NTNU AMOS
Centre for Autonomous Marine Operations and Systems

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Centre for Autonomous Marine Operations and Systems

Annual Report 2017

Norwegian Centre of Excellence
The Research Council of Norway

OUR VISION

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

excellent – generous – courageous

Editors: Ingvil Snøfugl, Thor I. Fossen and Asgeir J. Sørensen

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DIRECTOR'S REPORT

Last year, NTNU AMOS was devoted to ongoing research activities and the midterm evaluation process. The latter is a constructive and valuable way of "ruthlessly" evaluating the quality of the Centre and highlighting its strengths, weaknesses, opportunities and threats. It involved internal and external evaluations of the achievements and performances so far, as well as the adjustment to research plans during the last five years of operation.

Today, we still aim to maintain a steady course in several areas, such as focusing on fundamental research within marine technology and control engineering and leveraging ground breaking results on autonomous marine operations and systems. An important aspect of these focuses is enhancing the impacts and outcomes with associated research projects and innovation activities.

NTNU AMOS has two research areas:
- Autonomous vehicles and robotic systems
- Safer, smarter and greener ships, structures and operations

The AMOS project plan has been updated with more focused research topics that provide an improved balance and integrate research areas. During 2017, we have gradually transferred our research from nine to three projects:
- Project 1: Technology for mapping and monitoring of the oceans.
- Project 2: Marine robotic platforms.
- Project 3: Risk management and maximized operability of ship and ocean structures.

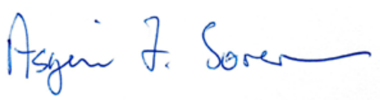
The NTNU AMOS and its associated projects aim for high impact results that *address global challenges* defined by the UN sustainability goals and *provide high standards for knowledge-based management* of the oceans and *value creation* related to the blue economy of Norway in terms of
- developing skills by graduating MSc and PhD candidates and training the next generation of researchers and decision makers,
- developing fundamental knowledge published in highly ranked peer-review journals, books and conferences,
- developing a culture for innovation and accelerating these innovations from fundamental research into existing industries, research institutes and governmental agencies, as well as establishing new organizations,
- education and the inspiration of students, partners, collaborators and society in general by the dissemination of important and exciting knowledge and findings.

Despite the high impact outcome from NTNU AMOS, which has graduated more than 300 MSc and 50 PhD candidates, published more than 370 peer-review journal papers and 550 conference papers, and contributed to five spin-off organizations, there is still room for improvement.

We may also use this opportunity to mention selected highlights, recognitions, and awards:
- NTNU AMOS researchers received the 2017 IEEE Transactions on Control Systems Technology Outstanding Paper Award.
- NTNU AMOS collaborates with the Kjell Inge Røkke and X Four 10 / REV team in the development of a research expedition vessel (REV). The REV is trailblazing in that it targets high impact solutions for the oceans. The REV will provide scientists and entrepreneurs in Norway and elsewhere with the capacity and opportunities to advance their scientific research and innovations, contribute to the knowledge-based management of the oceans and communicate knowledge regarding the oceans to the public.
- Based on research campaigns during January 2017, NTNU AMOS, in cooperation with UiT (the Arctic University of Norway), UNIS, Svalbard and international collaborators, have published scientific results in Science Advances using marine robotics for the mapping of marine ecosystems in the Arctic during polar nights.

I now take the opportunity to thank all colleagues, researchers, PhD and MSc students, partners and collaborators for our efforts in *creating the skills, knowledge and innovations for a better world.*

Sincerely



Professor Asgeir J. Sørensen
Director NTNU AMOS

A PROFESSOR WITH NATURE AS HIS PLAYGROUND

In his childhood, Geir Johnsen went hiking and bird watching for weeks, either alone or with friends. These trips sparked his interest in ecology.

He calls himself a nerd in regard to his interest for all life in the oceans, which existed before he was in school. On one of his trips to Giske, a hurricane moved over the island.

- We found shelter in a cowshed nearby. While the hurricane was passing over the island, my friends and I were lying in the hay listening to Black Sabbath together with cows and cats in the cowshed. We thought it was quite exotic, he smiles.
- Did you parents get worried?
- We had a lot of freedom in our childhood. But during this trip, one of the parents reported us missing, even though we were enjoying life, because we were clever enough to find shelter.

Environmental monitoring to ensure a healthy ecosystem

Professor Geir Johnsen, from the NTNU Department of Biology, has become key scientist of NTNU AMOS. He grew up in Kristiansund and moved to Trondheim to study marine ecology. His Master`s and PhD focused on light harvesting and the utilization of phytoplankton.

- Most of my studies have focused on utilizing tools in bio-optics and pigments. Organisms have different colors and different pigments. With advanced technology, identifying, mapping and monitoring the health status of living organisms in the oceans will become more and more automated, Johnsen says.
- Why is this important?
- We do not know that much about all organisms in the oceans. In a few years, when we need more food from the oceans, this knowledge is critical. Environmental monitoring is very important today and even more important in the future to ensure a healthy ecosystem. We need to understand that with more humans on Earth, we are rapidly degrading the ecosystems – humans need to change their behaviors and use new technology to solve this issue.

Connecting and enabling technology with natural science

In 2004, Johnsen, a marine ecologist, obtained a professorship at NTNU with the responsibility of connecting

Geir Johnsen during the launch of an autonomous underwater vehicle (AUV Remus 100), which is equipped with sensors and cameras to map the underside of North pole sea ice and the phytoplankton distribution water column at the Yermak Plateau (northwest of Svalbard). This is the first AUV mission under drifting polar ice that has mapped phytoplankton biomass and photosynthesis. AMOS personnel were provided new and enabled technology for marine science applications, environmental management and decision making.

enabling technologies with natural sciences. Several years later, it became clear that this was a perfect match with the AMOS (Autonomous Marine Operations and Systems) Centre.

- In AMOS, we perform environmental mapping and monitoring with advanced underwater vehicles. Natural scientists and technologists must work together to reach future goals when it comes to the more sustainable use of resources in the oceans, he says.

Johnsen loves working with the people at AMOS, not only because they are nice people, but also because of their interdisciplinary knowledge.

- Plankton algae produce 50 percent of the Earth's oxygen, and it is also crucial for all life in the oceans, he says.
- AMOS has succeeded by using innovative technology to generate new knowledge for science and people regarding environmental issues.

Important to reach out to people

One way to reach out to people is by publishing scientific articles in acknowledged academic journals. Another way is to achieve publicity in the media and through music, videos or exhibitions.

- We use many channels to reach out to people. For example, one of them is our exhibition Polar Night, which has toured in the United States, Canada, Russia, Svalbard, and Norway, and we have received requests from other places around the world, he says.

In his childhood, nature was his playground, and the professor still moved around a lot. Today, he travels and works out in the field and at sea for approximately three to four months per year.

- Field studies are a lot of fun, especially with students and colleagues. It is important to teach the new generation to take care of nature. In addition, I am able to experience the youthful eagerness for environmental issues, and that warms my heart, Geir Johnsen says.

BOARD REPORT

The Board is very satisfied with the activities undertaken at the NTNU Centre for Autonomous Marine Operations and Systems (AMOS) during 2017. The Centre and its staff show impressive momentum and are on track to reach the ambitious goals of the Centre. Research at the Centre is aligned with the strategic research vision of the NTNU in the field of oceanography, which represents a very important field of research for the NTNU.

The Centre has undergone an extensive review by the Research Council of Norway as part of the midway evaluation for the Norwegian Centre of Excellence programs. The Board met twice in 2017 to review progress, consider management issues, and offer advice on the strategic directions of the Centre. This process resulted in a strategy for developing a stronger and more focused research strategy for the period 2018-2022, which balances and integrates the different research areas that the Centre encompasses. The Board supports the research that was organized into three (previously nine) focused projects:

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

These new projects will be led by three key scientists, professors T. A. Johansen, K. Y. Pettersen and J. Amdahl. The Board believes that this will further strengthen the level of research, quality and impact of the Centre. The Board has also been active in developing a strategy to publish an increased percentage of AMOS papers in top-ranked journals and to co-publish more papers within the Centre. This involves the co-supervision of PhD candidates by forming interdisciplinary teams of researchers with backgrounds in engineering cybernetics, marine technology and biology.

During the first four years of operation, the Centre was organized into a joint research center, with three key scientists from the Department of Engineering Cybernetics and Marine Technology. In 2017, it was decided to make the Department of Biology a formal partner, which extended the number of key scientists to seven. The Board fully supported this decision and welcomed professor Geir Johnsen from the Department of Biology to the team.

The Board also acknowledges that the Centre has been instrumental in the establishment of the NTNU Ocean School of Innovation through cooperation with the NTNU Technology Transfer AS. All PhD candidates have experienced innovative training as part of their doctoral programs. By the end of the year, the Centre has contributed to the establishment of five spin-off organizations:

- *Norwegian Subsea*
- *Eelume*
- *BlueEye Robotics*
- *Scout Drone Inspection*
- *UBIQ Aerospace*

The last two organizations were founded in 2017.

The Board is very satisfied with the NTNU AMOS publication and dissemination. The Centre graduated 53 PhD candidates by the end of 2017, which is a remarkable number after 5 years of operation. This clearly demonstrates that PhD candidates are well integrated and receive excellent supervision and support. The Centre has succeeded beyond expectations in attracting funding in addition to that contributed by the Research Council of Norway and NTNU. Initial funding for the ten-year period (2012-2022) supported 36 PhD candidates. This number has now increased to 109. International publication was further strengthened by the publication of 100 journal papers and 100 conference papers in 2017. This is an impressive publication growth rate, and the increase in high-quality journal publications is particularly notable.

Finally, the Board looks forward to an exciting and productive year in 2018, with an increasing number of high-quality publications, excellent PhD candidates, and new spin-off organizations.

The Board's endorsement of the annual report

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

NATURAL SCIENCE AND OCEAN TECHNOLOGY COMBINED

For the first time, a person with a natural science background has become part of the Board of Directors for the Centre for Autonomous Marine Operations and Systems (AMOS).

- What`s unique about Norway is the high level of success and long history in regard to ocean technology research. We are also leading the front in biology and environmental research internationally. To enable the more sustainable use of resources in global oceans in the future, interdisciplinary collaboration is necessary, says Dean Øyvind Weiby Gregersen, NTNU.

Beginning ocean farming education paths

Gregersen became a member of the AMOS Board of Directors last fall. His educational background is in chemical process technology, with a specialization in paper technology. Gregersen`s plan was to start working in the industry after his Master`s, but an inspiring teacher recruited him to pursue a PhD, which changed his plans.

- First, I became a researcher. Then, I became a research manager, and today I am a Dean for the Faculty for Natural Science. I like working within education, he says.

Two things he is working on at the moment are new education routes for ocean farming leaders and ocean farming engineers.

- The ocean farming industry needs more people with technical backgrounds. The industry is developing all the time, and the challenges become increasingly technological, he says.

At the same time, the university has observed that an increasing number of students have combined technological and biological subjects in their education.

- This changed after oil prices went down and ocean farming began growing at a rapid rate, he says.

AMOS is very important for NTNU

AMOS uses technology to monitor the marine environment, both for security and environmental purposes.

- We need technology to learn more about the organisms that live in the ocean and how human activities influence them. We also need to monitor the oceans of security reasons. More activities over, under, and at the sea have become autonomous. This creates challenges and many possibilities, Gregersen says.

- I think that NTNU AMOS is very important for the university and the world. To combine knowledge regarding life in the ocean with technology is more important than before. I am happy to be a part of this top research community.

NEW AMOS CHAIRMAN WITH A GREAT ENVIRONMENTAL FOCUS

Dean Olav Bolland recently became Chairman of the Board of Directors for AMOS. His ambitions for AMOS are not only innovative regarding scientific development, but they also aim to ensure a healthy and sustainable eco-system.

- It is important to preserve resources in the ocean. AMOS and other organizations are developing many different methods and technologies to succeed in this endeavor, says the Dean of the Faculty of Engineering at NTNU, Olav Bolland.

Bolland became the Dean of the Faculty of Engineering in August 2017. He leads 1300 employees and 7000 students who research and educate in the fields of geology, energy, mechanical engineering, structural engineering, civil engineering and marine technology. The research focuses and activity levels have increased substantially over the last several years, which is mainly due to the close collaboration with the industry and the SINTEF research foundation.

- In 2017, the Faculty of Engineering had a turnover of 540 MNOK, which was only from externally financed projects. AMOS is focused on scientific research needs in industrial applications. Bolland states that they work closely with the industry to solve future challenges regarding future transport and surveillance technologies of the ocean, food production from oceans, off-shore wind power, installations for the production of oil and gas and, in a situation with climate change, the development of infrastructure in coastal areas.

After finishing his Master's degree in mechanical engineering, he started his research career at NTNU in 1987. His main focus was on CO_2 capture.

- Do you also have an environmentally friendly lifestyle?
- I take the bus to work four days a week and have a hybrid car. Therefore, I am reasonably ok , he smiles.

After being a department head for eight years, Bolland became Dean of the Faculty of Engineering.

- I am currently working a lot with the Ocean Space Center. It is very important for NTNU and Norway to succeed with this great infrastructure project because it will ensure Norway`s international position as a leading maritime nation, Olav Bolland says.

ORGANIZATION, INTERNATIONAL COLLABORATORS, AND FACTS AND FIGURES

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

NTNU AMOS Management
Asgeir J. Sørensen, Director
Thor I. Fossen, Co-director
Sigrid B. Wold, Senior Executive Officer
Renate Karoliussen, Economy

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

Innovation
Siri Bye Johansen, NTNU Technology Transfer
Anders Aune, NTNU Technology Transfer

Research Partners
DNV GL, SINTEF Ocean, SINTEF Digital, Statoil, Dept. of Marine Technology, Dept. of Biology and Dept. of Engineering Cybernetics at NTNU

User Panel
Members from research partners, companies and industry

Scientific Advisory Board
Randal W. Beard, Brigham Young University, USA
Robert F. Beck, University of Michigan, Ann Arbor, USA
Gianluca Antonelli, University of Cassio and Southern Lazio, Italy

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 co-operating with the following institutions:

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

Facts and Figures 2017

Personnel 2017

- 7 keypersons
- 15 adjunct prof/assoc.prof
- 18 affiliated scientists
- 2 Scientific Advisers
- 5 post docs/researchers
- 12 affiliated post docs
- 89 PhD candidates (incl. affiliated)
- 9 visiting prof/researchers
- 2 administrative staff
- 2 Management
- 2 technical staff

- 13 graduated PhD candidates financed by NTNU AMOS
- 4 graduated PhD candidates associated to NTNU AMOS (3 of those financed by CeSOS)

Revenues (NOK)

• Income	68 754 000
• Costs	70 964 000
• Year end allocation	-2 210 000

Publications

- 8 book chapters
- 100 refereed journal articles
- 100 refereed conference papers
- 7 international keynote lectures

MAIN RESEARCH AREAS AND PROJECTS

The NTNU AMOS has two research areas:

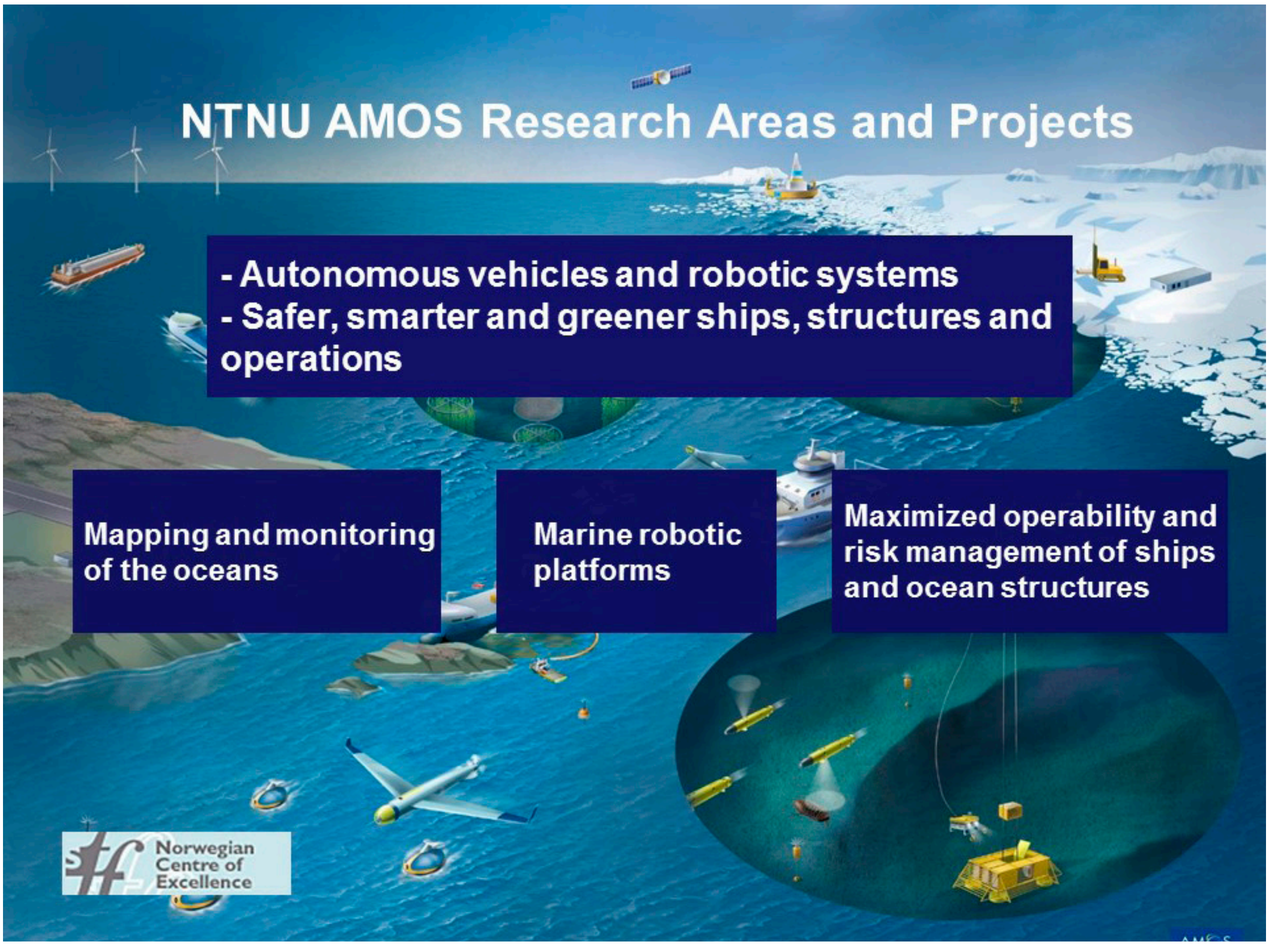
- Autonomous vehicles and robotic systems
- Safer, smarter and greener ships, structures and operations

The AMOS project plan has been updated with more focused research topics that provide improved balance and integrate the research areas. During 2017, we have gradually transferred our research from nine to three projects:

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

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

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



Technology for mapping and monitoring of the oceans

Project manager: Prof. Tor Arne Johansen
Key Scientists: Profs. Asgeir J. Sørensen, Geir Johnsen, and Thor Fossen.
Scientists at NTNU: Profs. Martin Ludvigsen, Jo Arve Alfredsen, Lars Imsland, Kanna Rajan, Annette Stahl, Rune Storvold, Martin Føre, Arne Fredheim, Nadia Sokolova, Francesco Scibilia, Kjetil Skaugset, Jørgen Berge, Jo Arve Alfredsen and Roger Skjetne

Research activities:
This project considers the modeling, mapping and monitoring of oceans and the seabed, including
- coordinated network operations
- real-time processing of payload data
- intelligent payload systems and sensor fusion
- big data analytics and machine learning
- adaptive sampling of spatio-temporal features from robotic vehicles

Main results

Underwater mapping and monitoring
Three new sensors for underwater mapping and monitoring were implemented in underwater robots and autonomous surface vehicles in 2017. The implementation of underwater silhouette camera "SilCam" (SINTEF Ocean) was used to identify and enumerate zooplankton from in situ profilers, and an ROV (RV Gunnerus) was used successfully during two NTNU AUR-Lab/AMOS cruises to Frøya in May and Runde in June of 2017. The second sensor, the fast repetition rate fluorometer (FRRF, NTNU), was used to simultaneously measure photosynthetic rates (i.e., the quantum yield of chlorophyll a and fluorescence from an oxygen evolving site with photosystem II in phytoplankton), irradiance and biomass (i.e., chlorophyll a concentration) from in situ profilers on the ROV with the SilCam. The third sensor, the underwater hyperspectral imager (UHI-4, Ecotone), was used to identify, map and monitor the sea floor using an ROV, AUV and USV as instrument carriers. The plan was to use a UHI on a USV simultaneously with drones, which were equipped with hyperspectral imagers in winter and spring of 2018. Remote sensing and in situ monitoring activities will be further aligned with near future mini-satellite activities as AMOS bridges activities between AMOS projects 1 and 2.

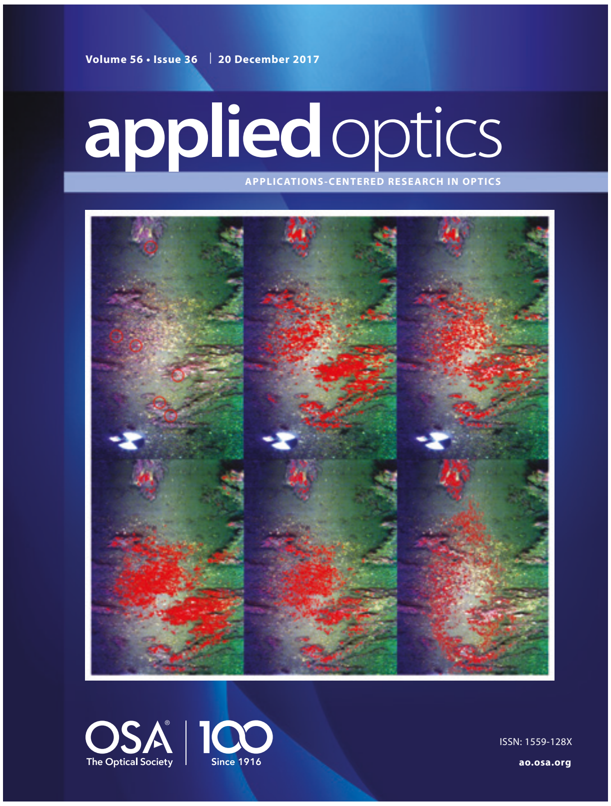


Figure 1: *PhD candidate Aksel Mogstad made the front page in Applied Optics (P1-R2), which shows mapping from the underwater hyperspectral imager deployed on the ROV with coralline algal coverage at a 30 m depth in a high Arctic fjord using different classification algorithms.*

Using Synthetic Aperture Sonar on Deepwater Shipwrecks

There are hundreds of thousands of shipwrecks along the deep seafloor (i.e., beyond the reach of conventional scuba diving). For decades, archaeologists have applied relevant technologies to access these wrecks using deep-towed side scanning sonars (SSS) and ROVs. Operating deep-towed and tethered systems become increasingly time consuming and expensive with depth, making AUVs a preferable platform for surveying large seabed areas. Synthetic aperture sonar (SAS) technology provides seabed imagery at wide swaths independent of frequency and unhampered by traditional range-resolution tradeoffs that are typical of underwater acoustic sensors, such as SSS. NTNU AMOS researchers and scientists from the Norwegian Defense Research Establishment (FFI) at the University of Southern Denmark and Northeastern University have studied how these technologies can be applied to marine archaeology (P1-R3).

In 2015 and 2016, comprehensive mapping of wrecks in Skagerrak, which is a large deep water area off the southern coast of Norway, was performed by the FFI and the Norwegian Coastal Administration using a HiSAS 1030 interferometric sonar deployed on a Hugin AUV. The survey area had been used as a dumping ground for chemical munitions after WWII, and an environmental assessment was the primary mapping objective. However, in addition to the expected CW wrecks older than 18 years, previously unknown wrecks of archaeological interest were also detected.

Data sets from two passes over the selected wreck site were subjected to several processing methods for enhanced analysis and interpretation. By fusing intensity, coherence and bathymetry plots and comparing data from the two passes, valuable information about the wreck site could be derived. In addition to the archaeological inferences about the state of the wreck, vessel type and possible age, the data sets were well suited as a baseline for planning further investigations. The spatial extent of the site was easily defined, and the objects of interest for closer examination using UAVs (e.g., ROV) were distinctly perceivable.

Precise data synchronization

The SenTiBoard is a timing sensor board that accurately records when sensor messages are validated. This means that frames from imaging sensors can be accurately synchronized with initial sensor data and position references (e.g., GPS). For fast moving sensor platforms such as unmanned aerial vehicles, time synchronization accuracy is often a bigger source of error than those of GPS and attitude sensors when referencing image data at the surface.

To achieve high accuracies, the SenTiBoard uses a 200 MHz microcontroller with a 100 MHz and 32-bit internal clock, resulting in a resolution of 10 ns. The board uses the microcontroller interruption capture function, which registers the timestamp when a flank on a pin is detected to record a sensor's reported time of validity (TOV) or pulse per second (PPS). In addition, the initial time of the

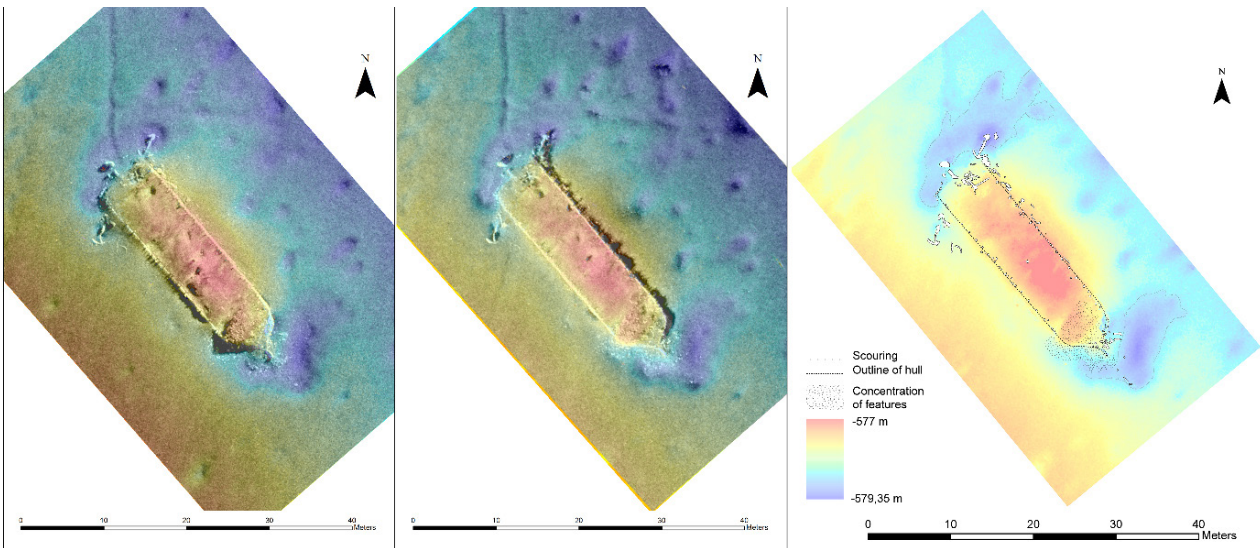


Figure 2. *Left: Fusion imagery of the wreck site from two HiSAS data sets. Right: Archaeological wreck site plan.*

first transferred byte is also recorded to support sensors that do not have dedicated TOV signals.

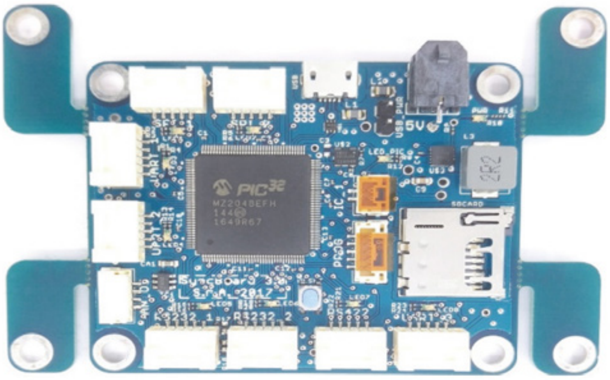


Figure 3: *The SenTiBoard*

Primarily, the SenTiBoard communicates and is configured through the USB interface. This allows the board to be configured and tested on a standard computer on an operating system of choice, which can then be transferred to the onboard payload computer. If the USB is not present on the onboard computer, other interfaces such as SPI or UART can be used, and sensor logging directly onto an SD-card can be planned. The SenTiBoard is designed to fit on top of the ODroid XU4 single board computer, with dimensions of 83 mm x 59 mm. To reduce the size further, the legs can be removed, resulting in a board of 60 mm x 50 mm.

To provide a quick and easy solution for accurate navigation, the SenTiStack consists of a compact setup with a set of sensors, which provides synchronized RTK GNSS measurements with INS data. The SenTiStack is composed of a SenTiBoard, a uBlox GNSS receiver, one or more tactical grade IMUs – typically an ADIS164XX and/or an STIM300, and an onboard computer. We are working on integrating a magnetometer and a uBlox receiver in a more convenient and compact package for the SenTiStack.

In addition to the pure hardware solutions, the SenTiStack aims to provide documentation and a well-tested software framework for logging data, configuring sensors, parsing sensor messages, and converting sensor information to higher-level formats, such as MATLAB and Python's NumPy. The SenTiBoard was developed by doctoral candidate Sigurd M. Albrektsen, and further information can be found in **P1-R4**.

