important in the monopile, but the influence of the soil model depended heavily on the calibration.

Liquified natural gas (LNG) vessels carry a cryogenic cargo at a temperature of -1630 C. If a leakage of LNG to unprotected steel occurs by human errors or accidents, 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 spills tests from a pool with liquefied nitrogen (LN2) in the centre of six unstiffened EH36 rectangular steel plates with an initial crack being conducted. The

Figure 11: *Left: Finite element models of the 5 MW (left), 10 MW (middle) and 15 MW (right) turbines used in the study. The hub height increases from 90 m for the 5 MW turbine to 150 m for the 15 MW turbine. The rotor diameter increases from 126 m to 240 m. Right: Design parameters studied.*



Wind Speed	U
Wind Direction	θ_{wi}
Turbulence intensity	TI
Wind shear	α
Yaw error	γ_Y
Significant wave height	H_s
Peak period	T_p
Wind-wave misalignment	θ_{rel}
Marine growth	t_{mg}
Drag coefficient	C_d
Undrained shear strength	s_u/σ'_{v0}
Void ratio	e
Monopile diameter	D_p
SN parameters	$\log(a_{1,2})$
Fatigue capacity	Δ_C
Unavailability	A

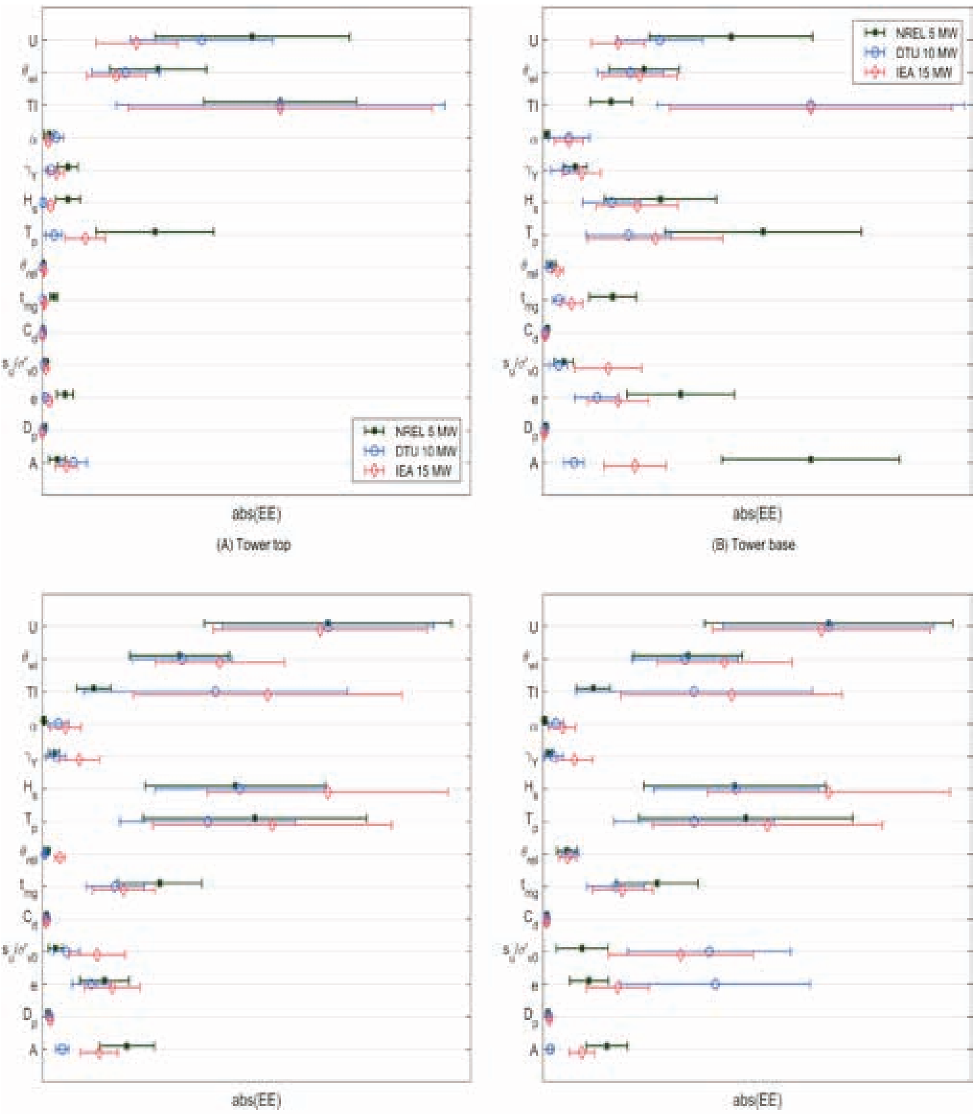


Figure 12: *Elementary effects (EE) for four locations of the support structure for the 5MW, 10 MW and 15 MW turbines. The mean values and standard deviation ranges are indicated. A large mean EE and standard deviation indicates a parameter that is important for the overall uncertainty.*

experiments and heat transfer analyses were reported in two papers highlighted in the Annual Report for 2021. The third part (P3-R8) of the three-companion paper deals with the structural analysis of the tests, and addresses the stress field, fracture initiation and crack propagation in the steel plates. The test plates reached a temperature of -1930 C in the pool, which caused thermal tensile stresses and strains in the crack region. Additional tensile forces were needed to trigger failure, which occurred in the elastic range. The fracture surface showed that crack initiation and propagation (Fig. 14) occurred in a brittle mode. A sequentially coupled thermal-stress analysis with large shell elements gave a satisfactory agreement with respect to reaction force and fracture path, refer to Fig. 15. The strain energy density (SED) criterion proposed by the authors in a previous paper was used to simulate fracture. Critical SED values were estimated by inverse analyses, and were comparable with values obtained by a numerical calibration in a previous investigation. The feasibility of the SED criterion in structural analysis with large shell elements was demonstrated, but the need for detailed calibration and an assessment of the SED criterion is acknowledged.

Design against ice actions in Arctic waters is of great concern for shipping, renewable energy developments, natural resource explorations, commercial fisheries and tourism. The economical design of marine structures against ice impact loads is challenging due to an incomplete knowledge of the behavior of ice, owing to its varied compositional and microstructural properties in different environments, as well as phase transition and microstructural transformations in different loading conditions. Because of its complex and stochastic properties, no widely accepted material model for ice exists.

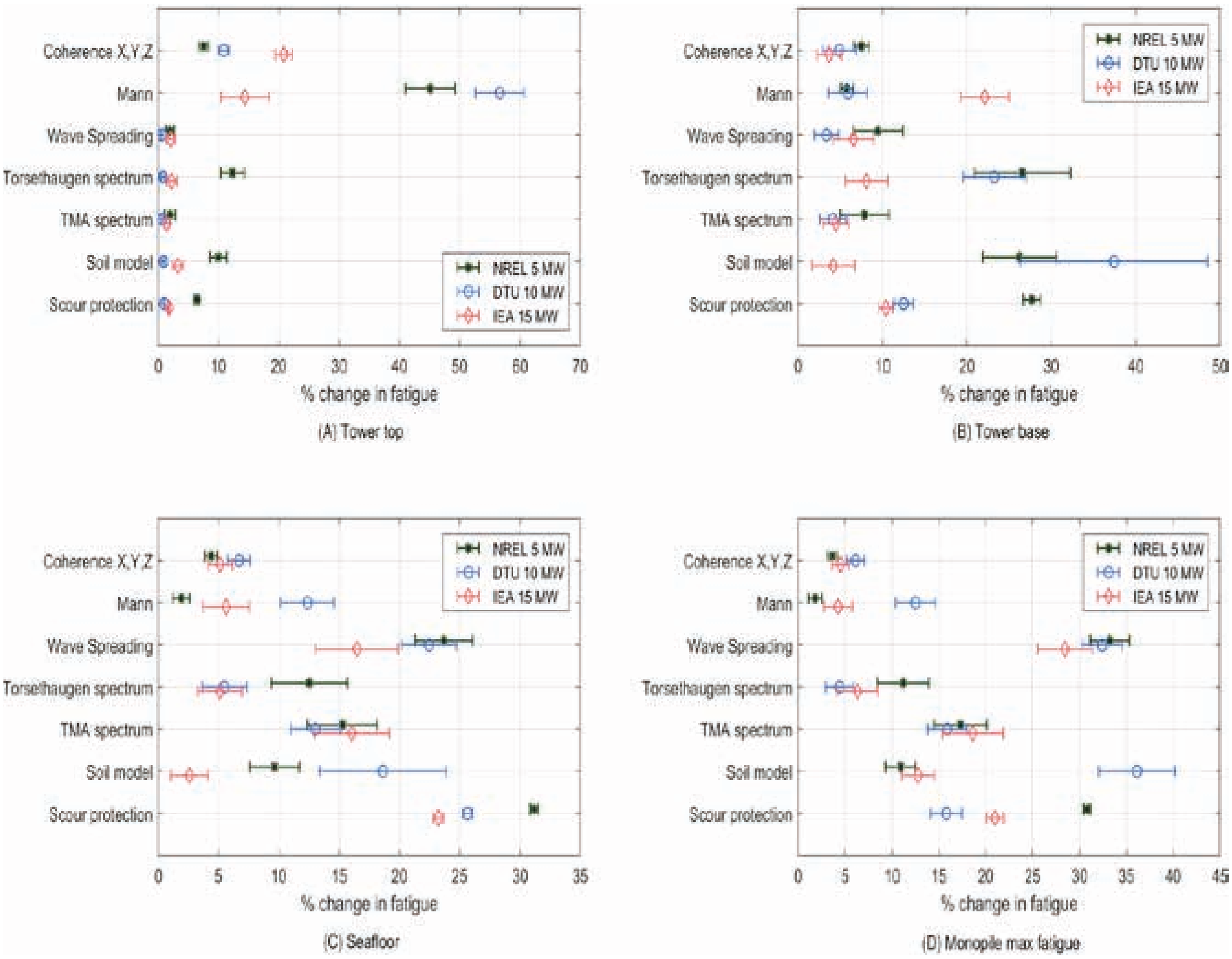


Figure 13: *Relative change in lifetime fatigue damage across the support structure using alternative models for wind coherence, wave spreading, wave spectrum, soil and scour protection.*

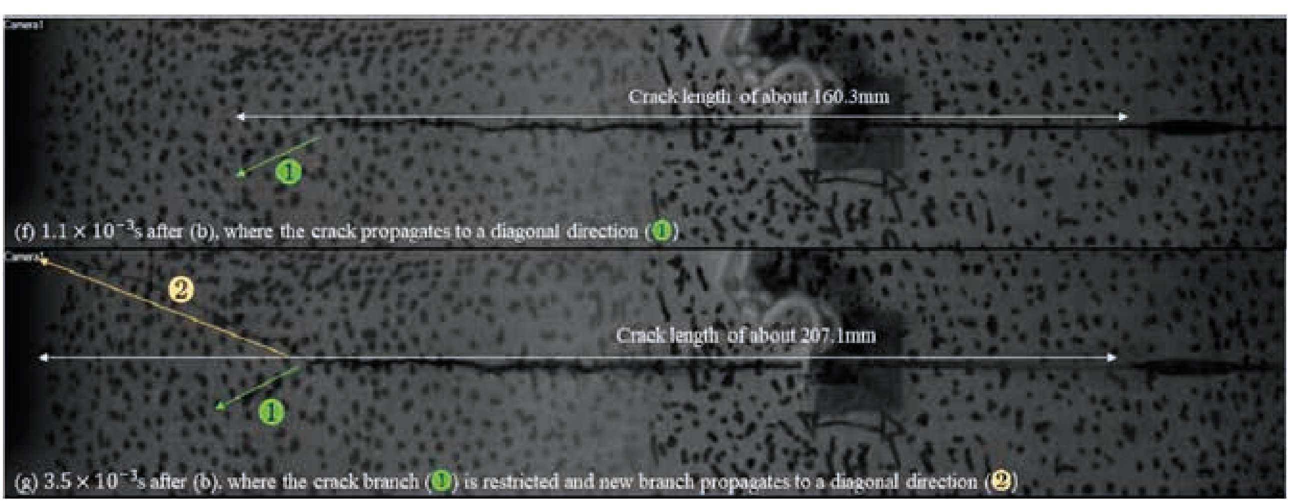


Figure 14: *Crack initiation at a propagation at two different stages captured by a high-speed camera*

