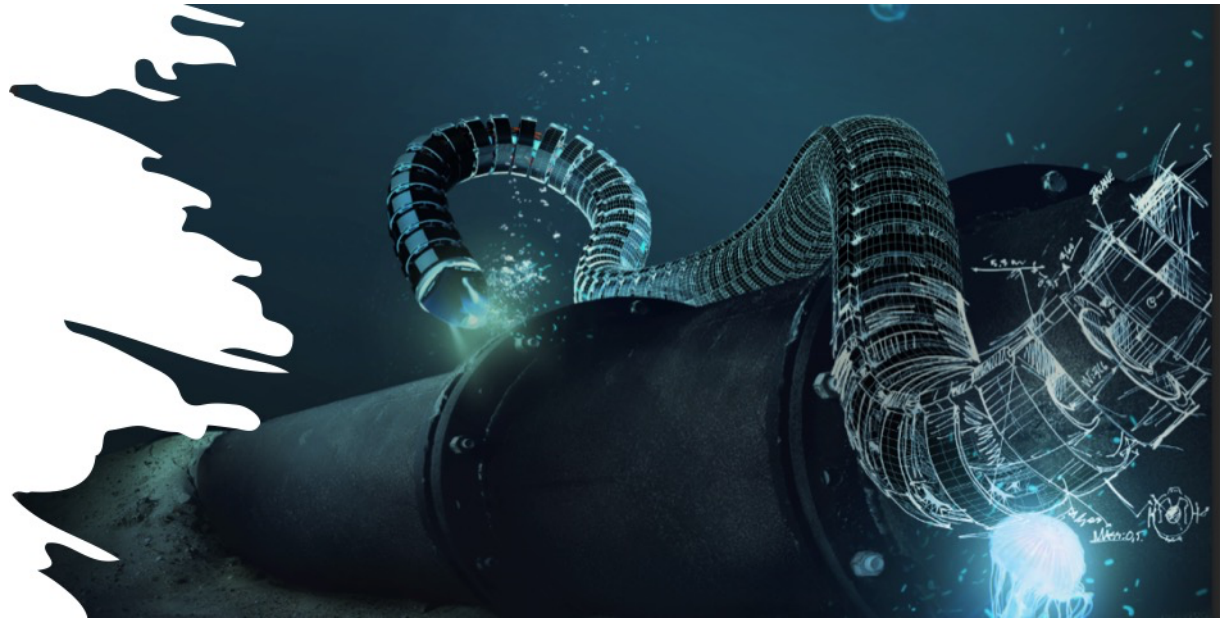
Annual Report 2023

NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS)



Det Norske Videnskaps-Akademi
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Director´s report

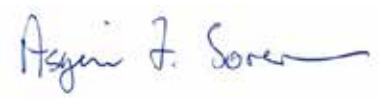
The NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS) is pursuing to become a world-leading research centre on autonomous underwater robotic operations with focus on resident and collaborating autonomous underwater vehicles (AUVs) that are supported by subsea docking systems for energy charging and communication. Together with ground-breaking research on articulated underwater robots and autonomy, we proceed towards a game changer in the offshore energy sector including offshore oil and gas and offshore renewable activities in terms of increased efficiency in marine operations and lower CO_2 footprint. The proposed scope will contribute to higher uptime of subsea production units and underwater assets, as well as higher marine environmental mapping and monitoring capabilities and shorter response time in case of incidents. The addressed research is also of high relevance for ocean science and marine industries such as maintenance and inspection of offshore wind installations and aquaculture structures. Security of ocean infrastructure is another area that has emerged the last couple of years. NTNU together with Equinor, Vår Energi and FFI are about to start up the project Safeguard financed by the Norwegian Research Council. The project is associated with VISTA CAROS and will investigate how critical infrastructures can be secured, how the production can be assured and ways to improve the risk management by developing intelligent autonomous systems.

All six PhD positions in CAROS are now occupied. In 2023 five MSc students have graduated on CAROS topics. Several research campaigns have been conducted in 2023 from Gunnerus, smaller boats and the quayside at Trondhjem Biological Station (TBS) and in the Arctic. Two bigger research campaigns have been carried out in collaboration with NTNU AMOS. In January and February 2023, we successfully completed seabed mapping and marine archeology campaign in Isfjorden at Svalbard in collaboration with the Governor using the ship Polarsyssel and the snake robot Eely, ROV 30k and Blueye ROVs. In May 2023 we completed a large integrated campaign in Trondheimsfjorden using RV Gunnerus, ROV 30k, Eely, Blueye, LAUV supported by the autonomous surface vehicle (ASV) Grethe.

I will also take the opportunity to acknowledge the valuable and inspiring meetings with personnel from Equinor and VISTA that are highly appreciated by the whole CAROS team.

Finally, I will thank all the colleagues, researchers, PhDs, postdocs and master's students, partners, and collaborators for their efforts in creating competence, knowledge, and innovations for a better world.

Sincerely,



Professor Asgeir J. Sørensen
Director NTNU VISTA CAROS

Vision and Objectives

The NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS) will:
Establish a world-leading research centre on autonomous underwater robotic operations with focus on resident and collaborating autonomous underwater vehicles (AUVs) that are supported by subsea docking systems for energy charging and communication.

Primary objectives are to:

- Create fundamental knowledge and competence through multidisciplinary research including marine technology and cybernetics.
- Provide cutting-edge interdisciplinary research to make autonomy and robot collaboration a reality for inspection and intervention AUVs.
- Leverage the capabilities of articulated intervention-AUV (AIAUV).
- Improve *future development solutions* and the international competitiveness of Norwegian oil and gas industries as well as to safety and protection of the marine environment.

The secondary objectives of CAROS are to:

- Graduate 6 PhDs and more than 20 MSc.
- Publish high-quality research results in top-ranked journals and international conferences. Outreach: Disseminate exciting research in media.
- Carry out a set of demonstrations in the national infrastructure AUR-Lab/Ocean lab.

Organization

Principal investigators (PIs)

- Professor Kristin Y. Pettersen. Core competence: cybernetics, nonlinear control, autonomy, articulated intervention robotics (snake robotics), marine robots incl. autonomous underwater vehicles (AUVs).
- Professor Martin Ludvigsen. Core competence: marine cybernetics, marine operations, remotely operated vehicles (ROVs), AUVs, underwater sensing.
- Professor Kjetil Skaugset. Core competence: marine structures, hydrodynamics, marine operations, control, autonomy, oil and gas operations.
- Professor Asgeir J. Sørensen. Core competence: marine cybernetics, hydrodynamics, marine operations, marine robotics incl. ROVs, AUVs, autonomy, testing and verification.

Administration

- Renate Karoliussen, NTNU, Economy, Adm. support
- Live Oftedahl, NTNU, Media and Outreach
- Marit Gjersvold, NTNU, HR
- Asgeir J. Sørensen, NTNU, Director
- Håkon Sandbakken, VISTA, Adm support, Board Secretary, Vista Day/Seminar

PhDs

1. Torje Steinsland Nysæther. WP1 Autonomous docking and intervention operations
   Project manager: Professor Kristin Y. Pettersen
2. Markus H. Iversflaten. WP2 Cooperative control for joint observation and intervention tasks
   Project manager: Professor Kristin Y. Pettersen
3. Gabriele Kasparaviciute. WP3 Mission planning
   Project manager: Professor Martin Ludvigsen
4. Ambjørn Waldum. WP4 Situation awareness
   Project manager: Professor Martin Ludvigsen
5. Awa Tendeng. WP5 Supervisory risk and organization control of marine robotics supporting subsea operation
   Project manager: Professor Kjetil Skaugset
6. Markus Fossdal. WP6 Formal and informal methods for robust design, testing and verification of autonomous control systems of subsea resident AUV
   Project manager: Professor Asgeir J. Sørensen

Associated PhDs, Postdoc and Researchers

1. PhD Bjørn Kåre Sæbø, ERC Advanced Grants.
   Project manager: Professor Kristin Y. Pettersen
2. Dr. Oscar Pizzaro, NTNU IMT/CAROS
3. Postdoc Dennis Langer, HYPSI – Small-satellites.
   Supervisor: Professor Asgeir J. Sørensen

Board of Directors

- Kenneth Ruud, FFI
- Professor Karin Andreassen, UiT The Arctic University of Norway
- Roger Sollie, Equinor
- Professor Olav Bolland, Dean Faculty of Engineering, NTNU
- Professor Sverre Steen, Head of Department of Marine Technology, NTNU
- Professor Ingrid B. Utne, Department of Marine Technology, NTNU

Scientific Advisory Board

- Professor Murat Arcak, University of California, Berkeley, US
- Professor João Sousa, University of Porto, Portugal
- Professor Gianluca Antonelli, University of Cassino and Southern Lazio, Italy
- Professor Hanumant Singh, Northeastern University, US

International Collaboration

NTNU VISTA CAROS has extensive international collaboration where the following partners are most prominent:

- Professor Murat Arcak, University of California, Berkeley, US.
- Professor Ricardo Sanfelice, University of California, Santa Cruz, US.
- Professor João Sousa, University of Porto, Portugal.
- Professor Gianluca Antonelli, University of Cassino and Southern Lazio, Italy.
- Professor Hanumant Singh, Northeastern University, US.
- Paul Brett and Kelley Santos, Marine Institute, Memorial University of Newfoundland, Canada.
- Dr. Knut I. Oxnevad, Jet Propulsion Laboratory (NASA), California Institute of Technology.
- Professor Kristi Morgansen, University of Washington, US.