Selected references:

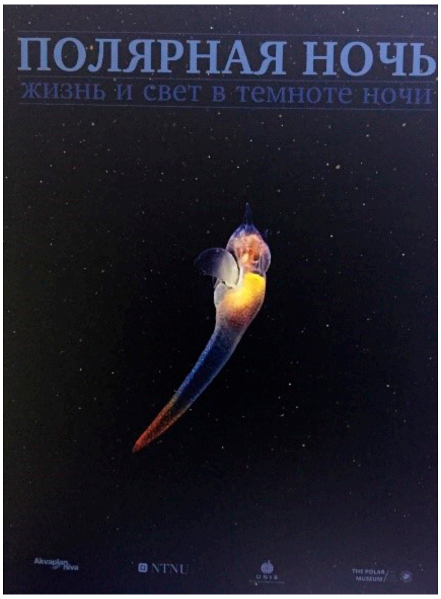
- **P1-R1**. Assmy P , , Fernández-Méndez M, D, uarte P, Meyer A, Randelhoff A, Mundy CJ, Olsen LM, Kauko HM, Bailey A, Chierici M, Cohen L, Doulgeris AP, Ehn JK, Fransson A, Gerland S, Hop H, Hudson SR, Hughes N, Itkin P, Johnsen G, King JA, Koch BP, Koenig Z, Kwasniewski S, Laney SR, Nicolaus M, Pavlov AK, Polashenski1 CM, Provost C, Rösel1 A , Sandbu M, Spreen G, Smedsrud LH, Sundfjord A, Taskjelle T, Tatarek A, Wiktor J, Wagner PW, Wold A, Steen H, Granskog MA (2017). Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice. Scientific Reports, 7:40850, DOI:10.1038/srep40850
- ***P1-R2.*** Mogstad AA, Johnsen G (2017) Spectral characteristics of coralline algae: a multi-instrumental approach, with emphasis on underwater hyperspectral imaging. Appl. Opt. 56, 9957-9975. https://doi.org/10.1364/AO.56.009957
- ***P1-R3.*** Ødegård, Ø., Hansen, R. E., Singh, H., & Maarleveld, T. J. (2018). Archaeological use of Synthetic Aperture Sonar on deepwater wreck sites in Skagerrak. Journal of archaeological science, 89, 1-,13. https://doi.org/10.1016/j.jas.2017.10.005
- ***P1-R4.*** S. M. Albrektsen, T. A. Johansen, SyncBoard - A high accuracy sensor timing board for UAV payloads, Int. Conf. Unmanned Aircraft Systems, Miami, 2017

Selected media:

- Polar night exhibition in Moscow in October 2017: Prof Jørgen Berge (UiT/UNIS/AMOS) and Geir Johnsen (NTNU/AMOS/UNIS), who were both main contributors, were at the opening of the "Polar night" exhibition at Lomonosov Moscow State University on 5 October (5000 visitors in two days) as part of Russian Science Week.

Plenary lectures at international conferences

- 7 th. October



Polar night exhibition in Moscow, October 2017. Norwegian participants (Jørgen Berge and Geir Johnsen, NTNU AMOS) with Russian and Norwegian colleagues in front of Lomonosov Moscow State University.

Marine Robotic Platforms

Project manager: Prof. Kristin Y. Pettersen
Key Scientists: Profs. Asgeir J. Sørensen, Thor I. Fossen, Tor A. Johansen, Marilena Greco and Geir Johnsen.
Scientists at NTNU: Profs. Odd M. Faltinsen, J. Tommy Gravdahl, Martin Ludvigsen, Ingrid Schjølberg, Roger Skjetne, Maarja Kruusmaa, Claudio Lugni, Kjetil Skaugset, Kanna Rajan, and Houxiang Zhang

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

- guidance, navigation and control of unmanned ships, underwater vehicles, aerial vehicles, and small-satellite systems
- dynamic optimization
- fault-tolerance
- cooperative multi-vehicle control
- situation awareness
- bio-mimics: bio-cyber-hydrodynamics
- multi-scale and distributed systems for sensing and actuation

Main results

Underwater swimming manipulators
The research on underwater snake robots is motivated by nature and the excellent mobility properties of biological snakes, which we wanted to obtain for our robot. A natural next question was, "What if we combine the best from biology with the best from technology and equip the snake robot with additional effectors?" In particular, for the underwater snake robots, a natural next step was to investigate what can be achieved by equipping the robot with thrusters along its body. By combining the slender, multi-articulated and thus flexible body of snakes with the efficient propulsion provided by thrusters, we created a new type of robot that is called an underwater swimming manipulator (USM). The USM combines several beneficial features of survey AUVs, work class ROVs and observation ROVs and AUVs into one tool. The robot shares the same advantageous hydrodynamic properties as the survey AUV, making it suitable for long range transportation. The flexible and slender body can access and operate in restricted areas of subsea structures, thus achieving excellent access capabilities compared to small observation ROVs/AUVs. Furthermore, the vehicle itself is a dexterous robotic arm that can operate tools and carry out intervention tasks, operating as a floating base robotic manipulator. The combined features of the USM make it an excellent choice for a subsea resident robot that can be permanently installed on the seabed, where it is ready 24/7 for planned and on-demand inspection and intervention operations. This new robotic platform will reduce the use of the expensive surface vessels that are currently needed to support such operations. Thus, this new platform will provide safer, greener and more cost-effective subsea operations. We have derived mathematical models of the USMs and have developed a control framework including inverse kinematic control, dynamic controllers, thruster allocation and collision avoidance. The theoretical results have been validated both by simulations and experiments.

Motion control for mapping of steep underwater walls
Operating underwater vehicles close to high rock walls or other vertical environments often poses navigational challenges since these locations are prone to acoustical multipaths for position references. At the same time, such locations are often important to investigate for multiple end users within the marine science and oil and gas industries. As a result, mapping of these areas has

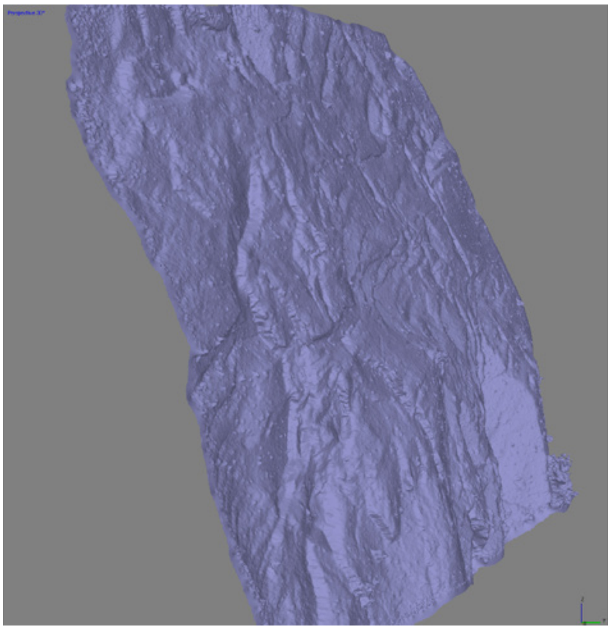


Figure 1: *A shaded relief 3D model of a 5 m x 5 m section of rock wall at Stokkbergneset in the Trondheimsfjord. The model was constructed from 340 still images recorded in a 5.5-minute automated ROV pattern.*

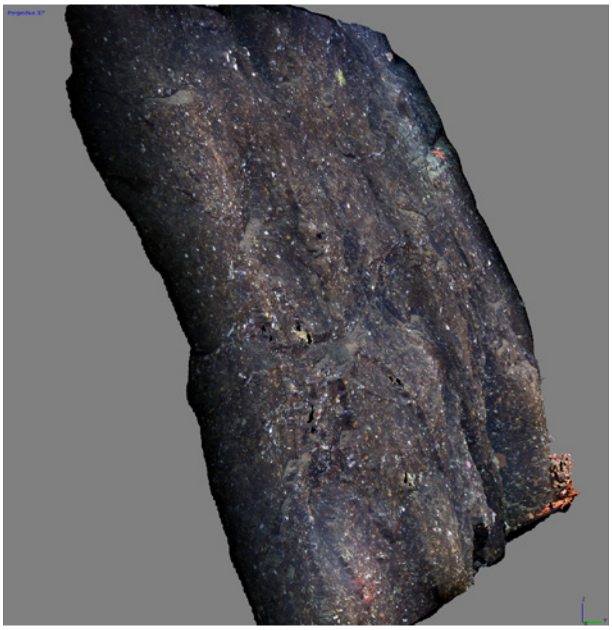


Figure 2: *A textured 3D model of the rock wall was produced by projecting the original still images onto the 3D mesh. The control system maintains a constant distance to the wall, ensuring high image quality.*

been performed using manually piloted ROVs for video and sampling surveys. These surveys can be time- and resource-consuming, while the results can be difficult to interpret, and there is no guarantee of completeness of coverage and sample representativeness.

Automated surveys with data acquisition for photomosaic and 3D photogrammetry models can improve the results by providing a panoptic view for both analysis and planning/re-planning of repeated surveys. The use of underwater photogrammetry, combining 2D still images into a 3D model, for close-up visual mapping and visualization of results has greatly increased over the past few years. This increase can be attributed to the improvements in computing power and photogrammetry software, leading to a reduced need for experts who manually align the images. Due to limited image swath width, image acquisition for photogrammetry requires low cross-track errors to ensure proper overlap, and it benefits from automated lawn mower pattern maneuvering. The quality of the images also depends on the distance to the scene, both directly due to the field of focus of the camera, and more indirectly from the amount of light that is attenuated in water by the round-trip distance of the light from lamps to cameras.

To perform an automated photogrammetry survey on steep underwater walls, we have developed a new relative motion control strategy for unmanned underwater vehicles. By incorporating measurements from a horizontally mounted DVL into the NTNU ROV control system, we are able to maintain optimal sensor positioning and scene distance for high quality data collection. The performance of the system has been verified through full-scale experiments on a near vertical rock wall in the Trondheimsfjord [P2-R5].

Multi robotic platform expedition to the bird island Runde in 18-25 June 2017

This cross-disciplinary project to identify, map and monitor physio-chemical-biological-geological objects of interests (OOI) and processes in the air, water surface, water column and sea-floor was organized by Runde Miljøsenter (RMS) and NTNU AMOS. AMOS used RMS as a base for the land-based activities and RV Gunnerus as a base for the sea-based activities. By combining robotics technologists (NTNU AMOS, Maritime Robotics, BluEye, Rolls Royce, and Norbit) with nature scientists (NTNU AMOS, SINTEF Ocean, NINA, NGU, Kystverket, RMS, and Havforskningsinstituttet), several activities were carried out to map sea-floor habitats, identify food sources (fish) for sea birds (focus on European shag mainly feeding on saithe in kelp forests). Correspondingly, another group (NTNU and SINTEF Ocean) identified, mapped and monitored the biomass, species distribution and production of phytoplankton and zooplankton, the major food source for fish and seabirds, by using the research vessel Gunnerus, AUVs, USVs and ROVs.

To obtain an overview of the population dynamics from phytoplankton, zooplankton, fish, and seabirds at Runde, we used several types of instrument carrying robotic platforms.

"Biological drones" (seabirds with GPS and environmental sensors) were followed by helicopter drones. After identifying site of European shag feeding activity, unmanned surface vehicles and remotely operated vehicles were used to reveal the dietary choices of European shag. Tracking seabirds to monitor their underwater feeding activity proved to be quite successful. The research generated new knowledge on ecology, platform control and sensor applications with AMOS researchers, PhD and MSc students working in concert with all partners in this cross-disciplinary project.

Figure 3: *NTNU MSc in marine biology Lisa H. Graham followed track routes of the European shag (sea bird) with GPS and depth sensors (biological drone) with a helicopter drone. After targeting feeding grounds for the seabirds, a corresponding underwater survey was performed by a mini ROV (BluEye) to identify fish prey speciation and abundance in the kelp forest.*

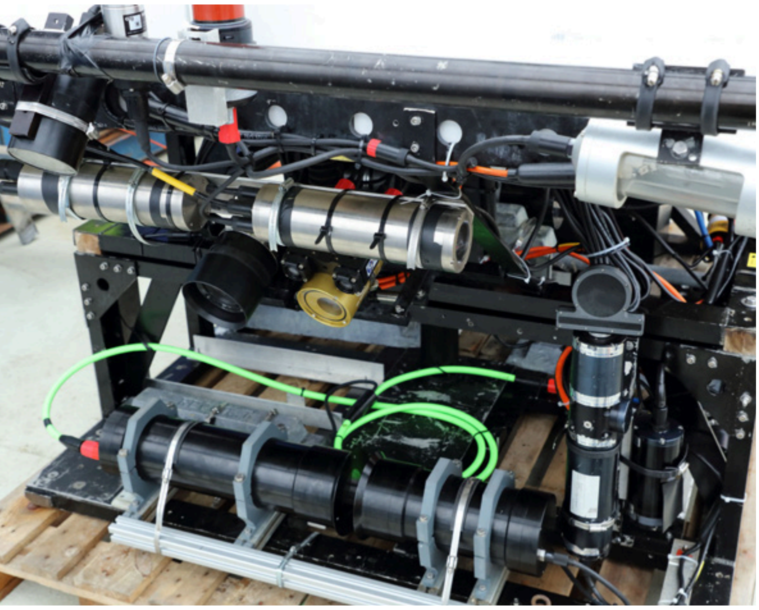


Figure 4: *The K30 ROV was used as an instrument carrier for the Silhouette camera (SilCam, black cylinder in front) to identify and enumerate zooplankton. Synchronously, a Fast Repetition Rate fluorometer (FRRf) was used to measure photosynthetic rate, biomass and light conditions of phyto-plankton – the basic food source for all marine life.*

The new PX-31 unmanned aerial platform

For some time now, unmanned aircraft have promised a revolution in how we acquire aerial data. Compared to their *manned* counterparts, small unmanned aircraft will eventually offer simpler, cheaper and more flexible operations. However, the current generation of small unmanned aircraft is typically not designed to fly in harsh Norwegian environments.

The new PX-31 is a small battery-powered unmanned air-craft that is designed from the ground up to be a robust, easy-to-use system and offer an unprecedented cargo flexibility. It is being developed in close cooperation with NTNU by the Trondheim-based firm Maritime Robotics A/S. The conceptual design was done by doctoral candidate Anthony Hovenburg at Maritime Robotics and is funded by the MarineUAS Innovative Training Network (ITN).

Unmanned aircraft conduct a variety of missions and are required to carry all sorts of payloads. The blended fuse-lage of the PX-31 provides a large cargo space that can accommodate larger sensors and systems. In addition, because the aircraft's center of gravity has a large range, the user can spend more time focusing on the sensor itself rather than determining how to exactly fit it inside the aircraft. The cargo compartment can be environ-mentally sealed and is also physically separated from the propulsion and avionics compartments. This further increases operational reliability and in-flight safety. The maximum cargo weight is estimated to be between 4-7 kilograms, depending on the mission requirements and environmental conditions.

Figure 5: *PX-31 during its first test flight at Eggemoen in 2017.*

The aircraft is electrically powered by a 6 kW brushless motor. This is a relatively powerful motor and ensures sufficient speed penetration in more windy conditions. The motor is powered by approximately 1 kWh of lithium polymer batteries. The aircraft is still in development, and its limits have not been tested. Based on current results, it is expected that the aircraft will offer between 120 and 140 kilometers of flight range.

Estimation of Wind Velocities and Aerodynamic Coefficients for UAVs

While operating any aircraft, it is vital to know its current flight state. Some of the most important variables to assess flight state are airspeed, the angle of attack and the sideslip angle. These variables provide direct indications of how large the margin is before the aircraft enters into a stall or other undesired conditions. This is particularly important when operating in strong winds with turbulence or during aggressive maneuvers with climbs and turns.

Larger aircraft are equipped with sensors specifically designed to measure these variables. However, on small unmanned aerial vehicles (UAVs), much stricter restrictions on size, weight and cost prohibit the use of such sensors. Therefore, we have developed methods to estimate the airflow variables utilizing only sensors that are part of a standard UAV autopilot. This includes an inertial measurement unit (IMU), a global navigation satellite system (GNSS) receiver and a pitot-static tube.

These measurements, together with kinematic and aerodynamic models, are fused within an estimator to estimate steady and turbulent wind velocities and aerodynamic coefficients. With these estimates, it is possible to calculate the angle of attack, the sideslip angle, and airspeed. A main challenge is distinguishing between changes in the aerodynamic coefficients and changes in wind velocity, since pitot-static tube measurements of the relative airspeed are only available in one direction at a time. Hence, the system is not always observable. Therefore, attitude changes are useful to achieve the persistence of excitation.

In the paper P2-R6, with doctoral candidate Andreas Wenz as the lead author, a Moving Horizon Estimator (MHE) was used for estimation. The simulation results show overall good estimation results and significant improvements compared to a previous Extended Kalman Filter approach. Root mean square errors (RMSE) are 0.25° for the angle of attack, 0.08 m/s for airspeed, and 1.06° for the side slip estimates.

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- **P2-R1. K.Y. Pettersen**, "Snake Robots", *Annual Reviews in Control*, Vol. 44, 2017, pp. 19-44.
- **P2-R2. Eleni Kelasidi, P. Liljebäck, K.Y. Pettersen and J.T. Gravdahl,** "Integral Line-of-Sight Guidance for Path Following Control of Underwater Snake Robots: Theory and Experiments", *IEEE Transactions on Robotics*, Vol. 33, No. 3, 2017, pp. 610-628.
- **P2-R3. K.Y. Pettersen,** "Lyapunov Sufficient Conditions for Uniform Semiglobal Exponential Stability", *Automatica*, Vol. 78, 2017, pp. 97-102.
- **P2-R4. A.M. Kohl, S. Moe, E. Kelasidi, K.Y. Pettersen and J.T. Gravdahl,** "Set-based path following and obstacle avoidance for underwater snake robots", Proc. 2017 IEEE Int. Conf. on Robotics and Biomimetics (ROBIO), Macau, China, Dec. 5-8, 2017. Awarded the *IEEE-ROBIO* 2017 Best Conference Paper.
- **P2-R5. S.M. Nornes, A.J. Sørensen, M. Ludvigsen,** "Motion Control of ROVs for Mapping of Steep Underwater Walls", *Sensing and Control for Autonomous Vehicles. Lecture Notes in Control and Information Sciences,* vol 474, 2017, pp. 51-69. Springer, Cham
- **P2-R6.** A. W. Wenz, T. A. Johansen, Estimation of Wind Velocities and Aerodynamic Coefficients for UAVs using standard Autopilot Sensors and a Moving Horizon Estimator, Int. Conf. Unmanned Aircraft Systems, Miami, 2017

Selected media coverage:

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- 01.07.2017: 300 000 sjøfugl er forsvunnet fra Runde. Av Inger Otterlei. Sunnmørsposten helg, 1 Jul 2017 pp 21-25. AMOS & Aur-lab activity.
- 31.08.2017.2017: Dagsrevyen – 31 Aug 2017. Runde – reduksjon av sjøfuglbestand. NTNU AMOS og Runde miljøsenter – kartlegging av sjøfugl, fisk og plankton ved hjelp av ny teknologi. http://tv.nrk.no/serie/dagsrevyen-21/NNFA21083117/31-08-2017

Plenary lectures at international conferences

- **Pettersen, Kristin Ytterstad.** Snake Robots: from Biology, through University, towards Industry. Plenary lecture at IFAC World Congress, Toulouse, France, July 9-14, 2017.
- **Johansen, Tor Arne.** Increasing the Operational Window of Unmanned Aerial Systems. Plenary lecture at the Workshop on Research, Education and Development of Unmanned Aerial Systems, Linköping, Sweden, October 3-5, 2017.

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, Kjetil Skaugset, Kjell Larsen, Ulrik D. Nielsen, Oleksandr Tymokha, Vahid Hassani, Trong Dong Nguyen, Claudio Lugni, Arne Fredheim and Martin Føre

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

Highlights

The aquaculture industry faces important issues related to fish escapes, sea lice, diseases, and pollution. **Closed Flexible Fish Cage**s (CFFCs) with an impermeable mem-

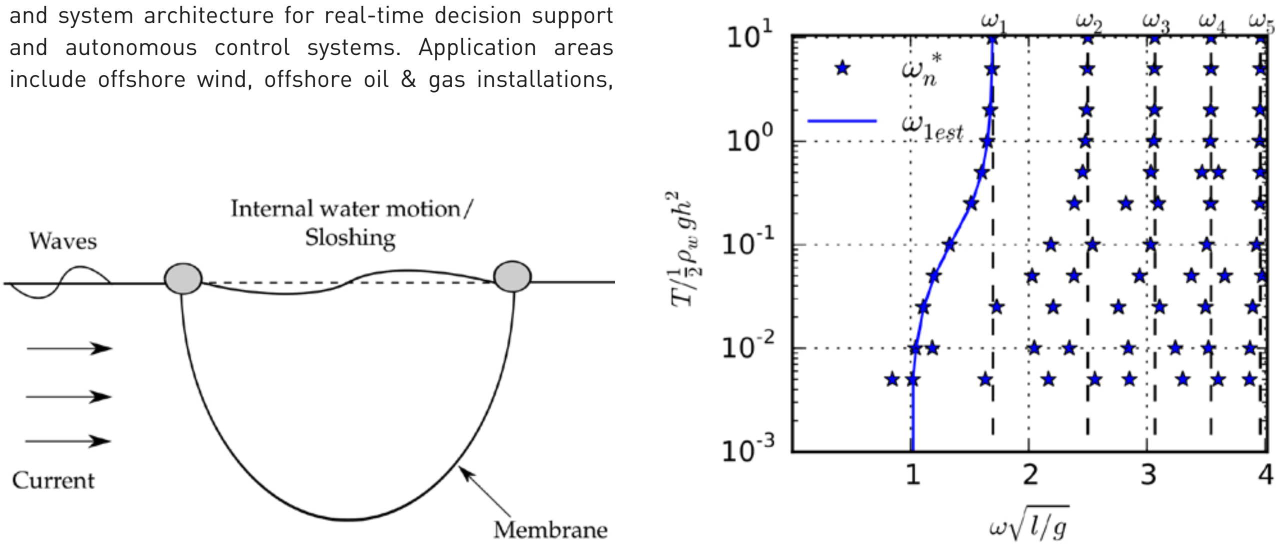


Fig. 1: *Left: Illustration of CFFC coupled system. Right: Non-dimensional eigenfrequencies ω_n* $(l/g)^{0.5}$ versus the membrane tension T in the left wall of a rectangular tank. ω_n are sloshing eigenfrequencies for a rigid tank. Water depth (h)-to-tank length (l) ratio = 0.5. Membrane length L = h.*

brane material have been proposed as a possible solution. The station-keeping behavior differs greatly from net-based cages and depends on the coupling of the following: (1) the internal water and related sloshing flows, (2) the membrane structure, and (3) the external environment (Fig. 1, left). The coupling mechanisms need to be identified. This involves important research challenges. Theoretically, one must study the coupled system, which will present several natural frequencies connected with rigid and flexible modes of the structure, combined and modified by the natural frequencies of the internal sloshing flow. It is expected that sloshing wave elevations and rigid motions will be different from those experienced by an equivalent closed rigid cage. Experimentally, the structural properties need to be properly reproduced for a cage behavior consistent with the full-scale system.

Using a step-wise approach, a systematic investigation was conducted to develop knowledge of the mutual influence between (1) the internal water and related sloshing flows and (2) the membrane structure within the linear potential-flow theory. This is relevant for CFFCs in incident waves. Three-dimensional (3D) geometrical and flow effects that could complicate and hide the involved phenomena were neglected. Then, the problem was simplified as a two-dimensional (2D) rectangular partially filled tank, with a fabric membrane at the left wall, in a forced harmonic sway motion [P3.R1]. It was solved both analytically, using mode decomposition, and numerically, using the harmonic polynomial cell (HPC) method, with consistent results. This simplified analysis confirmed that the eigenfrequencies differ from those of a rigid tank and are heavily influenced by the membrane tension and length. For low tensions, more than one eigenfrequency may exist between two neighboring sloshing frequencies for the rigid tank (Fig. 1, right). For large tensions, the eigenfrequencies tend to the sloshing frequencies of a rigid tank. Typically, a given eigenfrequency involves combinations of several structural and sloshing modes.

The relevance of this for a real CFFC system depends on the level of the actual tension, and this should include both static and dynamic effects. The next step, which also considers the coupling with the external flow, is crucial.

Violent resonant sloshing of the internal liquid in closed fish farms and liquefied natural gas (LNG) tanks may have a strong 3D character, which qualitatively and quantitatively affects the induced structural loads and may threaten the well-being of fish inside aquaculture cages. The type of sloshing-wave system that is experienced depends greatly on the initial conditions; thus, it

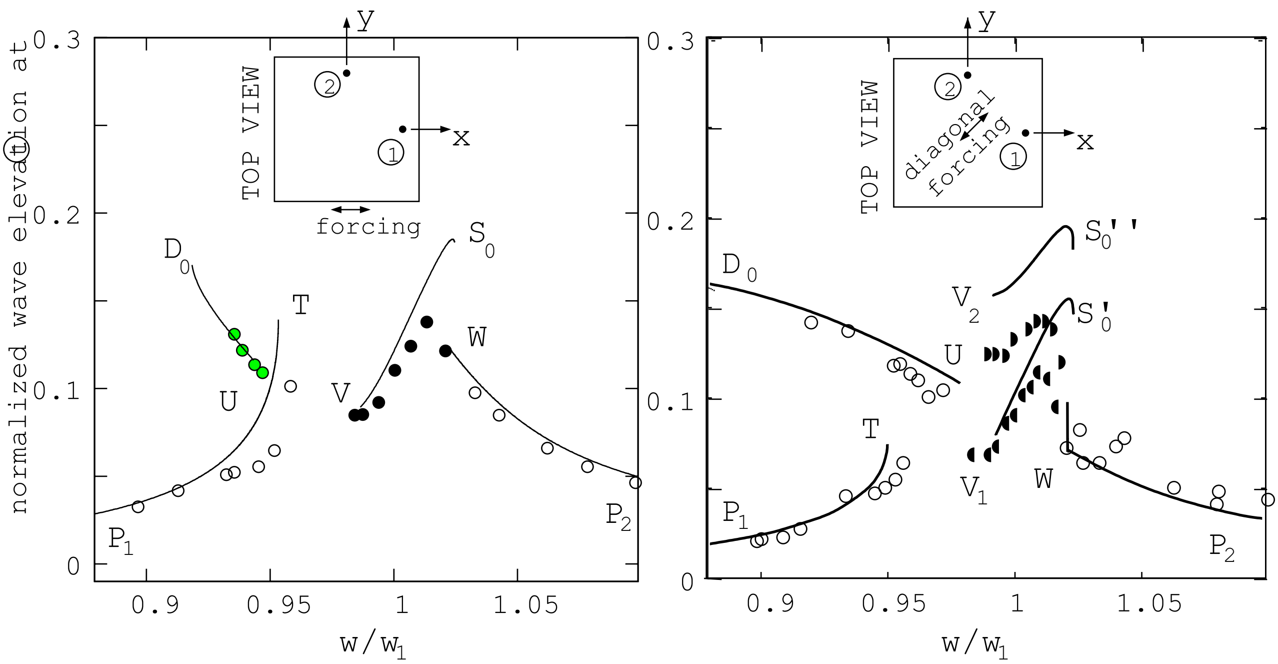


Fig. 2: *Experimental (symbols, Ikeda & Ibrahim, 2008-12) and theoretical (lines, modified theory) normalized maximum wave elevation at wave probe 1 for the longitudinal (left) and diagonal (right) forcing with frequency ω. The non-dimensional forcing amplitude is 0.00727 and mean non-dimensional liquid depth is 0.6 (scaled by the tank breadth). The viscous damping rate is taken from the experiments.*

is difficult to predict and classify the sloshing scenarios by using CFD simulations and/or model tests. Examples are the swirling wave mode, i.e., progressive waves in the angular direction (rotary waves) leading to a lower wave elevation near the tank center and water run-up along the vertical sides, and the wavy chaos, both expected when the forcing frequency, ω, of the tank is close to the lowest natural sloshing frequency, ω_1. An effective estimate of the resonant sloshing phenomena can be provided by analytical (e.g., multimodal) methods, which are well developed for inviscid liquids with irrotational flows. However, recent experiments by Reclari (2013) and Ikeda and Ibrahim (2008-12) on axisymmetric and rectangular containers established that sloshing may demonstrate a qualitatively complicated and, to some extent, paradoxical behavior due to viscous damping and vorticity. Modifications in the steady-state theoretical analysis by Faltinsen and Timokha (2009) were proposed [P3.R2] to analytically describe the damping-affected sloshing in a square-base tank. Fig. 2 provides the maximum wave elevation recorded near a sidewall in a longitudinal (left) and diagonal (right) oscillatory forcing from the modified theory (lines) and experimental (symbols) results. The different symbols indicate the occurring sloshing scenarios: planar (empty circles) and swirling (filled half and full circles) waves. From the results, even a relatively small damping prevents diagonal standing waves for a longitudinal forcing, replaced by swirling waves (green-filled circles). The viscous damping also destroys the symmetry of the swirling wave mode for a diagonal forcing so that the maximum wave elevation depends on the angular wave direction (right half-filled circles: swirl clockwise; left half-filled circles: swirl anti-clockwise). This cannot be predicted by an inviscid theory (not shown in the figure) and suggests consequences for the hydrodynamic loads along the tank.