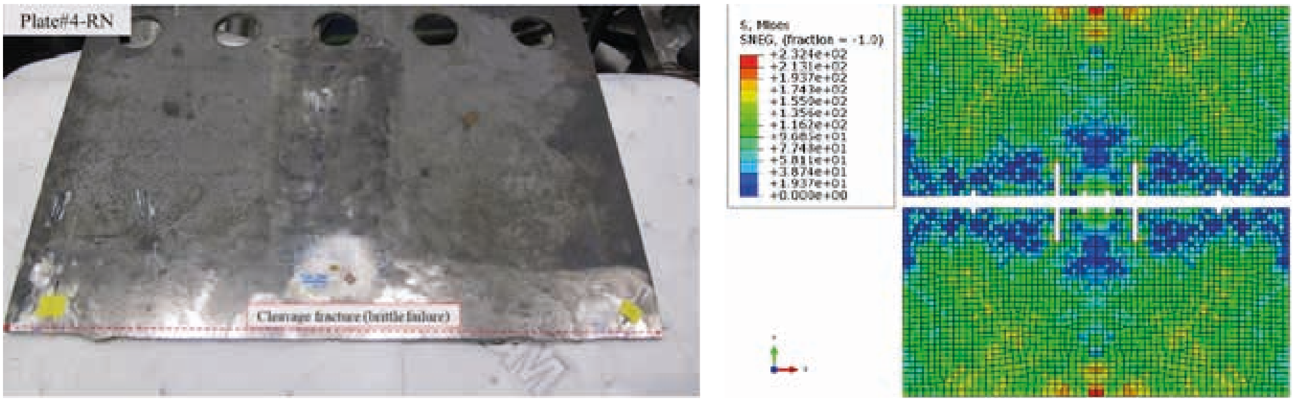


Figure 15: *Comparison of the experimental fracture path (left) and numerical (right) for specimen PLATE#4-RN*

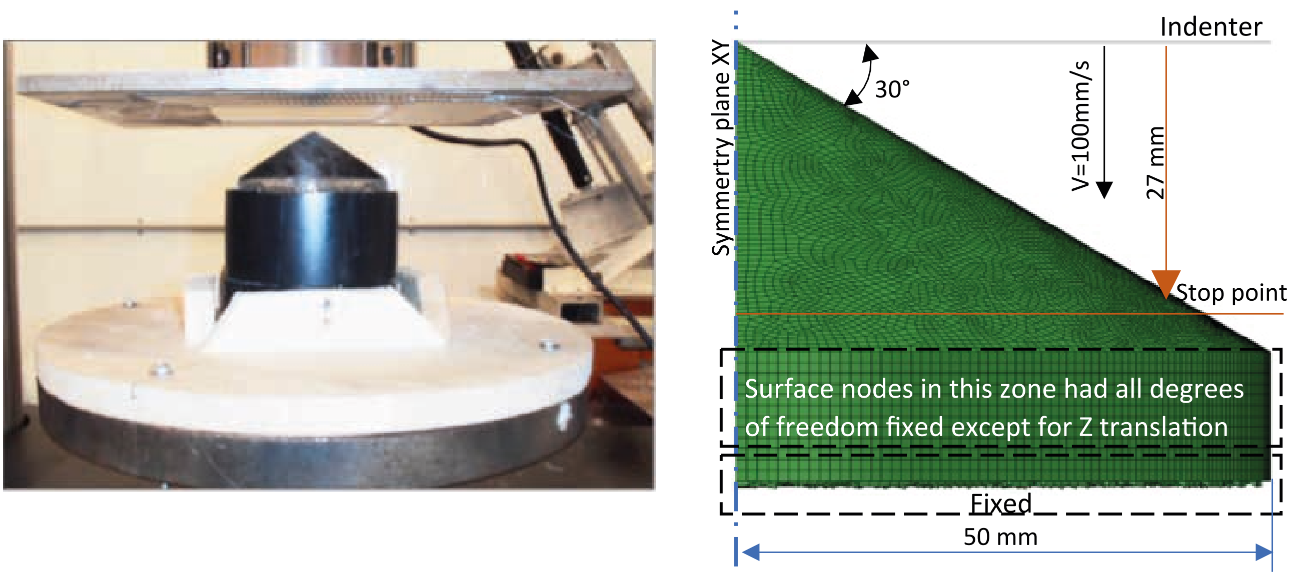


Figure 16: *Cone-shaped ice; left) test set-up; right) A quarter finite element model of the ice crushing test with 1 mm uniform discretization. The indenter speed is 100 mm/s.*

Two well-known plasticity-based material models are the Crushable Foam (CF) model and an elastoplastic material model (VUMAT) partly developed and applied in ice impact studies at IMT-AMOS. The accuracy and efficiency of these models to replicate ice loads were the subject of a systematic study conducted with the Abaqus explicit solver **[P3-R9]**. The two models were compared in eight single-element tests and 28 different simulations of a physical ice crushing test at laboratory scale (Fig. 16).

Despite their identical yield loci, the two plasticity models produced significantly different results. Unlike the VUMAT model, the CF model failed to simulate the confining pressure, while the unconfined behavior was similar. The von Mises stress, hydrostatic pressure, equivalent plastic strain and failure strain evolution for two of the single-element tests, with and without the confining walls, are shown in Fig. 17 (Left).

This means that the CF material model is incapable of generating high-pressure zones caused by high confining pressures in the ice domain during crushing, simply due to its zero plastic Poisson's ratio. The confinement insensitivity of the CF model was also noticed in the conical ice crushing test simulations, such that the CF model returned approximately 70% of a smaller hydrostatic pressure in the ice at the beginning of the simulation (2.8 mm indentation), which was reduced to 48% at a 14 mm indention. Fig. 17 (right) demonstrates that element size has a significant effect on the CF model results, while the VUMAT exhibits far less sensitivity to the element size. This means that the VUMAT can be more confidently used with large finite elements, as opposed to the CF model, thereby reducing the computational cost.

To help investigate the effect of strain rate on the ice rheological behavior, especially in low velocity ice-structure interactions, a nonlinear viscoelastic material model with progressive damage

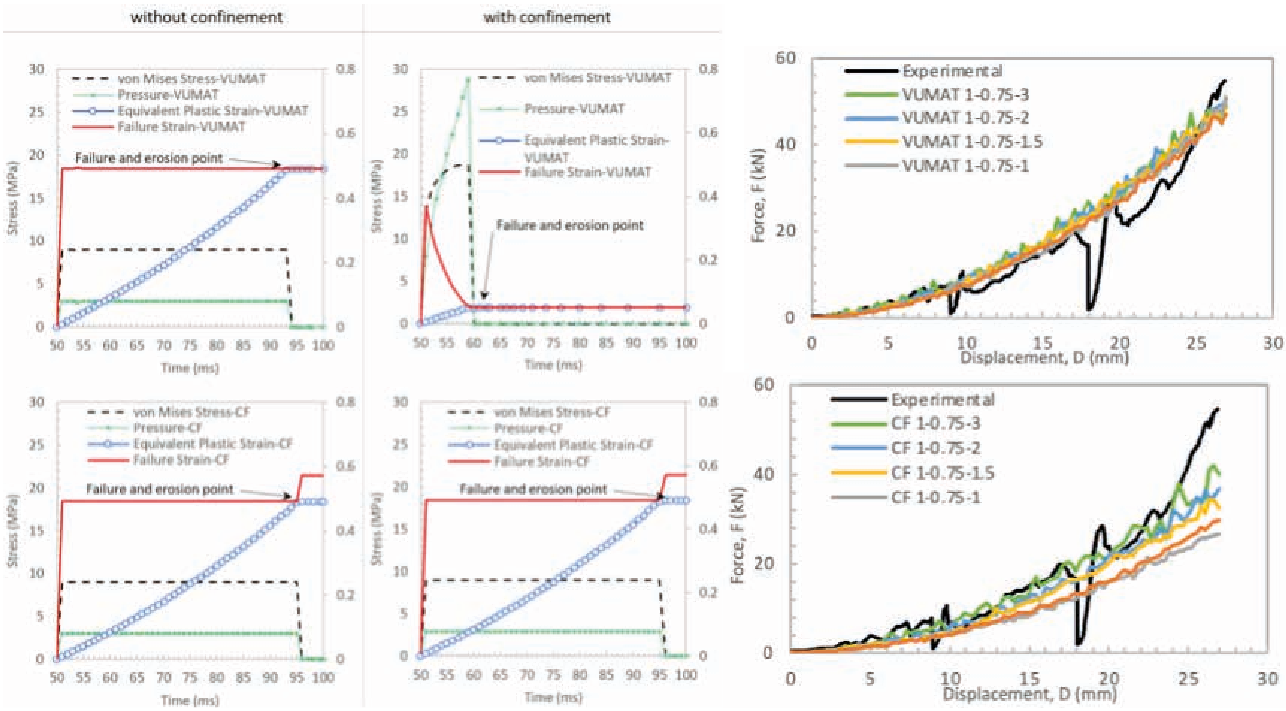


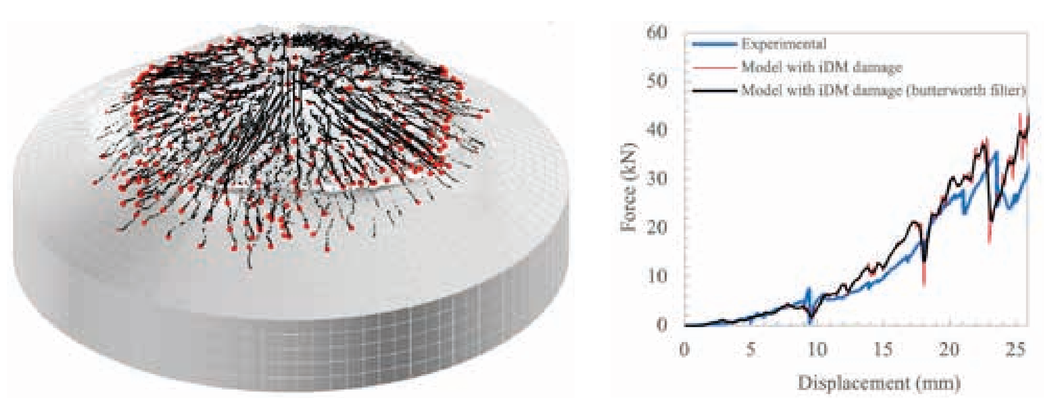
Figure 17: *lLeft: Single element test results produced by the VUMAT (top row) and the CF model (bottom row), Right.: Reaction force vs. displacement for five different element sizes (3, 2,1.5, 1 and 0.75 mm) in the ice crushing test produced by the VUMAT (top) and the CF model (bottom).*

was also developed [P3-R10]. This model, when implemented with the coupled FEM-SPH or arbitrary Lagrangian-Eulerian (ALE) methods, better captures ice-load oscillations due to microstructural changes in ice crushing, which also allows for a more accurate simulation of ice loads at relatively low strain rates when the viscoelastic behavior of ice governs the load response (Figure 18). However, the plasticity-based VUMAT outlined above is more practical for real-size collision simulations.

Offshore wind farms are generally located near the coast close to traffic lanes, and are exposed to the risk of collisions from visiting and passing ships. The potential consequences of collisions may vary from local structural damage to the detachment of turbine nacelles and rotors, and even tower collapse and the capsizing of the turbine platform, thus causing significant economic loss and fatalities.

