Annual Report 2024

NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS)

Det Norske Videnskaps-Akademi
The Norwegian Academy of Science and Letters

NTNU
Norwegian University of Science and Technology

Director´s report

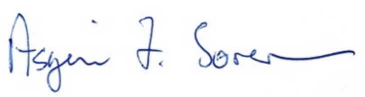
The NTNU VISTA Centre for Autonomous Robotic Operations Subsea (CAROS) is pursuing to become a world-leading research center on autonomous underwater robotic operations with a focus on resident and collaborating autonomous underwater vehicles (AUVs) that are supported by subsea docking systems for energy 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 highly relevant for ocean science, fisheries, and marine industries, such as the characterization and harvesting of zooplankton and the maintenance and inspection of offshore wind installations and aquaculture structures. Security of ocean infrastructure is another area that has emerged in the last couple of years. NTNU, Equinor, Vår Energi, and FFI, have started the project Safeguard, financed by the Norwegian Research Council. Safeguard is associated with VISTA CAROS and investigates how critical offshore infrastructures can be secured by developing intelligent autonomous systems.

In 2024 six PhDs are funded by VISTA CAROS, and 11 MSc students have graduated on CAROS topics. Several research campaigns have been conducted in 2024 from RV Gunnerus, smaller boats, and the quayside at Trondhjem Biological Station (TBS). In June 2024, we completed a large integrated campaign in Trondheimsfjorden using the RV Gunnerus, ROV Minerva, Eely, Blueye, and LAUV, supported by the autonomous surface vehicle (ASV) Grethe. In parallel, a team of NTNU and UC Berkeley researchers demonstrated new methods on symbolic control autonomous docking in the MC-Laboratory at NTNU. Another research campaign was carried out in October in collaboration with the NTNU program Mission Mjøsa using the snake robot Eely equipped with a multibeam echosounder and underwater hyperspectral imager (UHI) for classification and mapping of dumped munitions. This campaign resulted in broad media coverage in the national media.

I will also take the opportunity to acknowledge the valuable and inspiring meetings with the members of the Scientific Advisory Board (SAB) in June, personnel from Equinor and VISTA, who are highly appreciated by the whole VISTA CAROS team.

Finally, I will thank all my 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. Gabrielė Kasparavičiūtė. 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. Dr. Pizzaro was offered one of the Equinor funded professorships at NTNU in 2024.
3. Postdoc Dennis Langer, HYPSO I and II satellites and HYPSI project.
   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.
- Directeur de Recherche Elena Panteley, CNRS, L2S, CentraleSupélec, France.

From 2024, 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. In May and June three researchers from UC Berkeley visited NTNU on joint work related to Symbolic Control for Autonomous Docking of Marine Surface Vessels. Successful testing in the NTNU MC-Lab demonstrated the method.
- University of Porto: Joint research with Professor João Sousa on development of framework for autonomous robotic organizations for marine operations. A view paper authored by Skaugset, Sousa and Sørensen has been accepted for publication in Science Robotics, March 2025 issue.
- CNRS France: Joint research with Directeur de Recherche Elena Panteley on orbital control for swimming in underwater snake robots using Energy-Shaping and Consensus Control. The results were published at the IEEE Conference on Decision and Control in December 2024 and are now being extended into a journal paper.
- Markus H. Iversflaten and Gabrielė Kasparavičiūtė had a research visit at the Jet Propulsion Laboratory (NASA) in 2024.
- NATO/University of Porto: In September 2024, Professor Kjetil Skaugset attended the NATO exercise REPMUS24 (Robotic Experimentation and Prototyping with Maritime Unmanned System) in Portugal. The event is co-organized by the University of Porto and CAROS collaborator Professor João Sousa. This exercise brings together NATO commands, academia, research institutions, and industry to test the ability of autonomous systems to operate together and to increase alliance understanding of new threats in the maritime environment.
- Dr. Pushyami Kaveti, Northeastern University, visited NTNU fall-summer 2024, joining research activities on underwater computer vision with Ludvigsen and Pizarro as mentors.
- Professor Kjetil Skaugset gave the keynote “Autonomous Robotic Organizations” at the Air Power Conference 2024, themed “How artificial intelligence, autonomy and space will affect planning, command, and conduct of military operations”, February 7-8, 2024, arranged by the Royal Norwegian Air Force, Trondheim, Norway.

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) – Fig.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.

Selected Research Highlights

Here follows some selected highlights from research carried out in 2024.