According to linear theory, transversally symmetric ships should not experience roll in head and following seas. However, at certain wave frequencies and amplitudes, some vessels may heavily roll and even capsize due to **parametric resonance (PR) in roll**, an instability resulting from the oscillatory roll restoring moment induced by heave and pitch motions and wave passage along the ship's hull. In these conditions, a small lateral asymmetry could be amplified and cause large roll angles. Fishing vessels may particularly suffer PR occurrence; however, little research has been carried out to assess possible

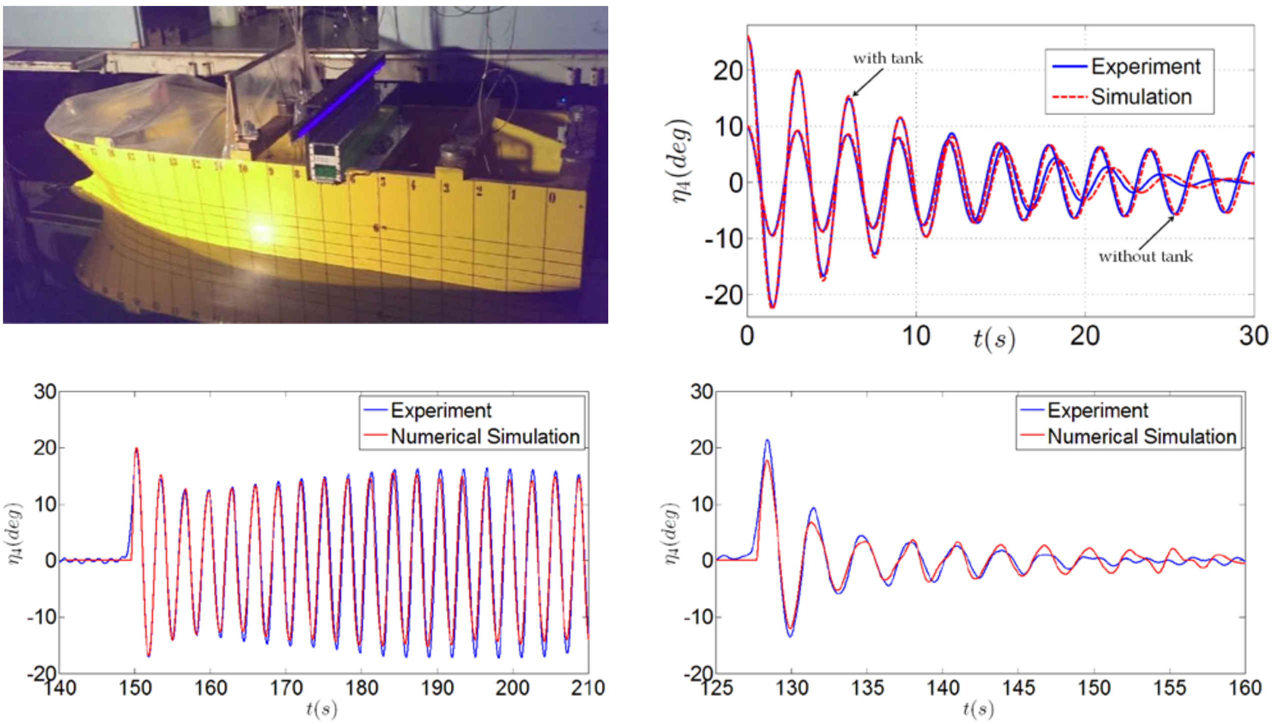


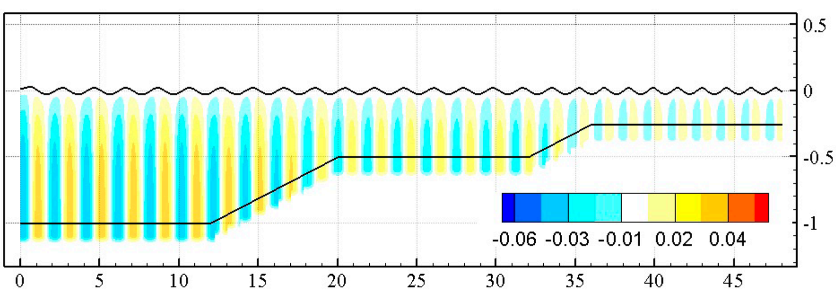
Fig. 3: *Top-left: Model with tank, tested at CNR-INSEAN. Top-right: Roll (η_4) decay in calm water without and with the tank. Bottom: Roll (η_4) evolution for the with-tank vessel in waves with initial forced roll. Natural roll frequency-to-incident wave frequency ratio ω_{4n}/ω and wave steepness $k\zeta_a$ are 0.5 and 0.2 (left) and 0.48 and 0.25 (right).*

solutions. As a contribution in this direction, the effect of a passive anti-roll free-surface tank on a fishing vessel at zero forward speed was investigated experimentally (Fig. 3, top-left) and numerically [P3.R3], within a collaboration with SINTEF Ocean and CNR-INSEAN. A mooring-line system was designed to control the horizontal motions with limited effect on PR occurrence. On the numerical side, the onboard tank was simulated using the open-source Computational Fluid Dynamics OpenFOAM solver, coupled with the weakly nonlinear seakeeping method by Greco and Lugni (2012). Model tests and numerical results highlighted the larger damping of the system with an on-board tank (Fig. 3, top right). Without the tank, a roll reduction of 6° was achieved in 16 oscillation periods, while it was obtained on average in less than 2 periods with an on-board tank.

The two results were also consistent in terms of the PR occurrence in waves and confirmed the effectiveness of the tank in preventing PR. For the examined cases, without the tank, PR occurred mostly spontaneously for the natural roll frequency-to-incident wave frequency ratio, ω_{4n}/ω, close to 0.5, reaching more than 20°. With the tank, PR occurred only after forcing an initial roll and did not always occur; examples with and without PR are shown in the bottom of Fig. 3. The corresponding cases without the tank showed PR with 20° and 24°, respectively. It was found that the initial roll amplitude and roll phase, relative to the heave motion, matter for triggering the instability when an on-board tank is used. This is important for the practical effectiveness of this device.

As free-surface waves travel from deep to shallow water regions, they undergo different changes caused by the increasing influence of the bottom topography. For instance, the flow variations along the water column and the dispersive effects are reduced, while nonlinearities become more pronounced. Handling this transition is important for predicting the incident wave scenarios and their evolution, as well as possible consequences for coastal structures and operations. The most widespread models for nearshore dynamics (e.g., Boussinesq-type equations) have intrinsic limits, making them unfit for the wave description far from the coastline. To overcome them, a numerical study was carried out in collaboration with CNR-INSEAN and the Marche Polytechnic University [P3.R4]. The theoretical basis is the **novel model for coastal dynamics** by Antuono and Brocchini (2013) that couples the main features of the classic depth-averaged scheme with a thorough description, via a Poisson-like equation, of the vertical component of the wave velocity. The former ensures solver efficiency; the latter allows the correct modeling of dispersive effects and of linear and nonlinear shoaling of waves when moving from deep to shallower water depths. The model's implementation was successfully assessed by reproducing solitary waves propagating in a constant-depth zone and shoaling on a uniform sloping bathymetry. Fig. 4 provides a proof of concept of a 2D train of monochromatic waves, which shorten and steepen while propagating from deep to shallower water.

Offshore wind harvesting has large potential as a renewable energy source. There has been an exponential growth in installed capacity over the past decade. The majority of offshore wind turbines are supported by cost-efficient monopile foundations. As the industry moves toward larger turbines and increased water depths, hydrodynamic loads are becoming more predominant. Consequently, the importance of the coupling between the wave loads, the turbine's control system and the structural response increases. The research at NTNU



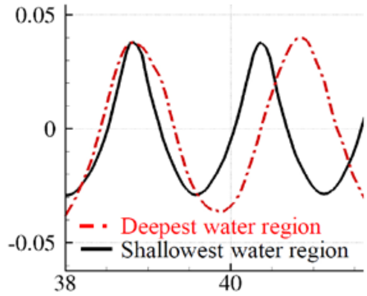


__Fig. 4:__ Left: A 2D train of monochromatic waves propagating from deep to shallower water. Contour lines refer to the integral of the vertical velocity component from the free-surface level to a certain quote. Right: Wave elevation in the deepest and shallowest water regions. Dimensions are relative to the depth of the deepest water region.

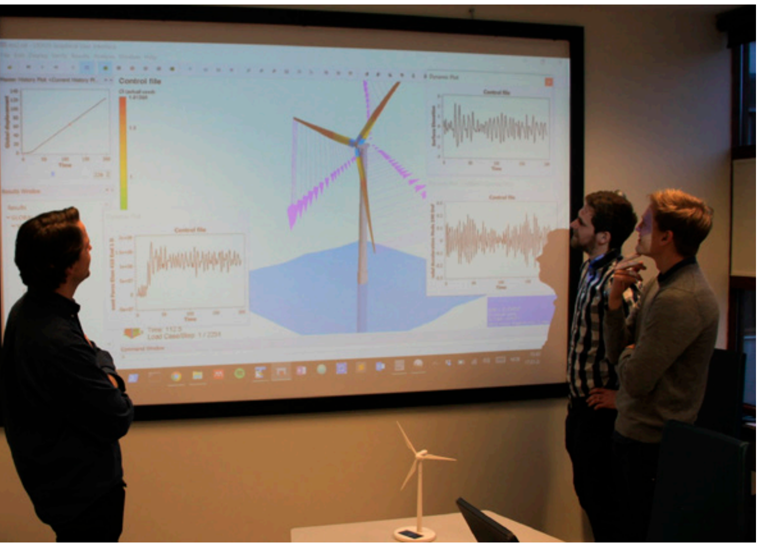


Fig. 5: PhD students Emil Smlden, Stian H Sørum and Jan-Tore Haugan Horn discussing research challenges for offshore wind turbines

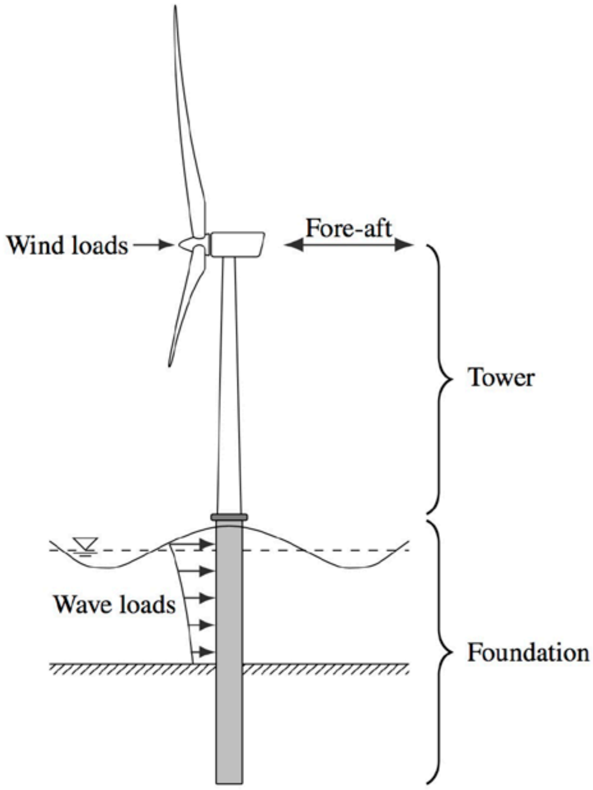


Fig. 6: Monopile offshore wind turbine.

AMOS focuses on understanding how this coupling can be utilized to allow for more economical designs, as well as for identifying and investigating load phenomena in offshore wind turbines.

Load reduction. An offshore wind turbine is subjected to wave and current loads in addition to wind (Fig. 6). The dimensions of offshore wind turbine foundations are often governed by fatigue considerations. The wind turbine's control system can be utilized to reduce the fatigue loads in the foundation. For instance, if information about the structural response is available, it is possible to design a pitch controller that opposes the fore-aft motion of the structure. Wave loads are often dominating in terms of fatigue utilization for the foundation. A control strategy that specifically targets these loads has been developed [**P3.R5**]. The proposed control strategy is compared with a conventional damping controller, shown in Fig. 7. Fig. 7 (left) shows the power spectral density of the tower top displacement. With conventional damping control, the tower vibrations are amplified in a frequency range around the wave peak frequency. With the proposed controller, the tower vibrations are reduced across a significantly broader frequency range. Fig. 7 (right) displays the power spectral density of the blade's pitch angle. Compared to a conventional damping control, the pitch activity is reduced. Consequently, a more favorable trade-off between foundation costs and adverse side effects is achieved.

Economies of scale are pushing the offshore wind industry towards larger wind turbines. The largest wind turbines currently available have a power rating in the range of 6 MW-8 MW. A design case considering the next generation of 10 MW monopile OWTs was established. Based on this design case, the applicability of different control strategies to reduce the foundation costs were analyzed [P3.R6]. By utilizing a combination of different control strategies, it was possible to double the design fatigue life of the foundation. This extra design life can be exploited to reduce the costs of materials, manufacturing and installation.

Control strategies that reduce the foundation costs may lead to adverse side effects in other wind turbine components, such as wear of the wind turbine's main shaft, or the actuators used to adjust the blades' pitch angle. The lifetime effect of various control strategies on selected components was analyzed, and a methodology to reduce these side effects was developed. By limiting the use of control strategies to some predefined situations, a more favorable trade-off between foundation costs and adverse side effects was achieved. The effectiveness of this approach was illustrated by an application to the 10 MW offshore wind turbine design case.

Site-specific conditions, such as water depth and soil conditions, may vary significantly within a wind farm. It is common design practice to divide the wind farm into

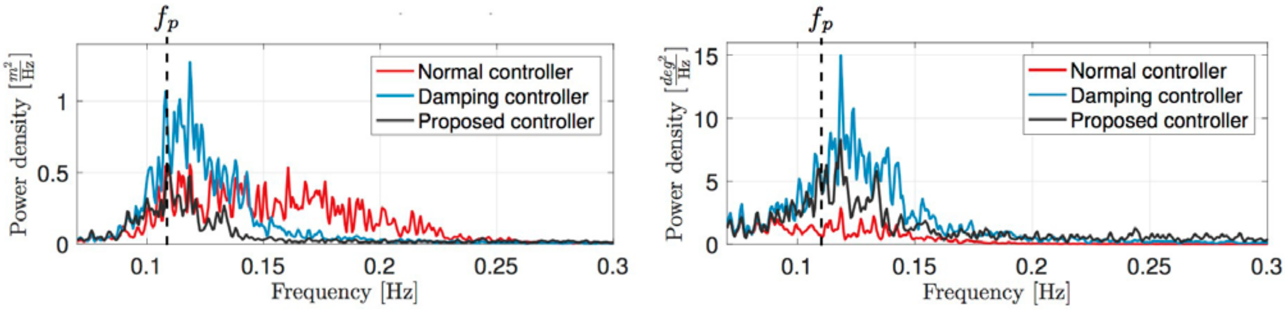


Fig. 7: *Power spectral density of the tower top fore-aft displacement (left) and the blade's pitch angle (right) with normal control (no load reduction), conventional damping control, and the proposed controller. The wave peak frequency for the considered sea state is indicated.*

sectors and customize the foundations for each sector. The need to customize the foundations increases the manufacturing costs of wind farms. To reduce the required number of customized foundation designs, a methodology was developed that utilizes the wind turbine's control system to compensate for variations in site-specific conditions. It also enables possible reprogramming of the controller during the lifetime of the wind turbine, thereby reducing the need for site-specific design conservatism. This is illustrated in Fig. 8, which shows the circumferential distribution of fatigue damage in the foundation for two different soil conditions.

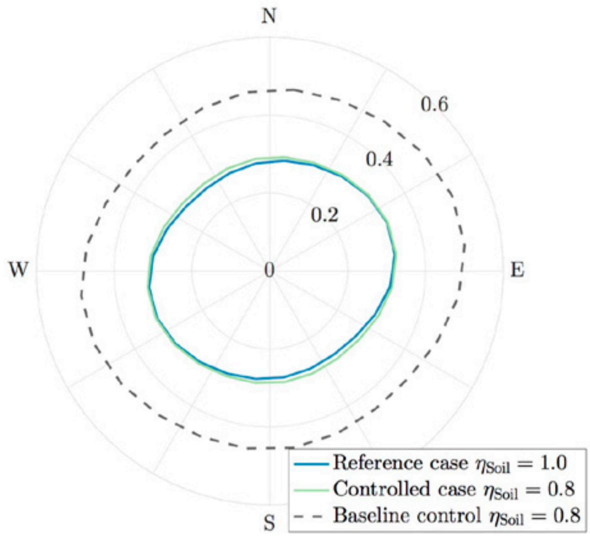


Fig. 8: *Radial distribution of fatigue damage in the foundation for normal (1.0) and reduced (0.8) soil stiffness. With the normal controller, the fatigue damage becomes larger for reduced soil stiffness, but the new wind control system is capable of compensating for this effect.*

Environmental loads and probabilistic design. Environmental loads and their statistics make up an important design basis of an offshore wind turbine (OWT). Consequently, good load models and statistical representation of the environmental processes are crucial for the performance evaluation and reliability of an OWT structure. Wave-load models for large OWTs are under development. The models consider higher-order loads and increasing wave-structure interaction. The goal is to establish an efficient engineering load model that preserves the important physics observed in model tests and CFD simulations and enables a quantification of the design conservatism.

For both fixed and floating OWTs, the design basis requires verification of the sensitivity to multi-directional loads, i.e., the load effects of mis-aligned wind and wave loads (Fig. 9). The introduction of load directionality and separate modeling of wind and swell waves are beneficial for the predicted lifetime of the structure. Therefore, probabilistic models of environmental parameters and their directions [**P3.R7**] were developed in collaboration with DNV GL. Efficient methods for a response statistical estimation that uses a design basis with many variables were also investigated **[P3.R8**]. By evaluating the impact of environmental loads, model uncertainties and control strategies, higher confidence in the results can be obtained. An example for the circumferential fatigue damage distribution is shown in Fig. 10.

The possibility of altering the system dynamics with the control system distinguishes an OWT from traditional oil and gas structures. This introduces sub-populations of response characteristics depending on whether the turbine is parked or producing energy. Both states must be considered in the design basis, and they will have various impacts on the failure probability of the structural components. Hence, a method that accounts for the structural reliability effect of a turbine in the parked condition has been developed. An example in shown in Fig. 11.

Software Comparison. A number of software tools are available for simulating the response of OWTs, and verification and validation of these tools is an ongoing activity in the research community. Differences between the individual codes do exist, mainly due to different aerodynamic load models and structural modeling approaches. Therefore, a study was performed to highlight the sensitivity to small modeling differences and model uncertainties of the predicted lifetime of an OWT [**P3.R9**]. Two commercial software programs, SIMA and vpOne, and the open-source software, FAST, were used. After verifying the basic turbine properties, a lifetime fatigue analysis was carried out. The analysis revealed significant variations in the predicted fatigue life, with a factor of 2.2 between the upper and lower estimate. This corresponds to an increase in the damage equivalent load of only 17 %.

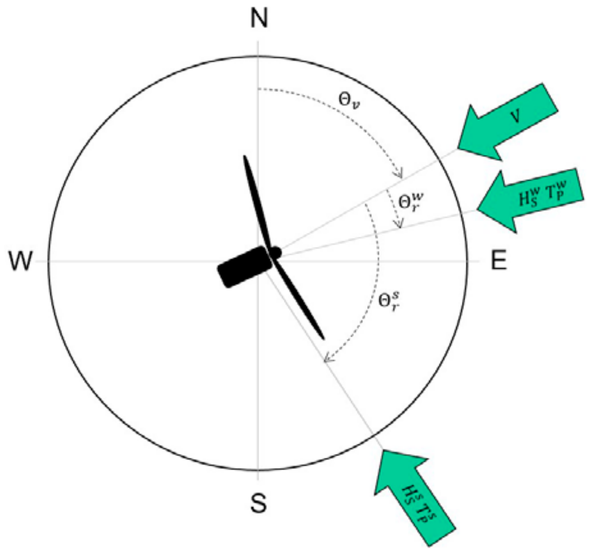


Fig. 9: Mis-aligned wind (v), wind sea (w) and swell waves(s). Waves are described individually by significant wave height, Hs, and peak period, Tp.

Real-time hybrid model testing

Real-time hybrid model testing is an experimental method for performing hydrodynamic model-scale testing, where systems/structures are partitioned into physical and numerical substructures. The physical substructure is then physically modeled in a laboratory facility, while the numerical substructure is numerically modeled using a simulation software. The two are then coupled in real-time using a measurement and control-system interface. In general, we want to perform model-scale testing to identify the characteristics and responses of structures. This is motivated by the fact that complex hydrodynamic phenomena are difficult to model numerically and analytically. Real-time hybrid model testing is an extension of conventional model-scale testing because it enables the inclusion of numerically simulated components into the classical experimental regime. Because this method is able to address some of the challenges and limitations of traditional model testing due to the complexity of structures, limitations of facilities, demand for rapid proto-

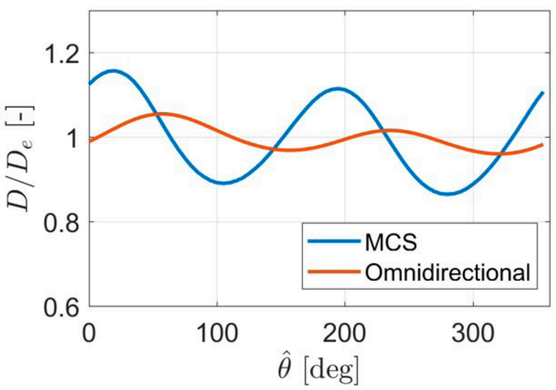


Fig. 10: Normalized fatigue damage on the pile circumference with (blue) and without (red) direction dependent wind speed

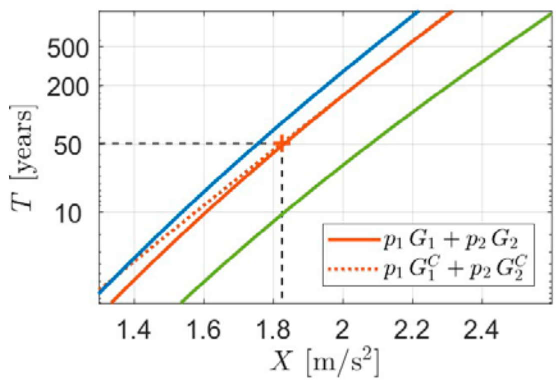


Fig. 11: Cumulative distribution function (CDF) for extreme nacelle acceleration for operational (blue), parked turbine (green) and their combined 50-year response (red) using an exact method (solid line) and simplified approach (dashed).

typing, or conflicts resulting from differences in scaling, it is not always feasible or practical to perform this method on the whole structure. One example is the study of floating offshore wind turbines, where the numerical simulation of wind loads was able to overcome the challenge of scaling discrepancies between aerodynamics and hydrodynamics [**P3.R10**]. Another example was overcoming the spatial limitations in basin infrastructures when studying structures moored in deep water by numerically simulating parts of the mooring lines. The Hybrid KNP project is a research project that was performed in close cooperation with NTNU, SINTEF Ocean, and their industry partners. Several large basin laboratories that perform model tests are located at Tyholt, which is in close proximity to NTNU AMOS and SINTEF Ocean. One of the main goals of the project is developing real-time hybrid model testing with a validated and well-tested method that is accepted and valued by the industry, which is regularly performed in these types of laboratories as a new best practice. The project began in its current form in 2016; since then, the experimental methods and control systems have been further developed, laboratory experiments have been performed, and theoretical studies have been conducted. The following will focus on the researchers at NTNU AMOS that have been particularly involved with the project; however, it should be noted that the work has been performed in conjunction with the rest of the project group.

Development, experiment and validation

The use and development of experiments to further develop, validate and identify challenges in this method is an integral part of this project. For this reason, a simple real-time hybrid laboratory test consisting of a mass-damper-spring system is continuously maintained. This allows for the fast and deterministic prototyping of the actuators, control system and the hybrid test loop as a whole and a deep understanding of the test system. Full tests, on the other hand, are performed through experimental campaigns in the Marine Cybernetics Laboratory (MC-Lab), where realistic sea conditions can be applied to the structures. Figure-12 illustrates this application, where the method was applied to the study of moored marine systems. In these tests, a moored cylindrical floating platform was partitioned into a physical substructure consisting of a model scale representation of the floating cylinder and a numerical substructure consisting of a full-scale mooring system, which was modeled using the nonlinear finite element software RIFLEX. The physical and numerical substructures were coupled in real-time by a designed control system with sensors and actuators. One of the key advantages when using this method on slender mooring systems is the opportunity to rapidly redesign or reconfigure the numerically simulated part of the system. A study was performed on the feasibility of using different types of simulation software for the numerical substructure using a linear simulation model, FhSim and RIFLEX. A sample of the results is presented in Figure-12, where the different numerical methods are compared. Furthermore, the MC-Lab was used to perform real-time hybrid model testing on a ship-shaped vessel, where activating the varying loads of the vessel was also an important challenge.

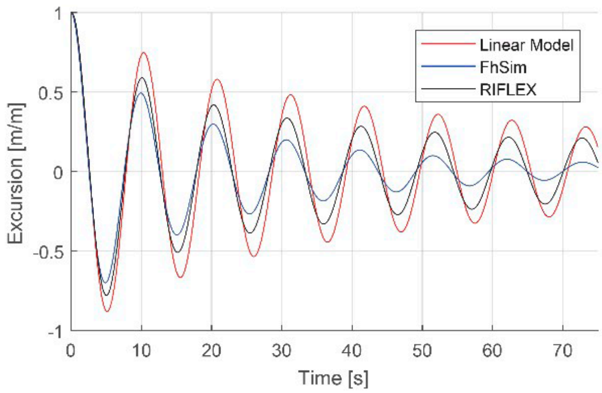


Figure-12. *Normalized displacement of the physical substructure during a decay test and a comparison of different simulation software for the numerical substructure.*

Theoretical work

Because real-time hybrid model testing for marine applications is a new idea, a proper theoretical assessment of the method is needed in order to ensure that it is viable for performing the model testing of marine structures. A key concept here is fidelity, which real-time hybrid tests define as the capacity to model systems that behave similarly to the original system under study. In practice, fidelity is jeopardized by artifacts (i.e., noise, sensor biases, delays, and actuator dynamics) that originate from the control system connecting the substructures. We developed a systematic analysis method based on the Sobol indices, which are instrumental in determining the sensitivity of the fidelity for each of the involved artifacts. The method provides valuable and objective indications on how to improve fidelity in an operational context. We also presented a computationally efficient method based on active learning to derive fidelity bounds, which translate into absolute requirements of the control system. Case studies involving the active truncation of a slender marine structure were performed, which resulted in complex mechanisms by combining the dynamics of the slender structures and the imperfect coupling at the truncation point. Furthermore, the effects of time-delay and sampling were further studied, where an idealized mass-damper-spring system was used to show how time-delays and sampling affect the real-time hybrid test metrics under investigation [**P3.R11**].

Selected references

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- **P3.R2** Faltinsen O.M., Timokha A.N., 2017, Resonant three-dimensional nonlinear sloshing in a square base basin. Part 4. Oblique forcing and linear viscous damping, *Journal of Fluid Mechanics*, 822.
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- **P3.R4** Antuono M., Colicchio G., Lugni C., Greco M., Brocchini M., 2017, A Depth Semi-Averaged model for coastal dynamics, *Physics of Fluid*, 29.
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- **P3.R7** Horn, J., Krokstad, J.R., Amdahl, J., 2018, A new combination of conditional environmental distributions, accepted for *Applied Ocean Research*.
- **P3.R8** Horn, J., Krokstad, J.R., Amdahl, J., 2017, Long-term fatigue damage sensitivity to wave directionality in extra large monopile foundations, *Journal of Engineering for the Maritime Environment.*
- **P3.R9** Sørum, S.H., Horn, J., Amdahl, J.,2017, Comparison of numerical response predictions for a bottom-fixed offshore wind turbine, *Energy Procedia*, 137.
- **P3.R10** T. Sauder, A. J. Sørensen, and K. Larsen, "Real-Time Hybrid Model Testing of a Top Tensioned Riser: a Numerical Case Study On Interface Time-Delay and Truncation Ratio.," in ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway, 2017.
- **P3.R11** S.A Vilsen, T. Sauder, A.J Sørensen, "Real-time hybrid model testing of moored floating structures using nonlinear finite element simulations", Dynamics of Coupled Structures, Volume 4, Chapter 8, Pages 79-92., The Society of Experimental Mechanics, 2017.