The dynamic response of the 10 MW OO-STAR semi-submersible floating offshore wind turbine, subjected to ship collision loads from a modern supply vessel of 7,500 tons (Fig. 19), and a shuttle tanker of 150,000 tons was investigated with USFOS and LS_DYNA software **(P3-R11)**.

Figure 18: *Left: Extrusion of crushed ice simulated with SPH particles (red points) with tracing visualized (black dotted lines). Right: Force vs. displacement obtained from the physical crushing test and the nonlinear viscoelastic material model implemented with the coupled FEM-SPH method. Indenter speed is 1 mm/s.*



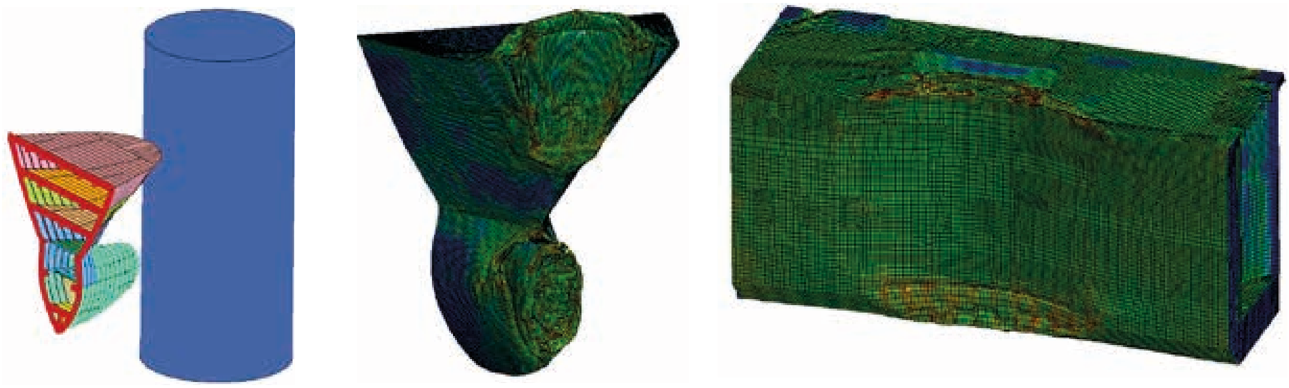


Figure 19: *Deformation of a 7,500-ton supply vessel after bow and broad side impact with one column of the OO-STAR floater.*

It was found that the wind turbine is generally safe when it is subjected to supply vessels' collisions with a design energy of 37 MJ for bow impact, and 21 MJ for broad side impact. However, the nacelle accelerations exceed the allowable operational limit, and may damage the delicate equipment inside the nacelle. It is generally more critical when a collision occurs during operation, with the worst case being when the vessel strikes from the opposite of the wind direction. The turbine thrust will induce a negative pitch angle of the platform. The combined actions of collision loads, wind thrust and the tightened mooring lines may significantly amplify the pitch motion, and cause a possible capsizing of the floater for a shuttle tanker impact (Fig. 20). The wind loads increase the tower bending moments and nacelle accelerations, hence increasing the risk of tower local buckling and exceedance of the nacelle operational limits. The compliance of floating offshore wind turbines is favorable, and they are therefore capable of resisting ship impacts of a much higher energy without collapse compared to bottom fixed installations and a speed 2 m/s (the spring element to the left side represents the nonlinear force deformation behavior of the tanker side).

Aluminum extruded panels are increasingly used in marine structures as lightweight solutions in high-speed vessels, helicopter decks, gangways and living quarters because less welding is needed than for traditional built-up profiles with a stiffener attached to plate sheets. Nonetheless, the buckling mode and ultimate strength of aluminum extruded panels are difficult to predict with existing formulas due to a different welding sensitivity.

The nonlinear finite element method was used to simulate the buckling of aluminum extruded panels (P3-R12). Numerical simulations were verified by a comparison, with experiments accounting for welding-induced geometric and mechanical imperfections (Fig. 21). The numerical study showed that the dynamic solver was superior to the static solver, notably when the stiffener-tripping mode occurs, because the inertia effects stabilize the solution and prevent an overprediction of the ultimate strength. The buckling modes, load end-shortening curves and ultimate loads were consistent with the results of the reference experiments

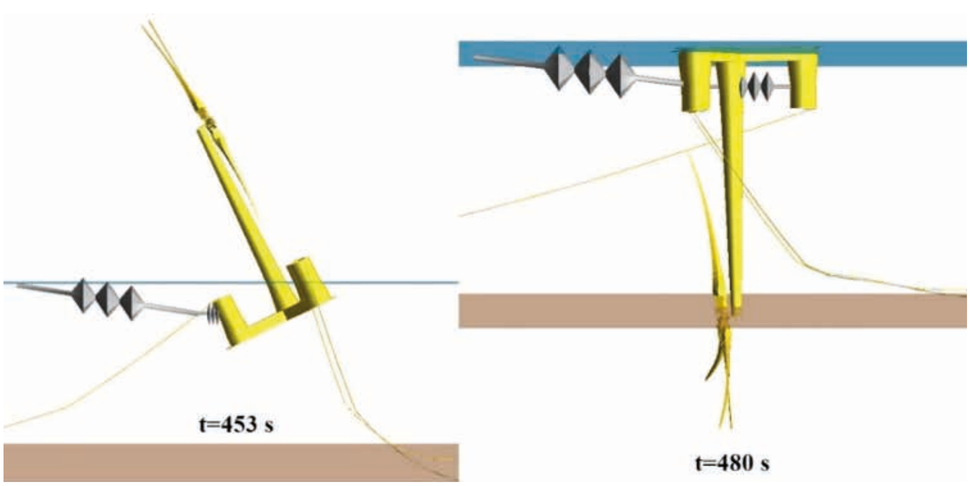


Figure 20: *Overturning of the floater after a broad side tanker impact with a kinetic energy of 420 MJ.*

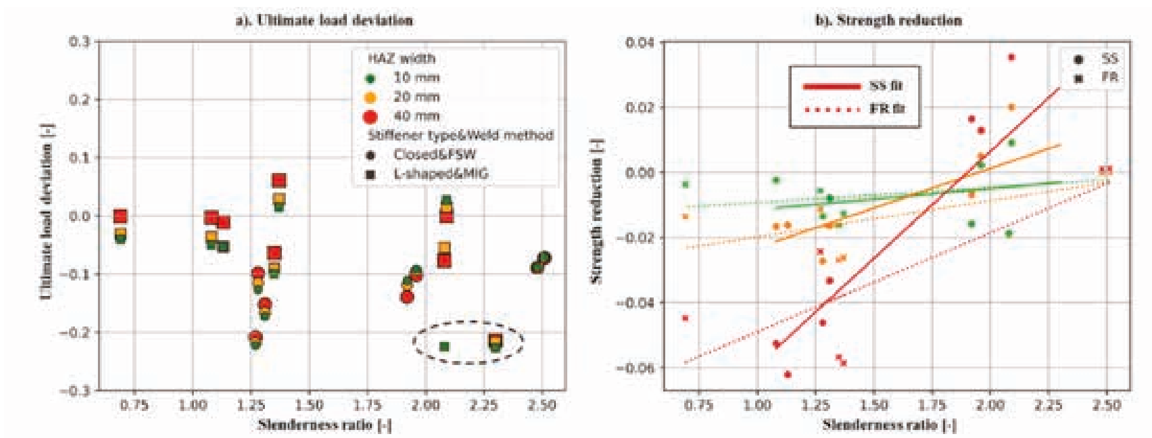


Figure 21: *Numerical results with varying HAZ width, including residual stresses. The width of the HAZ is indicated by different colors. The stiffener types and welding methods are indicated by different markers. 'SS' indicates simply supported boundaries, while 'FR' indicates free boundaries. Left: Simulated Ultimate strength deviation from experiments Right: Ultimate strength reduction relative to unwelded panel (negative values imply a higher strength). Experiments by A. Aalberg, M. Langseth and P. K. Larsen, 2001,* Stiffened aluminum panels subjected to axial compression *Thin-Walled Structure.*

The modeling of residual stress is essential. Inconsistencies in the predicted buckling mode can be corrected when residual stresses are considered. Yet, they may artificially strengthen the panels, and thus cause overestimations of the ultimate load. Large residual stress levels, comparable to HAZ material yield stress, should be avoided.

The reduced material strength in the heat affected zone (HAZ) has a small effect on the ultimate load. When both strength reduction and residual stresses are included, the impact on the ultimate strength highly depends on the slenderness ratio; stocky panels with a low slenderness ratios are more sensitive, probably due to different buckling modes being triggered. The residual stresses increase the ultimate load within a certain range of the slenderness ratio, which depends on the stiffener type, whereas they decrease the ultimate load for slender panels.

Selected references:

P3-R1 **Shen Y., Firoozkoohi R., Greco M., Faltinsen O.M.**, 2022, Comparative investigation: Closed versus semi-closed vertical cylinder-shaped fish cage in waves, Ocean Engineering, 245.

P3-R2 **Faltinsen O.M.**, 2022, Plenary lecture: Slamming load effects on ships and marine structures, PRADS 2022, Dubrovnik, Croatia.

P3-R3 **Abrahamsen B.C., Grytten F., Hellan Ø., Søreide T.H., Faltinsen O.M.**, 2022, Hydroelastic Response of Concrete Shells During Impact on Calm Water, accepted in 2022 and published in 2023 in Journal of Fluids and Structures, 116.

P3-R4 **Hanssen F-C. W., Helmers J.B., Greco M., Shao Y.**, 2022, A 3D fully-nonlinear potential-flow solver for efficient simulations of large-scale free-surface waves, International Journal for Numerical Methods in Engineering, 124.

P3-R5 **Siddiqui M.A., Hanssen F.-C., Greco M., Anda E.**, 2022, Investigation of CFD versus Potential-Flow Methods for Hydrodynamic Loads on a Floating Offshore Wind Turbine, accepted to the 14th International Conference on Hydrodynamics ICHD2022, Wuxi, China.

P3-R6 **Slagstad M., Yu Z., Amdahl J.**, 2023, A simplified approach for fatigue life prediction of aquaculture nets under waves and currents, Journal of Ocean Engineering 272

P3-R7 **Sørum, S. H., Katsikogiannis, G., Bachynski-Polic, E. E. , Amdahl, J. , Page, A. M. and Klinkvort, R.**, 2022, Fatigue design sensitivities of large monopile offshore wind turbines, Wind Energy, Vol. 25, Issue 10

P3-R8 **Nam, W., Hopperstad, O. S. and Amdahl, J.**, 2022 Thermal analysis of marine structural steel EH36 subject to non-spreading cryogenic spills: Part III: Structural response assessment, Ships and Offshore Structures, October 2022.

P3-R9 **Mokhtari, M., Kim, E., and Amdahl, J.**, 2022, Pressure-dependent plasticity models with convex yield loci for explicit ice crushing simulations, Marine Structures, 84, p. 103233.

P3-R10 **Mokhtari, M., Kim, E., and Amdahl, J.**, 2023, A non-linear viscoelastic material model with progressive damage based on microstructural evolution and phase transition in polycrystalline ice for design against ice impact, International Journal of Impact Engineering (*Accepted with minor revision*).

P3-R11 **Yu, Z., Amdahl, J., Rypestøl, M. and Cheng, Z.**, 2022, Numerical modelling and dynamic response analysis of a 10 MW semi-submersible floating offshore wind turbine subjected to ship collision loads, Renewable Energy Vol. 184, pp. 677-699.

P3-R12 **Wang, X., Amdahl, J. and Egeland**, O., 2022, Numerical study on buckling of aluminum extruded panels considering welding effects, Marine Structures 103230.