From Virtual Waters to Real Oceans: A Simulation-Driven Approach to ROV Control System Design

Ambjørn Waldum, Markus Fossdal, Erlend Andreas Basso, Martin Ludvigsen

Motivation

Field testing of underwater robotic systems is expensive, and it is therefore essential to get the most out of the time spent in the field. In this paper we present the approach we are using in the applied underwater robotics laboratory at NTNU to maximize our field trials, by identifying and resolving software errors through a software-in-the-loop approach prior to field tests. We also show how this process has been utilized by our researchers and students to take their experiments from simulation to the ocean.

Main Result

The goals were to design an approach where researchers and students could easily and properly test and run their experiment software in a simulated environment before attempting to run it in the field. To achieve this, we split our codebase into three distinct parts: code for simulation, code for interfacing with hardware, and code for running the control system. The simulation code consists of all the packages necessary to launch a vehicle simulation in Gazebo Harmonic, which takes care of physics simulation, 3D rendering, actuators and most of the necessary robotics sensors. In addition, we have some packages that simulate some underwater sensors, such as the DVL and FLS that are not available in Gazebo.
The hardware code consists of sensor parsers, actuator drivers and parsing of any fault messages coming from the real vehicle. These packages are designed in such a way that their input/output format corresponds to the format used by the simulated packages, which allows a package that can communicate with the simulator to also communicate with the real hardware seamlessly.

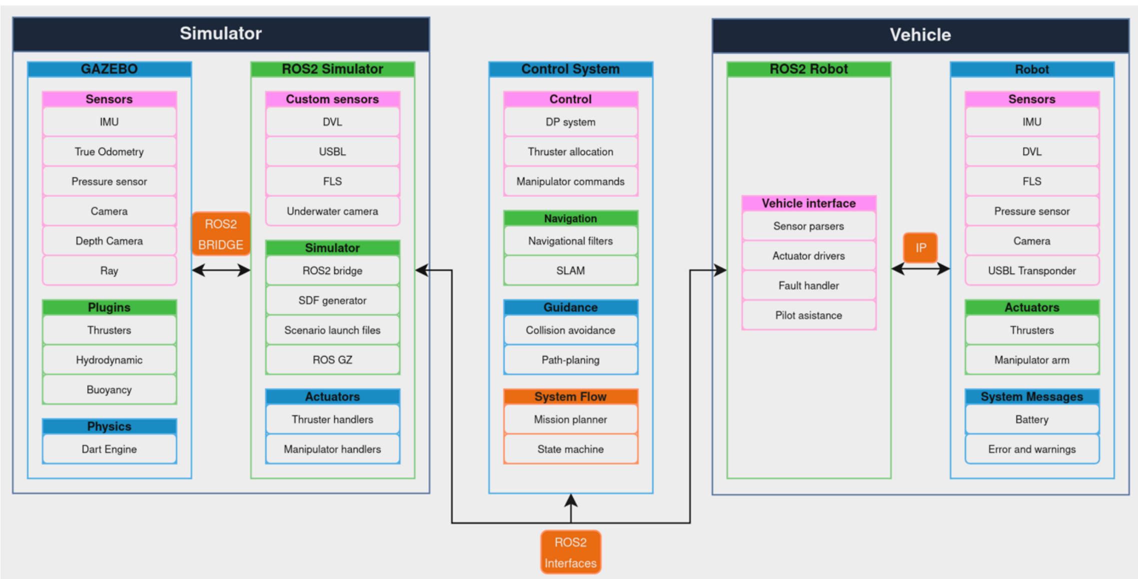


Figure 2: A diagram showcasing how the software is structured into three distinct blocks, ROS 2 Simulator, Control System, ROS 2 Robot, and modules that falls within each block. The software communicates with Gazebo through the ros_gz package and communicates with the real vehicle through IP communication.

Lastly, we have the control system packages, which include the navigation system, controllers, guidance blocks, state-machines etc. Since the simulator and hardware packages are designed in such a way that they use the same input/output, the full control system can be tested with the simulator and then run on the real vehicle without having to change anything in the code. As long as two vehicles are similar enough (For example, the same navigational sensor types or actuated degrees of freedom), many, if not all the blocks in the control system module can be reused.

This design philosophy allows us to have a robust modular control system design, in which a researcher or student can use a backbone for their experiment. Since the entire system is very modular, they can replace the specific parts of the control system, which is essential for their experiment, without having to worry about the remainder of the system.