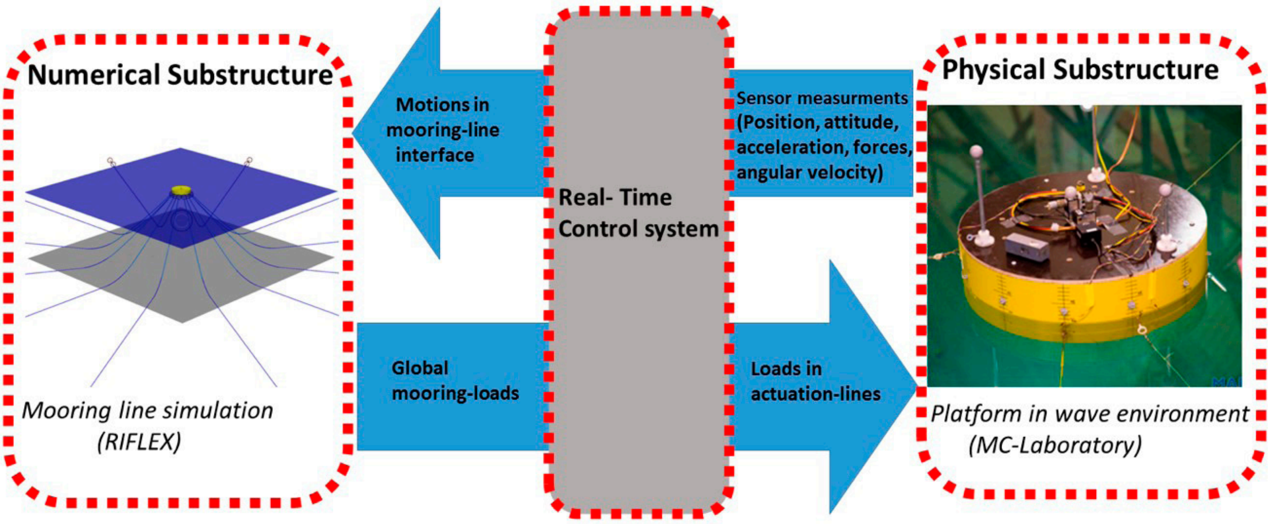

Figure-2. *A simplified illustration of the hybrid test loop used when performing the real-time hybrid testing of a moored platform in the Marine Cybernetics Laboratory.*

NTNU AMOS Participation in Ongoing Associated Projects

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Design and verification of control systems for safe and energy-efficient vessels with hybrid power plants (D2V)	Asgeir J. Sørensen	18,7 MNOK	2011-2017	NFR MAROFF	NTNU, Kongsberg Maritime, DNV GL	5+1 PhD AJS, TAJ, RS, IU
Next Generation subsea inspection, maintenance and repair operations	Ingrid Schjølberg	20 MNOK	2014-2017	NFR KPN Awarded	NTNU, FMC, Statoil, SINTEF IKT	4 PhD/Post docs IS, IBU, TIF
European Training Network funded by H2020 for 2015-2018 Marie Curie	Tor Arne Johansen Thor I Fossen	4 MEUR	2015-2018	EU project	NTNU, IST, UiP, LiU, NORUT, Maritime Robotics, Honeywell, Catec, iTUBS	15 PhD whereof 5 PhD or NTNU + project management
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 Conse-quences in an era of abrupt climate change (Arctic ABC)	Asgeir J. Sørensen Geir Johnsen	51,5 MNOK	2016-2019	Forsker-prosjekt NRC Polprog	UiT, NTNU, SAMS, APN, UiD, WHOI, UMA	1 PhD and Post doc for NTNU + Field experiments in the Arctic
Arctic ABCD	Geir Johnsen Asgeir J. Sørensen	13,5 MNOK	2016-2025	NFR INFRA	Same as ARCTIC ABC	1 Postdoc + Lab Equipment
Exposed Aquaculture Operations – Autonomous Systems and Offshore Structures	Ingrid Schjølberg	209 MNOK	2015-2022	SFI proposal	SINTEF FH, NTNU, MARINTEK, SINTEF IKT, Salmar, Grieg, Mainstream Norway, Biomar, Egersund Net, AkvaGroup, ACE, KM	PhD Postdoc Experiments IS, AJS, MG, JA
VISTA PhD-stipend Jørgen Sverdrup-Thygeson: Swimming Robot Manipulators for Subsea IMR.	Kristin Y. Pettersen	3 MNOK	2015-2018	VISTA	NTNU	1 Post doc/PhD
Center for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA)	Tor A. Johansen	3 MNOK	2015-2022	SFI proposal	UiT, NTNU ..	1 Post Doc/PhD for AMOS
Sensor Fusion and Collision Avoidance for Autonomous Surface Vehicles	Edmund Brekke Morten Breivik Tor A. Johansen	11,2 MNOK	2015-2018	RCN MAROFF	NTNU, DNV GL, Kongsberg Maritime, Maritime Robotics	2 PhD + 1 postdoc
VISTA Post doc –Eleni Kelasidi.	Kristin Y. Pettersen	3 MNOK	2016-2018	VISTA	NTNU	1 Postdoc
TerraDrone	Tor A 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 A. Johansen, Thor I Fossen	10 MNOK	2016-2019	NFR FRINATEK		1 PhD + 2 postdoc

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
UAV ice detection	Tor A. Johansen	1 MNOK	2016-2017	ERCIM / NTNU		1 postdoc
Integration of Manned, Autonomous and Remotely Controlled Systems for Coastal Operations	Tor A Johansen	1.2 MNOK til NTNU	2017-2019	NFR MAROFF	Radionor, Seatex, Maritime Robotics	
D-ICE	Tor A Johansen	6 MNOK	2017-2018	NFR FORNY	TTO	
SCOUT Inspection Drone	Tor A Johansen, Thor I Fossen	6 MNOK	2017-2018	NFR FORNY	TTO	
Intelligent monitoring of drilling operations in sensitive environments (project number 267793	Tor A Johansen	3 MNOK til NTNU	2017-2022	NFR PETROMAKS	Morten Alver, SINTEF Ocean	1 PhD
Forprosjekt design og konstruksjon av nyttelaster til NORSat	Tor A Johansen	250 kNOK	2017	Norsk Romsenter	Roger Birkeland, IET	
Safe operation of CLOSED aquaculture CAGES in WAVES	Odd Faltinsen C. Lugni	2,2 MNOK til NTNU	Q4 2017-Q3 2019	NFR MAROFF	SINTEF Ocean (P. Lader)	1 postdoc
Nonlinear Autopilot Design for Extended Flight Envelopes and Operation of Fixed-Wing UAVs in Extreme Conditions (AUTOFLY)	Thor I. Fossen Tor A. Johansen	10 MNOK	2017-2020	NFR Frinatek IKTPLUSS	NTNU	2 PhD + 1 Postdoc
AILARON - Autonomous Imaging and Learning Ai RObot identifying plaNkton taxa in-situ	Annette Stahl, Kanna Rajan, Nicole A-Malzahn, Geir Johnsen	11.5 MNOK 9.5 MNOK til NTNU	2017-2021	NFR FRINATEK IKTPLUSS	NTNU, SINTEF Ocean, Uporto, UPTC, Sequoia Scientific Inc. US	2 PhD
Collision avoidance for autonomous ferry	Edmund Brekke, Tor A. Johansen	4.1 MNOK	2017-2021	NTNU SO scholarship	NTNU	1 PhD
Drone air traffic control	Tor A Johansen	0.9 MNOK til NTNU	2017-2018	JU SESAR	Internasjonalt konsortium ledet av Airbus	
Center for Marine Operations in Virtual Environments (MOVE)	Zhen Gao	9 MNOK	2015-2022	SFI proposal	NTNU, SINTEF Ocean, Statoil, DNV-GL ...	
Coordinate aerial-underwater operations with gliders for large scale remote ocean monitoring	Tor A Johansen	2 MNOK	2017-2020	MarTERA	Alex Alcocer, HIOA	1 postdoc
Reducing risk of autonomous marine systems and operations (RISK-AMOS)	I. B. Utne, A.J. Sørensen, T.A. Johansen	12,5 MNOK	2018-2020	NFR FRINATEK	UCLA, QUT	3 PhD
Online risk management and risk control for autonomous ships (ORCAS)	I. B. Utne, A. J. Sørensen, T. A. Johansen	15,4 MNOK	2018-2021	NFR MAROFF KPN	RRM, DNV GL	3 PhD 1 Postdoc

Project Name	AMOS Coordinator	Budget	Time	Status	Partners	Comments
Legacy after Nansen - Arctic research project that provides integrated scien¬tific know-ledge base required for future sustainable management through the 21st century of the environment and marine resources of the Barents Sea and adjacent Arctic Basin	M. Ludvigsen, I. B. Utne, A. Sørensen, G. Johnsen,	20 mNOK (total budget 800 mNOK)	2017-2023	NFR, KUD and partners	NTNU, UiT, UiO, UiB, UNIS, IMR. NPI, MET, Akvaplan NIVA, Nansen Centre Env Remote sensing	2 post doc 5 PhD
ENabling Technology providing knowledge of structure, function and production in a complex Coastal Ecosystem (ENTiCE)	M. Ludvigsen, G. Johnsen, A. Sørensen	6 mNOK	2016-2019	NFR, Marinforsk	SINTEF Ocean, NTNU IBI and IMT, SAMS	1 post doc 1 PhD
Ice-algal and under-ice phytoplankton bloom dynamics in a changing Arctic icescape -"Boom or bust Boom or bust"	G. Johnsen	3 mNOK	2016-2018	NFR – Polprog	NP, NTNU, AWI	1 PhD

PHOTO GALLERY

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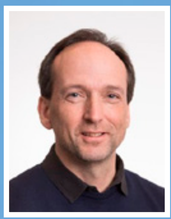
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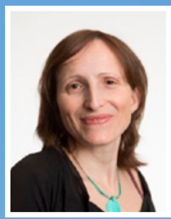
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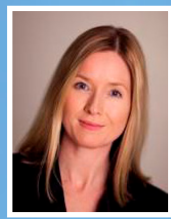
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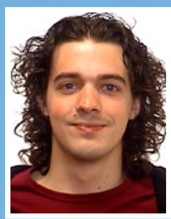
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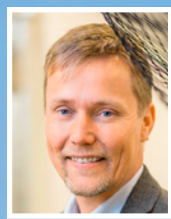
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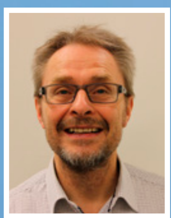
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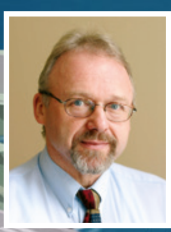
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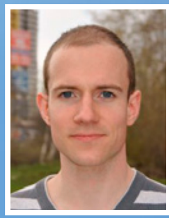
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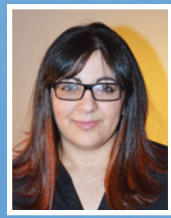
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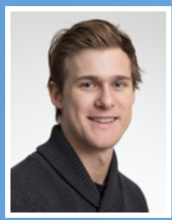
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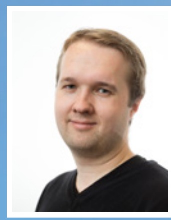
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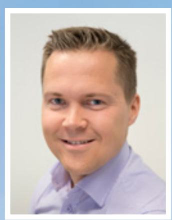
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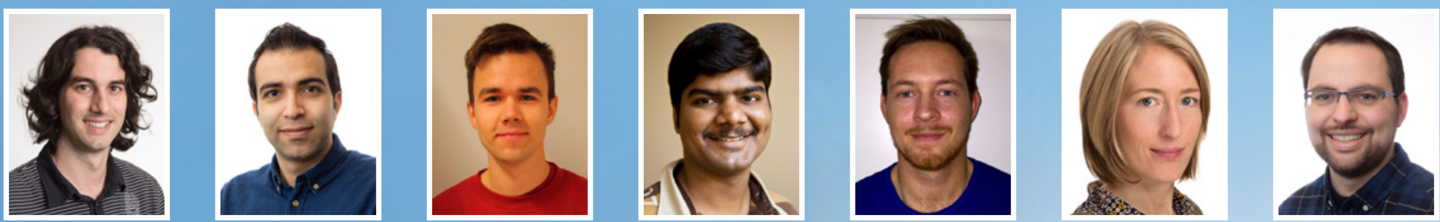

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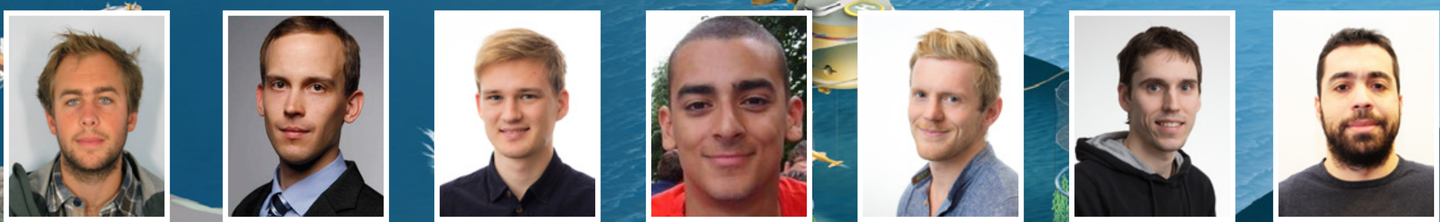

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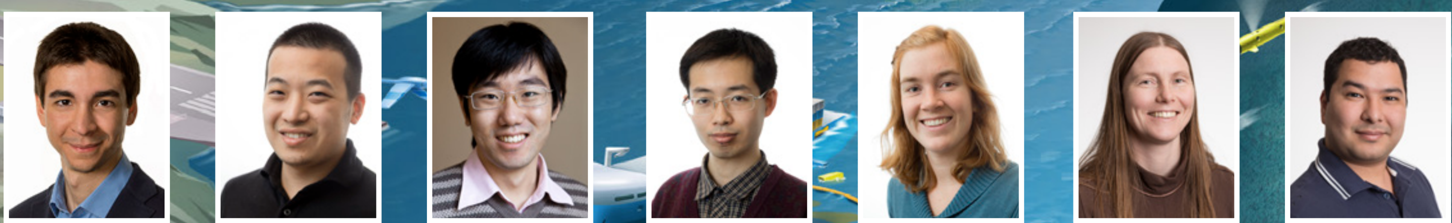

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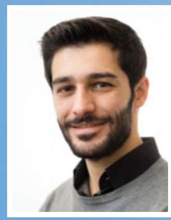
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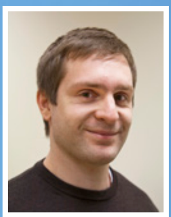
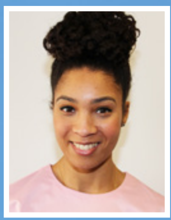

Morten D. Pedersen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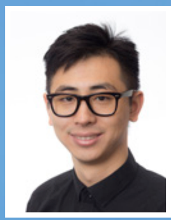
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Christopher D. Rodin


Børge Rokseth


Thomas Sauder


Henrik Schmidt-Didlaukies


Yugao Shen


Mohd A. Siddiqui


Espen Skjong


Emil Smilden


Carlos E. Silva de Souza


Bård B. Stovner


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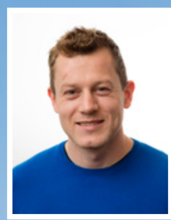
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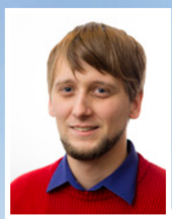
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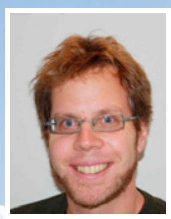
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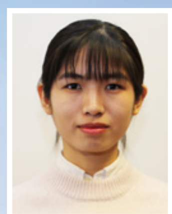
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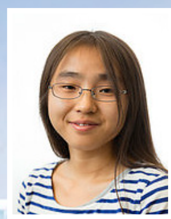
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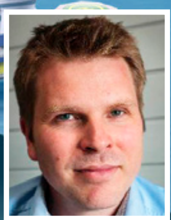

Øyvind Ødegård

LABORATORY HIGHLIGHTS AND RESEARCH CAMPAIGNS

Highlights of the Applied Underwater Vehicle Laboratory (AUR-lab)

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

To address the challenges in ocean research, the AUR-Lab runs and maintains a fleet of AUVs, ROVs, instruments, samplers, and navigation equipment with support systems on behalf of partners from five different faculties. The lab represents an interdisciplinary scientific community, where scientific questions are addressed by teams with specialists from many backgrounds. Opportunities for faculty, researchers, PhD and MSc students to perform tests and experiments are provided to enhance hypotheses and theoretical work. Several scientific questions in 2017 have been related to Arctic biology and system autonomy. The Department of Marine Technology hosts the AUR-lab, and the University Museum, the Department of Engineering Cybernetics and the Department of Biology are partners.

In January, the AUR-Lab participated in UNIS course AB334/834 by running AUV and USV operations in Kongsfjorden outside Ny-Ålesund. A USV was used to test multiple acoustic sensors investigating the biological area of Kongsfjorden in Svalbard during the polar night. Hydroacoustic instruments were used to map the distributions and abundances of various zooplankton species in the water column. Several AUV missions provided data for investigating water mass and seabed specifications in Kongsfjorden. Water column observations with the L-AUV Harald were completed at depths of 100 m.

In April, the AUR-Lab mobilized on the island of Mausundvær to collect data for RCN project ENTiCE. The topography of the Mausund region is complex, with a shallow

Figure 1: *AUV deployment from the beach in Ny-Ålesund in January 2017.* Photo: Asgeir Sørensen

bank area with small islands and complex bathymetry. During summer, northeasterly winds along the Norwegian coast provide upwelling conditions. The primary goal of ENTiCE is to quantify how physical forcing (e.g., tidal mixing and upwelling) controls productivity and community structure and function in sea areas outside of Mausund, considering that ocean model data, remote sensing, sampling and measurements are provided by autonomous vehicles. Using Gunnerus, samples were collected from predefined stations to provide information on the structures of the current marine micro ecosystems. To verify the modeling results and the remote sensing data, algorithms were developed and demonstrated for adaptive route planning, which made the AUV missions data driven.

In April 2017 the NTNU REMUS 100 AUV was deployed under ice in the Van Mijenfjorden in Svea to assess AUVs for future ice management operations and to prepare NTNU for future research below ice. The operation was organized with the RCN project FAABulous led by Akvaplan Niva. The scientific objective was to collect multibeam measurements of the underside of the ice. Two successful deployments were made. A small ROV (the Blueye ROV) was also used for the inspection of ice in the equipment and to capture video of the algae bloom under the ice.

The project "Underwater Robotics Ready for Oil Spills – URready4OS" provided a proof-of-concept for the use of AUVs and UAVs when mapping oil spills using cooperative multivehicle approaches. During the experiment in June, an oil spill was simulated by creating a plume using Rhodamine. The vehicles tracked the plume as a group, and the UAV was used as a data mule, which passed near the vehicles at the surface and downloaded the data through a Wi-Fi connection before returning to the operations center onboard the oil spill response vessel "Clara Campoamor". The AUR-Lab cooperated with the L-AUV Harald. The project and operation were led by prof. Javier Gilabert from the Universidad Politécnica de Cartagena.

In June, the NTNU AUR-Lab participated in a research campaign, MAREANO, in Runde with the Runde Environmental Centre, the Norwegian Geological Survey, the Norwegian Mapping Authority, Maritime Robotics AS, Havila and the Institute of Marine Research. The main objective was to investigate factors contributing to the decline in the seabird population on the Runde bird mountain. Vehicles documented the seabed, water column, surface and the airspace looking for causes of reduced seabird numbers. NTNU contributed to the operation with RV Gunnerus, ROV SF 30k, ROV Blueye and the two L-AUVs.

In August, the L-AUVs were used to investigate the seabed and water columns of three fjord systems in Svalbard as part of the UNIS course AT334/834. The students of the course conducted measurements with the AUVs and the ROV Blueye. A set of experiments were conducted in four separate fjords by measuring the parameters relevant to biological and oceanographic research. Sea column mapping with the LAUV Harald at various distances from calving glaciers and side scan measurements from the LAUV Fridtjof of salinity, temperature and certain biological parameters provided useful seabed information.

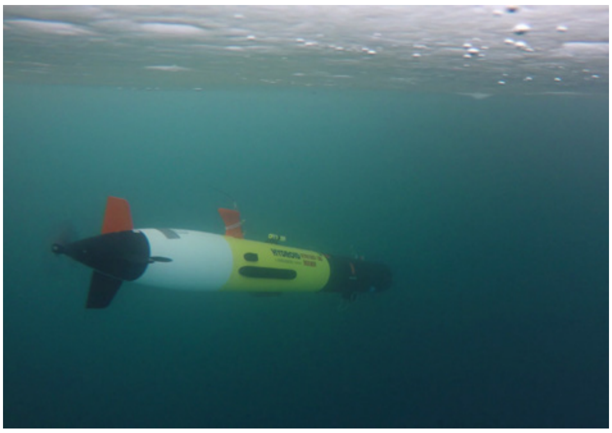


Figure 2: *AUV REMUS deployed under the ice in the Van Mijenfjorden.* Photo: NTNU AUR-Lab

Figure 3 *The oil spill response vessel Clara Campoamor departing for the plume tracking demonstration during project eUReady4OS.* Photo: Martin Ludvigsen

Figure 4: *PhD student Øystein Sture programming an AUV in front of the Nordenskiöld Glacier in Adolfbukta.*

Figure 5: *HUS Hugin AUV back on deck after autonomous trials near Agdenes.* Photo: Martin Ludvigsen

An autonomous co-processor running the DUNE software, which was developed by the LSTS lab at Porto University, was utilized onboard AUV Hugin to run the software developed at NTNU. The Hugin software provides sensor data and remote control inputs. Basic operations and remote controls were validated during a deployment at Tautra, where the primary objective was sonar data collection. The AUV running the NTNU developed autonomous software was also launched in the Korsfjorden. Fresh water runoff, tides, and the Coriolis created a number of highly dynamic processes in the water column, and a data-driven sampling algorithm that searched and located these phenomena was demonstrated. Another autonomous launch was performed at the seabed dumping field in Agdenes, which is south of Brekstad. The AUV performed an unsupervised image segmentation of sonar backscattering data, and algorithms autonomously defined a proper seabed survey through a camera.

Collision avoidance experiments in the Autosea project

Autonomous ships must be able to interact safely without colliding with each other or other vessels at sea. This is the main objective of the KPN project, "Collision avoidance and sensor fusion for autonomous surface vehicles" (Autosea), which is funded by the Research Council of Norway (DNV GL, Kongsberg Maritime and Maritime Robotics). Complete systems for collision avoidance were developed during 2016 and 2017 and tested during 4 consecutive field campaigns in 2017. The main vessel used in all of these experiments was the Maritime Robotics Telemetron.

May 2017: Dynamic Window and radar.
In these experiments, Telemetron was supposed to avoid small motorboats. This was challenging for several reasons: the motorboat was small and highly maneuverable, which made it difficult to track using a radar tracking system. Therefore, these experiments focused on last resort scenarios, where the Telemetron was instructed to not do anything more sophisticated than choosing a sufficient sharp turn to avoid the motorboat. This method is known as the dynamic window. The results were encouraging but far from perfect; often, the Telemetron struggled to decide the course angle of the motorboat, and it took so long to evade the motorboat that it came dangerously close to a collision. Perhaps to compensate for this, the Telemetron exerted highly exaggerated maneuvers.

May 2017: MPC and AIS.
In these experiments, the Telemetron encountered the larger tugboat Munkholmen II. Instead of using radar to track, Telemetron received information about its position using an automatic identification system (AIS). In these experiments, a different collision avoidance method based on model predictive control (MPC) was used. Using this method, Telemetron evaluated a refined cost function over a set of candidate trajectories. The cost function took several aspects of safety and traffic rules at sea into account. An important principle of these traffic rules at sea is that maneuvers should be readily observable. For this reason, the cost function included what we call transition costs, which make the system reluctant to change its interpretation of the scenario unless it must. These experiments went very well, even when Munkholmen II violated the traffic rules.

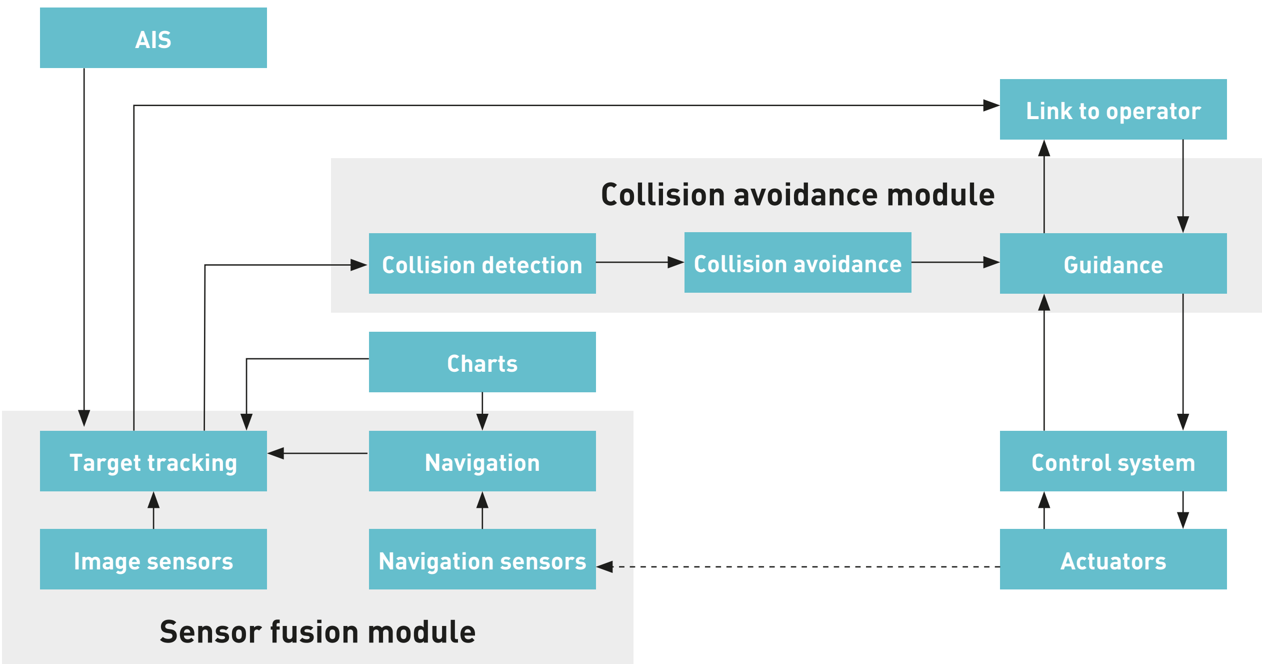


Figure 1: *Block diagram showing the overall software architecture of the Autosea project. The main research focuses are the sensor fusion and collision avoidance modules.*

October 2017: The Branching Course Dynamic Window and radar.

During early autumn, we tested a new collision avoidance method inspired by experiments using the dynamic window method. A key concept in this method is testing several potential trajectories, where each trajectory is constructed by three straight trajectories. This is consistent with the criterion that maneuvers should be readily observable, and it allows autonomous ships to plan further ahead. The method was also designed to be robust with respect to fluctuating obstacle estimates from the radar tracking system. In these experiments, the motorboat was replaced by the Kongsberg Ocean Space Drone, which is slightly larger and less maneuverable than the motorboat. The results were very convincing; the safety zones were never violated, and the course estimates fluctuated much less than those from the motorboat.

November 2017: MPC and AIS in the Netherlands.

Maritime Robotics was invited to participate in a test of collision avoidance methods, which was held outside of Den Helder in the Netherlands and arranged by Deltares and the Dutch Navy. For these experiments, a setup using MPC and AIS was chosen. These experiments were comprehensive and lasted several days. The collision avoidance system was tested in a much more complex environment than that of Trondheim Fjord due to a substantial amount of surrounding traffic. Regardless of the scenario that the Dutch managed to come up with, the MPC method settled on safe solutions. Additionally, its solutions were quite sensible and similar to those that a human operator might have chosen. Both these experiments and the earlier MPC experiments were conducted under high sea conditions, which pushed the capabilities of Telemetron to its limits.

Where are we and what remains?

The experiments have demonstrated that autonomous ship technology is possible. We are not aware of any other research groups in Norway who have developed systems for this type of collision avoidance, and our methods have

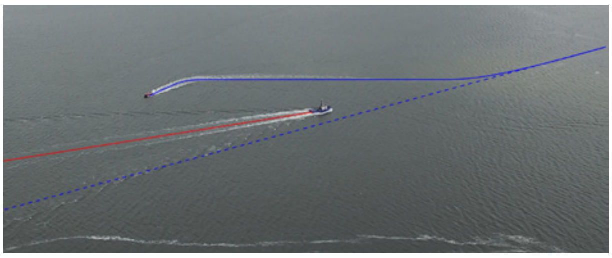


Figure 2: *Resolution of a head-on scenario during the MPC/AIS experiments in May. Notice how the Telemetron (blue track) follows a subsequent straight line to make it clear to the captain on the Munkholmen II (red track) that it is doing its job to avoid collision.*

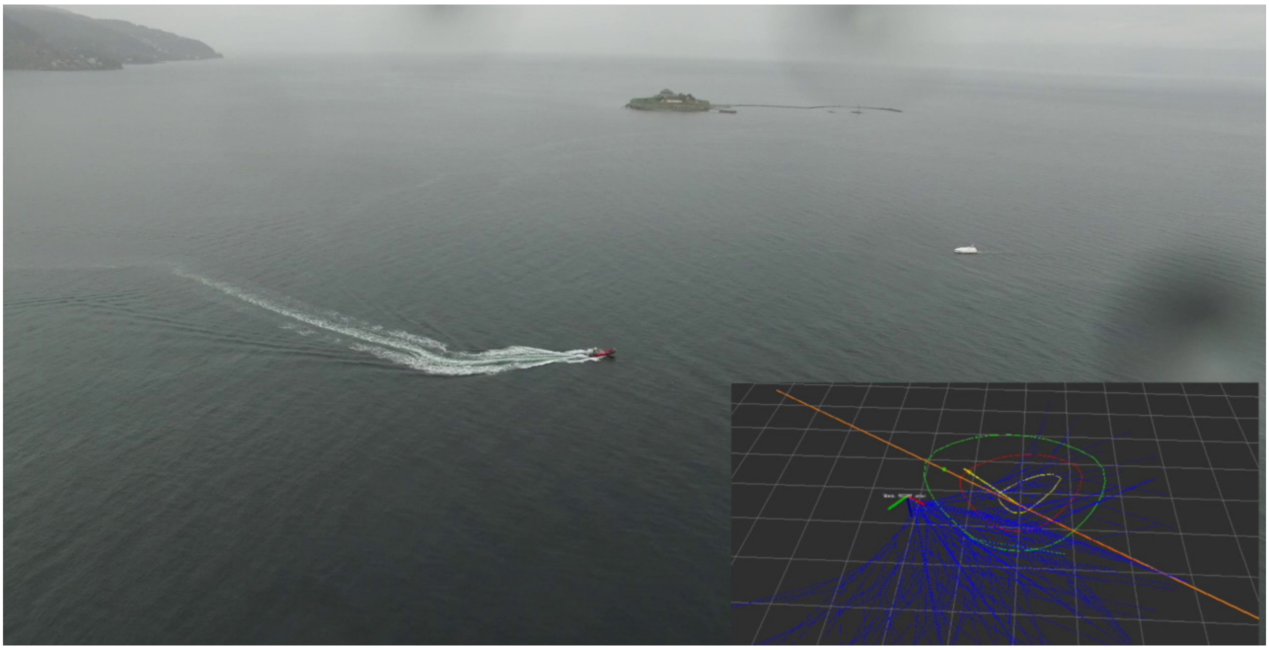


Figure 3: *Experiments using the branching course dynamic window method in October 2017. In the lower right corner, Telemetron's candidate trajectories are displayed in blue. The method uses three layers of safety zones around the target vessel.*

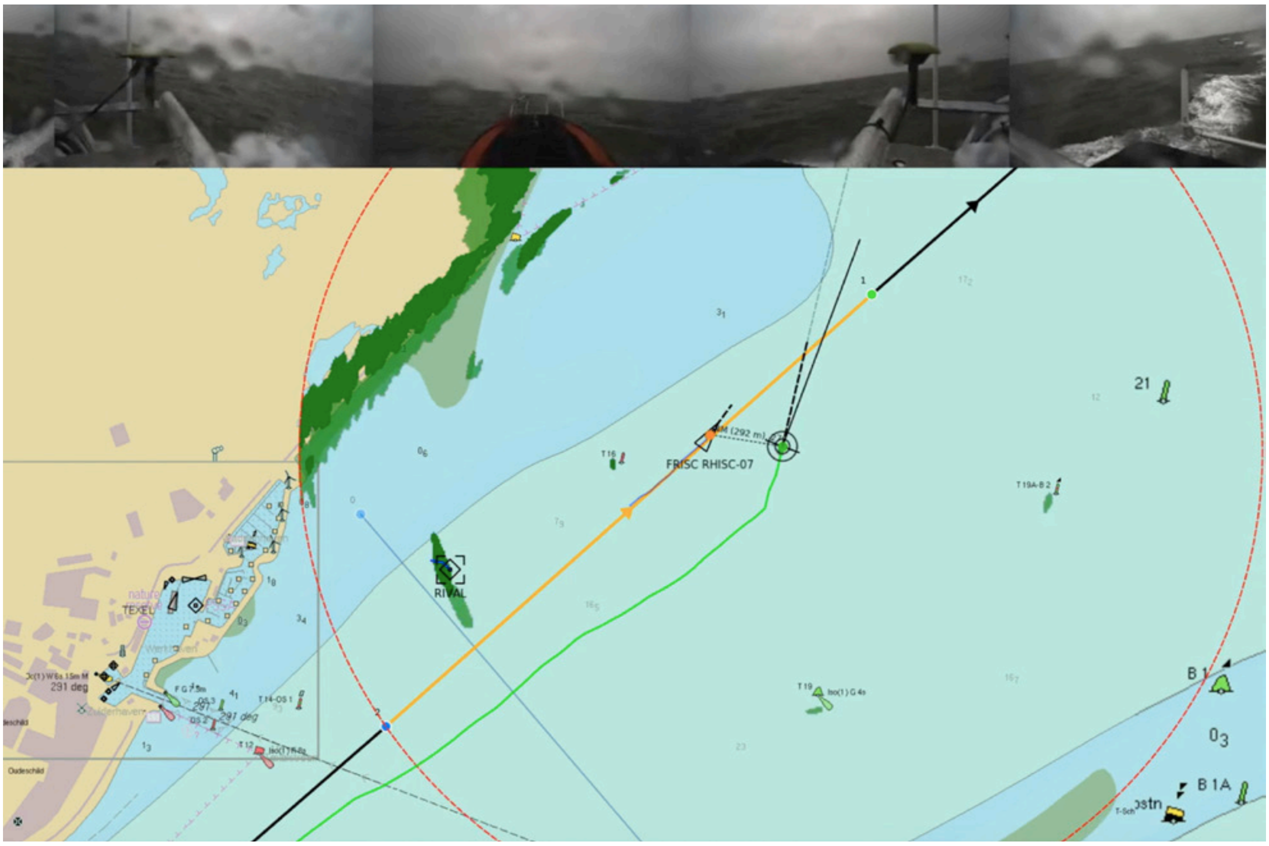


Figure 4: *Telemetron's situational awareness during the Den Helder experiments. Here, Telemetron (green) shows confidence when surpassing the target vehicle (yellow), which is a small RIB.*

important strengths when compared with the methods developed by other leading researchers in other countries (e.g., Germany or the USA). However, demonstrating that something can be done and that something can be done safely are two different things. More comprehensive simulations and tests with a larger variety of sensors, vehicles and weather conditions are needed to confirm the level of safety for these methods. Future research efforts must also delve further into the fundamentals of vehicle guidance, situational awareness and sensor fusion. More advanced methods, which do not yet exist, are needed to ensure that the collision avoidance system really has the same situational awareness as that of a human operator.