Photo: Asgeir J. Sørensen

NTNU AMOS PARTICIPATION IN ASSOCIATED PROJECTS

Awarded/Ongoing **Completed**

Awarded/Ongoing Projects

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

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

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

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

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
SFI Autonomous Ships	Mary Ann Lundteigen Tor Arne Johansen, Thor I. Fossen, Ingrid B. Utne, Edmund Brekke, Annette Stahl, Tasos Lekkas, Mortein Breivik Roger Skjetne	Not yet clear Ca 200 MNOK	2020-2028	SFI Centre	NTNU, SINTEF Ocean, Kongsberg	5 PhD Postdoc
NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS)	Asgeir J. Sørensen, Kristin Y Pettersen, Martin Ludvigsen Kjetil Skaugset	45 MNOK	2020-2025	VISTA	Equinor, NTNU, DNVA	6 PhD
Machine Piloted Unmanned Systems (MPUS)	Tor Arne Johansen	1MNOK	2020-2023	NFR MAROF	Radionor, MR, Seatex, NTNU	1 Postdoc
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		Researchers
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-Polic, 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-Polic	21 MNOK	2017-2020	KPN	SINTEF Ocean, NTNU, NGI, Equinor, RWE, EDF, Vattenfall, Multiconsult	1 PhD + 1 Postdoc
WINDMOOR Advanced wave and wind load models for floating wind turbine mooring system design	Erin Bachynski-Polic	16 MNOK	2019-2023	KPN	SINTEF Ocean, NTNU, Inocean, Equinor, APL NOV, MacGregor, RWE	1 PhD
FLOAWER (FLOAting Wind Energy network)	Erin Bachynski-Polic	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 ships, ports, and offshore structures	Asgeir J. Sørensen Erin Bachynski-Polic	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-Polic	14.5 MNOK	2020-2024	KPN	IFE, NTNU, U. Texas, Equinor, Aibel, GCE Node, Olav Olsen, Energy Valley	1 PhD
Marine archeology using marine robotics	Øyvind Ødegård Asgeir J. Sørensen	4 MNOK	2020-2023	NTNU VM		1 PhD
Perception & Fusion of Multidimensional Information & Cooperative Decision-making for Intelligent Diagnosis of Wind Turbine Critical Parts (InteDiag-WTCP)	Zhen Gao, Amir Nejad	8 MNOK	2020-2023	NFR IKTPLUSS (International Calls for Bilateral Project between Norway and China)	EDR & MEDESO AS, SAFETEC NORDIC AS	2 PhD
CONWIND: Research on smart operation control technologies for offshore wind farms	Amir Nejad, Trond Kvamsdal, Michael Muskulus, Zhen Gao	4 MNOK	2020-2023	NFR (International Calls for Bilateral Project between Norway and China on Energy)	NORCE, University of Bergen, SINTEF	1 Postdoc
Autonomous DP operation	Tor Arne Johansen, Edmund Brekke	4 MNOK	2020-2023	NFR	SINTEF Ocean Brunvoll	1 PhD
FME NORTHWIND – Norwegian Research Centre on Wind Energy	Zhen Gao, Erin Bachynski-Polic	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, Murat 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	Researcher
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
A system-of-systems approach to real-time integrated ocean environmental monitoring	Tor Arne Johansen, Geir Johnsen	12 MNOK	2022-2025	NFR IKTPLUSS	Grieg Seafood, Moen Marin, NTNU TTO	1 PhD + 2 Postdoc

Completed Projects

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

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

OBSERVING ARCTIC MARINE LIFE – FROM THE SEABED TO SPACE

NTNU researchers from AMOS, the Centre for Autonomous Marine Operations and Systems, used small satellites and subsea robots — and everything in between — to study marine life in Svalbard's Kongsfjorden in a first-ever experiment in May.

By **Live Oftedahl** – SciTech News Norway June 21 2022

In late May, NTNU researchers and students used a small satellite, an unmanned aerial vehicle, two unmanned boats and subsea robots to survey the same area simultaneously. This is an approach called an observational pyramid.

The Arctic is both an interesting and important area from which to observe climate change. At this latitude, temperature and ecosystem changes are evident sooner and clearer than in more temperate areas. For Professor Geir Johnsen, one of the critical questions to ask — and answer — is what is happening to phytoplankton, which form the base of the food web.

"Are they growing? Are they in good shape? Are they dying? Are they in rave party mode?" he wants to know.

Environmental monitoring

The approach the researchers have used, the observational pyramid, can be used to survey normal and harmful algal blooms and the kinds of changes global warming is causing in the ocean in a more continuous way.

"This concept can be developed and streamlined, especially when it comes to faster data interpretation. We have worked with biologists to customize this approach, according to what they need, but it can be used for other purposes as well," says Asgeir J. Sørensen, a professor of marine cybernetics and Director of NTNU AMOS.

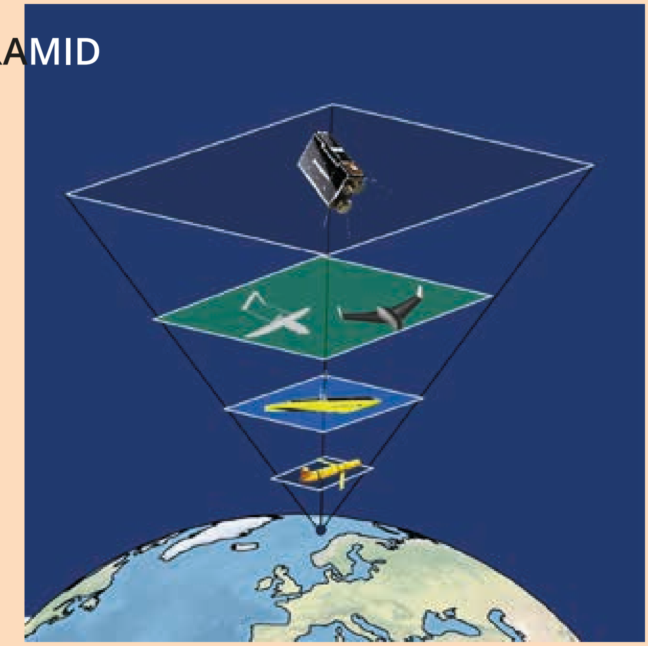
One driver for this development is the long collaboration with Equinor to develop methods and technologies to monitor the offshore oil and gas environment, as well as offshore renewable energy systems.

The first ever attempt of an observation pyramid was conducted in Ny-Ålesund in Svalbard in May 2022, with a team of students, PhD candidates, researchers and professors. A joint effort. Fun science!

Photo: Asgeir J. Sørensen

HERE'S THE OBSERVATIONAL PYRAMID

- NTNUs first research satellite, HYPSO-1, with a hyperspectral imager.
- One aerial drone with a hyperspectral imager, so-called UAV (Unmanned Aerial Vehicle)
- Unmanned boats with both underwater hyperspectral imager, acoustic sensors, and other types of sensors, so-called USVs (Unmanned Surface Vehicles).
- Subsea robots, called AUVs (Autonomous Underwater Vehicles).
- Biologists taking water samples to provide species details, photosynthesis datas, health condition and optical fingerprints to identify what the unmanned vehicles register. This was part of the UNIS course "Light and primary production in the Arctic".



A graphic showing the observational pyramid, in which the same area is monitored at different levels at the same time. Illustration: Department of Engineering Cybernetics, NTNU

Sørensen pointed out that the aquaculture industry can also benefit from more effective and automated ways of monitoring and surveying fish welfare conditions, and the environment near the fish pens.

This technology can also be used to learn more about freshwater systems in Norway, such as the national efforts to monitor the environmental health of Mjøsa Lake, Norway's largest.

An automated coast guard

Imagine an automated coast guard beneath the ocean surface that monitors ocean health and traffic in the ocean space. That's essentially what this approach offers, the researchers say.

Hyperspectral maps and aerial drones combined with unmanned surface vehicles and subsea drones can be used at the same time to collect more data over a shorter time frame.

"This will give us more knowledge and a better understanding of what is going on in the ocean," Sørensen says.

Dennis D. Langer is a doctoral candidate in marine technology. He took the course in marine biology to understand more of what the sensors he is helping to develop will actually investigate. Photo: Live Oftedahl

A number of master's students, PhD candidates and postdocs participated in the experiment.

"This could lead to new industries, value creation and new workplaces in Norway in the near future," Sørensen says.

The first test of the observational pyramid was done in close collaboration between the University of Tromsø and UNIS – the University Centre in Svalbard and several departments at NTNU. This research is also part of the Nansen Legacy project. Researchers from both the US and Australia came to Ny-Ålesund to see the observational pyramid in action.

See the article here: https://norwegianscitechnews.com/2022/06/observing-arctic-marine-life-from-the-seabed-to-space/

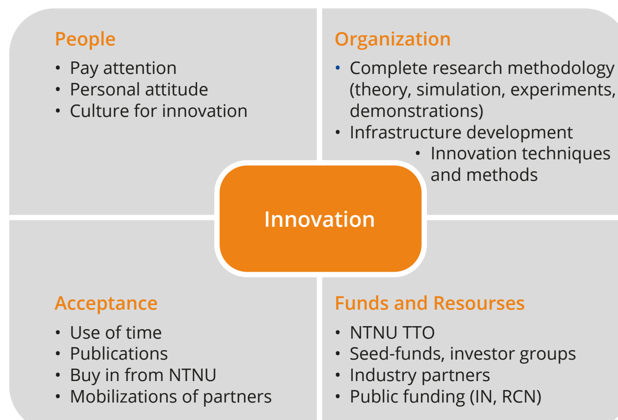
WITH A LICENSE TO CREATE,
RESEARCHER-DRIVEN INNOVATION AT NTNU AMOS

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, and NTNU AMOS was preparing to become a leading international player in heterogeneous robotic systems for marine mapping and monitoring. These efforts are strongly supported by the 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 already in 2010 before they become "hot¨ in Norway and elsewhere. This is also one reason for the great interest and rapid growth of AMOS in terms of funded PhDs and affiliated scientists. AMOS research topics have become an important part in the Norwegian transition towards a more digitalized future directed by a blue economy, which would create new possibilities and reduce the cost of operations.

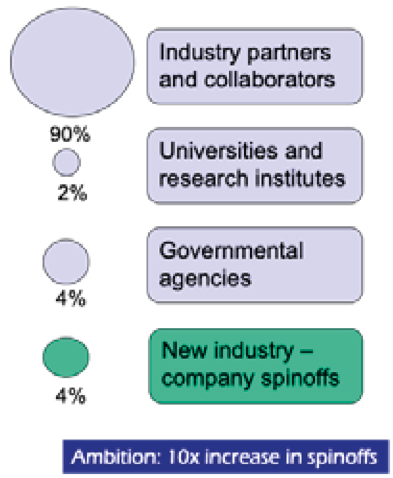
Because AMOS was clearly affected by this wave and rapid transition both socially and industrially, it became a huge responsibility to secure new industry positions that were about to be created. That is why the AMOS School of Innovation, later known as the Ocean School of Innovation, was established.



NTNU AMOS has systematically developed a culture for innovation in collaboration with the partners and NTNU TTO

Since 2003 NTNU has hosted two Centre of Excellence – CeSOS and NTNU AMOS. Since then, ten companies have been founded

The most important innovation areana for NTNU AMOS is primarly established industry.



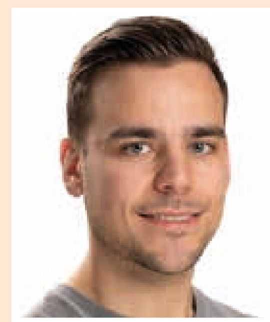
Research-driven innovations and entrepreneurships were then systematically explored, and PhD and postdoc candidates were offered training on innovation processes. To date, **eight** spinoff companies represent a direct measurable outcome of this in addition to several filed patents.