As an example, one of our students was looking into how to autonomously dock a Blueye vehicle to a docking plate. He remade a 3D model of our docking station and added it to the Gazebo simulation together. He was then able to experiment with different ArUco code setups, both in terms of placement and sizes in order to find a good setup for the real-world placements. He was also able to plan and test different guidance approaches by replacing the standard navigational filter with his own where he utilized ArUco code detection to find the vehicle's pose. Then he took the code developed in the simulated environment and showcased that it worked in real-world conditions. See the images below.

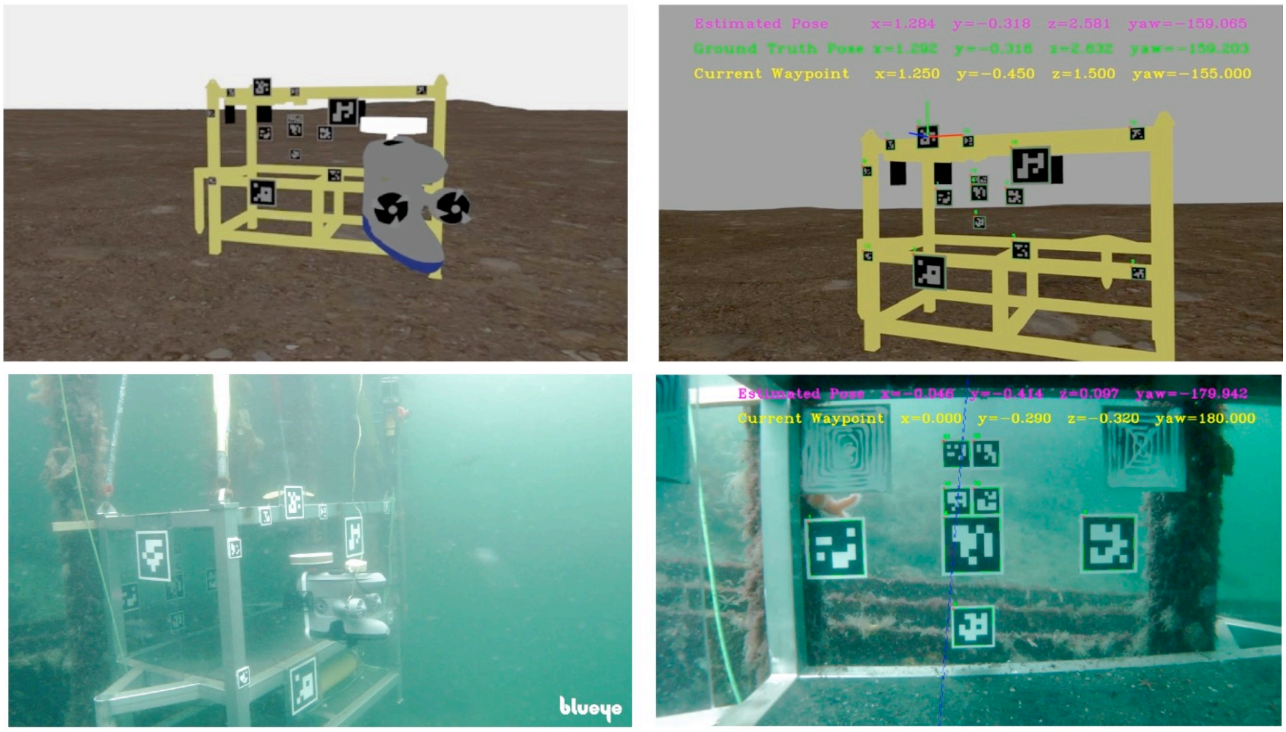


Figure 3: Blueye performing docking maneuver, both in simulation and real conditions.

Paper reference

Published 2025 IEEE Underwater Technology (UT), 2-5 March 2025, Tapai, Taiwan
https://ieeexplore.ieee.org/document/10947400/

Kinematic task-priority path following for articulated marine vehicles

Bjørn Kåre Sæbø, Kristin Ytterstad Pettersen, Jan Tommy Gravdahl

Motivation

Snake-like articulated vehicles have become increasingly common in recent years, both in aerial and marine applications. One of the main benefits of the articulated design is the increased maneuverability, allowing movement in cluttered environments where traditional vessels may not ft. However, research on the topic of path following for these types of vessels is fairly limited, not utilizing the flexibility of the articulated system to its full extent.

Main Results

In this work, a method for path following was developed where each link of the articulated system is kept on the path at all times. The general idea is to use an existing line-of-sight guidance method and combine it with a kinematic task-priority controller to control the joints of the system. The use of a task-priority controller allows controlling the links towards the path without interfering with the main path-following guidance approach.