From 2023, we would like to highlight the following international collaborative activities:

- UC Berkeley: Joint research with Professor Murat Arcak on formal and informal methods for robust design, testing and verification of autonomous control systems. Markus Fossdal is staying as exchange researcher in the period August 2023-April 2024. Asgeir J. Sørensen has been visiting professor in the period August - December 2023. He has also together with Fossdal visited UC Santa Cruz, MBARI, UC San Diego, Jet Propulsion Laboratory and UC Santa Barbara.
- University of Porto: Joint research with Professor João Sousa on development of framework for autonomous robotic organizations for marine operations. Sousa has been on research stays and meetings at NTNU in Trondheim.
- Joint research on task-priority operational space control of underwater vehicle-manipulator systems with Professor Gianluca Antonelli, University of Cassino and Southern Lazio, Italy.
- Bi-weekly joint PhD and researcher seminar between Northeastern University and NTNU organized by Professor Hanumant Singh and Professor Martin Ludvigsen.
- Development of joint research infrastructure and programs between NTNU and Marine Institute with support from Equinor. Simulators and remote-control functions are under development. Demonstration of remote control of Eely from Canada June 2023.
- Joint operation in Ny-Ålesund between NTNU VISTA CAROS and Northeastern University for robotic perception and change detection. The poster “High-resolution 3D mapping of sea-terminating glaciers using autonomous surface vehicle” was published at Northeast Robotics Colloquium in November 2023 presenting the results of the collaboration.
- Martin Ludvigsen has been visiting scientist at Jet Propulsion Laboratory (NASA) fall 2022 and spring 2023.
- University of Washington: Nick Andrews, former Boeing engineer and now PhD student in Kristi Morgansen´s group, has received a Fulbright scholarship to visit CAROS in 2024. The joint research will use fundamental concepts from control theory, robotics, and artificial intelligence to design algorithms that optimally orient the eel-like AIAUV to maximize its “observability”; a metric of the vehicle’s perception that quantifies how useful its sensors are in providing situational awareness information. Maximizing the vehicle’s perception will improve its robustness and efficiency in accomplishing tasks in variable ocean conditions.

Research Areas and Work Packages

The main outcome of NTNU VISTA CAROS is increasing the efficiency and quality of subsea inspections and light maintenance and repair (IMR) operations by advancing autonomous underwater vehicles (AUVs) being permanently docked on the seabed and collaborating in robotic organizations (robots helps robots). The project will develop suitable methods for robot collaboration, mission management, diagnostics, guidance, navigation, manipulation, and control. CAROS is organized in six work packages (WP) – Figure 1, where one PhD is assigned to each.

The following research questions are addressed:

- Q1. How to achieve high-accuracy autonomous docking and intervention operations of underwater manipulators such as ROVs and AIAUVs?
- Q2. How to perform coordinated control operations using heterogeneous teams of underwater robots, such as ROVs and AIAUVs operating together, first for cooperative observation and then for cooperative intervention tasks.
- Q3. How to adapt and improve autonomy in underwater vehicles working on various subsea installations through hybrid and deliberate mission planning and re-planning systems?
- Q4. How to obtain and maintain location and characteristics of scenery for operation?
- Q5. How to formulate and update the associated level of risk subject to mission complexity, environmental complexity, and human independence as input to the autonomy control system and robot organization for proper planning and re-planning as well as contingency handling?
- Q6. How can the operation, control and certification methods be formulated in the framework of formal methods using temporal logics and informal simulation-based test methods using digital twin that allows remote testing and verification of any software upgrades while the AUVs are docked subsea?

Based on these questions, six work packages (WPs) are defined:

1. WP1 Autonomous docking and intervention operations (Q1)
2. WP2 Coordinated control for joint observation and intervention tasks (Q2)
3. WP 3 Mission planning (Q3)
4. WP 4 Situation awareness (Q4)
5. WP5 Supervisory risk and organization control of marine robotics supporting subsea operation (Q5)
6. WP6 Formal and informal methods for robust design, testing and verification of autonomous control systems of subsea resident AUV (Q6)

Figure 1: Overview of work packages.

WP1 Autonomous docking and intervention operations (Q1)

PhD candidate: Torje Steinsland Nysæther**. Project manager:** Kristin Y. Pettersen
Contract period: August 2022 – August 2027 (Integrated MSc and PhD + duty year).

To achieve truly autonomous resident robots for inspection, monitoring and maintenance of subsea installations, the problems of autonomous docking and autonomous intervention need to be solved. A permanent docking station on the seafloor, where the vehicle can charge its batteries and transfer the data from a mission, will reduce the current need for frequent launch and recovery operations of ROVs and AUVs. To achieve fully autonomous operation of resident robots, autonomous docking is thus required. The lack of precise positioning systems such as GPS underwater, represents one of the most challenging aspects of a docking operation. This can be compensated for by using alternative positioning methods. Close to subsea templates, acoustic signals may be distorted, and thus vision-based methods are preferable. In this work package we will develop accurate and robust methods for vision-based autonomous docking.

Status

One of the main goals of my PhD is to investigate how the articulated structure of light vehicle-manipulator systems like the AIAUV can be exploited to increase performance in operations in proximity to underwater structures, for instance in the perception accuracy. To do this, a simulation environment with high fidelity in perception is needed, which I have worked on. Related to this, I have also investigated mapping of underwater structures performed by multilink underwater robots in a "Next-Best-View"-fashion to investigate how dynamic light placement can enhance the results. Apart from that, I have also spent some time investigating safe visual control in terms of Control Barrier Functions.

Completed courses

- TK8103 Advanced Nonlinear Systems (7.5 ECTS)
- IDT8002 Project development and management (2 ECTS)
- TK8109 Advanced Guidance, Navigation and Control (7.5 ECTS) (Pending evaluation)

Research activities

Research stay at North Eastern University in Boston, USA, under Prof. Hanumant Singh, for three weeks. Here, I worked mainly on visual perception and simulation of the snake robot. A conference paper, compiled and extended from my project thesis from the year before, was accepted and presented at the Oceans conference in Biloxi, USA, in September.

WP2 Coordinated control for joint observation and intervention tasks (Q2)

PhD candidate: Markus H. Iversflaten**. Project manager:** Kristin Y. Pettersen
Contract period: August 2021 - August 2026 (integrated MSc and PhD + duty year).

In this work package we will investigate cooperation between heterogeneous teams of underwater robots, e.g. consisting of ROVs and AIAUVs, operating together to perform subsea tasks. Cooperation between an ROV and an AIAUV can be advantageous for both inspection and intervention tasks and will provide capabilities that exceed those of any existing marine robots. Cooperative operations require tight synchronization between the motion of the ROV and the AIAUV, utilizing recent advances in cooperative control of nonlinear dynamical systems. Existing methods for cooperative control of robot manipulators mainly concern similar and fixed-base manipulators. In this work package, these methods will be extended to provide cooperative control between heterogeneous teams of underwater robots.

Status

Over this past year, I have been directing my attention to low-level control methods suitable for cooperating underwater vehicle-manipulator systems (UVMSs). I have continued my work with sliding mode control which proves to be viable for vehicles with unmodeled dynamics. Furthermore, I have started to investigate hybrid control theory for global attitude control and event-based control suitable for underwater communication schemes.

During the second part of the year, I have been preparing an experimental setup involving a BlueROV2 drone and the Eelume AIAUV. The goal of the experiments is to use high-precision navigation feedback such that the BlueROV2 can autonomously follow Eelume with a camera. This will increase the pilot's situational awareness and support their decision-making. In May, I completed my Master's thesis and later started as a full-time PhD candidate with CAROS.

Completed courses

- IDT8000 – Research Ethics
- IDT8001 – Basic University Didactics
- TK8109 - Advanced Guidance, Navigation and Control
- A week-long course on Hybrid Control Systems organized by the International Graduate School on Control

Research activities

1. Attendance of the 22nd World Congress of the International Federation of Automatic Control, Yokohama, Japan. I presented the research paper *Task-Priority Operational Space Control for Vehicle-Manipulator Systems with Modelling Errors,* which was equally co-first authored by Bjørn Kåre Sæbø.
2. Planning of research stay at NASA Jet Propulsion Laboratory March – May 2024. I will be visiting and working with the JPL research group 347N – Maritime and Multi-Agent Autonomy. The project title is "Autonomous Coordinated Behaviors for Maritime Robots" and will ideally result in deployment of algorithms and solutions on NTNU's robots.

Campaigns

1. I participated in the Isfjorden, Svalbard survey in February 2023. I was mainly responsible for configuration and piloting of the Eelume robot. The campaign was affected by bad weather and left only a small window for operation. We successfully gathered data of the shipwreck "Figaro" through the last night of the campaign. The campaign demonstrated the capabilities of the Eelume robot in extreme environments for the first time.
2. I was part of the first CAROS cruise in the Trondheim Fjord. My main contribution was the coordination of a remote piloting session of Eelume from Canada.

Duty work

I am working as a research assistant at the NTNU Applied Underwater Robotics Laboratory. In addition to the campaigns, I have been working with Eelume to maintain competency and develop knowledge about its systems and capabilities. The duty work helped me with the preparation of the BlueROV2/Eelume experiments.

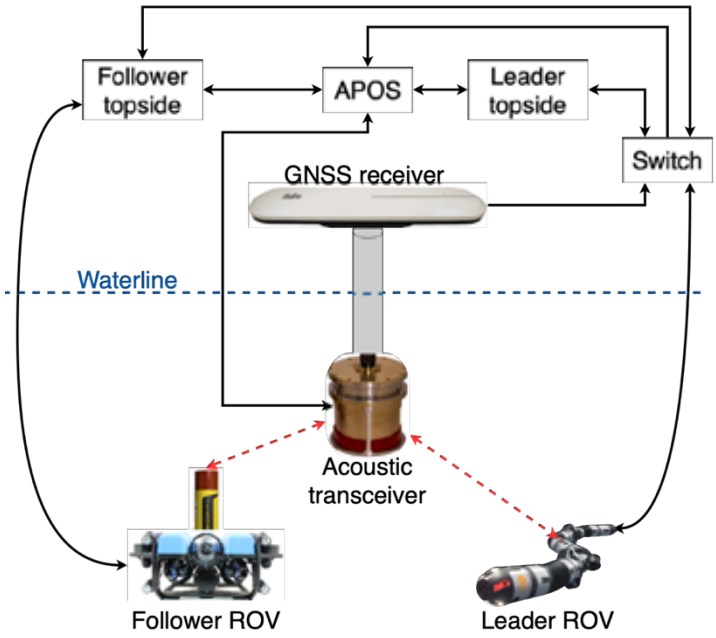


Figure 2: Upper: On Polarsyssel. Lower: Overview of the BlueROV2/Eelume system.