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

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

AWARDS AND HONOURS 2022


Basso receiving the award



Received the NOLCOS Best Student Paper Award

Erlend A. Basso and Henrik M. Schmidt-Didlaukies have received the Best Student Paper Award of the 12th IFAC Symposium on Nonlinear Control Systems in 2022.

In the justification for awarding the prize, it was stated that not only was this the best student paper, but the paper was ranked as one of the highest quality papers of the conference.

Title of the paper: E.A. Basso, H.M. Schmidt-Didlaukies, K.Y. Pettersen and J.T. Gravdahl, "Synergistic PID and Output Feedback Control on Matrix Lie Groups", Proc. 12th IFAC Symposium on Nonlinear Control Systems, Canberra, Australia, Jan. 4-6, 2023.

Young Author Award to Markus H. Iversflaten

Markus H. Iversflaten, PhD at NTNU AMOS and Caros, received the IFAC CAMS 2022 Young Author Award.

The title of the paper was Kinematic and Dynamic Control of Cooperating Underwater Vehicle-Manipulator Systems.

This was announced during the 14th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles.

Congratulations to Markus – and congratulations also to his co-author and fellow PhD-student Aurora Haraldsen and Kristin Y. Pettersen, Professor and supervisor.

Outstanding Paper Award at IEEE

Marie Bøe Henriksen, Fred Sigernes and Tor Arne Johansen got the best paper award for the paper «A closer look at spectrographic wavelength calibration", presented at the Twelfth Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing, in Rome in September 2022.

APPENDICES

ANNUAL ACCOUNTS AND MAN-YEAR EFFORTS

Annual accounts and man-year efforts

REVENUES IN 2022 (AMOUNT IN NOK 1000)	
Actual:	
Income	38 713
Costs	44 254
Year end allocation	- 5 541
In Kind	
Income	14 377
Costs	14 377
Total	
Income	53 090
Costs	58 631
Year end allocation	- 5 541
AMOS 1 end allocation	5 497

PERSONNEL 2022	
Keypersons	7
Adjunct prof/associated prof	13
Affiliated scientists	31
Scientific advisers	2
Postdoc/researchers	6
Affiliated postdocs/resarchers	15
PhD Candidates	24
Affiliated PhD candidates	105
Administrative staff	6
Management	2
Technical staff	2
Graduated PhD candidates financed by NTNU AMOS	3
Graduated PhD candidates associated to NTNU AMOS	9

Annual accounts and man-year efforts

ANNUAL ACCOUNTS	
Operating income	Accountes income and costs
The research council of Norway	8,061
NTNU	25,781
Others	4,871
in kind	14,377
Sum operating income	53,090
Operating costs	Accountes income and costs
Salary and social costs	32,442
Equipment investments	5,753
Procurement of R&D servises	550
Other operating costs	5,509
in kind	14,377
Sum operating costs	58,631
Year end allocation	-5,541
Opening balance 20180101	5,497
Closing balance 20181231	6,382

Total man-years efforts

MAN-YEARS	2022
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	2,45
Affiliated prof/scientists	6,67
Scientific advisor	0,50
Postdocs	4,12
Postdoc (affiliated)	10,88
Visiting researchers	-
PhD candidates	15,5
PhD candidates (affiliated)	64,34
Total research man-years	110,66

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

NATIONALITY	KEY PROFESSOR	ADJUNCT PROF/ ASS PROF	AFFILIATED SCIENTIST	SCIENTIFIC ADVISOR	POSTDOC/ AFFILIATED POSTDOC	VISITING PROFESSOR/ RESEARCHER	PhD	Assc PhD	ADMINISTRA-TIVE STAFF*)	SUM
Norwegian	6	7	20	2	8	-	16	59	6	
Other nationalities	1	6	10	-	13	-	8	46	-	
Sum	7	13	30	2	21	-	24	105	6	-
Man-years	3,50	2,45	6,67	0,50	15,00	-	15,50	64,34	2,20	110,16

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

AMOS PERSONNEL 2022

Management and administration

NAME	TITLE	ACRONYM
Prof. Fossen, Thor I	Co-director	TIF
Karoliussen, Renate	Senior executive officer	RK
Oftedahl, Live	Communication Officer	LO
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.Marine Technology	Structural load effects, resistance, accidental actions	JA
Prof. Fossen, Thor I.	NTNU, Dept.Engineering Cybernetics	Guidance, navigation and control	TIF
Prof. Greco, Marilena	NTNU, Dept.Marine Technology	Marine Hydrodynamics	MG
Prof. Johnsen, Geir	NTNU, Dept.Biology	Marine biology	GJ
Prof. Johansen, Tor Arne	NTNU, Dept.Engineering Cybernetics	Optimization and estimation in control	TAJ
Prof. Pettersen, Kristin Y.	NTNU, Dept.Engineering Cybernetics	Automatic control	KYP
Prof. Sørensen, Asgeir J.	NTNU, Dept.Marine Technology	Marine control systems	AJS

Senior Scientific advisers

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

PhD candidate Jens Einar Bremnes controlling and AUV during the first trial of the observation pyramid in Kongsfjorden in May 2022.

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. Larsen, Kjell	Equinor	Marine operations and structures	KL
Adj. Ass. Prof. Scibilia, Francesco	NTNU, Dept. 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.Engineering Cybernetics	Automation in fisheries and aquaculture	JAA
Ass. Prof. Alver, Morten Omholt	NTNU, Dept. Engineering Cybernetics	Automation in fisheries and aquaculture	MOA
Ass. Prof. Brekke, Edmund F.	NTNU, Dept.Engineering Cybernetics	Sensor fusion	EB
Prof. Bachynski, Erin E.	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	EEB
Ass.Prof. Brodtkorb, Astrid Helene	NTNU, Dept.Marine Technology	Marine Cybernetics	AB
Adj.Prof. Bryne, Torleiv Håland	NTNU, Dept. Engineering Cybernetics	Navigation systems	THB
Dr. Breivik, Morten	NTNU, Dept.Engineering Cybernetics	Nonlinear and adaptive motion control	MB
Ass. Prof. Bye, Robin T.	NTNU, Dept.Of ICT and Natural Sciences	Cyber-physical systems and AI	RTB
Ass. Prof. Eide, Egil	NTNU, Department of Electronic Systems	Nagvigation of autonomnous ships	EE
Ass. Prof. Føre, Martin	NTNU, Dept.Engineering Cybernetics	Fisheries and aquaculture	MF
Prof. Gao, Zhen	NTNU, Dept.Marine Technology	Wind energy/offshore renewable energy systems	ZG
Prof. Imsland, Lars S.	NTNU, Dept.Engineering Cybernetics	Automatic control, optimization	LI
Prof. Kristiansen, Trygve	NTNU, Dept.Marine Technology	Marine hydrodynamics	TK
Ass. Prof. Kim, Ekaterina	NTNU, Dept.Marine Technology	Marine structures	EK
Prof. Prof. Nguyen, Trong Dong	DNV GL	Marine control systems	MT
Prof. Lader, Pål	NTNU, Dept.Marine Technology	Aquaculture structures and Experimental hydrodynamics	PL
Ass. Prof. Lekkas, Anastasios	NTNU, Dept.Engineering Cybernetics	Fusing artificial intelligence with control engineering to develop cyber-physical systems of increased autonomy	AL
Prof. Ludvigsen, Martin	NTNU, Dept.Marine Technology	Underwater technology and operations	ML
Prof. Pedersen, Eilif	NTNU, Dept.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.Marine Technology	Marine control systems	RS
Ass. Prof. Stahl, Annette	NTNU, Dept.Engineering Cybernetics	Robotic vision	AS
Researcher Tymokha, Oleksandr	NTNU, Dept.Marine Technology	Marine hydrodynamics	OT
Prof. Utne, Ingrid B.	NTNU, Dept.Marine Technology	Safety critical systems and systems engineering	IBU
Prof. Zhang, Houxiang	NTNU, Dept. of Ocean Operations and Civil Engineering	Robotics and Cybernetics	HZ
Prof. Petrovic, Slobodan	NTNU, Dept. of Information Security and Com.Techonolgy	Information Security	SP
Prof. Gravdahl, Jan Tommy	NTNU, Dept.Engineering Cybernetics	Control Engineering	JTG
Prof. Konstantinos Alexis	NTNU, Dept.Engineering Cybernetics	Autonomous systems	KA
Prof. Nguyen, Trong Dong	NTNU, Dept.Marine Technology	Marine control systems	TDN
Ass.Prof. Rokseth, Børge	NTNU, Dept.Engineering Cybernetics	Safety critical systems and systems engineering	BR
Ass.Prof. Yu, Zhaolong	NTNU, Dept.Marine Technology	Marine structures	ZY

Technical staff, directly funded by NTNU AMOS

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


Photo: Asgeir J. Sørensen

Postdocs/researchers

NAME	INSTITUTION	MAIN FIELD OF RESEARCH	ACRONYM
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. 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
Hatlebakk, Maja	AMOS - Arven etter Nansen prosjektet	Zooplankton ecology unb the Arctic	GJ, NAM
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. Birkeland, Roger	NTNU, Dept. of Electronic Systems	Mission-oriented autonomous systems – with small satellites for maritime sensing, surveillance and communication	RB
Dr. Zolich, Artur Piotr	NTNU, Dept. Engineering Cybernetics	Coordination of unmanned vehicles in marine environment	APZ
Dr. Ravinder, Praveen Kumar Jain	NTNU, Dept. Engineering Cybernetics	Machine learning methods for adaptive sampling and control	PKR
Dr. Hann, Richard	NTNU, Dept. of Cybernetics	Icing and icing mitigation in UAV rotors and propellers	RH
Dr. Basso, Erlend	NTNU, Dept. of Cybernetics	Control of light vehicle-manipulator systems	EB
Dr. Tengesdal, Trym	NTNU, Dept. of Cybernetics	Machine learning for adapting COLREGS compliant collision avoidance algorithms for autonomous ships	TT
Dr. Bakken, Sivert	NTNU, Dept. of Cybernetics	Hyperspectral imaging for ocean color	SB
Dr. Alberto Dallolio	NTNU, Dept. of Cybernetics	Autonomous wave powered surface vessel for oceanography	AD

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	GNSS-free navigation for maritime surface vessels
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	Modelling of flexible membranes in waves
Haavardsholm, Trym Vegard	AST	Collaborative visual mapping and exploration for teams of unmanned systems

NAVN	SUPERVISOR	TOPIC
Hagen, Inger Berge	EB	Collision Avoidance for Autonomous Ferry
Haraldsen, Aurora	KYP	Autonomous Collision Avoidance
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	Fusion between AIS and exteroceptive sensors
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-Honoré, Evelyn	EE	Rapid systems engineering
Lorentzen, Ole Jacob	AJS	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
Mogstad, Aksel A.	GJ, AJS	Underwater hyperspectral imaging
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

NAVN	SUPERVISOR	TOPIC
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
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, Johan Bakken	BR	Thrust in autonomous systems
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	Thrustworthy autonomy for marine ferries from using video games
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	The ultimate- and fatigue strength of robot welded aluminium ships
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
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
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

AMOS graduates 2022

Supervised by Key Scientists at AMOS

NAME	DATE	TOPIC	SUPERVISOR
Bakken, Sivert	March 2022	Development of a Small Satellite with a Hyperspectral Imaging Payload and Onboard Processing for Ocean Color	TAJ
Basso, Erlend A.	November 2022	Motion Planning and Control of Articulated Intervention-AUVs	KYP
Berget, Gunhild	November 2022	Adaptive Sampling of Dynamic Fields using Autonomous Underwater Vehicles	TAJ
Bøhn, Eivind	March 2022	Reinforcement Learning for Optimization of Nonlinear and Predictive Control,	TAJ
Dallolio, Alberto	February 2022	Design and experimental validation of a control architecture for a wave-propelled USV,	TAJ
Reinhardt, Dirk	June 2022	On Nonlinear and Optimization-based Control of Fixed-Wing Unmanned Aerial Vehicles,	TAJ
Sollie, L. Martin	November 2022	Navigation and Automatic Recovery of Fixed-wing Unmanned Aerial Vehicles	TAJ
Tengesdal, Trym	September 2022	Risk-based Traffic Rules Compliant Collision Avoidance for Autonomous Ships	TAJ