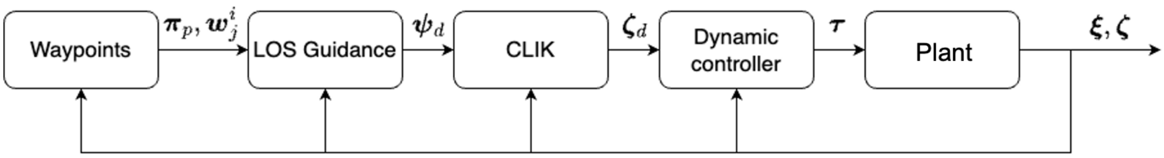


Figure 4: Block diagram of the proposed control framework.

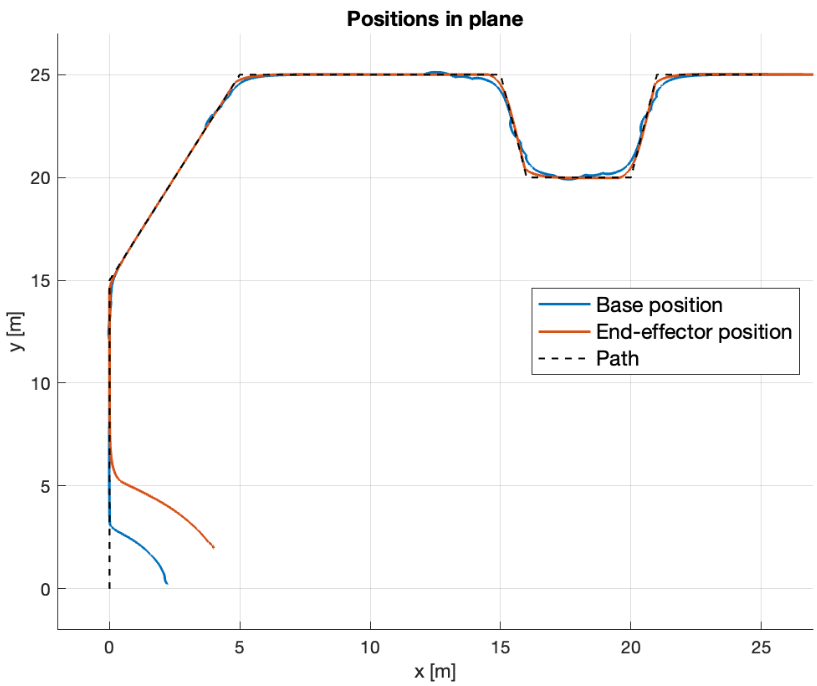


Figure 5: Path following performance of the two end-links of the system with the proposed path-following control framework.

The stability of the control law is proven theoretically, and the zero cross-track error origin of the closed-loop system dynamics is shown to be exponentially stable, implying good convergence properties and robustness to disturbances. Further, the method is validated in simulation, where it is shown that using the proposed method, the links follow the path much closer than by keeping the joints straight.

Paper reference

Sæbø, B. K., Pettersen, K. Y., & Gravdahl, J. T. (2024). Kinematic task-priority path following for articulated marine vehicles. *IFAC-PapersOnLine*, *58*(20), 65-72.

Unifying the Generalized Jacobian Matrix and prioritized task hierarchies, with application to free-floating VMSs

Marianna Wrzos-Kaminska, Bjørn Kåre Sæbø, Kristin Ytterstad Pettersen, Jan Tommy Gravdahl

Motivation

Free-floating vehicle manipulator systems (VMSs), such as those in space or underwater, experience a coupling effect between the motion of the manipulator arm and the vehicle base, since the motion of the joints induces a motion of the base relative to the system's center of gravity (CG). This effect, while also present in heavier work-class ROVs where the base is much heavier than the manipulator, is much more prevalent in lightweight VMS such as the Eelume AIAUV.

For heavier system, one can choose to ignore this effect and compensate for disturbances on the base using traditional control approaches. For lightweight UVMS however, this can lead to poor performance and require unnecessary energy usage. It is therefore desirable to investigate controllers that inherently compensate for this coupling effect.