Figure 5: *A close-up of Telemetron during rough sea conditions outside Den Helder.*

Figure 6: *Dr. Giorgio Kufoalor from the Department of Engineering Cybernetics was in charge of the collision avoidance system during the experiments outside Den Helder.*

CNR-INSEAN Sloshing Lab

The lab's webpage: **www.insean.cnr.it/en/content/sloshing-lab**

The lab consists of three different facilities: a single degree of freedom mechanical system, which is designed to enforce pure sway sinusoidal motion in a 2D and 3D prismatic sloshing tank; a six-degree of freedom mechanical system, 'Hexapode', for sloshing experiments in 2D and 3D tanks; and a 2D water-entry and exit facility.

In 2017, 'Hexapode' was used to perform experiments on a novel wave energy converter (WEC) system conceived by Prof. O.M. Faltinsen and Prof. C. Lugni within the post-doc project of Dr. Zhi-Jun Wei at NTNU AMOS. The system was based on the use of a free-surface sloshing tank, with two lateral closed air chambers, that was hosted in a floater (Fig. 1).

The sloshing motion of the water inside the tank, which is induced by floater oscillations due to sea waves, causes the compression and expansion of air in the chambers.

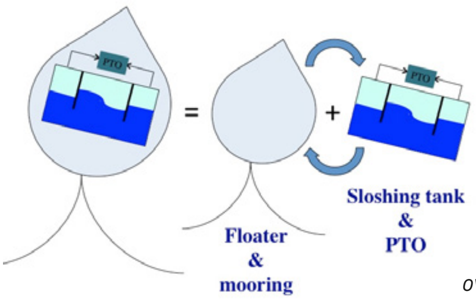


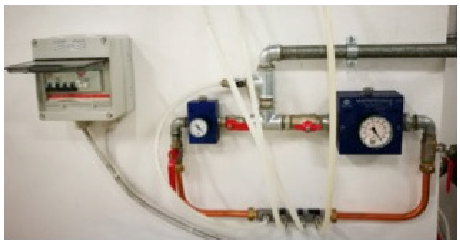
Fig. 1: *Sketch of the overall system.*

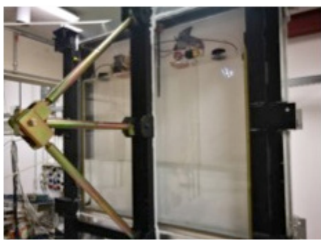
The related power is converted into electrical power through a PTO (power take-off) system. The system can be conceptually decomposed into a floater and a sloshing tank (Fig. 1); in the first phase, we focus the research on the sloshing tank + air chambers. Because the compressibility of air matters, the Froude number and Euler number must be the same in the model and at the prototype scale. The latter requires a depressurized condition, but cavitation must not occur. Therefore, the experimental setup was designed to allow variation in the ullage pressure in the tank, where pressure regulators and a vacuum pump were used to ensure an accurate depressurized condition (Fig. 2).

The tank was 0.96 m long and had two closed air chambers that were each 0.24 m long, 0.8 m high and 0.08 m wide. It was inserted inside a bigger tank that was properly reinforced to resist high loads due to the depressurized condition and mounted on the 'Hexapode' platform. To correctly reproduce the damping effects induced by the PTO system on the flow, a calibrated hole was drilled on the roof of each air chamber, which allowed for inflow/outflow between the air chamber and the Wells turbine. Crucial parameters were the opening area and the water-air density ratio. For each air chamber, two pressure transducers were mounted to measure the air pressure, as well as a camera with 100 frames per second, to measure the air-water interface evolution.

VACUUM PUMP

VACUUM PUMP





DEPRESSURIZED TANK

Fig. 2: *Experimental setup.*

CNR-INSEAN Depressurized Circulating Channel

The lab's webpage: **www.insean.cnr.it/en/content/circulating-water-channel**

The lab consists of a free-surface circulating channel that can be depressurized down to approximately 30 mbar. The testing section is 10 m long, 3.6 m wide and 2.2 m deep.

In 2017, the CNR-INSEAN lab was used to perform experiments on the dynamics of a conical body with large mass ratio, which impacts the free surface and entraps the air cavity above it. The project, which involved scientific cooperation among Prof. O.M. Faltinsen (NTNU-AMOS), Prof. C. Lugni (CNR-INSEAN/NTNU-AMOS) and Prof. Jingbo Wang (Chongqing Jiaotong Univ., China), was partially funded by the National Science Foundation of China. The tested body was composed of a cone with a radius of 125 mm and a deadrise angle of 45°, with a circular cylinder of the same radius and a height of 65 mm on top (Fig. 1). Three values of the mass ratio, defined as the ratio between the body mass and the infinite-frequency added mass of the cone, were considered in this project. They varied from 2.5 to 4.5.

Fig. 1: *Experimental setup of the water-entry tests.*

Due to air entrapment, compressibility matters, which involves scaling issues related to the simultaneous fulfilment of Froude (Fr) and Euler (Eu) numbers. As a result, a suitable experimental setup was designed to be used in the CNR-INSEAN depressurized circulating channel because the body is not accessible during the tests.

The main challenges concerning the design were i) the release and recovery mechanism and ii) the data acquisition (DAQ) system inside the body. For item i, a suitable stainless-steel dome was added to the traditional steel cover of the channel (Fig. 1). The dome allowed for a larger falling height (i.e., a larger impact velocity), as well as hosted a sealed mechanical system designed to recover and release the cone from outside the channel. For item ii, a CNR-INSEAN miniaturized DAQ system was proposed with local data storage and a Bluetooth protocol transfer (Fig. 2). The DAQ recorded up to 7 differential pressure transducers (3 along the cone perimeter to measure the impact loads and 4 on top of the cone to record the pressure in the air cavity), 1 tri-axial accelerometer and 1 triggering signal.

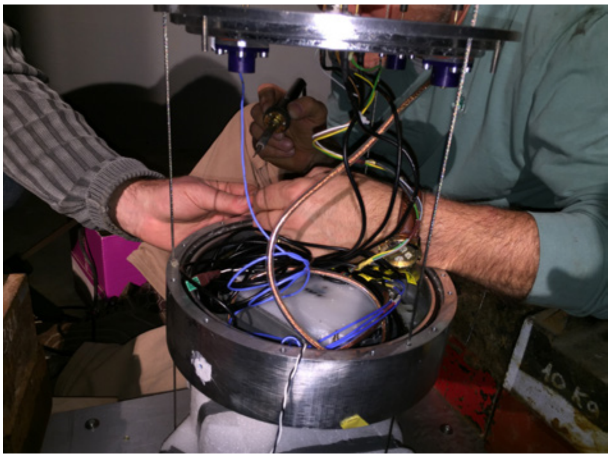


Fig. 2: *Miniaturized DAQ system.*

Three cameras with fast sample rates up to 4000 fps were used to observe the impact, air-cavity closure and the eventual evolution. Several Fr numbers (between 2 and 5) and several Eu numbers (leading to ullage pressures between the standard atmospheric pressure and 40 mbar) were considered. The minimum pressure was chosen to avoid cavitation phenomena, which do not occur in full scale (i.e., the ullage pressure must be larger than the water vapor pressure at ambient temperature).

Highlights of the Marine Cybernetics Laboratory (MC-lab)

The lab's webpage: www.ntnu.edu/imt/lab/cybernetics

During the last year, the C/S (cybership) Enterprise 1 and the C/S Inocean Cat I Drillship models have been fitted with inertial measurement units (IMU) for measuring angular rates and linear accelerations of the model. The IMUs derive from analog devices (ADIS 16364), which are sensors often found in UAVs (see Figure 1). The sensor unit contains a triple-axis accelerometer and a triple-axis gyro, which provided linear accelerations and angular rates, respectively. It has built-in compensation for bias, alignment, and sensitivity, which provides accurate measurements over a wide temperature range. A magnetometer is not installed; however, heading data can be obtained from the Oqus camera positioning system in the lab. When aligned with the body frame of the vessel, data from the IMU may be streamed directly into the National Instruments Compact RIO hardware-in-the-loop controller and be used directly in the control software. Data obtained from the IMU may be combined with data from the Oqus camera positioning system via the MC-lab, which simulates the presence of a global navigation satellite system. This additional instrumentation spurs the possibility of testing algorithms with different structures compared to those that rely on position and heading measurements only.

Both master students and researchers use the IMU installations. Several applications of the IMUs and highlights from the MC-lab are mentioned below.

Figure 1: *IMU installed in the C/S Enterprise 1.*
Photo: Hans-Martin Heyn (2017)

Student activities

Master of Science students have developed a dynamic positioning system with dead reckoning capabilities during the course, i.e., the Marine Control Systems II (TMR4243). They used the 1.1 m long C/S Enterprise 1 (Figure 2), which is a 1:50 scale model of the Aziz tug boat. The instrumentation onboard and the position reference systems allows for the testing of dynamic positioning systems, line-of-sight guidance algorithms, automatic path following, low-cost observations, and controlled use of virtual reality glasses.

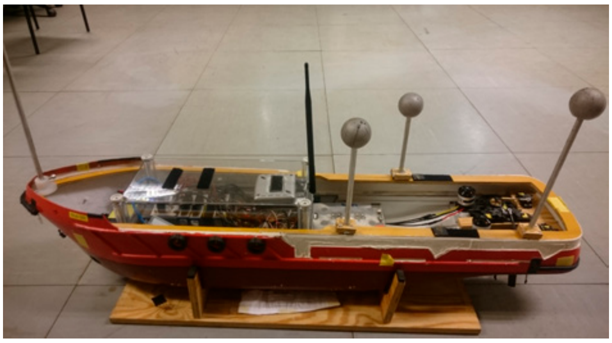


Figure 2: *C/S Enterprise 1.*

GNSS/IMU Integrated Motion Monitoring

An MC-Lab experiment has been conducted with the objective of verifying a GNSS/IMU integrated motion monitoring algorithm that can precisely position an offshore wind turbine hub during installation (see Figure 3). As part of a research collaboration between SFI MOVE and SFF AMOS, this application will reduce installation expenses and, consequently, improve lifecycle costs regarding the use of renewable energy. The Oqus camera system and the embedded IMU in the C/S Inocean Cat I Drillship model are used to simulate the low-frequency delayed GPS signal and the high-frequency IMU data. The scheme is based on a multirate Kalman filter, an online smoother, and a rapid simulator.

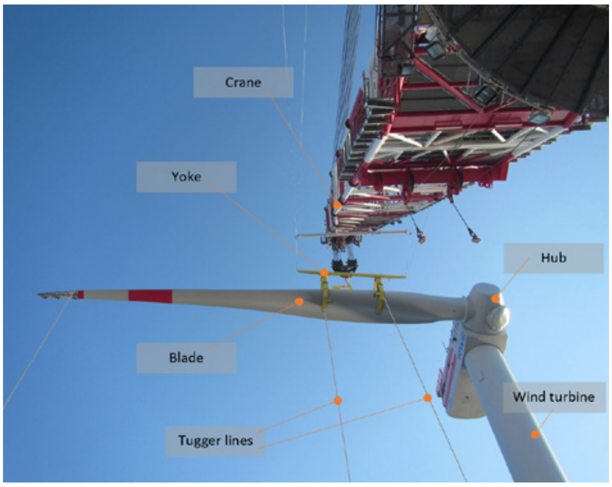


Figure 3: *RWE Innogy GmbH halfway through the turbine installation for the Nordsee Ost offshore wind farm, 2014 [Online; accessed 16-July-2017].*

Distributed sensing

Four IMU sensors that were spatially distributed along the hull of the C/S Inocean Cat I Drillship were used to determine the incident wave direction in real-time (see Heyn et al. (2017) and Figure 4). By measuring the temporal occurrence of the maximum heave acceleration in each sensor and using the phase velocity of the waves and the distance between the sensors, one can calculate the time it takes for the waves to travel between the sensors. As a result, the incident wave direction may be derived, which may be input into a heading controller for weather-vaning vessels.

Figure 5: *Astrid H. Brodtkorb and Svenn Are T. Værnø performing experiments with C/S Inocean Cat I Drillship.* Photo: Astrid H. Brodtkorb (2016)

Improving the transient performance of the C/S Inocean Cat I Drillship

IMU measurements, in addition to the position and heading measurements, are input into the signal-based (i.e., kinematic) observation algorithms for the estimation of smooth trajectories regarding the vessel position and velocity, which are suitable for control. These types of estimation algorithms react quickly to transient vessel responses, and may therefore be used as reactive control strategies. Brodtkorb et al. (2018) combined two observation types, model-based and signal-based observers in

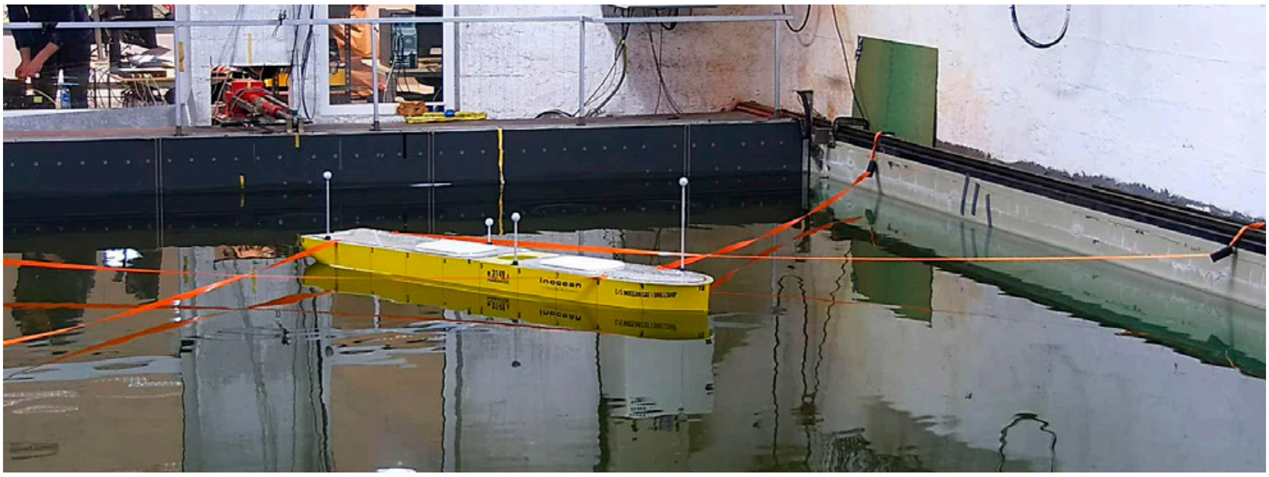


Figure 4: *C/S Inocean Cat I Drillship with relative wave heading 150 degrees.* Photo: Guttorm Udjus (2017)

a robust hybrid observer setup, in order to improve the transient response of the C/S Inocean Cat I Drillship (see Figure 5).

Actuation of forces on a barge subject compared to real-time hybrid model testing

Real-time hybrid model testing experiments were performed on a barge in the MC-lab. Position and motions of the barge were measured by the camera tracking system installed in the MC-lab, while a desired force was applied to the structure through four actuators (see Figure 6). In some of the test cases, these actuators simulated a horizontal anchor system. In addition to applying hybrid-testing on a new type of structure (i.e., a ship-shaped vessel), the main goals of the test were to further develop the control system, to verify improvements on the actuators, and to identify limitations and challenges that require further research.

Related publications:

- ***Heyn, Hans-Martin; Udjus, Guttorm; Skjetne, Roger*.** "Distributed motion sensing on ships," OCEANS 2017 – Anchorage, Anchorage, AK, 2017, pp. 1-9.
- ***Brodtkorb, Astrid H.; Værnø, Svenn Are T.; Teel, Andrew R.; Sørensen, Asgeir J.; Skjetne, Roger****.* Hybrid Controller Concept for Marine Vessels with Experimental Results. To appear in Automatica 2018

Selected AMOS-affiliated Master's theses using the MC-lab in 2017:

Using the C/S Inocean Cat I Drillship:

- ***Udjus, Guttorm****.* Force field identification and positioning control of an autonomous vessel using inertial measurement units
- ***Johannessen, Silje Aarvik***. Autonomous heading control in position mooring with thruster assist

Using the C/S Enterprise 1:

- ***Mykland, Alexander***. Low-cost observer and path-following adaptive autopilot for ships

Using ROV uDrone:

- ***Mo-Bjørkelund, Tore***. Camera-based SLAM for dynamic positioning of low-cost ROV
- ***Skinderhaug, Mads Sig***. Simultaneous Path Generation and Following for an ROV
- ***Mokleiv, Børge***. Fault-tolerant observer design for low-cost ROV

Using the C/S Saucer:

- ***Harbitz, Erlend Solbakk***. Camera-Based State Estimation for Surface Vessels
- ***Spange, Joachim***. Autonomous docking for marine vessels using a Lidar and proximity sensors.
- ***Follestad, Mats Håkon***. Autonomous path-planning and -following for a marine surface robot.

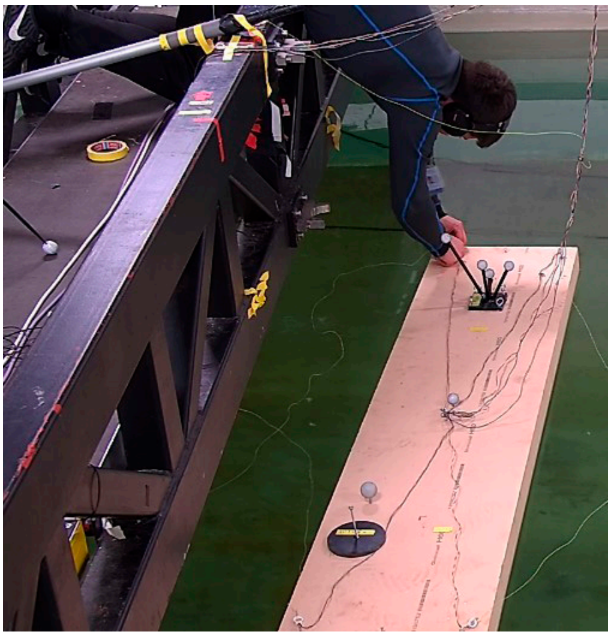


Figure 6: *Hybrid model testing.*

Photo: Einar Ueland (2017)

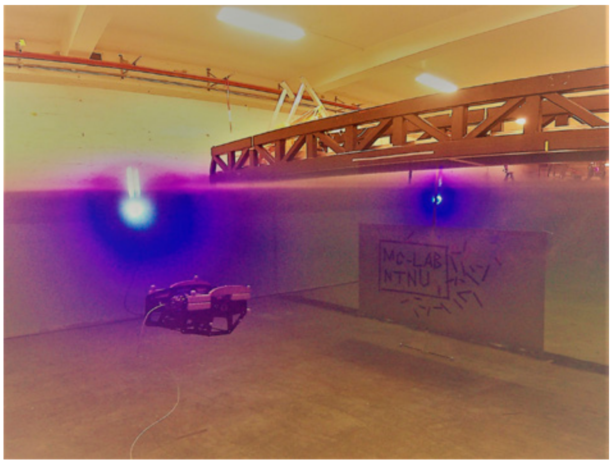


Figure 7: *ROV uDrone.*

Photo: Tore Mo-Bjørklund (2017)

UAVs for the Surveillance of the Sea Surface

Supervisors: Prof. Tor Arne Johansen and Prof. Thor I. Fossen
PhD candidates/Post Doc: Dr. Frederik S. Leira and Håkon H. Helgesen

Figure 1: *The NTNU AMOS Cruiser-Mini UAV platform at Ny Aalesund (Svalbard, spring 2017)*

Autonomous ships are expected to be part of sea traffic in the near future and must collaborate with other vehicles that are operated autonomously, as well as humans. Sea rules are defined in COLREGs (the International Regulations for Preventing Collisions at Sea), and all vessels are required to obey this set of rules. Nevertheless, it is also necessary to have the capability of adapting to the environment in case objects do not obey COLREGs. For example, these objects can be humans kayaking, fishing nets, smaller sail boats, and icebergs. Therefore, autonomous vessels must be able to detect other objects on the sea surface, estimate their position, velocity and course, and have strategies for avoiding possible collisions. Moreover, to save fuel and energy, these tasks should be solved in a cost-efficient manner that limit expensive actions with respect to specified optimization criterion.

To solve this collision avoidance challenge in an efficient manner, it is desirable to detect possible obstacles as early as possible. This can be demanding with sensors onboard the ship because they have a limited range and resolution. Moreover, several objects may be hidden in the waterline. An unmanned aerial vehicle (UAV) can be used to overcome some of these challenges, aid in the monitoring of sea surfaces and assist ships. In addition, UAVs can be used for surveillance in a specific area to detect environmental threats such as oil spills. UAVs also possess the ability to cover a large area in a short amount of time, which allows the future path of vessels to be evaluated and planned with plenty of time before the vehicle itself surrounds that area.

We wanted to address and investigate the abovementioned problem by conducting experiments with the Cruiser-Mini fixed-wing UAV. A tailor-made payload with a thermal camera, sensors for high precision navigation and a custom-made board for synchronization were developed in 2017. The aircraft and payload constitute a versatile platform that can be used for several applications, where target detection and tracking were the main goal of the design. The platform was especially suitable for target tracking because the aircraft position and

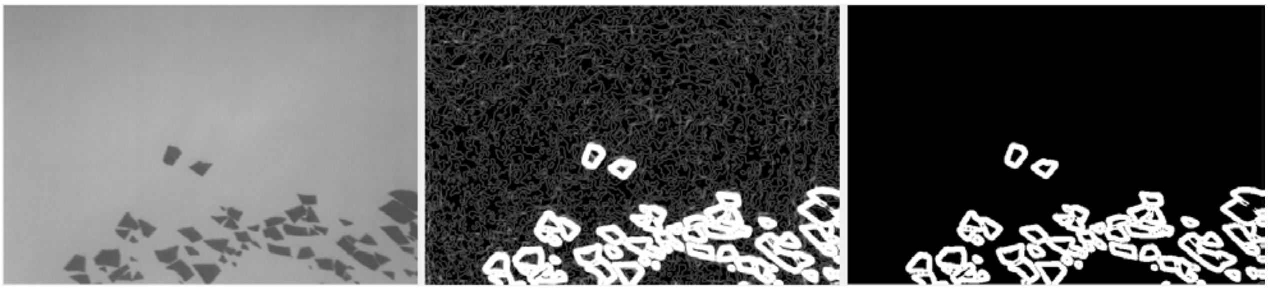


Figure 2: *Ice floes captured by the onboard thermal camera. Image processing techniques are then applied to automatically separate and detect the ice floes from the original image.*

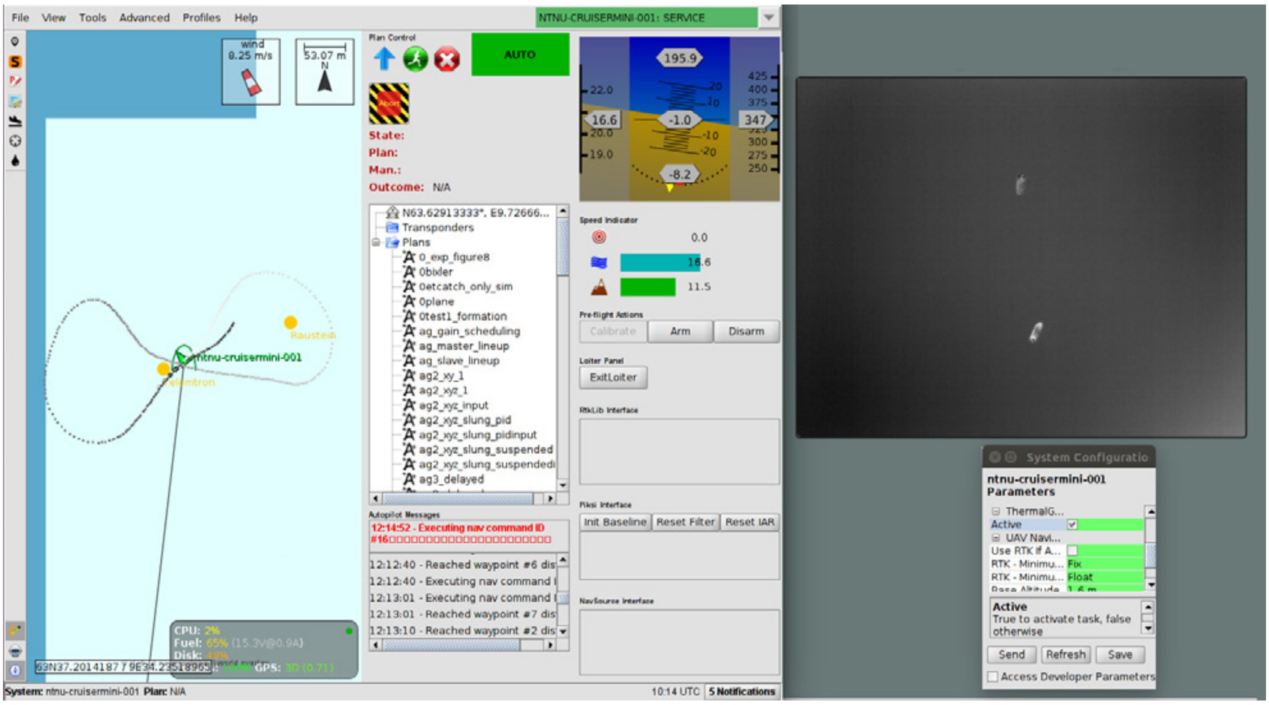


Figure 3: *The command and control software (Neptus) for the Cruiser-Mini thermal payload. On the left side, the UAV status, position and velocity are seen together with the position of the tracked objects (yellow circles). On the right side, one can see a live video stream of the thermal camera containing two boats at the sea surface*

altitude can be synchronized with the images using the synchronization board with an accuracy of microseconds. This enables the possibility of detecting and tracking objects on the surface using navigation data and the onboard thermal camera with uncertainties limited to only a few meters. Moreover, the aircraft is equipped with sensors for navigation, which allows autonomous operations with online navigation and target tracking to be possible in the future.

Two separate field test campaigns were planned and conducted during 2017. The first campaign was located in Ny Aalesund, Svalbard and took place during April; the goal was to detect icebergs in arctic environments with the thermal camera. By using the UAV to observe iceberg drift over time, the goal was to develop an iceberg flow map of the area that could be used to predict future iceberg positions. This was a beyond-line-of-sight operation (BLOS), where the aircraft was able to investigate areas that were out of reach for humans.

The second campaign was located in Raudstein, close to Agdenes, in September 2017. The main goal behind this campaign was to explore how useful the new platform could be when monitoring the sea surface. The experiments were conducted in collaboration with other researchers at AMOS and Maritime Robotics. Two smaller vessels were used as objects on the sea surface, and the idea was to investigate how well we were able to detect and track these objects with the new UAV platform and payload. Other objects, such as a human and a pallet, were also present on the sea surface throughout parts of the campaign. The campaign lasted several days, and a substantial amount of useful data were collected. This was also a BLOS operation, where the UAV operated several kilometers from the base station. Topics that can be studied and will be published using these data include georeferencing, object detection, data association and multiple target tracking.

Selected Publications:
Multiple publications on the same topics have been published previously, and more are planned in the near future based on the data collected in these experiments. A few selected publications are listed below:

- ***Helgesen, Håkon Hagen; Leira, Frederik Stendahl; Johansen, Tor Arne; Fossen, Thor I.*** Detection and Tracking of Floating Objects Using a UAV with Thermal Camera. Sensing and Control for Autonomous Vehicles - Applications to Land, Water and Air Vehicles, 2017.
- ***Leira, Frederik Stendahl, Johansen, Tor Arne; Fossen, Thor I.*** A UAV Ice Tracking Framework for Autonomous Sea Ice Management. International Conference of Unmanned Aircraft Systems, Miami, 2017.
- ***Albrektsen, Sigurd Mørkved; Johansen, Tor Arne.*** SyncBoard - A high accuracy sensor timing board for UAV payloads. International Conference of Unmanned Aircraft Systems, Miami, 2017.