Photo: Live Oftedahl

PUBLICATIONS

Conferences

1. **Akdag, Melih; Fossen, Thor I.; Johansen, Tor Arne.** Collaborative Collision Avoidance for Autonomous Ships Using Informed Scenario-Based Model Predictive Control. IFAC-PapersOnLine 2022; Volume 55.(31) pp. 249-256, NTNU

2. **Bakken, Sivert; Birkeland, Roger; Garrett, Joseph; Marton, Amund R.; Orlandic, Milica; Honoré-Livermore, Evelyn; Langer, Dennis D.; Haskins, Cecilia; Johansen, Tor Arne.** Testing of Software-Intensive Hyperspectral Imaging Payload for the HYPSO-1 CubeSat. IEEE/SICE International Symposium on System Integration 2022; Volume SII2023. pp. 258-264, NTNU

3. **Bakken, Sivert; Danielsen, Aksel Skrøvset; Døsvik, Kristine; Garrett, Joseph; Orlandic, Milica; Langer, Dennis D.; Johansen, Tor Arne.** A modular hyperspectral image processing pipeline for cubesats. Workshop on Hyperspectral Image and Signal Processing, Evolution in Remote Sensing 2022 s. -, NTNU OCEAN

4. **Bakken, Sivert; Honoré-Livermore, Evelyn; Birkeland, Roger; Orlandic, Milica; Prentice, Elizabeth Frances; Garrett, Joseph; Langer, Dennis D.; Haskins, Cecilia; Johansen, Tor Arne.** Software Development and Integration of a Hyperspectral Imaging Payload for HYPSO-1. IEEE/SICE International Symposium on System Integration 2022; Volume SII2023. pp. 183-189, NTNU

5. **Berget, Gunhild Elisabeth; Eidsvik, Jo; Alver, Morten; Py, Frédéric; Grøtli, Esten Ingar; Johansen, Tor Arne.** Adaptive Underwater Robotic Sampling of Dispersal Dynamics in the Coastal Ocean. I: Robotics Research: The 19th International Symposium ISRR. Springer 2022 ISBN 978-3-030-95458-1. pp. 610-625, NTNU SINTEF

6. **Birkeland, Roger; Quintana DÃaz, Gara; Honoré-Livermore, Evelyn; Ekman, Torbjörn; Agelet, Fernando Aguado; Johansen, Tor Arne.** A Multi-purpose Software Defined Radio Payload for the HYPSO-2 Satellite. IEEE Aerospace Conference. Proceedings 2022, NTNU

7. **Blindheim, Simon André Johnsen; Johansen, Tor Arne.** Particle Swarm Optimization for Dynamic Risk-Aware Path Following for Autonomous Ships. IFAC-PapersOnLine 2022, NTNU

8. **Borgersen, Jonas Nagell; Saad, Aya; Stahl, Annette.** 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 2022; Volume 12084. NTNU

9. **Brekke, Edmund Førland; Tokle, Lars-Christian Ness.** Hypothesis Exploration in Multiple Hypothesis Tracking with Multiple Clusters. I: 2022 25th International Conference on Information Fusion - FUSION. IEEE (Institute of Electrical and Electronics Engineers) 2022 ISBN 978-1-7377497-2-1. s. -, NTNU

10. **Cheung, Michael; Hann, Richard; Johansen, Tor Arne.** UAV Icing: A Unified Icing Severity Index Derived from Performance Degradation. I: AIAA AVIATION 2022 Forum. American Institute of Aeronautics and Astronautics (AIAA) 2022 ISBN 978-1-62410-635-4. NTNU

11. **Coates, Erlend M.; Reinhardt, Dirk Peter; Gryte, Kristoffer; Johansen, Tor Arne.** Toward Nonlinear Flight Control for Fixed-Wing UAVs: System Architecture, Field Experiments, and Lessons Learned. International Conference on Unmanned Aircraft Systems (ICUAS) 2022, NTNU

12. **Fyrvik, Torbjørn Reitan; Bremnes, Jens Einar; Sørensen, Asgeir Johan.** Hybrid Tracking Controller for an ASV Providing Mission Support for an AUV. IFAC-PapersOnLine 2022; Volume 55.(31) pp. 91-97, NTNU

13. **Garrett, Joseph; Singh, N; Johansen, Tor Arne; Necoara, Ion.** Accelerating support vector machines for remote platforms by increasing sparsity. Workshop on Hyperspectral Image and Signal Processing, Evolution in Remote Sensing 2022, NTNU

14. **Ge, Yaolin; Olaisen, André Julius Hovd; Eidsvik, Jo; Jain, Ravinder Praveen Kumar; Johansen, Tor Arne.** Long-Horizon Informative Path Planning with Obstacles and Time Constraints. IFAC-PapersOnLine 2022, NTNU

15. **Haavardsholm, Trym Vegard; Opsahl, Thomas Olsvik; Skauli, Torbjørn; Stahl, Annette.** Compact multimodal multispectral sensor system for tactical reconnaissance. Proceedings of SPIE, the International Society for Optical Engineering 2022, FFI NTNU

16. **Hagen, Inger Berge; Kufoalor, D. Kwame Minde; Johansen, Tor Arne; Brekke, Edmund Førland.**
Scenario-Based Model Predictive Control with Different Numbers of Decision Steps for COLREGS Compliant Ship Collision Avoidance. IFAC-PapersOnLine 2022, NTNU

17. **Haraldsen, Aurora; Syre Wiig, Martin; Pettersen, Kristin Ytterstad.**
Collision Avoidance for Underactuated Surface Vehicles in the Presence of Ocean Currents. IFAC-PapersOnLine 2022, NTNU FFI

18. **Haugo, Simen; Stahl, Annette.**
Progressive integration of visibility constraints for implicit functions. Proceedings of SPIE, the International Society for Optical Engineering 2022; Volume 12084. pp. 28-37, NTNU

19. **Helgesen, Håkon Hagen; Kristiansen, K S; Vik, Bjørnar; Johansen, Tor Arne.**
Detection of Contact with Quay for Ships using Motion Sensors and Machine Learning. IFAC-PapersOnLine 2022, NTNU

20. **Henriksen, Marie Bøe; Prentice, Elizabeth; Sigernes, Fred; Johansen, Tor Arne.**
Pre-Launch Calibration of the HYPSO-1 Cubesat Hyperspectral Payload. IEEE Aerospace Conference. Proceedings 2022, NTNU

21. **Henriksen, Marie Bøe; Sigernes, Fred; Johansen, Tor Arne.**
A closer look at a spectrographic wavelength calibration. Workshop on Hyperspectral Image and Signal Processing, Evolution in Remote Sensing 2022, NTNU

22. **Ho, Tu Dac; Grøtli, Esten Ingar; Johansen, Tor Arne.**
Path planning for UAV harvesting information from dynamical wireless sensor nodes at sea. I: 2022 IEEE Ninth International Conference on Communications and Electronics (ICCE). IEEE conference proceedings 2022 ISBN 978-1-6654-9744-2. UiT NTNU SINTEF

23. **Hodne, Lars Martin; Leikvoll, Eirik; Yip, Mauhing; Teigen, Andreas Langeland; Stahl, Annette; Mester, Rudolf.**
Detecting and Suppressing Marine Snow for Underwater Visual SLAM. IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops (CVPRW) 2022, NTNU

24. **Iversflaten, Markus Høgevoll; Haraldsen, Aurora; Pettersen, Kristin Ytterstad.**
Kinematic and Dynamic Control of Cooperating Underwater Vehicle-Manipulator Systems. IFAC-PapersOnLine 2022; Volume 55.(31) pp. 110-117, NTNU

25. **Jain, Ravinder Praveen Kumar; Brekke, Edmund Førland; Rasheed, Adil.**
Unsupervised Clustering of Marine Vessel Trajectories in Historical AIS Database. I: 2022 25th International Conference on Information Fusion - FUSION. IEEE (Institute of Electrical and Electronics Engineers) 2022 ISBN 978-1-7377497-2-1. pp. 1-6, NTNU

26. **Kleiven, Ruben; Gryte, Kristoffer; Johansen, Tor Arne.**
Robust and Gain Scheduled Flight Control of Fixed-Wing UAVs in Wind and Icing Conditions. IEEE Aerospace Conference. Proceedings 2022, NTNU

27. **Langer, Dennis D.; Johansen, Tor Arne; Sørensen, Asgeir Johan.**
Interactive hyperspectral data inspection during field operations. Workshop on Hyperspectral Image and Signal Processing, Evolution in Remote Sensing 2022 s. -, NTNU

28. **Langer, Dennis D.; Prentice, Elizabeth; Johansen, Tor Arne; Sørensen, Asgeir Johan.**
Validation of hyperspectral camera operations with an experimental aircraft. IEEE International Geoscience and Remote Sensing Symposium proceedings 2022 s. -NTNU

29. **Laurendeau, E; Bourgault-Côté, S; Ozcer, I; Hann, Richard; Radenac, E; Pueyo, A.**
Summary from the 1st AIAA Ice Prediction Workshop. I: AIAA AVIATION 2022 Forum. American Institute of Aeronautics and Astronautics (AIAA) 2022 ISBN 978-1-62410-635-4. NTNU

30. **Løw Hansen, Bogdan; Hann, Richard; Johansen, Tor Arne.**
UAV Icing: Ice Shedding Detection Methods for an Electrothermal De-Icing System. I: AIAA AVIATION 2022 Forum. American Institute of Aeronautics and Astronautics (AIAA) 2022 ISBN 978-1-62410-635-4. NTNU

31. **Madshaven, Arild; Schellewald, Christian; Stahl, Annette.**
Hole Detection in Aquaculture Net Cages from Video Footage. Proceedings of SPIE, the International Society for Optical Engineering 2022; Volume 12084. s. - OCEAN NTNU

32. **Marangoni, Laura; Davies, Thomas; Smyth, Tim; Rodríguez, Airam; Hamann, Mark; Duarte, Christian; Pendoley, Kellie; Berge, Jørgen; Maggi, Elena; Levy, Oren.**
Impacts of artificial light at night in marine ecosystems—A review. Global Change Biology 2022; Volume 28.(18) pp. 5346-5367, UNIS NTNU UiT

33. **Marley, Mathias; Skjetne, Roger.**
Mitigating Force Oscillations in a Wave Energy Converter Using Control Barrier Functions. I: ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering Volume 8: Ocean Renewable Energy. The American Society of Mechanical Engineers (ASME) 2022 ISBN 978-0-7918-8593-2. s. -NTNU

34. **Meier, Kilian; Hann, Richard; Skaloud, Jan; Garreau, Arthur.** Wind Estimation with Multirotor UAVs. Atmosphere 2022; Volume 13.(4) pp. 1-23, UNIS NTNU

35. **Müller, Nicolas Carlo; Hann, Richard; Johansen, Tor Arne.** UAV Icing: A Performance Model for a UAV Propeller in Icing Conditions. I: AIAA AVIATION 2022 Forum. American Institute of Aeronautics and Astronautics (AIAA) 2022 ISBN 978-1-62410-635-4. NTNU

36. **Orucevic, Amer; Gravdahl, Jan Tommy; Pettersen, Kristin Ytterstad; Chaillet, Antoine.** Uniform Practical Asymptotic Stability for Position Control of Underwater Snake Robots. I: 2022 IEEE Conference on Control Technology and Applications (CCTA). IEEE conference proceedings 2022 ISBN 978-1-6654-7338-5. NTNU