WP 3 Mission planning (Q3)
PhD candidate: Gabriele Kasparaviciute. **Project manager:** Martin Ludvigsen
Contract period: August 2021 - August 2025 (PhD + duty year).

Underwater vehicles engaged in inspection and maintenance tasks will undergo adaptive missions and on-board re-planning. During these missions, the operational conditions frequently undergo variations, including environmental factors such as sea state, current, and visibility. Moreover, the alteration of technical parameters pertaining to navigation, communication, energy, and diagnostics would inevitably impact the circumstances and prerequisites for accomplishing activities. To effectively organize the operation, it is necessary to incorporate both internal and external factors into the mission system which is the focus of the work.

Status

Course work

- Completed nearly double the required coursework credits in previous years, allowing 2023 to be free from course work.

Duty work

All duty work was done as part of the NTNU Applied Underwater Robotics Laboratory (AUR-Lab). The following were the candidate's main contributions:

- Experiments with Eelume**:** Conducted multiple experiments with the snake robot throughout 2023.
- Assistance in Bugwright Project in Lisbon, Portugal: In week 37, helped a colleague by piloting a Blueye for data collection and demonstration of successful trials.
- Illiad Project: Worked on an ocean observation project involving live data collection from sensors on a rig in Trondheimsfjord, with data dissemination through a website.

Research activities

- Acceptance for internship at NASA JPL: Accepted for a 3-month internship (yet to commence).
- CAROS activities in Trondheimfjord**:** Participated in weeklong campaign, gave an interview, and demonstrated work on path planners.
- OCEANS Conference in Limerick**,** Ireland**:** Presented paper "Genetic Algorithm-based AUV Mission Optimisation with Energy and Priority Constraints" which received significant interest.
- Development of a new Path Planner Focused on optimizing underwater pipeline inspection. Conducted trials and gathered data for an upcoming journal article entitled "Optimizing Underwater Pipeline Inspection with Energy-Efficient Path Planning for a Resident Autonomous Underwater Vehicle".

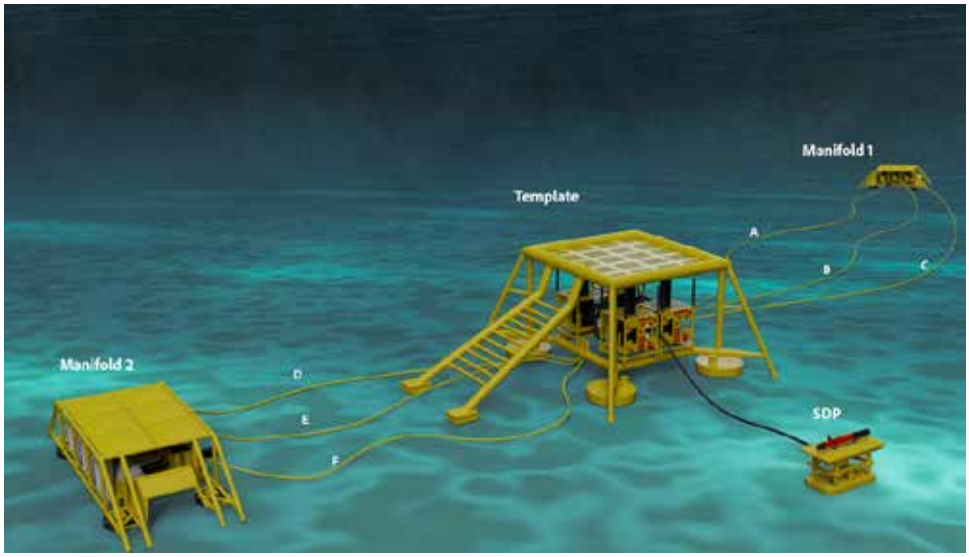


Figure 3: Sample Configuration of a Streamlined Oil Field Monitored by Resident Autonomous Underwater Vehicles (RAUVs) with a Focus on the SDP (Subsea Docking Plate) as the Central Recharge and Data Uploading Hub, as Featured in the Paper on Newly Developed Path Planning for RAUVs.

WP 4 Situation awareness (Q4)

PhD candidate: Ambjørn Grimsrud Waldum**. Project manager:** Martin Ludvigsen
Contract period: December 2021 - December 2024 (PhD).

Controlling and maneuvering an underwater vehicle would be a lot easier if a complete model of the environment were available. Unfortunately, accurate models of the subsea environment are rare. To enable higher levels of autonomy, situational awareness mechanisms need to be implemented. External factors like infrastructure for docking, other vehicles, objects like pipelines, valves, templates, and the surrounding terrain, need to be processed from measurements so a system can take informed decisions. To do this processing, optical and acoustical sensor data will need to be processed providing information on the current scenery and objects present and place them into a larger model of the environment created over time.

Status

The remaining required course work was finished this year:

- TK8155 - Advanced Visual Perception Systems
- MR8500 - PhD topics in marine control and hybrid power systems (Still doing some final edits in the final report but it will soon be done)

Main author of the conference paper: "*Sonar Object Detection from Synthetic Sonar Data Generated by a Sonar Simulator and an Adversarial Neural Network*".
Co-author of the conference paper: "*Visual close-range Navigation and Docking of Underwater Vehicles*"

Campaigns

1. Went to Svalbard for one week in February to assist in a campaign where the underwater archaeologists at NTNU wanted to look for and take images of two sunken ships using underwater vehicles.
2. As part of VISTA CAROS we had a campaign in the Trondheimsfjord one week in May. During this campaign we got to test the control and navigation systems we had been working on, and attempted to run some autonomous docking experiments where the vehicle started outside optical range having to rely on forward looking sonar in the beginning. Complex autonomous docking situations are something we will be looking more into in 2024.
3. In September I went on a four-week long campaign on the research vessel *Prinsesse Ingrid Alexandra* together with the Applied Underwater Robotics laboratory (AUR-lab) at NTNU as a ROV pilot. We were hired by Havforskningsinstituttet to assist them in picking corals close to fisheries both in the north of Norway around Steigen, and in the middle around Kristiansund and Molde. On this campaign I got a lot of experience flying large ROVs, giving me some thoughts about which extra tools could be nice to develop to aid a ROV pilot during operations.
4. In December I spent one day on Gunnerus testing a new stereo camera together with a new navigational set-up with the IMU and DVL of our navigation system being physically coupled together. During the day we recorded several datasets with the stereo camera of the pipelines we were able to find around Trondheim Biological Station. The goal is to use these datasets in the beginning of 2024 to start looking into pipeline segmentation and following.

Duty work

- Helped master students to use our Gazebo Garden Simulator and created a Blueye model for it.
- Continued work on AUR-labs large ROV. The first semester ROV31K, and then after the summer ROV111K. The work consists of fitting of sensors, creating control systems, updating software etc.
- The campaign with the research vessel *Prinsesse Ingrid Alexandra*.
- Worked on AUR-labs part of the Bugwright project. The goal of the Bugwright project is to combine drones, crawlers and AUVs to perform an inspection of a ship hull.

Research
The first two months consisted of conducting experiments and testing for the conference paper presented at OCEANS2023 - Limerick . The goal was to be able to generate synthetic sonar images that could be used for training convolutional neural networks to detect objects in the underwater scene, specifically shipwrecks in sidescan sonar and the infra structure the AUR-lab have in the Trondheimsfjord in forward looking sonar. The proposed pipeline that was developed can be seen below:

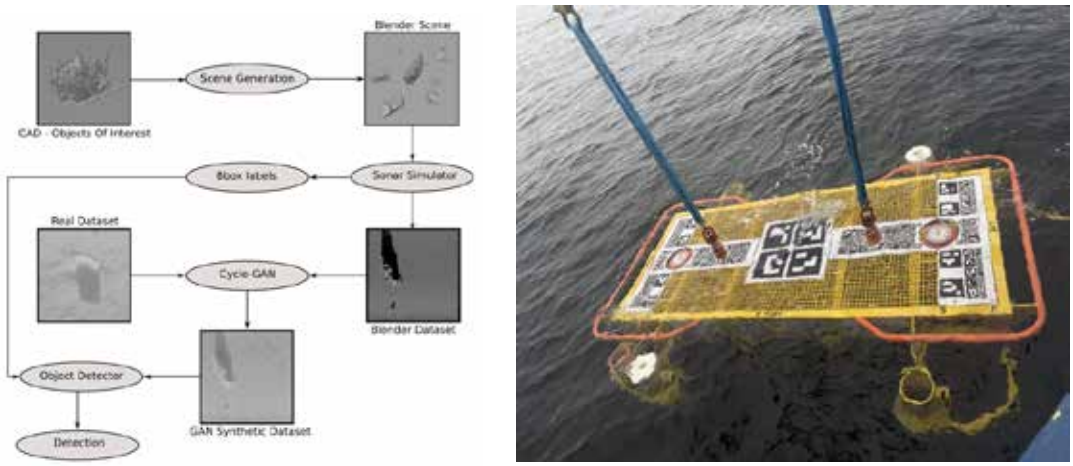


Figure 4: Left shows the presented synthetic sonar image generation pipeline, the right image shows the docking plate we were using with Aruco codes for experiments in May 2023.

The months before the summer vacation were used to prepare for the campaign in May. A lot of simulations were done on trying to first navigate using the sonar images, and then switch over to the Aruco codes on the underwater docking station when we were close enough for them to give a robust position estimate. The top of the docking plate with the Aruco codes can be seen above. In the autumn the focus has been on course work, duty work and the campaign in September.

WP5 Supervisory risk and organization control of marine robotics supporting subsea operation (Q5)
PhD candidate: Awa Tendeng**. Project manager: Kjetil Skaugset**
Contract period: March 2024 - December 2027 (PhD).