Highlights of the Unmanned Aerial Vehicle Laboratory

Testing a new aerial camera gimbal to assist station keeping of ships in sea ice

Station keeping trials occurred in Bothnian Bay between Sweden and Finland in the beginning of March 2017. The purpose was to perform a variety of experiments concerning ice management and station keeping with two anchor handling vessels: Magne Viking and Tor Viking. Doctoral candidate Christopher Rodin's task was to design a camera system for the Maritime Robotics' OceanEye moored balloon system and an unmanned aerial vehicle (UAV) in order to keep track of the size and position of ice floes surrounding the two vessels. The trials allowed Christopher to simultaneously obtain data on the efficiency of the designed camera system in a real-world scenario (see reference UAV-R1). The trials were funded and organized by Statoil.

Figure 1: *Doctoral candidate Christopher Rodin at a field test in Bothnian Bay.*

Figure 2: *Aerial image from the field trial in Bothnian Bay.*

Testing the Autonomous Precision Aerial Drop from a Small Unmanned Aerial Vehicle

One of the many operations that a fixed-wing unmanned aerial vehicle (UAV) should master autonomously is delivering an object to a precise position. Civilian applications include tagging sea ice and icebergs by dropping GPS trackers and the delivery of small goods to ships or people in emergency situations.

Among the several possible delivery approaches, in recent paper UAV-R2, doctoral candidate Siri H. Mathisen released an object from a UAV at a carefully calculated state and let it fall freely to the selected landing location. During such an operation, the computations of suitable release positions, velocity and altitude is essential. Due to time-varying disturbances such as wind, a previously calculated release state may not be suitable once it has been reached by the aircraft. Based on these challenges, the results suggest the dynamic calculation of the release state with respect to the wind velocity and the current state of the UAV by using a sufficient re-optimization frequency. This is tested via simulation and field tests in UAV-R2.

Navigation of the UAV using a Phased Array Radio

Navigation and communication are two major challenges when flying unmanned aerial vehicles (UAVs) beyond the visual line of sight (BVLOS), particularly when global navigation satellite systems (GNSS), such as GPS, are unavailable. The phased array radio system developed by Radionor Communications AS in Trondheim, which has been used in recent papers (UAV-R3 and UAV-R4) by doctoral candidate Sigurd M. Albrektsen, aims to solve both communication and navigation challenges with one system. To enable a high efficiency data transfer, the radio system uses electronic beamforming to direct energy from the ground radio towards the UAV; however, to do this, the ground radio must know the bearing and elevation angles toward the UAV. By measuring the round-trip time to compute the range and observe the direction of the incoming signal when computing bearing and elevation angles, the phased array radio system is able to find the position of the UAV relative to the ground radio in all three dimensions. The phased array system has been shown to provide absolute measurements for UAV navigation in the radio line of sight, which can be used as a redundant system for GNSS measurements (e.g., to enhance cyber security when the GNSS is jammed). By merging the radio measurements with altitude data, a mean accuracy of approximately 10-20 m is achieved on a UAV flight at a distance of 5 km (UAV-R3). Further advances in the accuracy and improvement of phased array radios are achieved by sensor fusion with inertial navigation sensors (UAV-R4).

Unmanned Aerial Vehicles as Data Mules: An Experimental Assessment

Communication in remote locations, especially in open oceans and the Arctic, is challenged by the lack of infrastructure and the limited availability of resources.

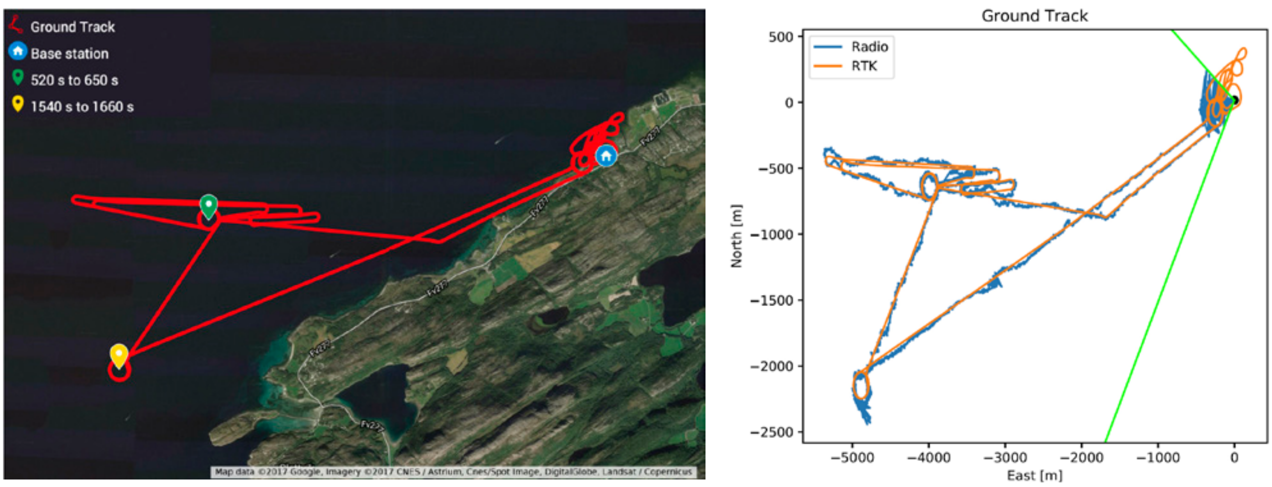


Figure 3: *The left figure shows the path flown by the UAV during the tests, while the right figure shows the position accuracy achieved by GPS (red) and the phased array radio system (blue). The green line indicates the sector covered by the ground radio antenna system.*

However, these regions may be of high importance and require efficient ways to transfer research data from different missions and deployed equipment. For this purpose, unmanned aerial vehicles (UAVs) are useful as data mules because they are capable of flying over large distances and retrieving data from remote locations. The concept is illustrated in Figure 4.

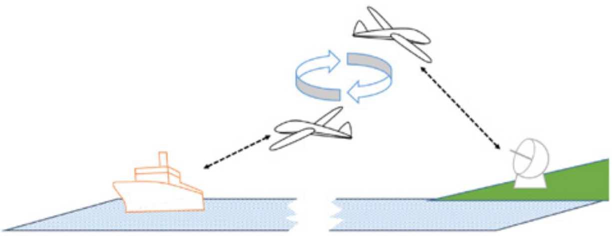


Figure 4: *Data muling using an unmanned aerial vehicle. The UAV may either relay data by taking advantage of its high altitude compared to that of the ship, it may exploit its substantial mobility when transporting data physically into a more favorable downlink position, or a combination to the two may be utilized.*

Although data muling is a well-known concept, its performance has not been thoroughly evaluated in realistic settings. In recent paper UAV-R5 such a solution is evaluated through a field experiment by exploiting the obtained results to define and implement an emulator for intermittent links. This emulator was designed as a mission planning tool, where we further analyzed the impact of different flight trajectories when retrieving data.

Additionally, we studied the overall performance of 4 well-known file-transferring protocols suitable for UAVs used as data mules. Our analysis shows that trajectories at higher altitudes, despite the increased distance between nodes, improves the communication performance. Moreover, the obtained results demonstrate that certain communication network protocols outperform other protocols.

Selected references:

- ***UAV-R1.*** C. D. Rodin, T. A. Johansen, Accuracy of Sea Ice Floe Size Observation from an Aerial Camera at Slant Angles, Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS), Linköping, 2017
- ***UAV-R2.*** S. H. Mathisen, V. Grindheim, T. I. Fossen, T. A. Johansen, Approach Methods for Autonomous Precision Aerial Drop from a Small Unmanned Aerial Vehicle, IFAC World Congress, Toulouse, 2017
- ***UAV-R3.*** S. M. Albrektsen, A. Sægrov, T. A. Johansen, Navigation of UAV using Phased Array Radio, Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS), Linköping, 2017
- ***UAV-R4.*** S. M. Albrektsen, T. H. Bryne, T. A. Johansen, Phased Array Radio System Aided Inertial Navigation for Unmanned Aerial Systems, IEEE Aerospace Conference, Big Sky, 2018
- ***UAV-R5.*** D. Palma, A. Zolich, Y. Jiang, T. A. Johansen, Unmanned Aerial Vehicles as Data Mules: An Experimental Assessment, *IEEE Access,* Vol. 5, pp. 24716 – 24726, 2017

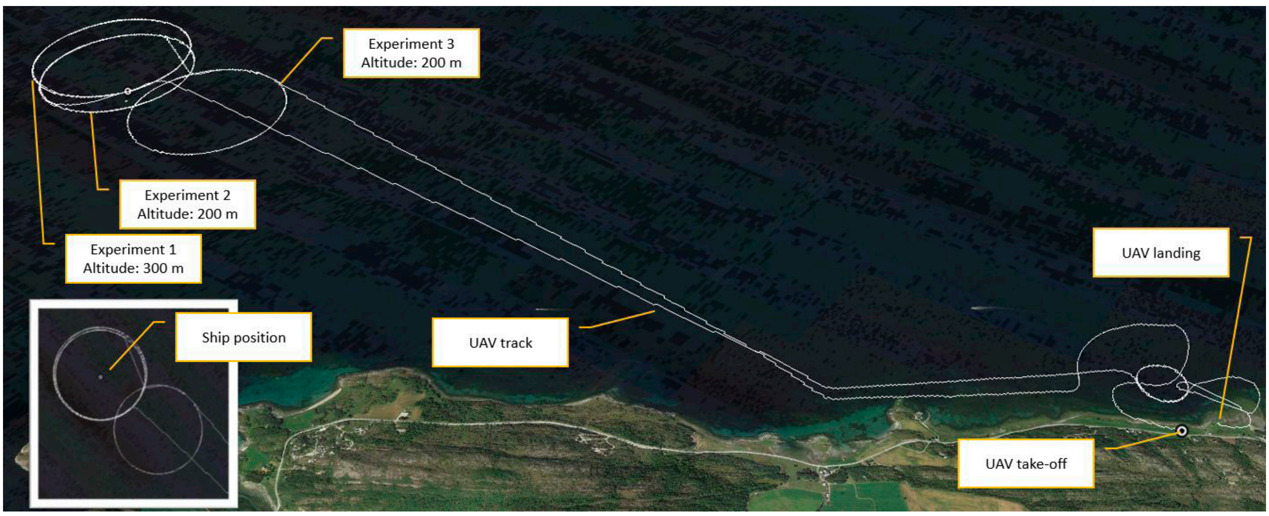


Figure 5: *UAV flight overview from a field test performed by the UAV-Lab at Agdenes.*

HONOURS AND AWARDS

Best pitching award: From Problem to Profit, Nor-Shipping 2017

On the 2nd of June, Daniele Borri and Dig Vijay Singh presented the concept "Clean Drinking Water to Millions from Ships" at Nor-Shipping 2017 held in Lillestrøm, which won the 'From Problem to Profit' pitching contest. NOR-Shipping is one of the most reputable international conferences and trade fairs for the shipping industry and has been held in Norway over the last 50 years. It attracts over 30000 professionals from the shipping industry and has global representation. The competition was aimed at finding innovative solutions within the shipping industry to address the UN's Sustainable Development Goals (SDGs). Daniele and Dig are PhD candidates in the department of Marine Technology at NTNU; Daniele is also associated with NTNU AMOS through his supervisor, professor Marilena Greco, and provided partial support in his research. They proposed that additional water produced onboard ships could be used to serve the most vulnerable communities that suffer from drinking water shortages worldwide. This water is produced by desalination using waste heat from ship engines; as a result, it is free of cost and does not contribute to additional emissions.

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Date November 15, 2017

Highly Cited Researcher

Onsager Fellow and associate professor Josef Kiendl was identified a highly cited researcher by Clarivate Analytics (Web of Science) for being among the top 1% of most cited researchers in computer science in 2017.

Honors received by Kristin Y. Pettersen

- Professor Kristin Y. Pettersen was appointed as a member of the Academy of the Royal Norwegian Society of Sciences and Letters (DKNVS).

- Professor Kristin Y. Pettersen was appointed as a member of the IFAC Council (International Federation of Automatic Control).

- IEEE International Conference on Robotics and Biomimetics 2017 Best Conference Paper Award for the following paper: "Set-based path following and obstacle avoidance for underwater snake robots", A.M. Kohl, S. Moe, E. Kelasidi, K.Y. Pettersen and J.T. Gravdahl. Proc. 2017, IEEE Int. Conf. on Robotics and Biomimetics, Macau, China, Dec. 5-8, 2017.

The paper titled "Integral Line-of-Sight Guidance and Control of Underactuated Marine Vehicles: Theory, Simulations, and Experiments" (IEEE Transactions on Control Systems Technology, Vol. 24, No. 5, pages 1623-1642, September 2016) was selected as the winner of the 2017 IEEE Transactions on Control Systems Technology Outstanding Paper Award.

Authors: Walter Caharija, Kristin Y. Pettersen, Marco Bibuli, Pedro Calado, Enrica Zereik, José Braga, Jan Tommy Gravdahl, Asgeir J. Sørensen, Milan Milovanović, and Gabriele Bruzzone,

This award was given to a paper that had been published during the past two years in *IEEE Transactions on Control Systems Technology* and was judged based on its originality, relevance, clarity of exposition, and demonstrated impact on control systems technology.

The award was presented during the CSS awards ceremony at the 2017 IEEE Conference on Decision and Control (CDC) in Melbourne, Australia and was received by Walter Caharija, Kristin Y. Pettersen and Milan Milovanović, who are representing the authors.

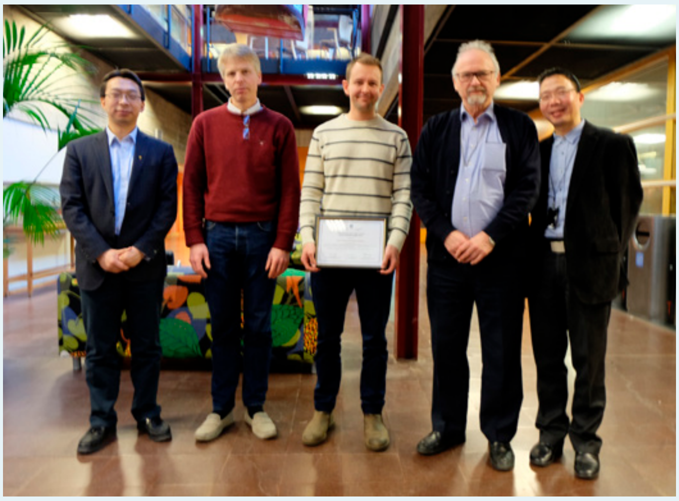
This picture is from the award ceremony in Melbourne, Australia, where Walter Caharija, Kristin Y. Pettersen and Milan Milovanović received the IEEE Transactions on Control Systems Technology Outstanding Paper Award in 2017.

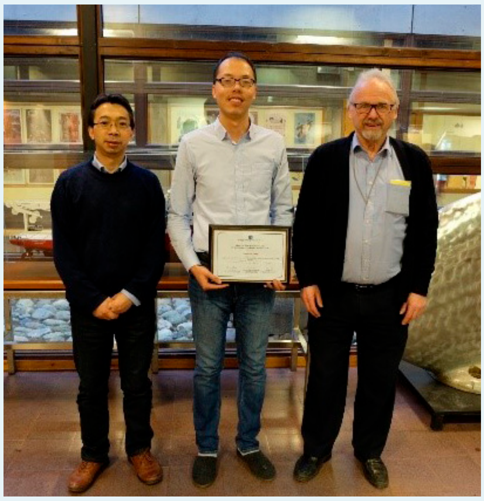
Moan-Faltinsen Best Paper Awards

The Moan-Faltinsen Best Paper Awards for 2017 were presented at the Christmas lunch presented by SINTEF Ocean and the Department of Marine Technology (NTNU) on December 20, 2017 at the Marine Technology Centre. The award winners for this year are Dr. Zhengshun Cheng and Finn-Christian Wickmann Hanssen. Both are affiliated with NTNU AMOS.

Zhengshun won the Best Paper Award on Marine Structural Mechanics/Dynamics for his paper, A Fully Coupled Method for Numerical Modelling and Dynamic Analysis of Floating Vertical Axis Wind Turbines, which was published in the Renewable Energy journal and was co-authored by Zhengshun Cheng, Helge Aagaard Madsen, Zhen Gao and Torgeir Moan.

Finn-Christian won the Best Paper Award on Marine Hydrodynamics for his paper, Free-surface Tracking in 2D with the Harmonic Polynomial Cell Method: Two Alternative Strategies, which was published in the International Journal of Numerical Methods in Engineering and was co-authored by Finn-Christian Wickmann Hanssen, Andrea Bardazzi, Claudio Lugni and Marilena Greco.





Left photo, from the left: Prof. Zhen Gao, Prof. Sverre Steen, Finn-Christian Wickmann Hanssen, Prof. Torgeir Moan, and Dr. Naiquan Ye. Right photo, from the left: Prof. Zhen Gao, Dr. Zhengshun Cheng, and Prof. Torgeir Moan.

Honors received by Torgeir Moan:

- The ASME (OOAE Division) Lifetime Achievement Award for significant life-time achievement contributions to the Risk and Reliability Assessment of Marine Structures.
- Symposium in honor of Torgeir Moan at the 36th International Conference on Ocean, Offshore and Arctic Engineering (OMAE Conference, June 2017)

Keynote lectures at international conferences

- WINERCOST'17, the International Conference on Wind Energy Harvesting; 20-21 April 2017, Coimbra, Portugal.
- The First International Conference on Computational Methods in Offshore Technology (CoTech Conference), Stavanger, 30 November to 01 December in 2017.

Best lecturer in 2017

NTNU AMOS director and Professor Asgeir J. Sørensen was chosen by the students at the department of marine technology at NTNU as the best lecturer in 2017.

Photo: NTNU

Best conference paper awards

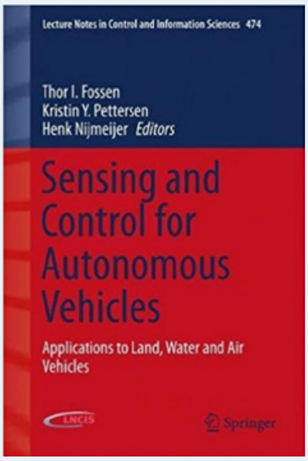
Anna M. Kohl, Signe Moe, Eleni Kelasidi, Kristin Y. Pettersen and Jan Tommy Gravdahl won the best conference paper award for the paper "Set-based path following and obstacle avoidance for underwater snake robots" at the IEEE International Conference on Robotics and Biomimetics in Macau (SAR of China) in December 2017.

Workshop on "Sensing and Control for Autonomous Vehicles", Ålesund, 20-22 June 2017

NTNU AMOS organized an invitation-based workshop with participation from international experts and leaders on autonomy. Each expert contributed a book chapter, which was presented at the workshop. A total of 23 book chapters were presented in three days, and Springer has published an editorial with same name as the workshop.

Thor I. Fossen, Kristin Y. Pettersen and Henk Nijmeijer (Eds.). Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles, Springer, May 2017. ISBN 978-3-319-55371-9.

From the publisher: This edited volume includes a thorough collection of studies on sensing and control for autonomous vehicles. Guidance, navigation and motion control systems for autonomous vehicles have become increasingly important in land-based, marine and aerial operations. Autonomous underwater vehicles may be used for pipeline inspection, light intervention studies, underwater surveys and the collection of oceanographic/biological data. Autonomous unmanned aerial systems can be used in a large number of applications, such as inspections, monitoring, data collection, and surveillance. Currently, vehicles operate with limited autonomy and minimum intelligence. There is a growing interest in collaborative and coordinated multivehicle systems, real-time replanning, robust autonomous navigation systems and the robust autonomous control of vehicles. Unmanned vehicles with high levels of autonomy may be used for the safe and efficient collection of environmental data and the assimilation of climate and environmental models, as well as to complement global satellite systems. The target audience is primarily composed of research experts in the field of control theory, but this book may also be beneficial for graduate students.



Key note lectures

- **Faltinsen, O.M.**, 2017, Keynote lecture: Fluid dynamic aspects common to high-speed vessels and other fields of marine technology. HSMV 2017. 11th Symposium on High-Speed Marine Vehicles, Naples, Italy 25-26 October.
- **Faltinsen, O. M., Shen, Y.**, 2017, Keynote lecture: Wave and current effects on floating fish farms, International Workshop on Wave Loads and Motions of Ships and Offshore Structures, Harbin 5-7 November 2017
- **Faltinsen, O.M.**, 2017, Invited lecture on Hydrodynamics of marine structures, "Lecture Series on Hydrodynamics", *36th International Conference on Ocean, Offshore and Arctic Engineering,* OMAE2017, June 25-30, 2017, Trondheim, Norway.
- **Moan, T.**, 2017, WINERCOST'17, The International Conference on Wind Energy Harvesting, 20-21 April 2017 Coimbra, Portugal.
- **Moan, T.**, 2017, The First International Conference on Computational Methods in Offshore Technology (CoTech Conference), Stavanger 30. November to 01. December 2017.
- **Fossen, T. I**. "Nonlinear Observer Design and Strapdown Inertial Navigation Systems for Unmanned Aerial Vehicles". ELLIIT Workshop 2017, Lund University, Sweden.
- **Pettersen, Kristin Ytterstad.** Snake Robots: from Biology, through University, towards Industry. Plenary lecture at IFAC World Congress, Toulouse, France, July 9-14, 2017.
- **Johansen, Tor Arne.** Increasing the Operational Window of Unmanned Aerial Systems. Plenary lecture at the Workshop on Research, Education and Development of Unmanned Aerial Systems, Linköping, Sweden, October 3-5, 2017.

RESEARCHER-DRIVEN INNOVATION FROM NTNU AMOS

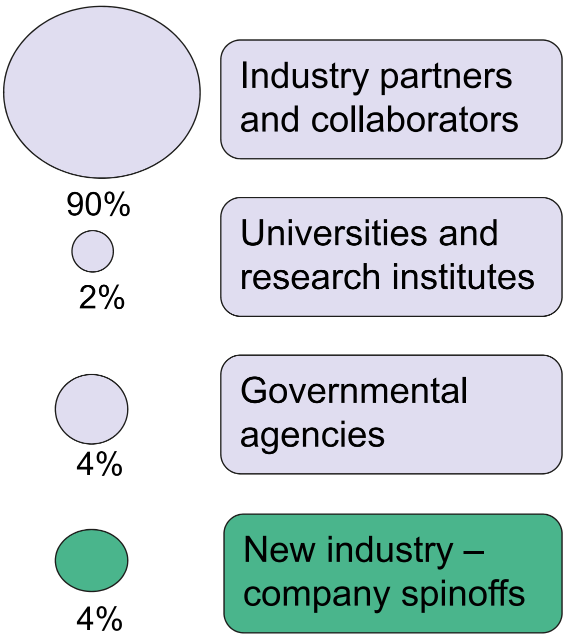
At AMOS, the main research direction developed in 2011/2012 was defined towards increased digitalization, robotics and autonomous systems, including artificial intelligence operating in a marine domain. Research accomplishments from AMOS have been true to this strategy. Major achievements were accomplished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

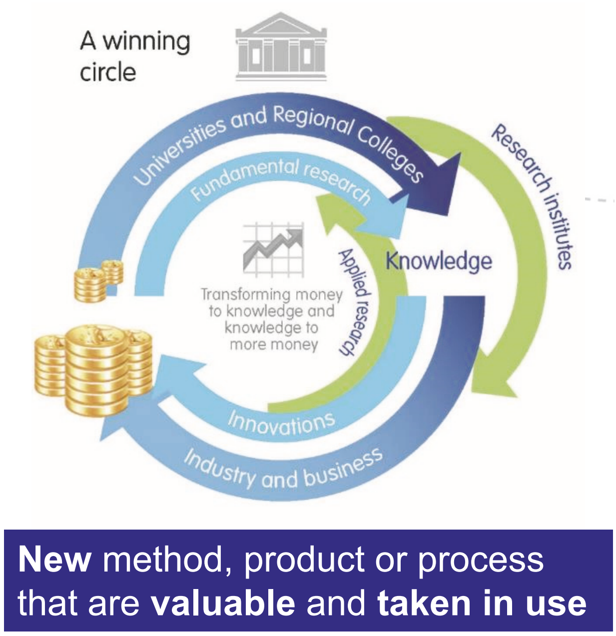
Key scientists hypothesized the importance of these topics 3-5 years before they become ¨hot¨ in Norway and elsewhere. This is also one reason for the great interest and rapid growth of AMOS in terms of funded PhDs and affiliated scientists. AMOS research topics have become an important part in the Norwegian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

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

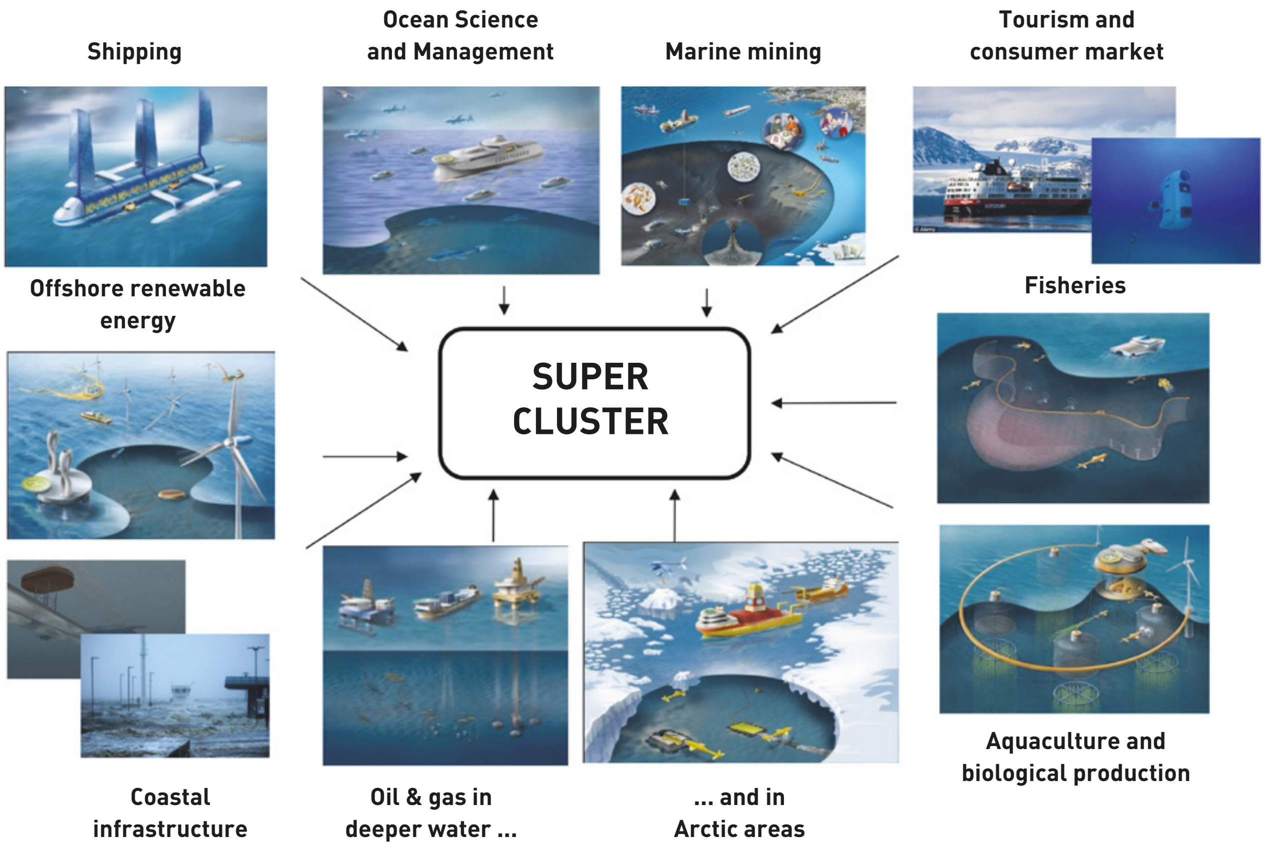
In the immediate future, we foresee the need to develop autonomous instrumental carrying platforms due to human impacts for improved knowledge-based mapping and monitoring of the marine environment; this will lead to better natural resource management and decision making and help to integrate AMOS disciplines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

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



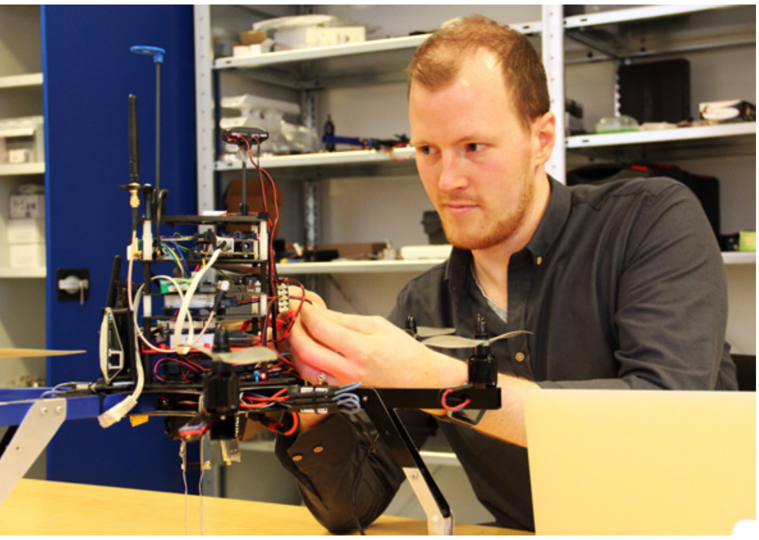


Innovation arenas at the NTNU AMOS



The blue economy that comprises a super cluster over Norway.

Using drones for the inspection of large tanks



Unmanned aircrafts can be used to inspect large tanks under the decks of cargo ships. This will make inspections much cheaper than they are today.

The AMOS spin-off SCOUT Drone Inspection is developing an unmanned aerial vehicle that is specifically designed for operating large tanks under the decks of large cargo ships. These tanks are usually extremely large, upwards of 20 meters wide and high. Today, these inspections are performed manually by people using large and cumbersome scaffoldings, which can take weeks to build and disassemble after use.

- We will make these inspections easier, safer and cheaper. Today, these inspections take a substantial amount of time and cost companies a lot of money, says Kristian Klausen, one of the founders of the SCOUT Drone Inspection, which is a spin-off from AMOS.

Developing new drone technology

Most drones available today use GPS and magnetic compasses to navigate; however, these technologies do not work below the deck of a cargo ship.

- Our goal is to develop a technology that allows drones to fly autonomously inside the tank. In addition to positioning and navigation systems, the avoidance of robust collisions is a key feature. This is a big step, and many companies are interested in our technology, he says.