37. **Oswald, Johannes Wolfgang; Enache, Adriana; Hann, Richard; Gertjan, Glabeke; Lutz, Thorsten.** UAV Icing: Experimental and Numerical Study of Glaze Ice. I: AIAA SciTech 2022 Forum. American Institute of Aeronautics and Astronautics (AIAA) 2022 ISBN 978-1-62410-631-6. NTNU

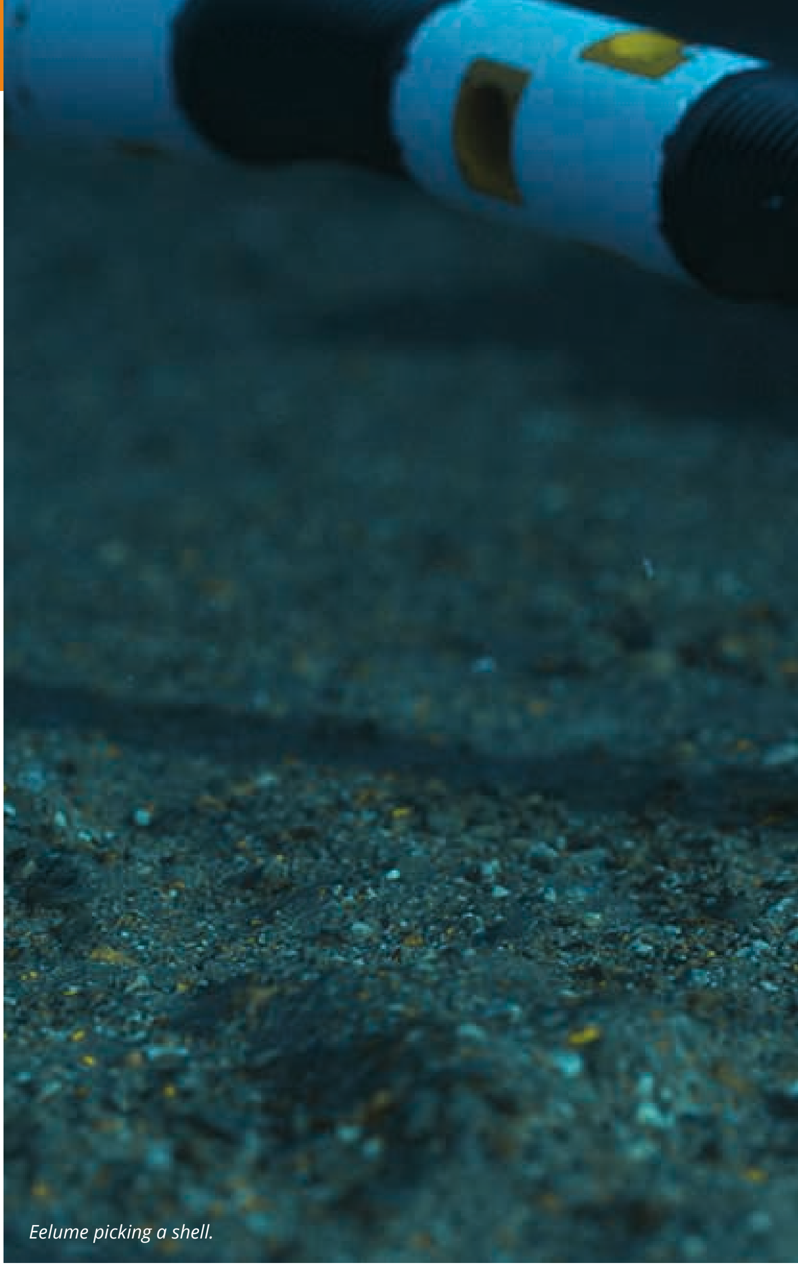
38. **Oudijk, Esmée; Hasler, Oliver Kevin; Overaas, H; Marty, Sabine; Williamson, David; Svendsen, T; Berg, Simen; Birkeland, Roger; Halvorsen, D; Bakken, S; Henriksen, Marie Bøe; Alver, Morten; Johnsen, Geir; Johansen, Tor Arne; Stahl, Annette; Kvaløy, Pål; Dallolio, Alberto; Majaneva, Sanna; Fragoso, Glaucia Moreira; Garrett, Joseph.** Campaign For Hyperspectral Data Validation In North Atlantic Coastal Waters. Workshop on Hyperspectral Image and Signal Processing, Evolution in Remote Sensing 2022, NTNU NIVA

39. **Prentice, Elizabeth; Henriksen, Marie Bøe; Johansen, Tor Arne; Navarro Medina, F; Gomez San Juan, A.** Characterizing Spectral Response in Thermal Environments, the HYPSO-1 Hyperspectral Imager. IEEE Aerospace Conference. Proceedings 2022, NTNU

40. **Reinhardt, Dirk Peter; Gryte, Kristoffer; Johansen, Tor Arne.** Modeling of the Skywalker X8 Fixed-Wing UAV: Flight Tests and System Identification. International Conference on Unmanned Aircraft Systems (ICUAS) 2022, NTNU

41. **Salvesen, Eivind; Saad, Aya; Stahl, Annette.** Robust Deep Unsupervised Learning Framework to Discover Unseen Plankton Species. Proceedings of SPIE, the International Society for Optical Engineering 2022; Volume 12084.NTNU

42. **Schaanning, Sigrid Kjønnø; Kristiansen, Bjørn Andreas; Gravdahl, Jan Tommy.** Maximum Hands-Off Attitude Control. American Control Conference (ACC) 2022, NTNU


Eelume picking a shell.

43. **Schellewald, Christian; Stahl, Annette.** Irregularity Detection in Net Pens Exploiting Computer Vision. IFAC-PapersOnLine 2022; Volume 55.(31) pp. 415-420, OCEAN NTNU

44. **Schmidt-Didlaukies, Henrik; Basso, Erlend Andreas; Sørensen, Asgeir Johan; Pettersen, Kristin Ytterstad.** A Generalization of Synergistic Hybrid Feedback Control with Application to Maneuvering Control of Ships. I: IEEE 61st Conference on Decision and Control (CDC 2022). IEEE conference proceedings 2022 ISBN 978-1-6654-6761-2. pp. 1986-1992 NTNU

45. **Sæbø, Bjørn Kåre; Pettersen, Kristin Ytterstad; Gravdahl, Jan Tommy.** Robust Task-Priority Impedance Control for Vehicle-Manipulator Systems. I: 2022 IEEE Conference on Control Technology and Applications (CCTA). IEEE conference proceedings 2022 ISBN 978-1-6654-7338-5. NTNU

46. **Thiagarajah, Dinosshan; Helgesen, Håkon Hagen; Kjerstad, Øivind Kåre; Johansen, Tor Arne.**
Localization for Ships during Automated Docking using a Monocular Camera. I: Proceedings European Control Conference. IEEE conference proceedings 2022 ISBN 978-3-9071-4407-7. s. - NTNU

47. **Wallisch, Joachim; Hann, Richard.**
UAV Icing: Experimental Investigation of Ice Shedding Times with an Electrothermal De-Icing System. I: AIAA AVIATION 2022 Forum. American Institute of Aeronautics and Astronautics (AIAA) 2022 ISBN 978-1-62410-635-4. NTNU

48. **Wang, Xintong; Amdahl, Jørgen.**
Analysis of Welding Influences on Extruded Aluminum Panel Buckling. I: ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering. Volume 2: Structures, Safety, and Reliability. The American Society of Mechanical Engineers (ASME) 2022 ISBN 978-0-7918-8586-4. s. - NTNU

49. **Williamson, David R; Kvæstad, Bjarne; Hansen, Bjørn Henrik; Ludvigsen, Martin; Davies, Emlyn John**.
Laboratory and in-situ imaging and automated analysis of marine particles. Ocean Sciences Meeting 2022. OCEAN, NTNU https://app.cristin.no/results/show.jsf?id=2002793

50. **Williamson, David R; Løvås, Håvard**
Monitoring the Arctic with Autonomous Underwater Vehicles. Arctic Frontiers 2022. NTNU https://app.cristin.no/results/show.jsf?id=2019926

51. **Zolich, Artur Piotr; Fonseca Palma, David; Birkeland, Roger; Cisek, Krzysztof Piotr; Johansen, Tor Arne.**
Wi-Fi based Telecommunication Infrastructure Delivered as a Service by UAV for Emergency Response. I: 2022 International Conference on Unmanned Aircraft Systems (ICUAS). IEEE (Institute of Electrical and Electronics Engineers) 2022 ISBN 9781665405935. NTNU

Journals

1. **Akdag, Melih; Solnør, Petter; Johansen, Tor Arne.** Collaborative collision avoidance for Maritime Autonomous Surface Ships: A review. Ocean Engineering 2022; Volume 250. s. -NTNU

2. **Bosdelekidis, Vasileios; Bryne, Torleiv Håland; Sokolova, Nadezda; Johansen, Tor Arne.** Navigation Algorithm-Agnostic Integrity Monitoring based on Solution Separation with Constrained Computation Time and Sensor Noise Overbounding. Journal of Intelligent and Robotic Systems 2022; Volume 106. s. -NTNU SINTEF

3. **Brekke, Edmund Førland; Eide, Egil; Eriksen, Bjørn-Olav Holtung; Wilthil, Erik Falmår; Breivik, Morten; Skjellaug, Even; Helgesen, Øystein Kaarstad; Lekkas, Anastasios M.; Martinsen, Andreas Bell; Thyri, Emil Hjelseth; Torben, Tobias Valentin Rye; Veitch, Erik Aleksander; Alsos, Ole Andreas; Johansen, Tor Arne.** milliAmpere: An Autonomous Ferry Prototype. Journal of Physics: Conference Series (JPCS) 2022; Volume 2311. s. -NTNU

4. **Brodtkorb, Astrid Helene; Nielsen, Ulrik Dam.** Automatic sea state estimation with online trust measure based on ship response measurements. Control Engineering Practice 2022; Volume 130. s. -NTNU

5. **Cao, Qun; Bachynski-Polic, Erin Elizabeth; Gao, Zhen; Xiao, Longfei; Cheng, Zhengshun; Liu, Mingyue.** Experimental and numerical analysis of wind field effects on the dynamic responses of the 10 MW SPIC floating wind turbine concept. Ocean Engineering 2022; Volume 261. pp. 1-27, NTNU

6. **Chen, Bang-Fuh; Wu, Chih-Hua; Faltinsen, Odd Magnus.** The mechanism of switching direction of swirling sloshing waves. Journal of Fluid Mechanics 2022; Volume 954. s. -NTNU

7. **Connan-McGinty, Stacey; Banas, Neil S.; Berge, Jørgen; Cottier, Finlo Robert; Grant, Stephen; Johnsen, Geir; Kopec, Tomasz Piotr; Porter, Marie; Mckee, David.** Midnight Sun to Polar Night: A Model of Seasonal Light in the Barents Sea. Journal of Advances in Modeling Earth Systems 2022; Volume 14.(10) s. -UiT NTNU UNIS

8. **Dallolio, Alberto; Øveraas, Henning; Johansen, Tor Arne.** Gain-scheduled steering control for a wave-propelled unmanned surface vehicle. Ocean Engineering 2022; Volume 257. pp. 111618-111618, NTNU

9. **De Finis, Stefano; Lugni, Claudio; Bellotti, Giorgio; Brocchini, Maurizio.** Filling flows by wave impacts on walls: Laboratory and numerical experiments. Physics of Fluids 2022; Volume 34.(9) s. - NTNU

10. **Dirdal, Johann Alexander; Skjetne, Roger; Roháč, Jan; Fossen, Thor I..** Online wave direction and wave number estimation from surface vessel motions using distributed inertial measurement arrays and phase-time-path-differences. Ocean Engineering 2022; Volume 249. s. - NTNU