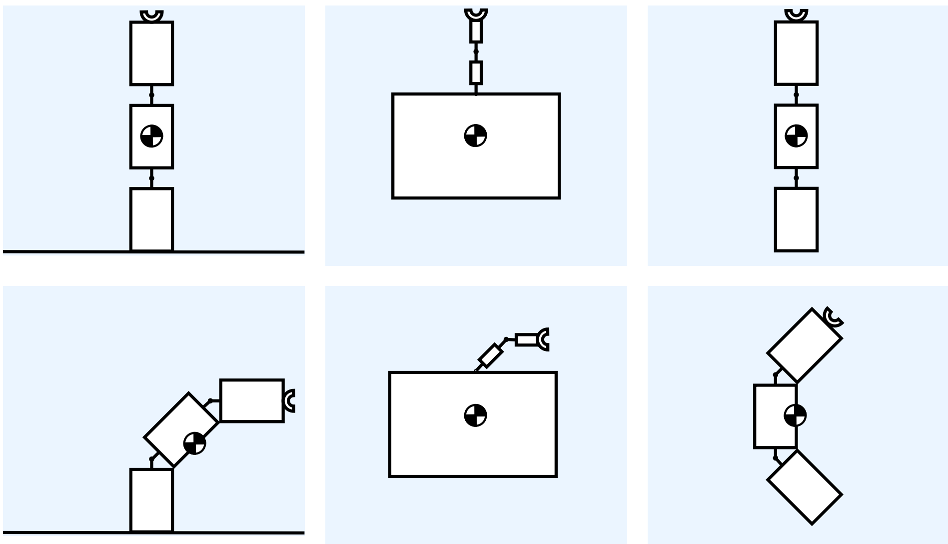


Figure 6: Movement of the system center of mass for the same joint motion. For (a) fixed-base system, (b) heavy floating base, (c) lightweight floating base

Main Results

In this work a control framework was proposed that takes this coupling effect into account, selecting the motion of the CG as the highest priority task in a dynamically consistent task hierarchy. This reduces the need for counteracting disturbances while controlling the position of the manipulator workspace. In this way, joint motions are calculated that lets the end-effector follow a desired trajectory without moving the systems center of gravity.

The proposed approach generalizes previous works using the Generalized Jacobian matrix to allow the completion of several prioritized tracking tasks. Control allocation is performed in a manner ensuring that the thrusters are used only for controlling the overall position of the VMS, while the joints are used for tasks requiring higher accuracy.
The set in which all tracking error dynamics are zero is shown to be uniformly asymptotically stable, and the performance of the proposed control method is validated in a simulation study. The results of the simulation study are shown in the figure below, showing good tracking performance for all the tasks, even when the controller design is based on a much simpler model than used in the simulation.