NTNU and TTO (the NTNU Technology Transfer, which works to create valuable research results) are working with this technology development and the commercialization of this technology.

- We are working closely with the industry to develop the product and convince them to use it for inspections, he says.

The Norwegian Research Council also supports this work, and upwards of 15 people are involved today in both the marketing and technological aspects of the SCOUT Drone Inspection.

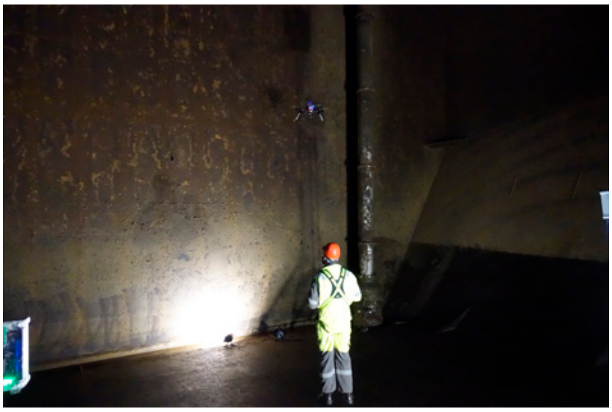
Innovation culture in AMOS

- I am very lucky. It also feels slightly strange to finish my PhD and be able to go straight into this opportunity. It is so much fun, but it is also a lot of work. However, that is part of the game, he smiles.

The PhD program is supported by NTNU AMOS, which works between disciplines to create an international center that leads in the field of autonomous marine operations and control systems.

- One of their goals is to create the culture of innovation; because of that, I actually had a patent as part of my PhD. Without the knowledge and positive attitude of AMOS, this spin-off would have never been possible, he says.

- When do you think your product will be on the market?
- We plan to have the first version ready for our early customers by the end of 2018.



Aims to prevent icing on unmanned aircrafts

Kim Lynge Sørensen is attempting to solve one of the biggest problems in unmanned aviation: aircraft icing.

Sørensen received his Bachelor's and Master's degrees at the Technical University of Denmark and Stanford University (U.S.), respectively, before he went on to pursue a Ph.D. at NTNU AMOS, where he now works as a postdoctoral fellow.

The outcome of his Ph.D. was the beginning of an innovation adventure. During his Ph.D., Sørensen was part of the team that invented the world`s first autonomous icing protection solution for unmanned aircrafts, known as D•ICE technology. The first flight of D•ICE occurred in the spring of 2015, and only two years later the AMOS spin-off UBIQ Aerospace was established by Kasper Trolle Borup, Professor Tor Arne Johansen, NTNU TTO and Sørensen himself. The focus of UBIQ Aerospace is to work with potential customers to trademark the D•ICE technology.

- Working at NTNU AMOS in the UAV laboratory means being part of one of the world's largest research communities in the field of unmanned aircraft technology. Without the support of the highly skilled people at NTNU AMOS and NTNU TTO, we would not have been able to pursue our entrepreneurial dreams. It is inspiring to be a part of this research community and NTNU AMOS, says Kim Lynge Sørensen.

Collaborating with a U.S. research organization

International interest in the D•ICE technology has been massive since the beginning. During his Ph.D. Kim collaborated with an American research organization, NASA, at the Ames Research Center, which is located in California, U.S. NASA Ames was initially founded to conduct wind-tunnel research on the aerodynamics of propeller-driven aircraft. However, the role of this research center has expanded to encompass spaceflight , global weather monitoring, and the increasing utilization of unmanned aircraft. During his stay as a visiting researcher in California, he worked on the aircraft icing issue for the large NASA and NOAA (the National Oceanic and Atmospheric Administration) unmanned aircraft fleet. Interest in his work is widespread, and various U.S. military organizations have also expressed enthusiasm for the D•ICE technology.

During his Ph.D., Kim Lynge Sørensen was part of the team that invented the world`s first autonomous icing protection solution for unmanned aircrafts, known as the D•ICE technology. Photo: NTNU AMOS

- The unmanned aircraft industry is growing rapidly right now. Unmanned aircrafts are used more and more in applications such as agriculture, search and rescue operations, ice flow monitoring, inspection, and surveillance. However, icing is a big problem; it limits operational capabilities and costs operators a lot of money because their unmanned aircraft face the ultimate risk of crashing. This is the primary reason why there is a lot of interest in D•ICE and our unique and combined skillset, he says.

Electrically conductive nanomaterial and intelligent algorithms solve the problem

A key element in D•ICE technology is carbon-based electrically conductive nanomaterial. Currently, this material is applied to all exposed aircraft surfaces. The uniqueness of D•ICE is the combination of this material with innovative and intelligent estimations, detections, and control algorithms that allow for the optimization of power consumption.

- Our system chooses the right strategy for ice prevention or mitigation, with a focus on power optimization. The D•ICE technology focuses on autonomy. This is unique, he says.

Sørensen is now working with potential customers, nationally and internationally, and hopes that the first sale will occur in 2019.

- Our dream for UBIQ Aerospace is to become an international provider of avionic solutions for unmanned aircrafts. In addition, maybe we one day we will develop our own unmanned aircraft, he smiles.

Launching the Cruiser-mini, an NTNU AMOS UAV laboratory UAV platform, with the D•ICE technology, in Ny-Ålesund, Svalbard. UAV lab pilot Lars Semb is pictured with the controls. Photo: NTNU AMOS, UAV Laboratory

INTERVIEWS WITH PHD CANDIDATES IN AMOS

Developing more advanced control systems for snake robots

Ida-Louise Garmann Borlaug has a unique interest. She is performing research on underwater snake robots with thrusters.

Different types of snake robots have already been tested. They can be used on land and underwater. However, there are still many challenges: how can the control system be robust given uncertainties and disturbances? How can we obtain the measurements we need to create such a control system?

PhD candidate Ida-Louise Garmann Borlaug wants to improve the control system of underwater snake robots with thrusters.

- My control system will be more robust than that which is being used today, she says.

In a few years, snake robots will assist in search and rescue missions after earthquakes and perform maintenance operations inside process pipes. Borlaug finds it challenging and fun to take part in this technology development.

- When I got the chance to obtain my PhD, I could not say no. This is a once in a lifetime experience. During the next three years, I have the opportunity to work with the things I liked the most during my Master studies, she says.

Borlaug will continue the work from her Master`s degree, where most of her focus was on sliding mode control.

- Sliding mode control is a robust and nonlinear control approach, and this type of controller has an advantage over the methods used today regarding disturbances and modeling errors, she says.

- What is the most challenging part about pursuing a PhD?

- I spend more time on things than I expected due to problems with simulations or programs I use. The creative part of the development is the most exciting, while writing articles for publication is time consuming and often not that fun, she says.

Exploring the ocean with hyperspectral imaging

Aksel Alstad Mogstad works hard on his PhD at the Trondhjem Biological Station. His supervisor is Professor Geir Johnsen. Photo: NTNU AMOS

His fascination for organisms living in the ocean started when he was a small kid. Now, Aksel Alstad Mogstad is using innovative technologies to learn more about marine organisms that a majority of people have never heard about.

- I have always wanted to be a marine biologist. I don`t know why, but my fascination for water and living organisms in water have always been there, he says.

Today, Mogstad is working on his PhD at NTNU, and his office is right by the Trondheim Fjord at the Trondhjem Biological Station. His focus is on coralline algae, and the results from his Master`s thesis have already given him the front page in the scientific magazine Applied Optics.

Planning an expedition

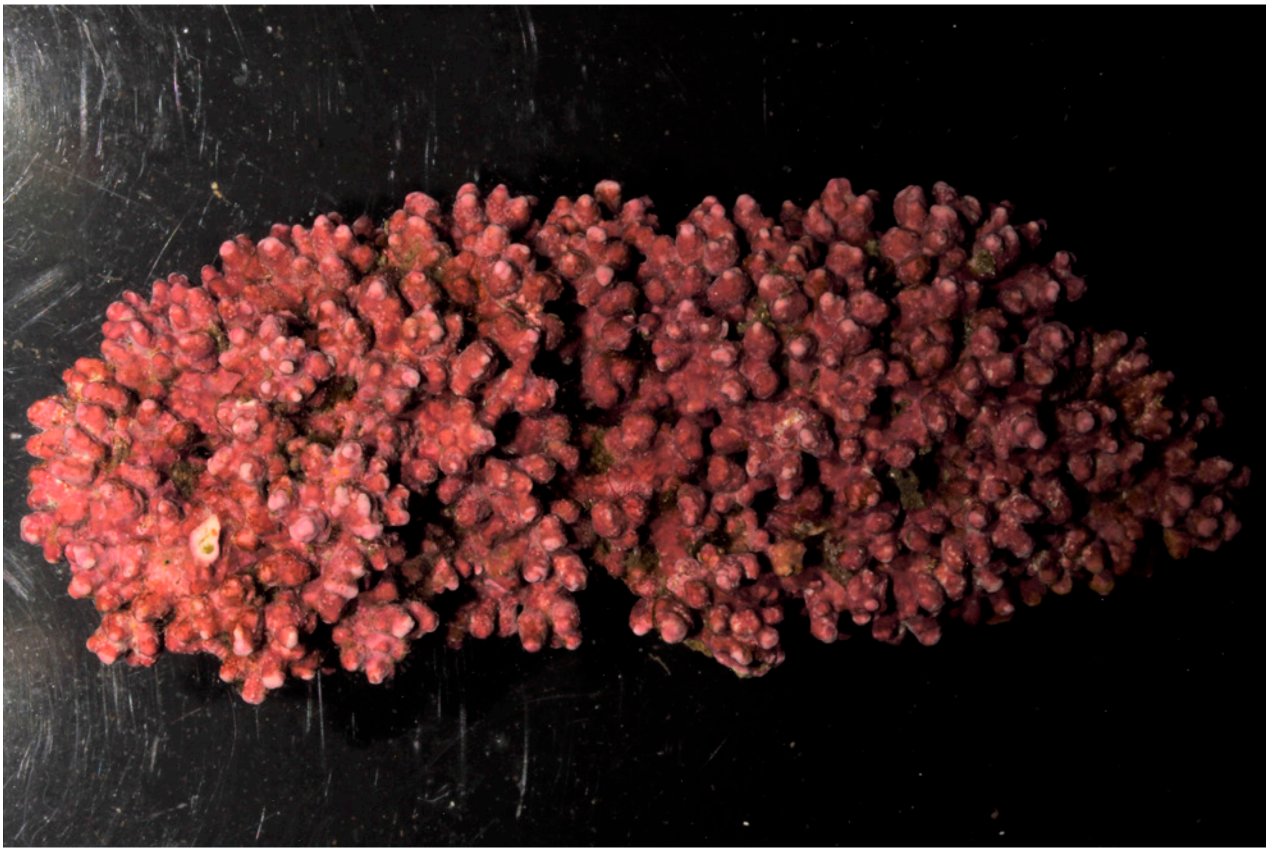
Right now, he is planning an expedition to Hopavågen in Agdenes, where he is going to use underwater hyperspectral imaging (UHI) to learn more about coralline algae and seagrass. Because people or boats cannot go to this location, the inspection and identification of objects and organisms can now be tackled by the objective of automatic and precise machine vision.

During a research cruise outside Svalbard, they used underwater hyperspectral imaging to visualize the seafloor. Here, you can see the camera on the underwater ROV.
Photo: Aksel Alstad Mogstad

- My last expedition was outside Svalbard. We placed the UHI on an underwater vehicle called an ROV (remotely operated vehicle). This time, we are going to use a new platform called an unmanned surface vehicle (USV). Because there is shallow water in Hopavågen, we hope the pictures taken from the USV are going to be nice, he says.

- What is the main goal of the trip?

- I hope to collect additional data for my PhD. The data set we collected outside Svalbard for my Master`s was fairly small. We are also going to be more systematic this time and use cutting edge technology. It is going to be so much fun, but also a lot of work, he smiles.

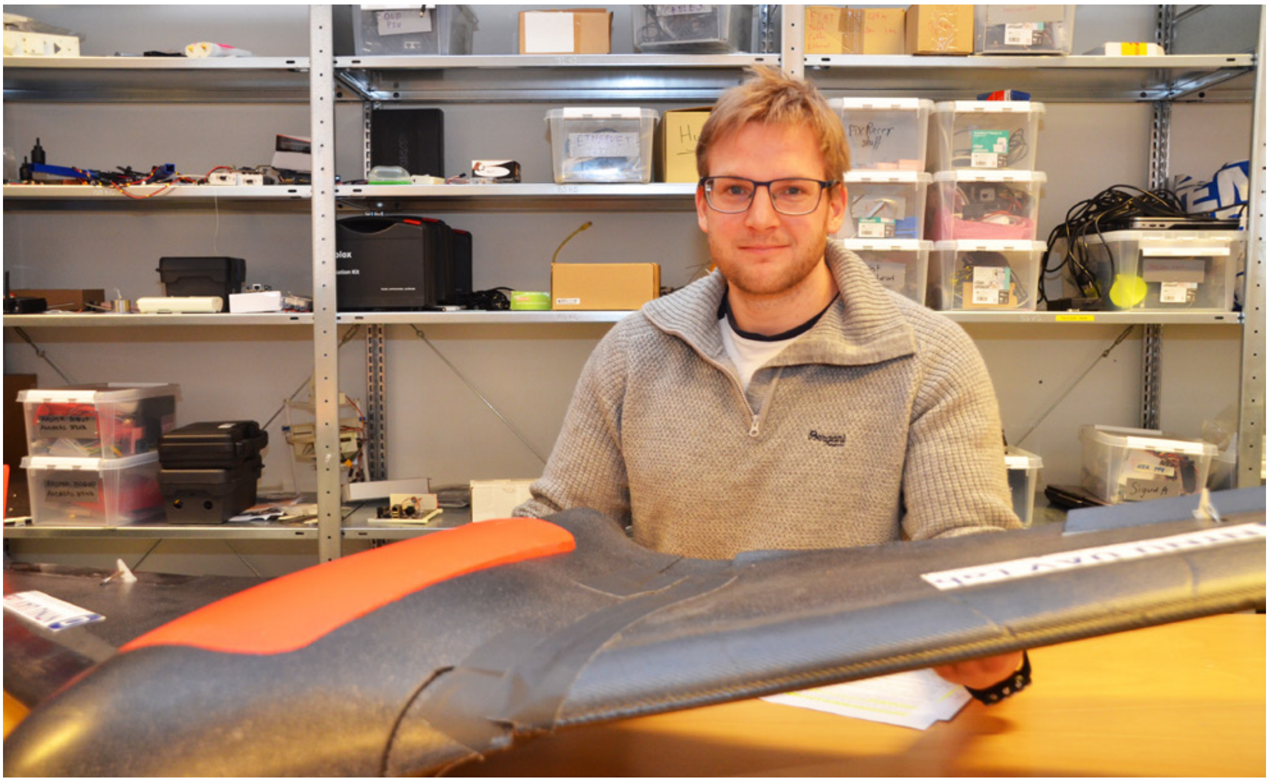


Aksel Alstad Mogstad is trying to learn more about coralline algae during his PhD studies at NTNU AMOS.
Photo: Aksel Alstad Mogstad

Aksel Alstad Mogstad is part of NTNU AMOS and is proud of this accomplishment.

- I admire the people in AMOS that are developing new technology. It is very inspiring for me to work close with so many smart people. It is also necessary for me and other biologists to use technology for monitoring and exploring life in the ocean. I learn a lot about both technology and biology, and I feel privileged to be a part of AMOS, which is a Norwegian Centre of Excellence (SFF), he says.

Flying start to his PhD



Dirk Peter Reinhardt just started his PhD on unmanned aerial vehicles (UAVs). Operations under extreme conditions is one of his research challenges.

Reinhard`s PhD title is a long one: Nonlinear autopilot design for extended flight envelopes and the operation of fixed-wing UAVs in extreme conditions . His work background is in biomedical engineering, but his educational background is in cybernetics. Therefore, instead of using his knowledge on technology in the field of anthropology, his will use it to improve UAVs.

- I think this is a great challenge and I am very excited. I have worked a lot with control systems previously, but not on drones, he smiles.

He moved from Berlin to Trondheim in 2016 and obtained his first job at Toppidrettssenteret near Granåsen. However, obtaining a PhD was his main goal.

- There are so many nice people at AMOS. I do not know much about drone technology yet, but I am going to read a lot and take some classes. It is going to be fun, he says.

Trondheim is a small city compared to Berlin. However, Dirk likes his new home near Kyvatnet and appreciates hiking in Bymarka.

- I hope I will be able to complete my PhD and improve my knowledge for future jobs, Dirk Peter Reinhardt concludes.

Using UAVs to monitor autonomous ships

How can we use an unmanned aerial vehicle (UAV) to search and track ships and other objects at sea; this is what fellow Håkon Hagen Helgesen spends most of his time researching.

- With UAVs, we can detect objects at sea to secure operations for autonomous ships, says Håkon Hagen Helgesen.

With thermal cameras installed in the payload of the drone, the UAV can detect objects in real-time. Moreover, the positions and velocities of the objects can be estimated so that it is possible to predict the future behaviors of the objects. This information can be shared with autonomous ships, which would allow them to operate in a safer and more efficient manner.

- The ultimate goal is to autonomously accomplish all of this in real-time, but I am uncertain if that will happen during my PhD, he smiles. Hopefully, this will be a topic that can be continued when I am finished with my PhD.

He has worked on his PhD, titled "Search and track of objects at sea using UAV with optical instruments", since August 2015. During this time, he has accomplished a large amount of reading and writing, has been part of a new payload development, and teaches and conducts large-scale tests at Trondheim Fjord.

- We used two ships and one UAV during the tests outside Agdenes. Our main goal was to gather a large set of data that could be used to investigate several main challenges that we are working with now. This includes data association, tracking multiple objects, georeferencing and the efficient detection of objects through image analysis. It was challenging to organize the experiments, but we were able monitor the images through a video stream that was sent to the ground station from the UAV in real-time. Moreover, we implemented a system that sends the position of the ships to the ground station. We gathered a lot of data, and I am currently in the process of analyzing the data. That is a lot of fun, he says.

- How does it feel to be a PhD candidate?
- It is very interesting and rewarding, but it can also be slow and frustrating at times. The people at AMOS are great. I like being around them a lot, and I also receive a lot of support from my supervisors.

Aiming to prevent collisions between ships

Inger Berge Hagen has a great interest in autonomous ships because there are a substantial amount of people with whom she can discuss technological challenges.

- I wanted to work further on this topic because I think it is exciting and challenging, says Inger Berge Hagen.

- Another factor that eased the decision to obtain a PhD was the NTNU Autosea project. They are working with the same technological challenges and are very good discussion partners.

Her PhD focuses on finding technological solutions for avoiding collisions when driving an autonomous ferry. In addition, part of solving this problem is tracking because sensors can identify other boats in the same area. An autonomous ferry will to be used in short distances just outside Ravnkloa in Trondheim.

- My Master`s degree focused on avoiding collisions, but my knowledge on tracking is not as good, she says.

- Most of my work will focus on developing algorithms that the ferry can follow. In addition, some of the rules and regulations on sea must be changed to allow autonomous shipping.

Hagen is from Dalene in Rogaland, but she has lived in Trondheim since 2011. She has a great time at NTNU with the people in AMOS.

- Many people at AMOS are working with autonomous ferries (for example, Kongsberg, DNV GL and of course NTNU AMOS). I am also collaborating with the Ocean School of Innovation at NTNU, she says.

Inger Berge Hagen started her PhD in August 2017, but she has already written her first article, which was accepted by the international conference ICRA. In August, she is going to present the article in Brisbane, Australia.

- It is nice to get started with writing. I look forward to the rest of the PhD work, she smiles.

APPENDICES

NTNU AMOS personnel and collaborators

Annual accounts and man-year efforts

PhD Graduates

Publications in 2017

NTNU AMOS personnel and collaborators

Management and administration

Name	Title	Acronym
Prof. Sørensen, Asgeir J.	Director	AJS
Prof. Fossen, Thor I.	Co-director	TIF
Wold, Sigrid Bakken	Senior executive officer	SBW
Bremvåg, Annika	Higher executive officer	AB
Renate Karoliussen	Economy	RK

Key scientists

Name	Institution, department	Main field of research	Acronym
Prof. Amdahl, Jørgen	NTNU, Dept. Marine Technology	Structural load effects, resistance, accidental actions	JAM
Prof. Fossen, Thor I.	NTNU, Dept. Engineering Cybernetics	Guidance, navigation and control	TIF
Prof. Greco, Marilena	NTNU, Dept. Marine Technology	Marine hydrodynamics	MG
Prof. Johansen, Tor Arne	NTNU, Dept. Engineering Cybernetics	Optimization and estimation in control	TAJ
Prof. Johnsen, Geir	NTNU Dept. Biology	Marine biology	GJ
Prof. Pettersen, Kristin Y	NTNU, Dept. Engineering Cybernetics	Automatic control	KYP
Prof. Sørensen, Asgeir J	NTNU, Dept. Marine Technology	Marine control systems	AJS

Senior scientific advisers

Name	Institution, department	Main field of research	Acronym
Prof. Faltinsen, Odd M.	NTNU, Dept. Marine Technology	Marine hydrodynamics	OF
Prof. Moan, Torgeir	NTNU, Dept. Marine Technology	Marine structures	TM

Adjunct professors and adjunct associate professors

Name	Institution	Main field of research	Acronym
Adj. prof. Berge, Jørgen	UiT, The Arctic University of Norway	Marine biology	JB
Adj. prof. Blanke, Mogens	DTU	Automation and control	MB
Adj. prof. Fredheim, Arne	SINTEF Ocean	Fisheries and aquaculture	AF
Adj. ass. prof. Føre, Martin	SINTEF Ocean	Fisheries and aquaculture	MF
Adj. ass. prof. Hassani, Vahid	SINTEF Ocean	Marine control	VH
Adj. prof. Johansson, Karl H.	KTH	Automation and control	KHJ
Adj. prof. Kanna, Rajan	NTNU	Artificial intelligence	RK
Adj. prof. Kruusmaa, Maarja	Talin University of Technology	Marine robotics	MK
Adj. prof. Larsen, Kjell	STATOIL	Marine operations and structures	KL
Adj. prof. Lugni, Claudio	CNR-INSEAN	Marine hydrodynamics	CL
Adj. ass. prof. Nguyen, Trong Dong	DNV GL	Marine control systems	TDN
Adj. ass. prof. Nielsen, Ulrik Dam	DTU	Wave-ship interactions	UDN
Adj. ass. prof. Scibilia, Francesco	NTNU, Dept. Engineering Cybernetics	Remote sensing and autonomy	FS
Adj. prof. Skaugset, Kjetil	STATOIL	Marine operations and structures	KS
Adj. ass. prof. Sokolova, Nadezda	SINTEF Digital	Integrated navigation systems	NS
Adj. ass. prof. Storvold, Rune	NORUT	Aircraft and remote sensing	RS

Postdocs/researchers

Name	Institution	Main field of research	Acronym
Dr Bryne, Torleiv Håland	Dept. of Cybernetics, NTNU	Inertial navigation systems	TB
Dr Cheng, Zhengshun	NTNU, CeSOS	Characteristic environmental loads and load effects for ULS and ALS design check of floating bridges; offshore wind turbines	ZC
Dr Colicchio, Giuseppina	INSEAN	Marine hydrodynamic: numerical modeling of multiphase flows	GC
Dr Haring, Mark	NTNU, Dept. Engineering Cybernetics	Nonlinear filtering and observer theory	MH
Dr Jiang, Zhiyu	Dept. of Marine Techn., NTNU	Marine operation; offshore wind turbine; design of marine structures	ZJ
Dr Kelasidi, Eleni	NTNU, Dept. Engineering Cybernetics	Resident robot manipulators for subsea IMR	ElK
Dr Kim, Ekaterina	NTNU, Dept. Marine Technology	Understanding rare, extreme ice-structure collisions	EK
Dr Klausen, Kristian	Dept. of Cybernetics, NTNU	Research on drones for industrial inspection.	KK
Dr Kohl, Anna	Dept. of Cybernetics, NTNU	Underwater swimming manipulators for subsea intervention	AK
Dr Kufoalor, Giorgio Kwame	NTNU, Dept. Engineering Cybernetics	To develop an overall system architecture of a future navigation and control system with sensor fusion and collision avoidance (COLAV)	GKK
Dr Leira, Frederik S.	Dept. of Cybernetics, NTNU	Multiple Object Detection and Tracking with fixed-wing UAVs	FL
Dr Liljebäck, Pål	NTNU, Dept . Engineering Cybernetics	Snake robots	PL
Dr Ommani, Babak	MARINTEK	Numerical modelling for nonlinear stochastic processes	BO
Dr Raskehi Nejad, Amir	NTNU, CeSOS	Dynamic analysis, design, condition monitoring and fault detection of drivetrains in floating wind turbines	ARN
Dr Rogne, Robert H.	Dept. of Cybernetics, NTNU	Airborne gravimetry using inertial navigation systems.	RHR
Dr Rotondo, Damiano	NTNU, Dept . Engineering Cybernetics	Gain-scheduled control systems, fault detection and isolation (FDI) and fault tolerant control (FTC) of dynamic systems	DR
Dr Sha, Yanyan	NTNU, Dept. Marine Technology	Ship collision analysis of floating bridges in ferry-free-E39 project	YS
Dr Sørensen, Kim Lynge	NTNU, Dept . Engineering Cybernetics	Development of icing protection solution for small unmanned aircraft	KLS
Dr Yu, Zhaolong	Dept. of Marine Techn., NTNU	Marine Structures	ZY
Dr Wei, Zhi-Jun	Dept. of Marine Techn., NTNU	Marine hydrodynamics – Renewable energy resources	ZJW

Affiliated scientists

Name	Institution	Main field of research	Acronym
Ass. prof. Aberle-Malzahn, Nicole	NTNU, Dept. of Biology	Marine biology	NAM
Ass. prof. Alfredsen, Jo Arve	NTNU, Dept. Engineering Cybernetics	Automation in fisheries and aquaculture	JAA
Ass. prof. Bachynski, Erin E .	NTNU, Dept. Marine Technology	Wind energy/offshore renewable energy systems	EEB
Dr Breivik, Morten	NTNU, Dept. Engineering Cybernetics	Nonlinear and adaptive motion control	MBR
Ass. prof. Brekke, Edmund	NTNU, Dept. Engineering Cybernetics	Sensor fusion	EB
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	LSI
Ass. prof. Kim, Ekaterina	NTNU, Dept. Marine Technology	Marine structures	EK
Ass. prof. Kindl Josef	NTNU, Dept. Marine Technology	Marine structures	JK
Prof. Kristiansen, Trygve	NTNU, Dept. Marine Technology	Marine hydrodynamics	TK
Prof. Ludvigsen, Martin	NTNU, Dept. Marine Technology	Underwater technology and operations	ML
Prof. Molinas, Marta	NTNU, Dept. Engineering Cybernetics	Marine power systems	MM
Prof. Olsen, Yngvar	NTNU, Dept. of Biology	Marine biology	YO
Prof. Schjølberg, Ingrid	NTNU, Dept. Marine Technology	Underwater robotics	IS
Prof. Skjetne, Roger	NTNU, Dept. Marine Technology	Marine control systems	RS
Ass. prof. Stahl, Annette	NTNU, Dept. Engineering Cybernetics	Robotic vision	AS
Prof. Utne, Ingrid B.	NTNU, Dept. Marine Technology	Safety critical systems and systems engineering	IBU

Technical staff, directly funded by NTNU AMOS

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

Visiting researchers

Name	Institution, department	Main field of research	Acronym
Prof. Arcak, Murat	Univ. of California, Berkeley, USA	Cooperative control design	AM
Dr Colicchio, Giuseppina	CNR-INSEAN, Italy	Mesh generation and analysis for computational fluid mechanics	GC
De Figueiredo Vieira, Ricardo	Inst. Superior de Engenharia de Lisboa	Analyses of wind turbine offshore structures	RFV
Macias, Alberto Ramirez	Universidad Pontifica Bolivariana	ROV design, modelling, hydrodynamics, control	ARM
Prof. Prpic-Orsic, Jasna	Univ. of Rijeka, Croatia	CO_2 emission from ships in waves	JP
Dr Wang, Jingbo	National Science Foundation of China/ CNR-INSEAN	Water impact	JW
Prof. Andy Teel	Univ. of California, Santa Barbara, USA	Nonlinear control	AT

PhD candidates with financial support from NTNU AMOS

Name	Period (yyyymmdd)	Supervisor	Topic
Bore, Pål Takle	20150901-20180901	JAM	Intelligent aquaculture structures
Borlaug, Ida-Louise	20170807-20200806	KYP	Robust control of articulated intervention AUV
Brodtkorb, Astrid H.	20140101-20170630	AJS	Dynamic positioning in extreme seas
Cisek, Krzysztof	20140501-20170430	TAJ	Multi-body unmanned aerial systems
Henrik Schmidt-Didlaukies	20170814-20200813	AJS	Modellering og Regulering av Hyper-Redundante Undervanns-manipulatorer
Eidsvik, Ole A.	20150801-20180701	IS	Design and development of unmanned underwater vehicles
Fortuna, João	20140815-20170814	TIF	Autonomous UAV recovery and rendezvous on moving ships
Gryte, Kristoffer	20150811-20180810	TIF	Fixed-wing UAV operations from autonomous floating docking station
Hanssen, Finn- Christian W.	20130826-20160816	MG	Nonlinear wave loads on marine structures in extreme sea states
Horn, Jan-Tore Haugan	20150101-20180430	JAM	Stochastic dynamic simulations of offshore wind turbines with integrated control and monitoring
Jørgensen, Erlend Kvinge	20140818-20170817	IS	Autonomous subsea IMR operations using sensor fusion and structure knowledge
Klausen, Kristian	20130805-20160804	TIF	Deployment, search and recovery of marine sensors using multiple rotary wings UAVs
Kohl, Anna	20140801-20170731	KYP	Hyperredundant underwater manipulators and next generation intervention-AUVs
Leira, Fredrik Stendahl	20130625-20160624	TIF	Infrared object detection & tracking in UAVs
Ma, Shaojun	20140805-20170804	MG	Manoeuvring of a ship in waves
Merz, Mariann	20130812-20160811	TAJ	Deployment, search and recovery of marine sensors using a fixed- wing UAV
Mogstad, Aksel Alstad	20170724-20220623	GJ	Marine biological applications for underwater hyperspectral imaging (UHI)
Muntadas, Albert Sans	20140501-20170430	KYP	Integrated underwater navigation and mapping based on imaging and hydro-acoustic sensors
Nam, Woongshik	20140811-20170810	JAM	Structural resistance of ships and offshore structures subjected to cryogenic spills
Nielsen, Mikkel Cornelius	20140815-20170814	MB	Fault-tolerance and reconfiguration for collaborating heterogeneous underwater robots
Nornes, Stein M.	20130826-20160825	AJS	Simultaneous mapping, navigation and monitoring with unmanned underwater vehicle using sensor fusion
Paliotta, Claudio	20140106-20170105	KYP	Marine multi-agent systems: coordinated and cooperative control for intelligent task execution and collision avoidance
Ramos, Nathalie	20171101-20201031	JK	4D printing of intelligent marine structures
Sauder, Thomas	20150803-20180802	AJS	Real-time hybrid testing of floating systems
Shen, Yugao	20130812-20160811	MG	Limiting operational conditions for a well boat
Siddiqui, Mohd Atif	20140813-20170812	MG	Manoevring of a damaged ship in waves
Smilden, Emil	20150101-20180430	AJS	Reduction of loads, fatigue and structural damage on an off-shore wind turbine
Sørum, Stian Høegh	20160901-20200115	JAM	How to design and operate sustainable and autonomous systems for offshore renewable energy in shallow-to-deep waters
Vilsen, Stefan A.	20140201-20180131	AJS/HG	Hybrid model testing of marine systems