11. **Dona AR, Evertsen J, Johnsen G (2022)** Fluorescent proteins in parapodia of Sacoglossan sea slug Plakobranchus ocellatus provide photoprotection for kleptoplasts incapable of photoacclimation. Coral Reefs. https://doi.org/10.1007/s00338-022-02224-z

12. **Dong, Xiaochen; Gao, Zhen; Li, Demin; Huang, Shu-ting; Shi, Hongda.** Power Absorption of A Two-Body Heaving Wave Energy Converter Considering Different Control and Power Take-off Systems. China Ocean engineering 2022; Volume 36.(1) pp. 15-27, NTNU

13. **Fossen, Thor Inge.** Line-of-sight path-following control utilizing an extended Kalman filter for estimation of speed and course over ground from GNSS positions. Journal of Marine Science and Technology 2022, NTNU

14. **Fossum, Knut Robert; Honoré-Livermore, Evelyn; Veitch, Erik Aleksander; Haskins, Cecilia; Palmer, Erika.** Toward an integrated project complexity narrative – A case study of academic organizations. Systems Engineering 2022; Volume 25.(5) pp. 443-456, SAMFORSK NTNU USN

15. **Fragoso, Glaucia Moreira; Davies, Emlyn John; Fossum, Trygve Olav; Ullgren, Jenny; Majaneva, Sanna; Aberle-Malzahn, Nicole; Ludvigsen, Martin; Johnsen, Geir.** Contrasting phytoplankton-zooplankton distributions observedthrough autonomous platforms, in-situ optical sensors and discrete sampling. PLOS ONE 2022; Volume 17.(9) pp. 1-24, NTNU OCEAN HAVFORSK

16. **Helgesen, Håkon Hagen; Fuglestad, Torbjørn; Cisek, Krzysztof Piotr; Vik, Bjørnar; Kjerstad, Øivind Kåre; Johansen, Tor Arne.** Inertial Navigation aided by Ultra-Wideband Ranging for Ship Docking and Harbor Maneuvering. IEEE Journal of Oceanic Engineering 2022; Volume 48.(1) pp. 27-42, NTNU

17. **Helgesen, Øystein Kaarstad; Vasstein, Kjetil; Brekke, Edmund Førland; Stahl, Annette.** Heterogeneous multi-sensor tracking for an autonomous surface vehicle in a littoral environment. Ocean Engineering 2022; Volume 252. NTNU

18. **Henriksen, Marie Bøe; Prentice, Elizabeth Frances; van Hazendonk, Charlotte Maartje; Sigernes, Fred; Johansen, Tor Arne.**
Do-it-yourself VIS/NIR pushbroom hyperspectral imager with C-mount optics. Optics Continuum 2022; Volume 1.(2) pp. 427-441, UNIS NTNU

19. **Heyn, Hans-Martin; Skjetne, Roger.**
Fast onboard detection of ice drift changes under stationkeeping in ice. Cold Regions Science and Technology 2022; Volume 196. pp. 1-14, NTNU

20. **Jellum, Erling Rennemo; Orlandic, Milica; Brekke, Edmund Førland; Johansen, Tor Arne; Bryne, Torleiv Håland.**
Solving Sparse Assignment Problems on FPGAs. ACM Transactions on Architecture and Code Optimization (TACO) 2022; Volume 19.(4), NTNU

21. **Jiang, Zhiyu; Yang, Limin; Gao, Zhen; Moan, Torgeir.**
Integrated dynamic analysis of a spar floating wind turbine with a hydraulic drivetrain. Renewable Energy 2022; Volume 201. (1) pp. 608-623, UIA NTNU

22. **Johansen, Thomas; Utne, Ingrid Bouwer.**
Supervisory risk control of autonomous surface ships. Ocean Engineering 2022; Volume 251. s. - NTNU

23. **Lupu, Daniela; Necoara, Ion; Garrett, Joseph Landon; Johansen, Tor Arne.**
Stochastic Higher-Order Independent Component Analysis for Hyperspectral Dimensionality Reduction. IEEE Transactions on Computational Imaging 2022, NTNU

24. **Mogstad, Aksel Alstad; Løvås, Håvard; Sture, Øystein; Johnsen, Geir; Ludvigsen, Martin.**
Remote Sensing of the Tautra Ridge: An Overview of the World's Shallowest Cold-Water Coral Reefs. Frontiers in Marine Science 2022; Volume 9. s. -, NTNU UNIS

25. **Mokhtari, Mojtaba; Kim, Ekaterina; Amdahl, Jørgen.**
Pressure-dependent plasticity models with convex yield loci for explicit ice crushing simulations. Marine Structures 2022; Volume 84. s. 103233- NTNU

26. **Nordvik, Kristoffer; Johansen, Tor Arne.**
On compensation for wave-induced roll in dynamic positioning control. Journal of Marine Science and Technology 2022 s. -NTNU

27. **Okuhara, Mika; Bryne, Torleiv Håland; Gryte, Kristoffer; Johansen, Tor Arne.**
Phased Array Radio Navigation System on UAVs: In-flight Calibration. Journal of Intelligent and Robotic Systems 2022, NTNU

28. **Paniccia, Damiano; Graziani, Giorgio; Lugni, Claudio; Piva, Renzo.**
The fish ability to accelerate and suddenly turn in fast maneuvers. Scientific Reports 2022; Volume 12.(1) s. -NTNU

29. **Prentice, Elizabeth; Honoré-Livermore, Evelyn; Bakken, Sivert; Henriksen, Marie Bøe; Birkeland, Roger; Hjertenæs, Martine Aasen; Gjersvik, Amund; Johansen, Tor Arne; Agelet, Fernando Aguado; Navarro-Medina, Fermin.**
Pre-Launch Assembly, Integration, and Testing Strategy of a Hyperspectral Imaging CubeSat, HYPSO-1. Remote Sensing 2022; Volume 14.(18) s. -NTNU

30. **Ragazzon, Michael Remo Palmén; Messineo, Saverio; Gravdahl, Jan Tommy; Harcombe, David M.; Ruppert, Michael G..**
The Generalized Lyapunov Demodulator: High-Bandwidth, Low-Noise Amplitude and Phase Estimation. IEEE Open Journal of Control Systems 2022; Volume 1. pp. 69-84, NTNU

31. **Ren, Zhengru; Han, Xu; Yu, Xingji; Skjetne, Roger; Leira, Bernt Johan; Sævik, Svein; Zhu, Man.**
Data-driven simultaneous identification of the 6DOF dynamic model and wave load for a ship in waves. Mechanical systems and signal processing 2022; Volume 184. pp. 1-16, NTNU

32. **Rothmund, Sverre Velten; Tengesdal, Trym; Brekke, Edmund Førland; Johansen, Tor Arne.**
Intention modeling and inference for autonomous collision avoidance at sea. Ocean Engineering 2022; Volume 266.(4), NTNU

33. **Silva de Souza, Carlos Eduardo; Bachynski-Polic, Erin Elizabeth.**
Design, structural modeling, control, and performance of 20 MW spar floating wind turbines. Marine Structures 2022; Volume 84. s. -NTNU

34. **Sollie, Martin Lysvand; Gryte, Kristoffer; Bryne, Torleiv Håland; Johansen, Tor Arne.**
Outdoor Navigation Using Bluetooth Angle-of-Arrival Measurements. IEEE Access 2022; Volume 10. pp. 88012-88033, NTNU

35. **Summers, Natalie; Johnsen, Geir; Mogstad, Aksel Alstad; Løvås, Håvard; Fragoso, Glaucia Moreira; Berge, Jørgen.**
Underwater Hyperspectral Imaging of Arctic Macroalgal Habitats during the Polar Night Using a Novel Mini-ROV-UHI Portable System. Remote Sensing 2022; Volume 14.(6) s. -NTNU UNIS UiT

36. **Sørum, Stian Høegh; Bachynski-Polic, Erin Elizabeth; Amdahl, Jørgen.**
Wind and soil model influences on the uncertainty in fatigue of monopile supported wind turbines. Journal of Physics: Conference Series (JPCS) 2022; Volume 2362. s. -NTNU

37. **Tengesdal, Trym; Johansen, Tor Arne; Grande, Tom Daniel; Blindheim, Simon André Johnsen.**
Ship Collision Avoidance and Anti Grounding Using Parallelized Cost Evaluation in Probabilistic Scenario-Based Model Predictive Control. IEEE Access 2022; Volume 10. pp. 111650-111664, NTNU

38. **Torben, Tobias; Glomsrud, Jon Arne; Pedersen, Tom Arne; Utne, Ingrid Bouwer; Sørensen, Asgeir Johan.**
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; Volume January 2022. s. -NTNU

39. **Vagale, Anete.**
Evaluation Simulator Platform for Extended Collision Risk of Autonomous Surface Vehicles. Journal of Marine Science and Engineering 2022; Volume 10.(5) s. -NTNU

40. **Wang, Xintong; Amdahl, Jørgen; Egeland, Olav.**
Numerical study on buckling of aluminum extruded panels considering welding effects. Marine Structures 2022; Volume 84. s. -NTNU

41. **Weydmann-Zwolicka, Agata; Cottier, Finlo Robert; Berge, Jørgen; Majaneva, Sanna; Kuklinski, Piotr; Zwolicki, Adrian.**
Environmental niche overlap in sibling planktonic species Calanus finmarchicus and C. glacialis in Arctic fjords. Ecology and Evolution 2022; Volume 12.(12) s. -NTNU UiT

42. **Williamson, David R; Nordtug, Trond; Leirvik, Frode; Kvæstad, Bjarne; Hansen, Bjørn Henrik; Ludvigsen, Martin; Davies, Emlyn John.** A flow-through imaging system for automated measurement of ichthyoplankton. MethodsX 2022, Volume 9. OCEAN, NTNU https://app.cristin.no/results/show.jsf?id=2056660

43. **Zhao, Shujie; Meng, Xun; Gao, Zhen; Li, Huajun.**
Numerical modeling of nonstationary hydrodynamic forces and induced motions of a coupled offshore floating installation system. Ocean Engineering 2022; Volume 246. pp. - NTNU

44. **Zhou, Hongyu; Ren, Zhengru; Marley, Mathias; Skjetne, Roger.**
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 2022;Volume 30.(6) pp. 2630-2645, NTNU

Book chapters

1. **van den Berg, Marnix Albert; Bjørnø, Jon; Lu, Wenjun; Skjetne, Roger; Lubbad, Raed; Løset, Sveinung.**
The Value of High-Fidelity Numerical Simulations of Ice-Ship and Ice-Structure Interaction in Arctic Design with Informed Decision-making. I: Building Common Interests in the Arctic Ocean with Global Inclusion. Springer 2022 ISBN 9783030893118. pp. 151-177, NTNUHyperspectral Image and Signal Processing, Evolution in Remote Sensing 2021 s. -

Approved by the
NTNU AMOS Board of Directors March 2023

Editors
Live Oftedahl
Asgeir J. Sørensen

Contributors
Key personnel at NTNU AMOS
Researchers at NTNU AMOS
Renate Karoliussen

Artwork frontpage and other illustrations
Bjarne Stenberg

Photography
Kai T. Dragland, Geir Johnsen,
Asgeir J. Sørensen, Live Oftedahl

Layout and print
Skipnes Kommunikasjon AS

NORDIC SWAN ECOLABEL
Printed matter
2041 0731

NTNU

Centre for Autonomos Marine
Operations and Systems

Annual Report NTNU AMOS 2022

NTNU – The Norwegian University of Science and Technology
Knowledge for a better world

NTNU AMOS – Centre for Autonomous Marine Operations and Systems
Marine Technology Centre
NO-7491 Trondheim, NORWAY

Phone: +47 (735) 95535
Fax: +47 (735) 95528
E-mail: contact@amos.ntnu.no

www.ntnu.edu/amos