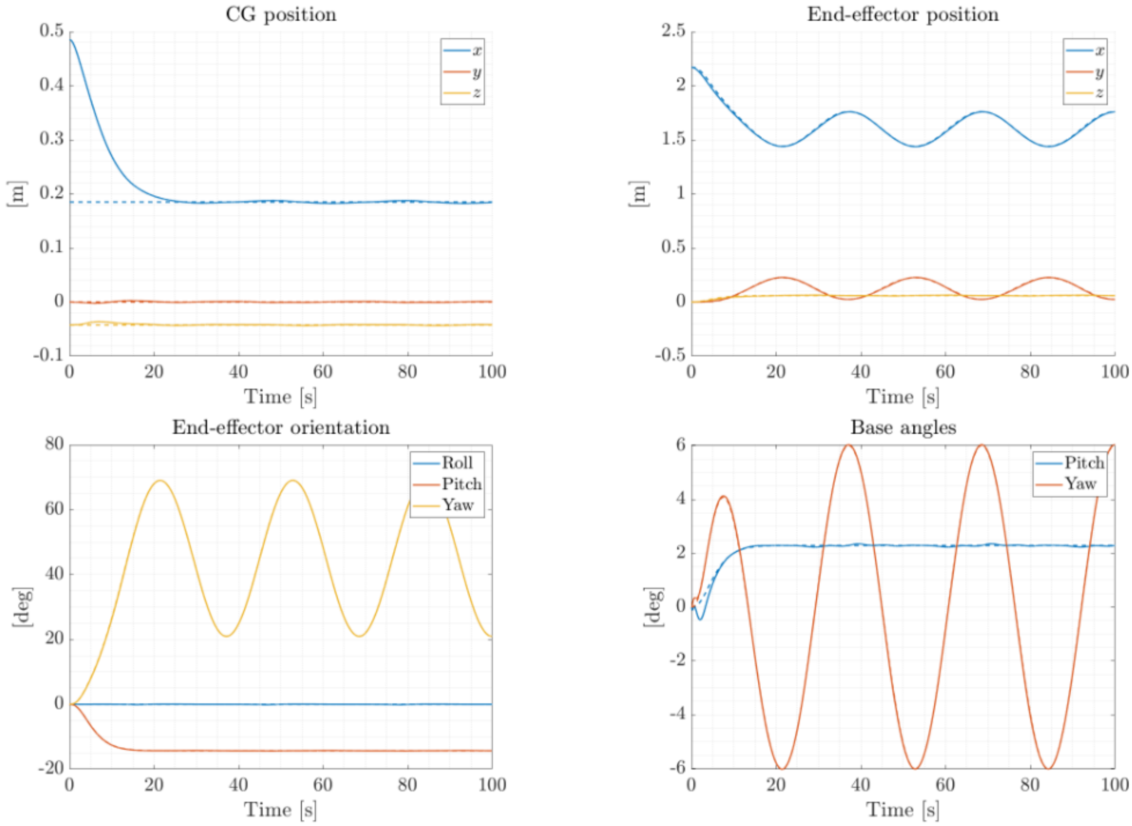


Figure 7: Positions and orientation of center of gravity, end-effector, and base (The tasks considered in the simulation study).

Paper reference

Wrzos-Kaminska, M., Sæbø, B. K., Pettersen, K. Y., & Gravdahl, J. T. (2024). Unifying the Generalized Jacobian Matrix and prioritized task hierarchies, with application to free-floating VMSs. *IFAC-PapersOnLine*, *58*(20), 79-86.

Energy-efficient route planning for optimizing underwater pipeline inspections using Resident Autonomous Underwater Vehicles

Gabrielė Kasparavičiūtė, Kjetil Fagerholt, Martin Ludvigsen

Motivation

The motivation behind this research is to optimize the inspection of subsea pipelines using Resident Autonomous Underwater Vehicles (RAUVs). Given the critical nature of maintaining subsea infrastructure, traditional methods (using remotely operated vehicles dependent on support vessels) are limited by weather conditions, operational costs, and environmental impact. RAUVs, capable of autonomous long-term operations, provide an effective alternative but face challenges due to limited battery capacity. Therefore, efficient and adaptive route planning methods are essential to ensure mission success and sustainability. Field trials conducted in Trondheimsfjord (Norway) using the LAUV Fridtjof as an RAUV validated simulation results. The real-world tests highlighted the algorithm's practical applicability, robustness under actual oceanic conditions, and compatibility with standard LAUV hardware. Simulation and experimental outcomes matched closely, confirming the reliability of simulated results and demonstrating that the RAUV could operate autonomously and effectively in complex underwater environments.

Main Results

1. Inspection Network Setup

The RAUV operates in a subsea infrastructure network designed to resemble realistic conditions encountered in offshore oil and gas fields. The network consists of essential subsea elements, including pipelines, two templates (Template 1 and Template 2), a central manifold, and a Subsea Docking Plate (SDP), as clearly depicted in Fig. 8.

In this network, each template (Template 1 and Template 2) is connected to the central manifold via three distinct pipelines labeled A, B, and C (Template 1) and D, E, and F (Template 2) (see Fig. 8). The lengths of these pipelines significantly vary, closely mimicking actual operational scenarios where pipeline segments often differ considerably in length. This variability introduces complexity into mission planning, as energy consumption during inspections is directly proportional to pipeline length, requiring meticulous route optimization to ensure efficiency and safety.

The RAUV starts each mission from the SDP, a strategically placed docking station critical for battery recharging and data transfer, enabling sustained underwater operations. During inspection missions, the RAUV traverses through multiple pipelines, returning periodically to the SDP to recharge. Effective mission planning must account for both the travel distance along inspection segments and the additional distances involved in returning to the docking station for recharging. Thus, the primary challenge addressed by the routing algorithm is maintaining efficient route coverage across these uneven pipeline lengths while consistently managing the RAUV's limited battery resources.

This network setup forms the fundamental context for evaluating the performance of both the static and dynamic routing algorithms described subsequently, highlighting the importance of energy-efficient route planning under realistic operational constraints.