Name	Period (yyyymmdd)	Supervisor	Topic
Værnø, Svenn Are T.	20140101-20161231	RS	Topics in motion control of offshore vessels
Wiig, Martin Syre	20140815-20180814	KYP	Motion planning for autonomous underwater vehicles
Yu, Zhaolong	20140811-20170810	JAM	Ship/ship and ship/offshore installation collisions including fluid structure interaction
Zolich, Artur	20140401-20170331	TAJ	Autonomous control and communication architectures for coordinated operation of unmanned vehicles (UAV, AUV, USV) in a maritime mobile sensor network
Ødegård, Øyvind	20130820-20170819	AJS	Autonomous operations in marine archaeology - technologies and methods for managing underwater cultural heritage in the Arctic

PhD candidates associated with NTNU AMOS with other financial support

Name	Period (yyyymmdd)	Supervisor	Topic
Aamot, Inga	20120316-20160316	GJ/AJS	Use of underwater robotics and optical sensors in distribution-mapping and monitoring of physiology of brown, red and green macroalgae
Albert, Anders	20130826-20170825	LI	Mission and path optimisation for mobile sensor network operations
Albrektsen, Sigurd M.	20140101-20161231	TAJ	Integrated observer design with a north-seeking strapdown MEMS-based gyrocompass and machine vision
Andersson, Leif Erik	20140316-20170315	LI	Iceberg and sea ice drift estimation and prediction
Andrade, Fabio	20160701-20190701	RSt	Sea ice drift tracking using real time UAV path planning for maritime situational awareness
Berget, Gunhild	20170807-20200806	TAJ	Intelligent monitoring of drilling operations in sensitive environments
Bitar, Glenn Ivan	20170911-20200910	MB	Researching autonomy in ferries. Optimal path planning and path following, collision avoidance and docking.
Bjørne, Elias	20150815-20180814	TAJ	Nonlinear observer theory for simultaneous localization and mapping
Borri, Daniele	20100811-20151031	MG	Hydrodynamics of oil spills from oil tankers
Borup, Kasper T.	20130516-20160515	TIF	Model-based nonlinear integration filters for INS and position measurements
Bryne, Torleiv H.	20130815-20160804	TIF	Optimal sensor fusion for marine vessels using redundant IMUs and position reference systems
Cho, Seong-Pil	20140804-20170803	TM/ZG	Dynamic modelling and analysis of floating wind turbines with emphasis on the behavior in fault conditions
Dahl, Andreas Reason	20130819-20160818	RS	Nonlinear and fault-tolerant control of electric power production in Arctic DP vessels
Eriksen, Bjørn-Olav H.	20150803-20180802	MBR	Collision avoidance for autonomous surface vehicles
Flåten, Andreas L .	20150803-20180802	EB	Multisensor tracking for collision avoidance
Fossum, Trygve Olav	20160501-20181130	ML	Artificial intelligence for AUVs
Fusini, Lorenzo	20121001-20151231	TIF	Robust UAV attitude and navigation system for marine operations using nonlinear observers and camera measurements
Ghane, Mahdi	20150101-20171231	TM/ZG	Dynamic modelling and analysis of floating wind turbines with emphasis on the behavior in fault conditions
Gunnu, Giriraja Sekhar	2016xxx-20170601	TM	Safety and efficiency enhancement of anchor handling operations with particular emphasis on the stability of anchor handling vessels

Name	Period (yyyymmdd)	Supervisor	Topic
Grøtte, Mariusz Eivind Santora	20170703-20200702	TG	Attitude Determination and Control for Hyperspectral Imaging Small Satellite in Multi-Agent Observation System
Haavardsholm, Trym Vegard	20170201-20210131	ASt	Collaborative visual mapping and exploration for teams of unmanned systems
Hagen, Inger Berge	20170801-20201231	EB	Collision Avoidance for Autonomous Ferry
Hann, Richard	20160615-20190614	TAJ	Icing and anti-icing of UAVs
Hansen, Jakob Mahler	20130801-20160731	TIF	Nonlinear observers for tight integration of IMU and GNSS pseudo-range and carrier-phase-ambiguity resolution
Haring, Mark	20110921-20160623	TAJ	Extremum-seeking control, convergence improvements and as-ymptotic stability
Hassel, Martin	20140101-20161231	IU	Risk and safety of marine operations
Haugo, Simen	20170801-20200731	ASt	Computer vision methods for assisted teleoperation of unmanned air vehicles
Hegde, Jeevith	20140822-20170821	IS	Safety and reliability of marine underwater autonomous vehicles
Hegseth, John Marius	20170101-20191231	EB	Efficient Modelling and Design Optimization of Large Floating Wind Turbines
Helgesen, Håkon Hagen	20150817-20181116	TAJ	UAV scouting system for autonomous ships
Henriksen, Eirik H .	20140804-20170803	IS	Next generation subsea factories for autonomous IMR operations
Heyn, Hans-Martin	20140813-20180812	RS	Fault-tolerant control and parameter estimation for thruster as-sisted position mooring in Arctic offshore conditions
Hovenburg, Anthony	20160101-20181231	RSt	Modular design framework for RPAS operating in marine environ-ments
Jørgensen, Ulrik	20100830-20140331	RS	Autonomous underwater ice observation system
Katsikogiannis, George	20171101-20201031	EB	Loads and Responses of Large-Diameter Monopile Wind Turbines
Kjerstad, Øivind K .	20100801-20141231	RS	Dynamic positioning of marine vessels in ice
Leonardi, Marco	20160815-20190814	AS	Visual odometry and servoing for 3D reconstruction
Li, Qinyuan	20110710-20160709	TM	Long-term extreme response prediction for offshore wind turbines
Luan, Chenyu	2010xxxx-20170601	TM	Efficient stochastic dynamic response analysis for design of off-shore wind turbines
Mathisen, Siri Holthe	20140818-20170817	TAJ	Embedded optimization for autonomous unmanned aerial vehicle mission planning and guidance
Miyazaki, Michel Rejani	20130503-20170502	AJS	Control of hybrid power plants
Nilssen, Ingunn	201204xx-201604xx	GJ/AJS	Integrated environmental monitoring; taking environmental data into decision making processes
Norgren, Petter	20130301-20170428	RS	AUVs for subsurface monitoring of sea-ice and icebergs
Olofsson, Harald L . J .	20151012-20181011	TIF	Bayesian iceberg risk management
Pedersen, Morten D .	20100110-	TIF	Modeling and control systems for wind turbines
Ren, Zhengru	20160101-20181231	RS	Monitoring and control of crane operations for fixed and floating offshore wind turbines
Rodin, Christopher Dahlin	201508xx- 201807xx	TAJ	Intelligent data acquisition in maritime UAS
Rogne, Robert	20130801-20160731	TAJ	Fault-tolerant sensor fusion by exploiting redundant inertial measurements
Rokseth, Børge	20140815-20170814	IU	A new approach for handling risk in dynamic position systems for marine vessels

Name	Period (yyyymmdd)	Supervisor	Topic
Verma, Amrit Shankar	20160818-20190817	ZG	Development of explicit response-based criteria for operability assessment for installation of offshore wind turbines using floating vessels
Skjong, Espen	201408xx- 201708xx	TAJ	Optimization based design of modular power management systems for modern ships, with focus on efficiency and fuel consumption
Souza, Carlos E. Silva de	20160812-20200811	ErB	Structural modeling and optimization of floating wind turbines
Stovner, Bård Bakken	20140801-20170731	IS	Localization and perception for safe underwater ROV intervention
Strand, Ida M.	20130801-20160731	AJS	External sea loads and internal hydraulics of closed flexible cages
Sverdrup-Thygeson, Jørgen	20150301-20180531	KYP	Motion control and redundancy resolution for hybrid underwater manipulators
Sørensen, Mikkel Eske Nørgaard	20140825-20170824	MBR	Nonlinear and adaptive control of unmanned vehicles for maritime applications
Thieme, Christoph A.	20140901-20170731	IU	Human and organizational factors in unmanned underwater operations
Ueland, Einar S.	20160815-20190814	RS	Study of fundamental constraints in the hbrid test loop, and optimal control and estimation strategies for actuation of effort on the physical system
Wan, Ling	20140101-20160630	TM	Experimental and numerical study of a combined offshore wind and wave energy converter concept
Wenz, Andreas Wolfgang	20150601-20180531	TAJ	Fault tolerant control and automatic de-icing for unmanned aerial vehicles
Wilthil, Erik F.	20150803-20180803	EB	Target tracking under navigation uncertainty
Wu, Xiaopeng	20100810-20150615	TM	Numerical analysis of anchor handling and fish trawling operations in a safety perspective
Zhao, Yuna	20140901-20170831	TM/ZG	Safety assessment of marine operations related to installation of offshore wind turbine

Annual accounts and man-year efforts

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

Nationality	Key professor	Adjunct prof./Ass. prof.	Affiliated scientists	Scientific advisor	Post doc/ researcher	Visiting professor/ researcher	PhD	Assoc. PhD	Administrative staff *)	SUM
Norwegian	6,00	5,00	14,00	2,00	6,00		20,00	27,00	5,00	85,00
Other nationalities	1,00	6,00	8,00		11,00	16,00	15,00	26,00	1,00	84,00
SUM	7,00	11,00	22,00	2,00	17,00	16,00	35,00	53,00	6,00	169,00
Man-years	3,67	2,96	5,90	1,00	11,33	3,24	22,00	41,04	4,41	95,55

*) incl. Technical staff

Total man-years efforts

Man-years	2017
Centre director	0,30
Co-director	0,28
Adm.personnel	2,83
Technical staff	1,00
Summary	*4,41*
Key professor	3,67
Adjunct prof/ass.prof	2,96
Affiliated prof/scientists	5,90
Scientific advisor	1,00
Postdocs	2,41
Postdoc (affiliated)	8,92
Visiting researchers	3,24
PhD candidates	22
PhD candidates (affiliated)	41,04
Total research man-years	**95,55**

Annual accounts

Annual Accounts	Note	Accounted income and costs
Amount in NOK 1000		
Operating income		
The Research Council of Norway		17 998
NTNU	1	25 461
Others	2	7 049
In-kind	3	18 246
Sum operating income		68 754
Operating costs		
Salary and social costs	4	43 280
Equipment investments		2 080
Procurement of R&D services		820
Other operating costs	5	6 538
In-kind	3	18 246
Sum operating costs		70 964
Year end allocation		-2 210
Opening balance 20170101		7 707
Closing balance 20171231		5 497

Note 1: Accounted income: Fellowships and cash contribution to operation
Note 2: Accounted income: Contribution from industry sponsors: DNV GL, Statoil, SINTEF Ocean, SINTEF Digital
Note 3: In-kind contribution: SINTEF Ocean, SINTEF Digital, NTNU
Note 4: Accounted costs: Personnel costs (salary and and social costs) covered by AMOS
Note 5: Accounted costs: Other operating costs, including travelling, computer equipment

PhD Graduates

PhD degrees 2017

Supervised by Key Scientists at AMOS

Name		Topic	Supervisor
Leira, Frederik Stendahl	January 19	Object Detection and Tracking With UAVs	TAJ/TIF
Hansen, Jakob Mahler	March 23	Nonlinear Observers for Inertial Navigation Systems aided by Real-Time Kinematic Global Navigation Satellite System	TIF
Rogne, Robert	March 30	Observer Design For Fault-Tolerant Dynamic Positioning Using MEMS Inertial Sensors	TAJ
Bryne, Torleiv Håland	March 31	*Nonlinear Observer Design for Aided Inertial Navigation Systems of Ships"*	TIF
Skjong, Espen	June 2nd	Optimization-based Control in Shipboard Electric Systems	TAJ
Klausen, Kristian	June 23	Coordinated Control of Multirotors for Suspended Load Transportation and Fixed-Wing Net Recovery	TIF/TAJ
Miyazaki, Michel Rejani	June 29	Modeling and Control of Hybrid Marine Power Plants	AJS
Pedersen, Morten Dinhoff	June 30	Stabilization of Floating Wind Turbines	TIF
Paliotti, Claudio	Sept.14th	Control of Under-actuated Marine Vehicles	KYP
Kohl, Anna	Oct. 20	Guidance and Control of Underwater Snake Robots Using Planar Sinusoidal Gaits	KYP
Fusini, Lorenzo	August 30th	Camera-aided Inertial Navigation for Unmanned Aerial Vehicles using Non-linear Observers	TIF
Yu, Zhaolong	Sept.21th	Hydrodynamic and Structural Aspects of Ship Collisions	JAM
Brodtkorb, Astrid	Dec. 4th	Hybrid Control of Marine Vessels - Dynamic positioning in varying conditions	AJS

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

Name		Topic	Supervisor
Li, Peng	April 4th	A theoretical and Experimental Study of Wave-Induced Hydroelastic Response of a Circular Floating Collar	OF
Bardestani, Mohsen	May 8	A two-dimensional numerical and experimental study of a floater with net and sinker tube in waves and current	OF
Giriraja Sekhar Gunnu	July 3rd	Safety and Efficiency Enhancement of Anchor Handling Operations with Particular Emphasis on the Stability of Anchor Handling Vessels	TM

Supervised by Affiliated Scientists at AMOS

Name		Topic	Supervisor
Hassel, Martin	November 28th	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations	IBU

Publications in 2017

Books

Fossen, Thor I.; Nijmeijer, Henk; Pettersen, Kristin Ytterstad. Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles. Springer 2017 (ISBN 978-3-319-55371-9); Volume 474.518 s. Lecture notes in control and information sciences(-), NTNU

Book chapters

1. **Belleter, Dennis Johannes Wouter; Pettersen, Kristin Ytterstad.** Leader-Follower Synchronisation for a Class of Underactuated Systems. I: *Nonlinear Systems Techniques for Dynamical Analysis and Control*. Springer 2017 ISBN 978-3-319-30356-7. s. 157-179, NTNU
2. **Eriksen, Bjørn-Olav Holtung; Breivik, Morten.** Modeling, Identification and Control of High-Speed ASVs: Theory and Experiments. I: Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles. Springer 2017 ISBN 978-3-319-55371-9. s. 407-431, NTNU
3. **Fusini, Lorenzo; Fossen, Thor I.; Johansen, Tor Arne.** Nonlinear Camera- and GNSS-aided INS for Fixed-Wing UAV using the eXogenous Kalman Filter. I: Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles. Springer 2017 ISBN 978-3-319-55371-9. s. 25-50, NTNU
4. **Helgesen, Håkon Hagen; Leira, Frederik Stendahl; Johansen, Tor Arne; Fossen, Thor I..** Detection and Tracking of Floating Objects using an UAV with Thermal Camera. I: Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles. Springer 2017 ISBN 978-3-319-55371-9. s. 289-316, NTNU
5. **Nornes, Stein Melvær; Sørensen, Asgeir Johan; Ludvigsen, Martin.** Motion Control of ROVs for Mapping of Steep Underwater Walls. I: *Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles*. Springer 2017 ISBN 978-3-319-55371-9. s. 51-69, NTNU
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7. **Vilsen Stefan A., Thomas Sauder, Asgeir J. Sørensen**. Real-Time Hybrid Model Testing of Moored Floating Structures Using Nonlinear Finite Element Simulations. In: Allen M., Mayes R., Rixen D. (eds) Dynamics of Coupled Structures, Vol. 4, pp. 79-92. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham. ISSN 2191-5644
8. **Wilthil, Erik Falmår; Flåten, Andreas Lindahl; Brekke, Edmund Førland.** A Target Tracking System for ASV Collision Avoidance Based on the PDAF. I: *Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles*. Springer 2017 ISBN 978-3-319-55371-9. s. 269-288, NTNU

Journal articles

1. **Abdollahpouri, Mohammad; Quirynen, Rien; Haring, Mark; Johansen, Tor Arne; Takács, Gergely; Diehl, Moritz; Rohal'-Ilkiv, Boris.** A homotopy-based moving horizon estimation. *International Journal of Control* 2017 s. 1-10, NTNU
2. **Antuono, M; Colicchio, Giuseppina; Lugni, Claudio; Greco, Marilena; Brocchini, M.** A depth semi-averaged model for coastal dynamics. Physics of fluids 2017 ;Volume 29.(5) p. -, NTNU
3. **Assmy, P ; Fernández-Méndez, M; Duarte, P; Meyer, A; Randelhoff, A; Mundy, CJ; Olsen, LM; Kauko, HM; Bailey, A; Chierici, M; Cohen, L; Doulgeris, AP; Ehn, JK; Fransson, A; Gerland, S; Hop, H; Hudson, SR; Hughes, N; Itkin, P; Johnsen, G; King, JA; Koch, BP; Koenig, Z; Kwasniewski, S; Laney, SR; Nicolaus, M; Pavlov, AK; Polashenski, CM; Provost, C; Rösel, A; Sandbu, M; Spreen, G; Smedsrud, LH; Sundfjord, A; Taskjelle, T; Tatarek, A; Wiktor, J; Wagner, PW; Wold, A; Steen, H; Granskog, MA.** Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice. Scientific Reports. 2017. 7:40850, DOI:10.1038/srep40850
4. **Blanke, Mogens; Nguyen, Dong Trong.** Fault-tolerant Position-Mooring Control for Offshore Vessels. *Ocean Engineering* 2018; Volum 148.(jan) s. 426-441, NTNU
5. **Bryne, Torleiv Håland; Fossen, Thor I.; Johansen, Tor Arne.** Design of inertial navigation systems for marine craft with adaptive wave filtering aided by triple-redundant sensor packages. *International Journal of Adaptive Control and Signal Processing* 2017; Volum 31.(4) s. 522-544, NTNU
6. **Bryne, Torleiv Håland; Rogne, Robert Harald; Fossen, Thor I.; Johansen, Tor Arne.** A virtual vertical reference concept for aided inertial navigation at the sea surface. *Control Engineering Practice* 2017 ;Volum 70. s. 1-14, NTNU
7. **Bryne, T. H., J.M. Hansen, R.H. Rogne, N. Sokolova, T. A. Johansen and T. I. Fossen.** Nonlinear Observers for Integrated INS/GNSS Navigation – Implementation Aspects. *IEEE Control Systems Magazine*, Volume: 37, Issue 3, June 2017, pp. 59-86
8. **Bø, Torstein Ingebrigtsen; Johansen, Tor Arne.** Dynamic Safety Constraints by Scenario Based Economic Model

Predictive Control of Marine Electric Power Plants. *IEEE Transactions on Transportation Electrification* 2017 , NTNU

9. **Candeloro, Mauro; Lekkas, Anastasios M.; Sørensen, Asgeir Johan.** A Voronoi-diagram-based dynamic path-planning system for underactuated marine vessels. *Control Engineering Practice* 2017 ;Volum 61. s. 41-54, NTNU
10. **Chernova, MO; Lukovsky, IA; Timokha, Alexander.** Differential and variational formalism for acoustically-levitating drops. Journal of Mathematical Sciences 2017 ;Volum 220.(3) s. 359-375, NTNU
11. **Cheng, Zhengshun; Madsen, Helge A.; Gao, Zhen; Moan, Torgeir.** A fully coupled method for numerical modeling and dynamic analysis of floating vertical axis wind turbines. *Renewable Energy* 2017 ;Volum 107. s. 604-619, NTNU
12. **Cheng, Zhengshun; Madsen, Helge Aagard; Gao, Zhen; Moan, Torgeir.** Effect of the number of blades on the dynamics of floating straight-bladed vertical axis wind turbines. *Renewable Energy* 2017 ;Volum 101. s. 1285-1298, NTNU
13. **Cheng, Zhengshun; Wang, Kai; Gao, Zhen; Moan, Torgeir.** A comparative study on dynamic responses of spar-type floating horizontal and vertical axis wind turbines. *Wind Energy* 2017 ;Volum 20.(2) s. 305-323, NTNU
14. **Cheng, Zhengshun; Madsen, Helge Aagard; Chai, Wei; Gao, Zhen; Moan, Torgeir.** A comparison of extreme structural responses and fatigue damage of semi-submersible type floating horizontal and vertical axis wind turbines. Renewable Energy 2017 ;Volum 108. s. 207-219, NTNU
15. **Choi, ju-hyuck; Jensen, Jørgen Juncher; Kristensen, Hans Otto; Nielsen, Ulrik Dam; Erichsen, Henrik.** Intact Stability Analysis of Dead Ship Conditions using FORM. Journal of Ship Research 2017 ;Volum 61.(3) s. 167-176, NTNU, DTU
16. **Cristofaro, Andrea; Johansen, Tor Arne; Aguiar, A Pedro.** Icing Detection and Identification for Unmanned Aerial Vehicles using Adaptive Nested Multiple Models. International Journal of Adaptive Control and Signal Processing 2017 ;Volum 31.(11) s. 1584-1607, NTNU
17. **Cristofaro, Andrea; Polycarpou, Marios M.; Johansen, Tor Arne.** Fault-tolerant control allocation for overactuated nonlinear systems. Asian journal of control 2017 s. -, NTNU
18. **Du, Jingjing; Johansen, Tor Arne.** Control-relevant nonlinearity measure and integrated multi-model control. Journal of Process Control 2017 ;Volum 57. s. 127-139, NTNU
19. **Faltinsen, Odd Magnus.** Sloshing. Advances in Mechanics 2017 ;Volum 47. s. -, NTNU
20. **Faltinsen, Odd Magnus; Timokha, Alexander.** Resonant three-dimensional nonlinear sloshing in a square-base basin. Part 4. Oblique forcing and linear viscous damping. Journal of Fluid Mechanics 2017 ;Volum 822. s. 139-169, NTNU
21. **Fortuna, João; Martens, Harald.** Multivariate data modelling for de-shadowing of airborne hyperspectral imaging. Journal of Spectral Imaging 2017 ;Volum 6.(a2) s. -, NTNU
22. **Fossen, Thor I.; Lekkas, Anastasios M..** Direct and Indirect Adaptive Integral Line-of-Sight Path-Following Controllers for Marine Craft Exposed to Ocean Currents. International Journal of Adaptive Control and Signal Processing 2017 ;Volum 31.(4) s. 445-463, NTNU
23. **Fusini, Lorenzo; Fossen, Thor I.; Johansen, Tor Arne.** Nonlinear Observers for GNSS- and Camera-Aided Inertial Navigation of a Fixed-Wing UAV. IEEE Transactions on Control Systems Technology 2017 s. -, NTNU
24. **Geoffroy, Maxime; Cottier, Finlo Robert; Berge, Jørgen; Inall, Mark E..** AUV-based acoustic observations of the distribution and patchiness of pelagic scattering layers during midnight sun. ICES Journal of Marine Science 2017 ;Volum 74.(9) s. 2342-2353, UiT UNIS
25. **Ghane, Mahdi; Nejad, Amir Rasekhi; Blanke, Mogens; Gao, Zhen; Moan, Torgeir.** Diagnostic monitoring of drivetrain in a 5 MW spar-type floating wind turbine using Hilbert spectral analysis. Energy Procedia 2017 ;Volum 137. s. 204-213, NTNU
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27. **Guachamin Acero, Wilson Ivan; Gao, Zhen; Moan, Torgeir.** Methodology for assessment of the allowable sea states during installation of an offshore Wind turbine transition piece structure onto a monopile foundation. Journal of Offshore Mechanics and Arctic Engineering-Transactions of The Asme 2017 ;Volum 139.(6) s. -, NTNU
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31. **Hassani, Vahid; Sørensen, Asgeir Johan; Pascoal, A.M.; Athans, Michael.** Robust Dynamic Positioning of offshore vessels using mixed-**μ** synthesis modeling, design, and practice. Ocean Engineering 2017 ;Volum 129. s. 389-400, OCEAN NTNU
32. **Hassel, Martin; Utne, Ingrid Bouwer; Vinnem, Jan Erik.** Allision risk analysis of offshore petroleum installations

on the Norwegian Continental Shelf—an empirical study of vessel traffic patterns. WMU Journal of Maritime Affairs (JoMA) 2017 ;Volum 16.(2) s. 175-195, NTNU

33. **He, Zhao; Faltinsen, Odd Magnus; Fredheim, Arne; Kristiansen, Trygve.** The influence of fish on the mooring loads of a floating net cage. Journal of Fluids and Structures 2018 ;Volum 76, OCEAN NTNU
34. **Helgesen, Håkon Hagen; Leira, Frederik Stendahl; Fossen, Thor I.; Johansen, Tor Arne.** Tracking of Ocean Surface Objects from Unmanned Aerial Vehicles with a Pan/Tilt Unit using a Thermal Camera. Journal of Intelligent and Robotic Systems 2017 s. 1-19, NTNU
35. **Horn, Jan-Tore H.; Bitner-Gregersen, Elzbieta M.; Krokstad, Jørgen R; Leira, Bernt Johan; Amdahl, Jørgen.** A new combination of conditional environmental distributions. *Applied Ocean Research* 2018; Volume 73. s. 17-26, NTNU
36. **Horn, Jan-Tore H.; Krokstad, Jørgen R; Amdahl, Jørgen.** Long-Term Fatigue Damage Sensitivity to Wave Directionality in Extra Large Monopile Foundations. *Journal of Engineering for the Maritime Environment (Part M)* 2017, NTNU
37. **Ivanov, Ivan; Imsland, Lars Struen; Bogdanova, Boryana.** Iterative algorithms for computing the feedback Nash equilibrium point for positive systems. *International Journal of Systems Science* 2017 ;Volum 48.(4) s. 729-737, NTNU
38. **Jensen, Jørgen Juncher; choi, ju-hyuck; Nielsen, Ulrik Dam.** Statistical prediction of parametric roll using FORM. *Ocean Engineering* 2017 ;Volum 144. s. 235-242, NTNU, DTU
39. **Johansen, Tor Arne.** Toward Dependable Embedded Model Predictive Control. *IEEE Systems Journal* 2017 ;Volum 11.(2) s. 1208-1219, NTNU
40. **Johansen, Tor Arne; Fossen, Thor I..** The eXogenous Kalman Filter (XKF). *International Journal of Control* 2017 ;Volum 90.(2) s. 161-167, NTNU
41. **Johansen, Tor Arne; Hansen, Jakob Mahler; Fossen, Thor I..** Nonlinear Observer for Tightly Integrated Inertial Navigation Aided by Pseudo-Range Measurements. *Journal of Dynamic Systems Measurement, and Control* 2017 ;Volum 139.(1) s. -, NTNU
42. **Kauko, Hanna Maria; Taskjelle, Torbjørn; Assmy, Philipp; Pavlov, Alexey K.; Mundy, C.J.; Duarte, Pedro; Fernández-Méndez, Mar; Olsen, Lasse Mork; Hudson, Stephen R.; Johnsen, Geir; Elliott, Ashley; Wang, Feiyue; Granskog, Mats A..** Windows in Arctic sea ice: light transmission and ice algae in a refrozen lead. *Journal of Geophysical Research - Biogeosciences* 2017 ;Volum 122.(6) s. 1486-1505, NTNU UiB
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45. **Klausen, Kristian; Fossen, Thor I.; Johansen, Tor Arne.** Nonlinear Control with Swing Damping of a Multirotor UAV with Suspended Load. *Journal of Intelligent and Robotic Systems* 2017 ;Volum 88.(2-4) s. 379-394, NTNU
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47. **Kufoalor, D. Kwame Minde; Frison, Gianluca; Imsland, Lars Struen; Johansen, Tor Arne; Jørgensen, JB.** Block factorization of step response model predictive control problems. *Journal of Process Control* 2017 ;Volum 53. s. 1-14, NTNU
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49. **Luan, Chenyu; Gao, Zhen; Moan, Torgeir.** Development and verification of a time-domain approach for determining forces and moments in structural components of floaters with an application to floating wind turbines. *Marine Structures* 2017 ;Volum 51. s. 87-109, NTNU
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emphasis on underwater hyperspectral imaging. *Applied Optics* 2017 ;Volum 56.(36) s. 9957-9975, NTNU UNIS

56. **Nematbakhsh, Ali; Gao, Zhen; Moan, Torgeir.** Benchmarking of a computational fluid dynamics- based numerical wave tank for studying wave load effects on fixed and floating offshore structures. *Journal of Offshore Mechanics and Arctic Engineering-Transactions of The Asme* 2017 ;Volum 139.(3) s. -, NTNU
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64. **Nikoofard, Amirhossein; Johansen, Tor Arne; Kaasa, Glenn-Ole.** Reservoir characterization in Under-balanced Drilling using Low-Order Lumped Model. *Journal of Process Control* 2017 ;Volum 62. s. 24-36, NTNU
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Honours

Professor Kristin Y. Pettersen was appointed member of the Academy of the Royal Norwegian Society of Sciences and Letters (DKNVS).

Professor Kristin Y. Pettersen was appointed member of the IFAC Council (International Federation of Automatic Control).

Professor Torgeir Moan received the ASME (OOAE Division) Lifetime Achievement Award for significant life-time achievement contributions to Risk and Reliability Assessment of Marine Structures.

Symposium in Honor of Torgeir Moan in the 36th International Conference on Ocean, Offshore and Arctic Engineering (OMAE Conference June 2017)

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