The different phases of an AUV mission - departure, docking, transit, station keeping/hoovering, and manipulation - will require different control objectives and control strategies coping with a set of operational, environmental, and internal constraints subject to varying elements of risks. Indeed, adding multiple underwater robots (eg. AUVs) as well as mission supporting robots (eg. USVs) on the sea surface and potentially in air (airborne drones) require heightened risk awareness and organization control. Eg. the logistics operation of bringing robotic assets (such as AUVs) to a desired location might call for cooperation between several heterogeneous robots acting in different elements. Organization of robots to coordinate and collaborate to reach a common mission objective will require new organization layers, optimization, control, and computational frameworks. Emerging risks are involved, related to lack of knowledge and operational experience with permanently submerged AUVs and robot organizations, the dependency on complex software-based control systems that may include dynamic learning algorithms, as well as a limited ability to verify the safe performance of such systems. Crucial for a safe operation is situational awareness for online risk control, where the robot organization should be designed to perform complex tasks under significant uncertainties in the system and when operating in an unstructured environment. The robot organization should be able to handle external events and internal faults including reconfiguration, planning and re-planning, and to learn, adapt and improve. An extra autonomy layer (supervisor) which enables the autonomous control system to online model, estimate and control risk will be developed. E.g., for robot cooperation, transit, safe navigation, energy

efficiency and anti-collision are the most important, while for tracking and station keeping, high precision positioning is of highest priority. Avoiding collision in a multi-body dynamic environment where interaction is required for successful mission completion will be of high priority.

WP6 Formal and informal methods for robust design, testing, and verification of autonomous control systems of subsea resident AUV (Q6)

PhD candidate: Markus Fossdal**. Project manager:** Asgeir J. Sørensen
Contract period: August 2021 - August 2025 (PhD + duty year).

AUVs for seabed and water column mapping have been a reality for a while. However, permanently submerged AUVs for inspection and manipulation work are new. Safety and efficiency for such operations require robust software designs that can be updated, tested, and verified without bringing the vehicles out of water. Formal methods**,** e.g. temporal logics and model checking, are used to design and verify properties of communication and control algorithms including finite-state logical behaviors. Even if the design methods may be sound, the implementation in terms of software code and the corresponding configurations may be wrong. Informal test and verification methods known as e.g. hardware-in-the loop (HIL) testing and software-in-the loop (SIL) testing. This WP addresses both formal and informal methods for robust design, testing, and verification of autonomous control systems of the AUV and robotic organizations from the design phase into operation phase that includes upgrades of software. Important aspect of the robotic organization is efficient and secure methods for communication and interoperability.

Status

The key highlights of 2023 are summarized below. At the bottom of this section, assorted pictures from the year are attached.

Duty work
The duty work consisted of work as part of NTNU Applied Underwater Robotics Laboratory (AUR-Lab). The main participations from the candidate were:

- Extensive preparations in front of the Svalbard cruise in Isfjorden. The preparations included several dives with Eelume from the quay at Trondheim Biologiske Stasjon (TBS) (Jan-Dec).
- Preparations onboard MS Polarsyssel. The vessel operated by the governor at Svalbard is a modified Offshore Supply Vessel (OSV), not intended for operating remotely operated vehicles (ROV). Hence, extensive planning on how AURLab's Work Class ROV and Eelume snake robot could be operated from the vessel were done prior to the equipment leaving Trondheim, but also onboard MS Polarsyssel on arrival in Longyearbyen. The preparations in Longyearbyen happened January 18- January 20. The cruise in Isfjorden was originally planned from Monday, Januray 23 until Friday, January 27. The cruise however was postponed, as MS Polarsyssel was ordered on a separate prioritized task by the governor in Svalbard, leading to a halt and cancellation of the planned Isfjorden cruise. February 6th until February 12th, the cruise was given a second attempt, this time successful. The highlight of the cruise was the long enduring dive with Eelume at the wreck Figaro, lasting almost nine hours.
- During March, April, and May of 2023 development and testing of software and hardware for a control system for AURLab's work class ROV was developed. The work was done in preparations for the CAROS cruise planned for May 2023. The work was done by the candidate, CAROS PhD candidate Ambjørn Waldum and Erlend Andreas Basso, PhD.

Academic work

The academic work of 2023 consisted of the following:

- CAROS Cruise in Trondheimsfjorden, Norway, where experimental testing of a docking sequence was done by Markus Fossdal, Ambjørn Waldum and Erlend Andreas Basso.
- Completion of the PhD-level course: MR8500 – PhD topics in marine control and hybrid power systems.
- Research stay at University of California Berkeley, Berkeley, USA. from August 2023 until February 2024.
- Visit to University of California, Santa Cruz, USA.
- Visit to Monterey Bay Aquarium Research Institute, Moss Landing, USA.
- Visit to NASA Jet Propulsion Laboratory, Los Angeles, USA.
- Visit to Scripps Institution of Oceanography, San Diego, USA.

(1): Onboarding MS Polarsyssel, Longyearbyen

(2): Hardware preparation, IMU for ROV.

(3): Visit to NASA Jet Propulsion Laboratory

(4) Visit to MBARI

Figure 5: Pictures from various field and laboratory work.

Affiliated: ERC Crème Motion planning and control of light-UVMS
PhD candidate: Bjørn Kåre Sæbø**. Project manager:** Kristin Y. Pettersen
Contract period: August 2021 – August 2026 (Integrated MSc and PhD + duty year).

The project considers control methods for lightweight underwater vehicle-manipulator systems (light-UVMSs) including both remotely operated vehicles (ROVs) with a lightweight base, and articulated intervention-AUVs (AIAUVs) which are lightweight and with no separate base. Light-UVMSs reveal a control challenge which has so far has been neglected: the motion of the base will be closely connected to the motion of the arm. When the arm moves, this will make the base move as well (and more obviously also the motion of the base will affect the motion of the arm). This coupling is not so clear for large work class ROVs where the motion of the heavy base can be assumed almost decoupled from the motion of the arm, even though experience shows that there are indeed significant couplings also here making the base move when the arm moves.

Status
Duty work
Working at the Autonomous Underwater Robotics lab (AUR-lab) at NTNU. In 2023 the Eelume 500 has gone through some repairs and upgrades from Eelume, and has been used both with a underwater hyperspectral imager (UHI) and a forward looking sonar to gather data for various projects. In preparation for mission Mjøsa, we made a solution for launching the Eelume vehicle from the AUR-labs work boat FLYER, a much smaller vessel than we're normally using. This included both a "GPS-anchor" to keep the boat in place and a Kongsberg μPAP accousting positioning system for positioning the vehicle under water.

Research activities
An article written by me and Markus H. Iversflaten titled "*Task-Priority Operational Space Control for Vehicle-Manipulator Systems with Modelling.*
was presented by Markus at the IFAC world congress in Yokohama, Japan.

Another article I co-authored with the researchers from the Robotic Systems Laboratories at the technical university of Vienna titled "*Hardware-in-the-Loop Simulation of Vehicle-Manipulator Systems for Physical Interaction Tasks"*, was presented at the international conference on intelligent robotic systems (IROS) in Detroit, USA during the fall.

Currently, I am continuing the collaboration with the RSL group, working on both hardware-in-the-loop simulation methods and whole-body control approaches. Additionally, working on path following algorithms for articulated vehicles such as the Eelume.

Completed courses
- TK8109 - Advanced Guidance, Navigation and Control
- IDT8000 - Research Ethics
- IDT8001 - Basic University Didactics

In addition, I attended a week-long seminar on hybrid control systems in Lucca, Italy arranged by the European embedded control institute and taught by prof. Sanfelice.

VISTA CAROS Campaign:
Training underwater robots to find charging stations — on the seabed

Cruise manager: Martin Ludvigsen

From May 2023. NTNU's largest laboratory – the Trondheim fjord – is something of an Eldorado for researchers developing underwater robots. A charging station has been installed on the seabed, and to ensure the robots can find the shortest route to the charging station, they train in the fjord.
Slightly edited version of article in Gemini by Idun Haugan, 2023

Seven years ago, Trondheim fjord was declared the world's first test site for autonomous vehicles. NTNU is highly active in the development of robotics that operate under water, on the surface of the water and in the air.

The researchers make frequent use of the large ocean laboratory. We joined the research vessel Gunnerus out on to the fjord to see how some of the underwater robotics work.

Out on the rolling sea

Gunnerus fills up with eager students, doctoral research fellows, researchers and partners from trade and industry. A robot measuring approximately 1 cubic metre and resembling an open crate filled with technology is loaded on board.

Figure 6: The research vessel Gunnerus is regularly used by Professor Martin Ludvigsen and the AMOS community to test and train new innovations. Photo: Live Oftedal, NTNU.

As we leave the quayside, the sun struggles to break through the rain showers that thrash across the deck. For now, we are able to seek shelter in the galley as the vessel chugs towards its destination: a charging station located on the seabed.

In 2022, the charging station was established not far from Munkholmen at a depth of 350 metres. This station is a joint venture between NTNU and Equinor. It has recently been moved a little closer to Trondheim Biological Station and is located close to another subsea installation belonging to Equinor.

The robots can connect themselves to these stations when they need to top up their batteries. This means it is important that the robots can find their way to the charging station – and as efficiently as possible.

Eelume the pioneer

The first underwater drone developed at NTNU is a snakelike robot called Eelume. It is based on technology developed by both NTNU and SINTEF. Eelume is strongly inspired by how snakes and sea eels move through water.

Professor Kristin Y. Pettersen is the brain behind the fully developed version of Eelume, which is now in production. Enormous amounts of mathematical calculations form the basis for adaptations and efficiency improvements.