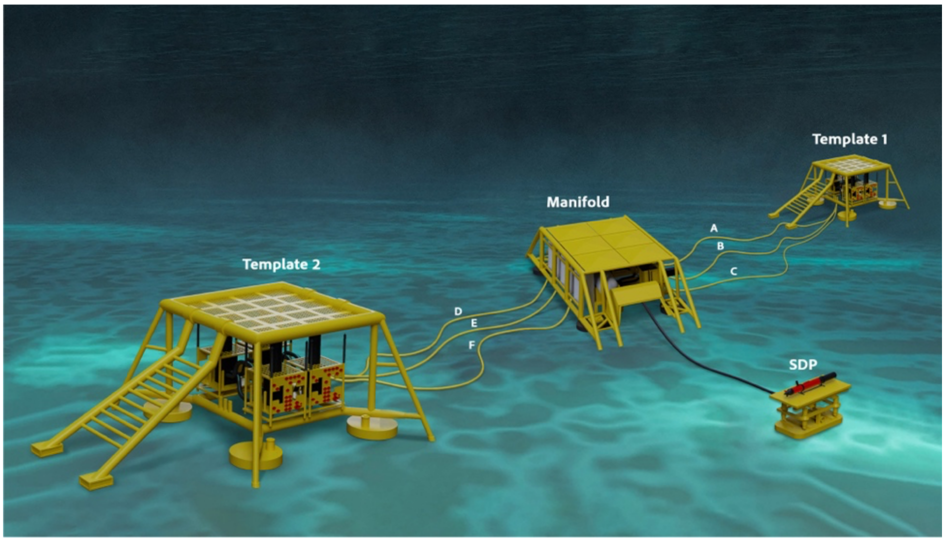


Figure 8. Example layout of a simplified oil field with six pipelines, two Templates, a Manifold and a Subsea Docking Plate.

2. Optimized Static Route Planning

The algorithm's static version computes inspection routes before missions, focusing on efficiently covering all pipeline segments while minimizing energy consumption and recharge stops. Experimental results demonstrated the effectiveness of this static approach clearly:

- The optimized static route reduced recharge stops by 50%, decreasing from 6 stops required by a short-sighted approach to only 3 stops.
- Throughout the static planning scenario, the RAUV maintained consistent battery safety margins, always remaining above the critical 20% threshold. Observed battery levels before each recharge ranged from 38% to 50%, with an average around 42%. These metrics indicate safe, reliable energy management.
- The timeline in Fig. 9 clearly shows each inspection segment, including precise pipeline coverage order and the timing of recharge stops at the SDP. By visually displaying these strategically reduced recharge points and the associated battery levels, the figure confirms the algorithm's ability to optimize the RAUV's path effectively.

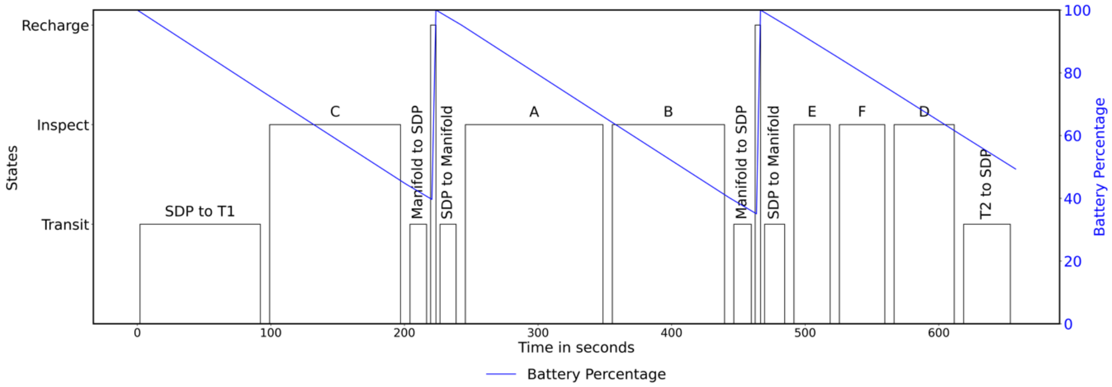


Figure 9: A maintenance route timeline without priority or triggers.

3. Adaptive Dynamic Re-routing

- The dynamic re-routing algorithm efficiently adapts to sudden changes in inspection priorities, ensuring the RAUV can respond quickly to unexpected mission demands.
- Experiments validated the algorithm's real-time adaptability; for instance, dynamic route recalculations typically completed within just 4 seconds onboard.
- Battery safety margins were consistently maintained, demonstrating robustness and reliability in real operational conditions.
- Figure 10 demonstrates a dynamic re-routing scenario where the RAUV receives an urgent request mid-operation to prioritize pipeline F. Initially following the static route, the RAUV dynamically adjusts its mission plan, determining the immediate need for a recharge before inspecting the newly prioritized pipeline. The figure effectively illustrates the real-time decision-making and rapid adaptation capability of the algorithm, as well as its continued adherence to battery constraints and safe operational standards.