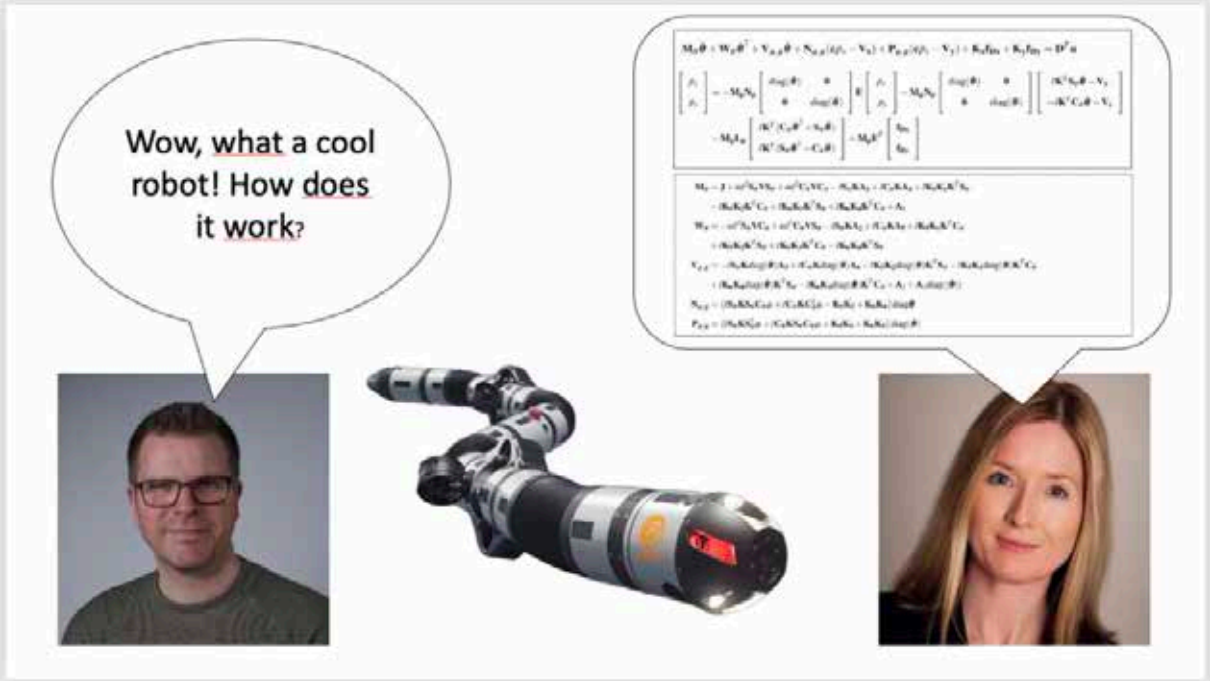


Figure 7: Marine archaeologist Øyvind Ødegård (left) made this illustration with Professor Kristin P. Ytterstad, the mind behind the snakelike robot, to show how many mathematical calculations are in a robot.

Oil leaks

The robot accompanying us out on the Trondheim fjord is the square crate filled with technology that we loaded on board before departure. Once Gunnerus has reached the correct position, the robot is slowly lowered into the sea.

Figure 8: The robot is lowered into the fjord. Photo: Ole Martin Wold.

The goal is for it to find the charging station as efficiently as possible.

A container standing on the deck is filled with powerful computers with large screens. Researchers, students and doctoral research fellows all pay close attention to the screens and monitor how the robot moves under water when searching on its own for the charging station.

One of them is doctoral research fellow Gabrielė Kasparavičiūtė from the Department of Marine Technology.

“A hypothetical scenario might be that there has been a leak at an installation, such as an oil platform. We would send down an autonomous underwater robot to examine the damage. The robot then has to check whether it has enough energy to reach the accident site, and it has to find the right algorithm to solve the task,” says Gabrielė Kasparavičiūtė.

This team of researchers is working to solve a variety of problems facing the underwater robots. The team includes several other doctoral research fellows from VISTA CAROS, NTNU AMOS and ERC Creme.

The robot’s journey towards the charging station takes time. Kasparavičiūtė has fed it algorithms that should give it a few extra challenges. The robot must figure these out and ends up getting a hard, but useful workout.

Independent and ‘intelligent’ robots

“What we are testing and demonstrating here is a planning algorithm that enables the robot to choose a route to an inspection point. The choice of route is based on how much activity or work it must

perform, and this is then linked to how much energy the robot has at its disposal," explains Martin Ludvigsen.

Figure 9: Through the computers set up inside the container on the deck, the researchers monitor the robot's journey underwater. Photo: Ole Martin Wold.

He is a professor at the Department of Marine Technology and one of the leading researchers in the field of underwater robotics.

A lot of work is being done in this research community to make the robots as autonomous as possible and able to make independent and smart choices.

It involves a robot choosing which tasks it has the capacity to complete based on how much power it has left, finding the shortest route to the places it will conduct inspections, and calculating how much power it requires to return to the charging station.

Figure 10: These researchers use powerful computers to follow the robots' progress in the ocean depths. From left :Markus Fossdal, Gabrielė Kasparavičiūtė, Ambjørn Waldum, Kay Arne Skarpnes and Erlend Basso. This team works with other PhD candidates in VISTA CAROS and ERC Creme, led by Kristin Y. Pettersen. Photo: Idun Haugan, NTNU.

VISTA CAROS and AMOS Campaign: Marine Archeology at Svalbard

Cruise manager Øyvind Ødegård, NTNU

Background

Estimates based on written sources indicates that there are more than 1000 shipwrecks in the waters between Greenland and the Svalbard archipelago representing a rich but untapped resource for gaining knowledge that may contribute to a fuller understanding of Svalbard's cultural history. So far only one underwater cultural heritage (UCH) site in Svalbard has been archaeologically investigated. In management strategies, historical shipwrecks in Svalbard waters have been highlighted as critical knowledge gaps, but effectively seen little attention mainly due to lack of capacity and specialized competency. Over the last 60 years, only a few attempts to locate and survey wrecks have been documented.

With the changing environmental situation in the Arctic, cultural heritage is under threat due to warmer temperatures, coastal erosion, and changes in the ecosystem. These threats may also be relevant for UCH, and the current lack of direct knowledge of the extent and state of UCH is a barrier for making knowledge-based management decisions to protect and preserve the values this heritage represents for our society.

During the last decade, NTNU has in collaboration with UiT – The Arctic University of Norway, University Centre in Svalbard (UNIS) and other partners built considerable competence in surveying for and investigations of UCH in Arctic areas. Through projects involving the Applied Underwater Robotics Laboratory (AUR-Lab), there have been consistent efforts within testing and development of technologies and methods for mapping and documentation of the seabed including benthic habitats, marine ecosystems, and historical shipwrecks. In addition to building operational experience and expertise, these projects also provide data of high value for archaeological research on Arctic UCH and not least for building a better knowledge base for management decisions.

The NTNU AMOS and VISTA CAROS research cruise was a continuation of these efforts, extending our competence and capabilities within application of underwater robotics and sensors in Arctic marine environments while also building a better knowledge base and increasing our understanding of UCH in Svalbard. This was the first campaign NTNU AUR-Lab has conducted on the Governor's vessel MS Polarsyssel (Fig. 11).

Figure 11: The Governor of Svalbard's vessel "Polarsyssel"

Areas of interest

Five wreck positions in Trygghamna and Grønfjorden (Fig.12) were selected for mapping and investigations with selected underwater robots and sensors. Due to bad weather conditions, only the sites "Figaro" and Isbjørn" could be visited.

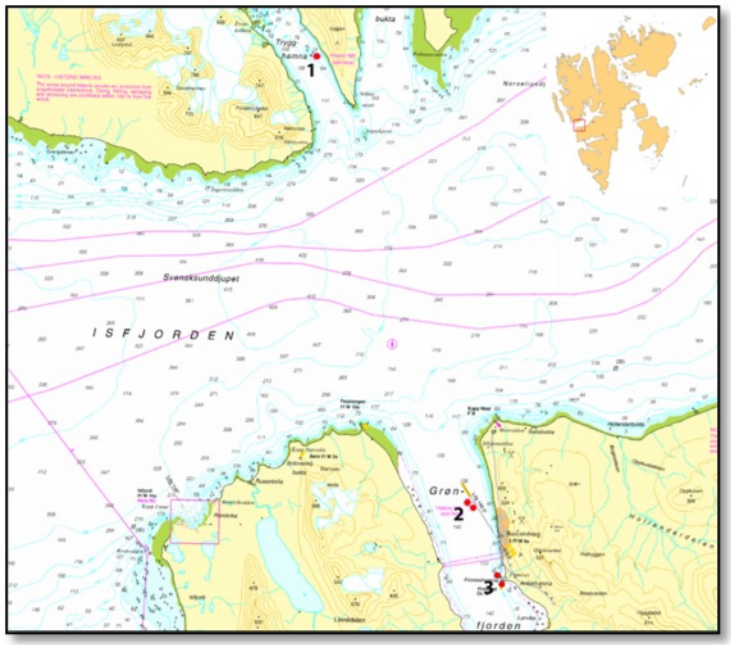


Figure 12 Sites and areas of interest. 1) Figaro, 2) Selis & Isbjørn, 3) Finneset 1 & 2.

Figaro

In September 2015, a team of researchers and students from NTNU and UNIS conducted initial investigations of a wreck discovered in Trygghamna by the Norwegian Hydrographic Service in 2007. The Trygghamna fjord is surrounded by mountain ridges and has been favored as a safe anchorage by whalers and seafarers through history, hence the name Trygghamna – *Safe haven* in Norwegian. The wreck rests at 30-40-m water depth on a shallow shelf-like area on the east side of the fjord. The seafloor is covered in fine-grained sediment, which is typical for fjords with glacial runoffs and moderate exposure to currents and rough sea states. Following the initial investigations with AUV Side Scan Sonar and mini-ROV, the wreck was identified as the *Figaro.* (Fig. 13). The *Figaro* was a floating whalery that burned and sank in 1908 containing an array of distinct and task-specific equipment, including steam boilers and cooking vats for processing of whale oil. Based on the data from the 2015 survey, a full ROV survey of the wreck conducted as part of a Polar Night Research Cruise with *RV Helmer Hanssen* (UiT) in January 2016. During the process of collecting stereo camera data for the wreck site photogrammetry on January 12th 2016, an underwater hyperspectral imaging (UHI) transect from the top of the *Figaro* wreck site was also acquired.

Figure 13 Figaro leaving Larvik harbor for Svalbard in 1904.

For planning operations on the Figaro we had the following data sets available: MBES data from 2007; four Side Scan Sonar datasets acquired with REMUS 100 in 2015; stereo camera images from 2016; UHI datasets from 2016, and ROV video from 2015, 2016 and 2019. A site plan sketch (Fig. 14) was made for planning and discussing areas and features of the site during operations.

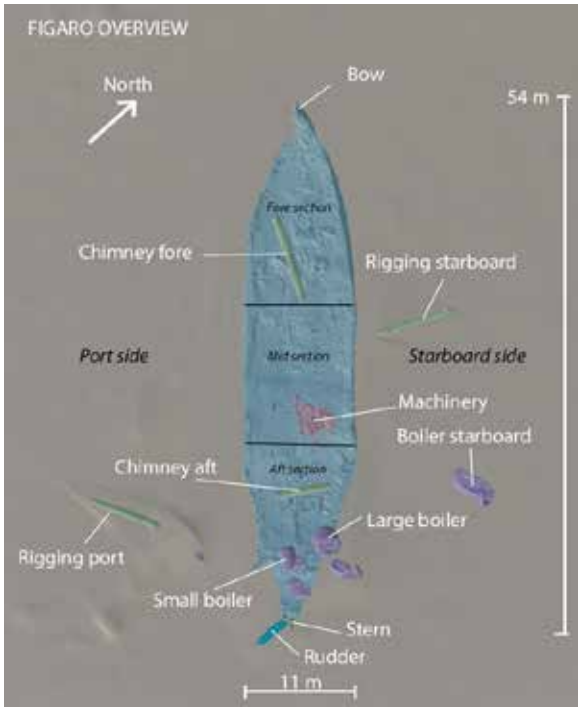


Figure 14 Schematic overview of wreck site with demarcated areas for planning, orientation and communication during operations.

Operations

The Eelume snake robot was configured with two joints, enabling different configurations and shapes during operations. Forward looking sonar in the nose section and a multibeam sonar in the mid-section

provided acoustic data for navigation and to create bathymetry model of the wreck site. A fixed camera in the nose section, a downward facing camera in the mid-section and a forward-facing camera in the aft section were used for navigation. Four GoPro cameras and external LED-lamps were positioned along the vehicles body with overlapping fields of view for photogrammetric mapping of the wreck (Fig.15).

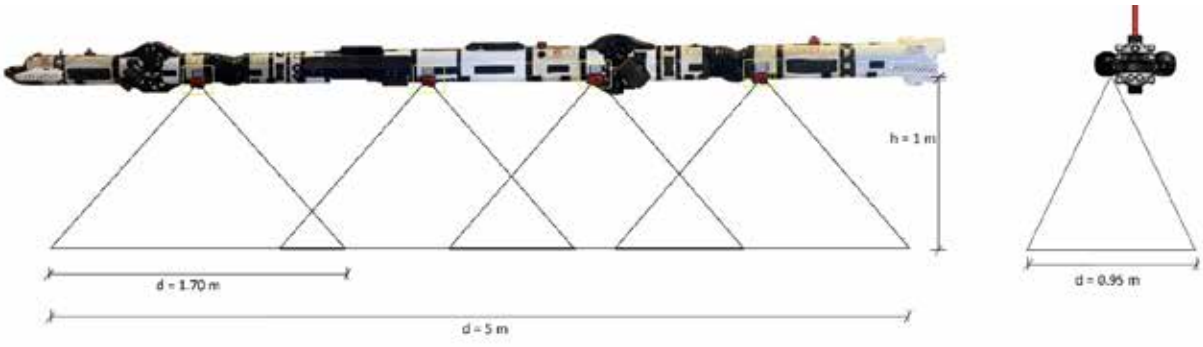


Figure15 Eelume vehicle with external Go Pro camera's FOV related to altitude.

Mission goal 1: Acquire full bathymetric model of wreck site. Gain experience with mission planning and execution for lawn mower pattern surveys (Fig. 16). Mission was executed successfully and according to plan. A comparison with bathymetry acquired in 2016 (Fig. 17) indicates significant movement of structures on the wreck, especially boilers in the aft section.

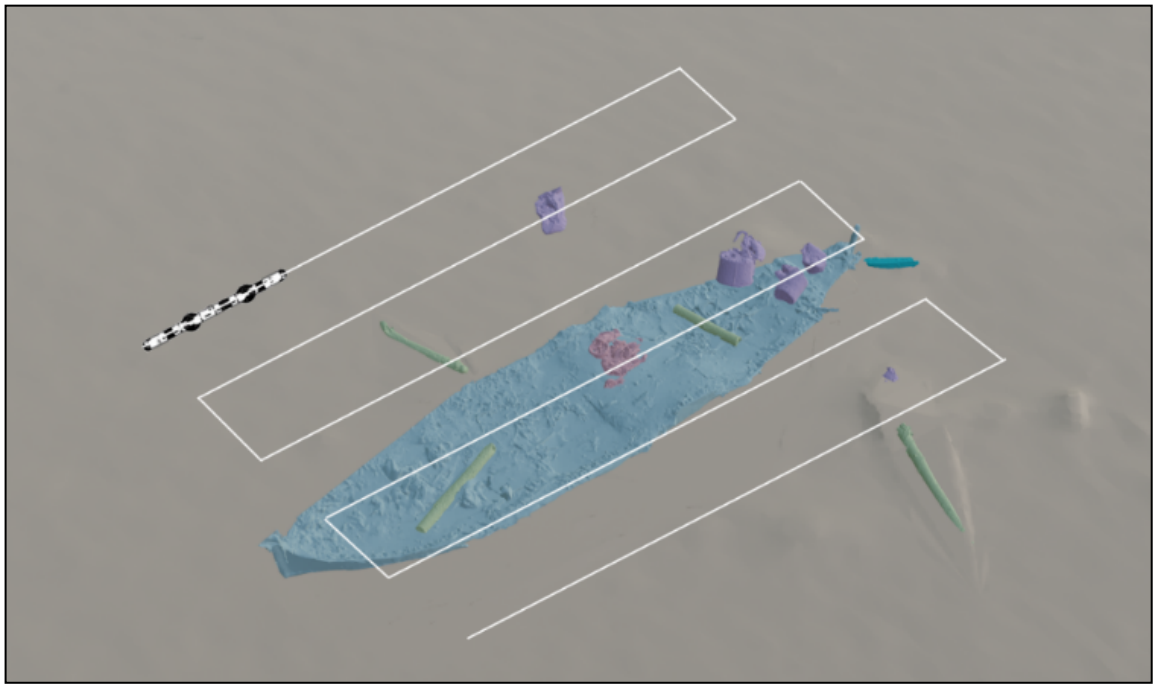


Figure 16 Mission lawn mower pattern – surge.

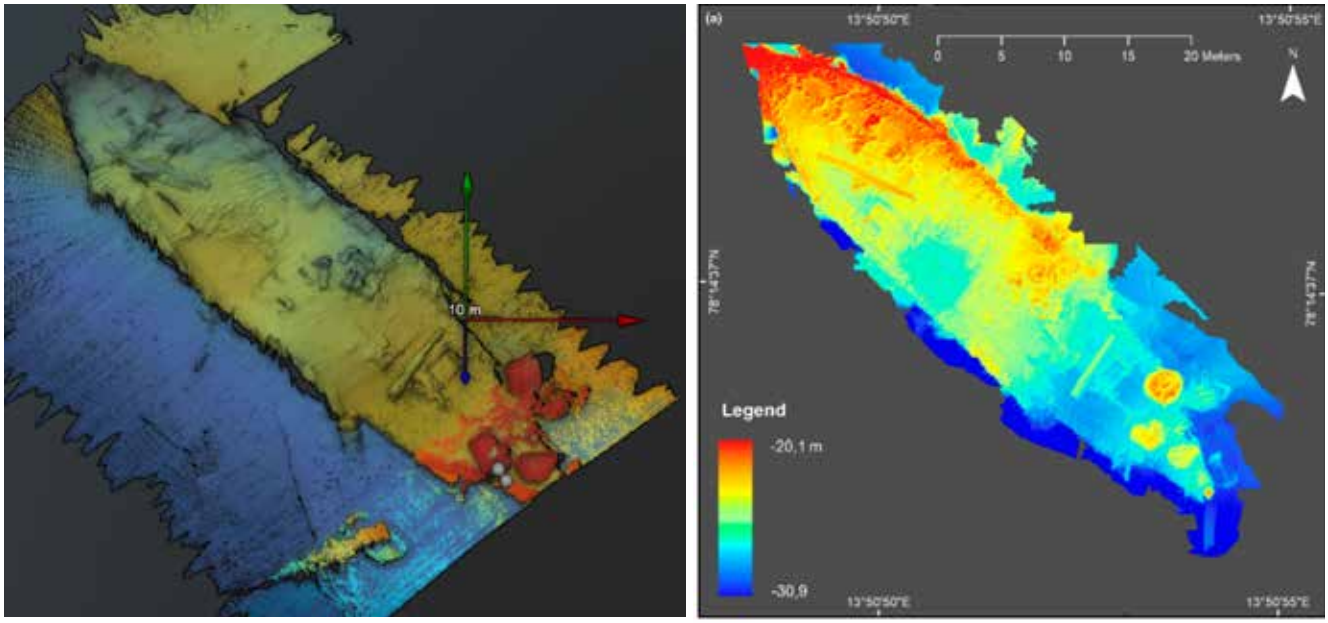


Figure 17 Left: Mission lawn mower pattern – surge. Right: Bathymetry model based on 2016 cruise data.

Mission goal 2: Acquire full photo mosaic of wreck interior. Gain experience with navigation of vehicle with limited visual input from FLS and front facing camera, using a priori knowledge of wreck site bathymetry. Gain experience with mission planning and execution for lawn mower pattern surveys navigating in sway (Fig. 18). Operations were executed successfully and according to plan. Due to limited time, the mission was rescheduled for coverage of a selected area of the wreck's interior in the forward section. GoPro images are shown in Fig. 19.

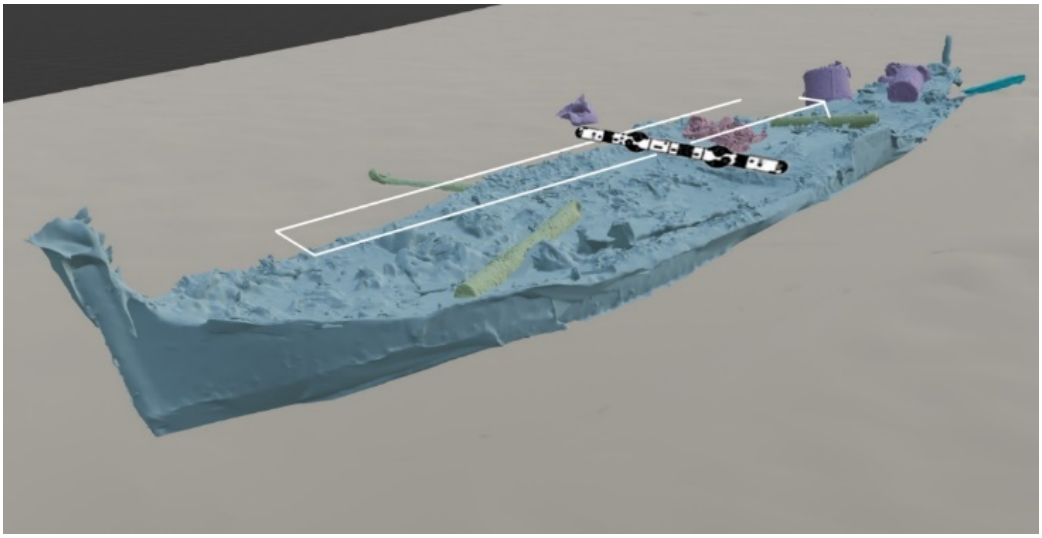


Figure 18 Lawn mower pattern – sway.

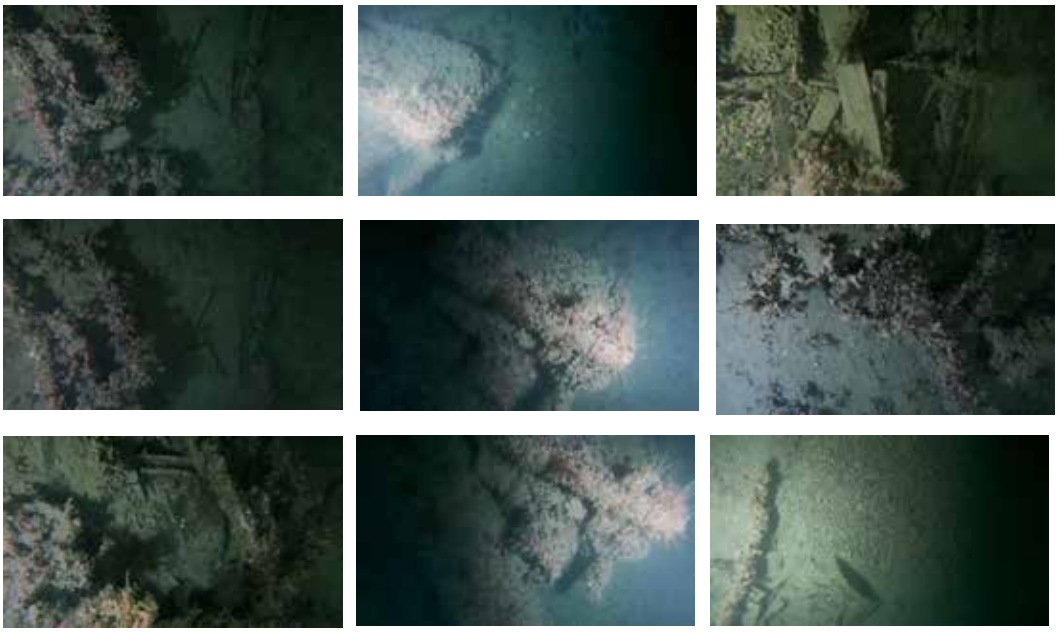


Figure 19: GoPro camera images.

Research Infrastructure

The research methodology is based on theoretical studies, numerical simulations, model testing and field studies. By extensive use of laboratories, we aim for high quality research and fast tracks from research results to tangible innovations.

The most important infrastructure for NTNU VISTA CAROS is the Applied Underwater Robotics Laboratory (AUR-Lab), RV Gunnerus and the new national infrastructure, the OceanLab.

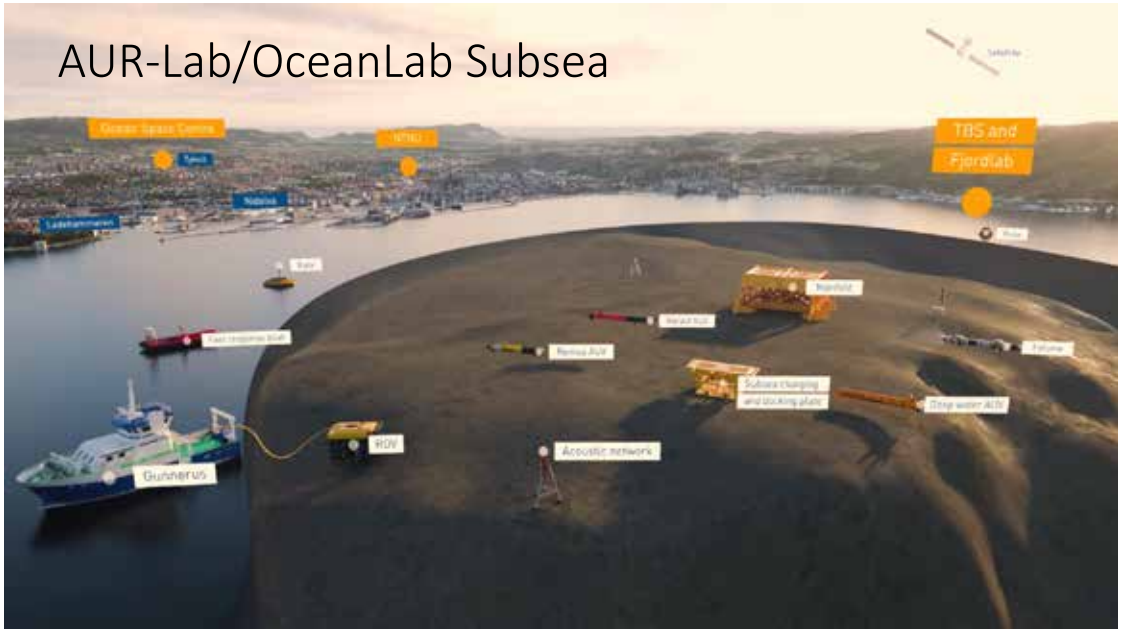


Figure 20: Overview of AUR-Lab/OceanLab in port of Trondheim.

In the port of Trondheim, we have access to permanently installed infrastructures such as subsea manifold, subsea docking station, and navigation sensors. In addition, we have in partnerships with NTNU, SINTEF, UiT, Equinor, and FFI access to mobile robots operating from outer space into the oceans. In 2022 we have upgraded the snake robot Eely to also operate in AUV mode.

The Oceanlab infrastructure (https://www.ntnu.edu/oceanlab) was completed in 2023 and is operated in close collaboration with AUR-Lab (https://www.ntnu.edu/aur-lab). These facilities are instrumental for the field work of CAROS and provides unique opportunities for the project. A control center has been established to facilitate coordinated robotic operations integrating data from buoys and fixed seabed infrastructure with the mobile vehicles in our operations. The Oceanlab subsea infrastructure includes two cabled installations. At 90 meters depth a Pig Loop Module (PLM) is installed as a mock-up to develop inspection and intervention tasks. The installation is equipment with online cameras acoustic modems and environmental sensors. Approximately 2.5 kilometers further out in the fjord, a Subsea Docking Plate (SDP) is placed at 365 meters depth to match the depth of the Norwegian Continental Shelf. Connected to the SDP, and instrument station holds a multibeam sonar, a camera, lights and environmental sensor to support docking experiments for underwater vehicles.
The Eelume Articulated Intervention Autonomous Underwater Vehicle (AIAUV) or snake robot is also part of the Oceanlab. This is a flexible vehicle with up to four two—axis joins and can maneuver in all six degrees of freedom. The vehicle can operate both tethered and autonomous and is equipped with a high-class navigation system, an acoustic modem, a forward looking multibeam sonar for obstacle avoidance and a profiling sonar for seabed mapping.
The work class ROV Minerva II is a powerful platform equipped with seven electrical thruster each fifteen kW. Two strong precise and agile hydraulic manipulator arms enable the vehicle to complete demanding intervention tasks, both to maintain the subsea infrastructure and to perform technical research experiments. For perception and situational awareness, both multibeam sonar and cameras

provides high quality data. NTNU has develop a control system for the ROV based on ROS2 to enable station keeping, path following and other autonomous functionality.

Figure 21: Subsea Docking Plate.

Figure 22: Automatic docking operations.

Key Economy Figures –2023

Revenue (Thousand NOK)

Cost:	
Personal cost:	5 366
Field trials:	1 160
Other cost	521
SUM:	**8 548**
Income:	
VISTA:	5 366
NTNU:	3 182
SUM:	**8 548**

Dissemination and Outreach 2023

Master Theses

1. Abdelrahman Sayed Sayed Emam Ibrahim (AJS). Risk Aware Control of Underwater Snake Robots in Confined Environments
2. Christoffer Hajum (AJS). Collision Free Trajectory Optimization of Autonomous Ferry Using Ship Domain Analysis
3. Sondre Mikalsen-Schwenke (AJS). Methods for visualizing spatial and temporal space in marine environments using AR and VR
4. Harald Minde Hansen (KYP). Collision Avoidance for two Autonomous USVs in Formation with Maneuvering Limitations.
5. Nina Valberg Nyegaarden (KYP). Multi-Task Attention-Based Convolutional Neural Network for SAS Change Detection with Self-Supervised Pre-Training.
6. Espen Aune Sande (KYP). Investigating Monocular Depth Estimation for UAV Navigation and Localization.
7. Erling Syversveen Lie (KYP). Formation Path Following of Autonomous Underwater Vehicles using the Second-Order Null-Space- Based Behavioral Algorithm.

Publications at Conferences

1. E.S. Lie, J. Matouš and K.Y. Pettersen, «Formation Control of Underactuated AUVs Using the Hand Position Concept", *Proc. 62nd IEEE Conference on Decision and Control,* Marina Bay Sands, Singapore, Dec. 13-15, 2023.
2. H. Das, B.K. Sæbø, K.Y. Pettersen and C. Ott, "Hardware-in-the-Loop Simulation of Vehicle Manipulator Systems for Physical Interaction Tasks", *Proc. 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems,* Detroit, USA, Oct. 1-5, 2023.
3. T. Nysæther, K.Y. Pettersen and J.T. Gravdahl, "Hierarchical compliance-control-based docking of an UVMS", *Proc. OCEANS,* Mississippi Gulf Coast, Sep. 25-28, 2023.
4. I. Gushkov, A. Orucevic, K.Y. Pettersen, W. Yao and J.T. Gravdahl, "Vector Field Path Following of Static Sinusoidal Paths for Underwater Snake Robots", *Proc. 7th IEEE Conference on Control Technology and Applications*, Bridgetown, Barbados, Aug. 16-18, 2023.
5. A. Haraldsen, M.S. Wiig and K.Y. Pettersen, "Dynamic Obstacle Avoidance for Nonholonomic Vehicles using Collision Cones: Theory and Experiments", *Proc. 7th IEEE Conference on Control Technology and Applications*, Bridgetown, Barbados, Aug. 16-18, 2023.
6. G. D'Antuono, K.Y. Pettersen, L.R. Buonocore, J.T. Gravdahl, M. Di Castro, "Dynamic model of a tendon-actuated snake robot using the Newton-Euler formulation", *Proc. 22nd IFAC World Congress*, Yokohama, Japan, July 9 – 14, 2023.
7. M.E.B.Lysø, E.I. Grøtli and K.Y. Pettersen, "Torque-Minimizing Control Allocation for Overactuated Quadrupedal Locomotion", *Proc. 22nd IFAC World Congress*, Yokohama, Japan, July 9 – 14, 2023.
8. M.H. Iversflaten, B.K. Sæbø, E.A. Basso, K.Y. Pettersen and J.T. Gravdahl, "Task-Priority Operational Space Control for Vehicle-Manipulator Systems with Modelling Errors", *Proc. 22nd IFAC World Congress*, Yokohama, Japan, July 9 – 14, 2023.
9. J.I. Dyrhaug, E. Tveter, H.M. Schmidt-Didlaukies, E.A. Basso, K.Y. Pettersen and J.T. Gravdahl, "Robust Hierarchical Tracking Control of Vehicle-Manipulator Systems", *Proc. 22nd IFAC World Congress*, Yokohama, Japan, July 9 – 14, 2023.
10. J. Matouš, K.Y. Pettersen, D. Varagnolo and C. Paliotta, "Singularity-free Formation Path Following of Underactuated AUVs", *Proc. 22nd IFAC World Congress*, Yokohama, Japan, July 9 – 14, 2023.
11. A. Orucevic, M.E.B.Lysø, H.M. Schmidt-Didlaukies, K.Y. Pettersen and J. T. Gravdahl, "Optimal Positioning of Snake Robots in Vortex Wakes using Extremeum-Seeking Control", *Proc. 22nd IFAC World Congress*, Yokohama, Japan, July 9 – 14, 2023.

12. E.A. Basso, H.M. Schmidt-Didlaukies A. J. Sørensen and K.Y. Pettersen, "Synergistic PID and Output Feedback Control on Matrix Lie Groups", *Proc. 12th IFAC Symposium on Nonlinear Control Systems,* Canberra, Australia, Jan. 4-6, 2023. **IFAC NOLCOS 2022+ Young Author Award.**
13. Langer, D., T. A. Johansen and A. J. Sørensen (2023). Consistent Along Track Sharpness in a Push-Broom Imaging System. *IGARSS 2023 - 2023 IEEE International Geoscience and Remote Sensing Symposium*, Pasadena, CA, USA, 2023, pp. 4486-4489
14. Chan, W.Y., M. Ludvigsen, and E. Kelasidi. Predicting underwater vehicle manipulator system dynamics using time-series methods. *in OCEANS 2023 - MTS/IEEE U.S. Gulf Coast. 2023*.
15. A Cardaillac, H.B. Amundsen, E Kelasidi, M Ludvigsen. Application of Maneuvering Based Control for Autonomous Inspection of Aquaculture Net Pens. *in 2023 8th Asia-Pacific Conference on Intelligent Robot Systems (ACIRS).* 2023.
16. Rannnestad, T.L., A. Waldum, and M. Ludvigsen. Visual close-range Navigation and Docking of Underwater Vehicles. *in OCEANS 2023 - Limerick. 2023.*
17. Kasparavičiūtė, G. and M. Ludvigsen. Genetic Algorithm-based AUV Mission Optimisation With Energy and Priority Constraints*. in OCEANS 2023 - Limerick. 2023*.
18. Waldum, A.G., O. Pizarro, and M. Ludvigsen. Sonar Object Detection from Synthetic Sonar Data Generated by a Sonar Simulator and an Adversarial Neural Network. *in OCEANS 2023 - Limerick. 2023.*
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Plenary Lectures

1. Pettersen, Kristin Ytterstad.
   Snake robots and the power of nonlinear control, Plenary lecture at the 12th IFAC Symposium on Nonlinear Control Systems, Canberra, Australia, 4-6 January 2023.

Journal Publications

1. Nielsen, U.D., H. B. Bingham, A. H. Brodtkorb, T. Iseki, J. J. Jensen, M. Mittendorf, R. E. G. Mounet, Y. Shao, G. Storhaug, A. J. Sørensen and T. Takami (2023). Estimating waves via measured ship responses. Scientific Reports 13, 17342 (2023). ISSN 2045-2322
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3. Shakeri, N., W. Chen, M. Zadeh, A. Abdelhakim, A. J. Sørensen and K. Tai (2023). Modeling and Stability Analysis of Fuel Cell-Based Marine Hybrid Power Systems. In IEEE Transactions on Transportation Electrification, ISSN: 2332-7782
4. Løvås, H. S., M. K. Larsen, O. Pizarro, and A. J. Sørensen (2023). Semi-analytical model for deep-water hyperspectral imaging. Applied Optics, Vol. 62, pp.. 8832-8848. ISSN:2155-3165
5. Langer, D. D., M. Orlandić, S. Bakken, R. Birkeland, J. J. Garrett, T. A. Johansen, A. J. Sørensen (2023). Robust and Reconfigurable On-Board Processing for a Hyperspectral Imaging Small Satellite. Remote Sensing 15(15), 3756, pp 1-23, ISSN: 2072-4292
6. Torben, T. R., Ø. Smogeli, J. A. Glomsrud, I. B. Utne, A. J. Sørensen (2023). Towards contract-based verification for autonomous vessels. Ocean Engineering. Volume 270, 15 February 2023, 113685. Online ISSN: 1873-5258.
7. Løvås, H. S., O. Hasler, D. D. Langer, A. J. Sørensen (2023). Coregistration of Hyperspectral Imagery with Photogrammetry for Shallow-Water Mapping. IEEE Transactions on Geoscience and Remote Sensing. 29 March 2023.

8. Johansen, T., S. Blindheim, I. B. Utne, T. A. Johansen, A. J. Sørensen (2023). Development and testing of a risk-based control system for autonomous ships. Reliability Engineering & System Safety, Volume 234, June 2023, 109195, ISSN: 0951-8320
9. Bakken, Sivert. Marie B Henriksen, Roger Birkeland, Dennis D Langer, Adriënne E Oudijk, Simen Berg, Yeshi Pursley, Joseph L Garrett, Fredrik Gran-Jansen, Evelyn Honoré-Livermore, Mariusz E Grøtte, Bjørn A Kristiansen, Milica Orlandic, Paul Gader, Asgeir J Sørensen, Fred Sigernes, Geir Johnsen, Tor A Johansen (2023). HYPSO-1 CubeSat: First Images and In-Orbit Characterization. Remote Sensing. 2023, 15(3), 755; EISSN 2072-4292
10. A. Orucevic, M. Wrzos-Kaminska, J.T. Gravdahl and K.Y. Pettersen, "Uniform Practical Asymptotic Stability for Position Control of Underwater Snake Robots", *IEEE Transactions on Control Systems Technology,* 2023.
11. E.A. Basso, H.M. Schmidt-Didlaukies and K.Y. Pettersen, "Global Asymptotic Position and Heading Tracking for Multirotors using Tuning Function-based Adaptive Hybrid Feedback", *IEEE Control Systems Letters,* Vol. 7, 2023, pp. 295 – 300.
12. I.-L. Borlaug, K.Y. Pettersen and J.T. Gravdahl, "The generalized super-twisting algorithm with adaptive gains", *International Journal of Robust and Nonlinear Control,* Vol. 32, No. 13, 2022, pp. 7240 - 7270.
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14. M Leonardi, A Stahl, EF Brekke, M Ludvigsen, "*UVS: underwater visual SLAM—a robust monocular visual SLAM system for lifelong underwater operations.*" Autonomous Robots, 2023. 47(8): pp.1367-1385.
15. Cardaillac, A. and M. Ludvigsen, "*Camera-Sonar Combination for Improved Underwater Localization and Mapping.*" IEEE Access, 2023. 11: p. 123070-123079.
16. Vasilijevic, A., J.E. Bremnes, and M. Ludvigsen, "*Remote Operation of Marine Robotic Systems and Next-Generation Multi-Purpose Control Rooms.*" Journal of Marine Science and Engineering, 2023. 11(10): p. 1942.
17. Sture, Ø. and M. Ludvigsen, "Feature-based Bathymetric Matching of Autonomous Underwater Vehicle Transects using Robust Gaussian Processes." *Field Robotics*, 2023. 3: p. 544–559. 48(2): pp. 462-473.

International Guest Lectures

1. Pettersen, K.Y. (2023). From snake robotics research to a new class of marine robots, R.T. Chien Distinguished Lecture, University of Illinois, March 23, 2023.
2. Sørensen, A. J. (2023). Towards robotic organizations and the observation pyramid for mapping and monitoring of the oceans. 17 November. UC Santa Cruz, US
3. Sørensen, A. J. (2023). Step-up in spatial and temporal coverage in ocean mapping and monitoring by multi-agent systems – The observation pyramid. 27 October. UC Santa Barbara, US
4. Sørensen, A. J. (2023). Risk Perception and Supervisory-Switched Control of Marine Robotics. 9 October. UC Berkeley, US
5. Sørensen, A.J., M. Ludvigsen, E.S. Sivertsen (2023). The Observation Pyramid: Enabling a Quantum Leap in Mapping and Monitoring Capabilities of the Oceans. Johns Hopkins University Applied Physics Laboratory, 22 March, Maryland, US