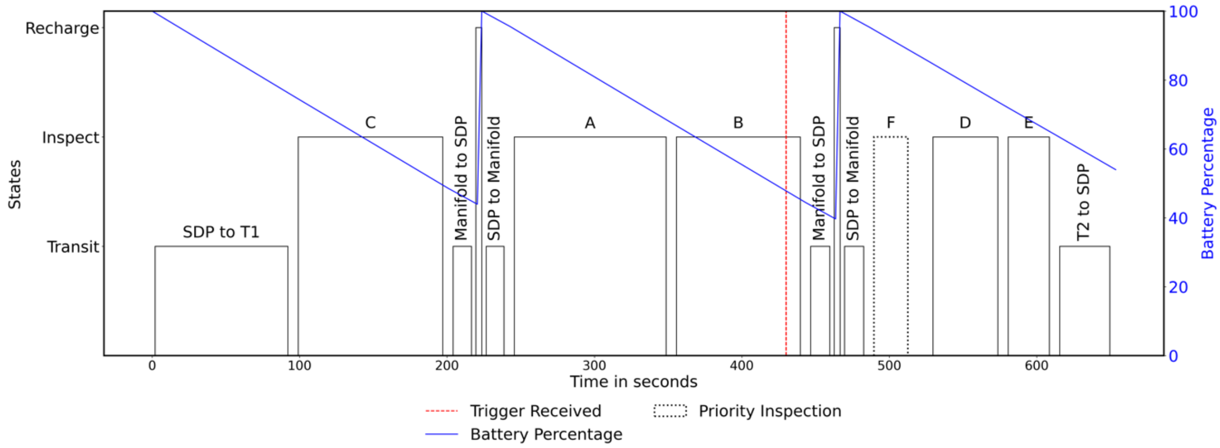


Figure 10: It shows an example of dynamic replanning in which pipeline F was identified as a priority inspection while inspecting pipeline B.

Paper reference

Kasparavičiūtė, Gabrielė, Kjetil Fagerholt, and Martin Ludvigsen. "Energy-efficient route planning for optimizing underwater pipeline inspections using Resident Autonomous Underwater Vehicles." *Ocean Engineering* 315 (2025): 119756. https://doi.org/10.1016/j.oceaneng.2024.119756

Centralized Cooperative Underwater Transport with Safety Constraints

Markus H. Iversflaten, Henrik Schmidt-Didlaukies, Jan Tommy Gravdahl, Kristin Y. Pettersen

Motivation

Cooperative guidance and control of autonomous underwater robots can provide a solution to the problem of transporting large objects in the ocean. In this paper, we present modelling and control approaches for transporting large rigid objects using two underwater vehicle-manipulator systems (UVMSs). As the UVMSs grab the object to be transported, they form a system kinematically similar to a dual-arm UVMS. We first construct a cooperative system model using kinematic model knowledge of the individual UVMSs' kinematics. Subsequently, we propose a line-of-sight guidance law for the system for the purpose of long-distance transport. The extra degrees of freedom of the total system are used to complete safety-related and secondary tasks in an inverse kinematics task-priority control framework. Obstacle collision avoidance is thus incorporated in the proposed control scheme. The efficacy of the proposed control approach is demonstrated in a simulation study.

Main Results

This work explored the efficacy of centralized control for the purpose of cooperative underwater transport. Other similar works have instead considered decentralized control for the same purpose. There are distinct disadvantages to decentralized control: the generation of competing control inputs, high internal forces on the transported object, and suboptimal performance. Centralized control, on the other hand, avoids these issues and can offer improved coordination and performance. However, to enable centralized control, there is a need for high-bandwidth, low-latency communication between the UVMSs. We argue that this can be achieved with optical communication—when the UVMSs are rigidly attached to the object, their relative motions are limited so that their optical modems stay within range.

To leverage the benefits of centralized control, we created a mathematical model of the cooperative system based on the individual parts: the two UVMSs and the object. Both UVMSs rigidly grasp the object, hindering both translational and rotational motions in the grasping points. As such, they effectively combine to form a single system. The new system can still be modelled as a UVMS, though with a new body frame and joint configuration. We derive the cooperative system model using the individual UVMSs’ kinematics which are already known. The model is thus easily obtained and expandable to additional vehicles.

The new system model kinematically resembles a multi-arm UVMS. The system exhibits quite different dynamics, however. The mass distribution of the system is quite extreme; most of the mass is generally concentrated at the end-points of the system’s “arms” (i.e. the UVMSs themselves, see Fig. 11). This proves to be a challenge during controller synthesis. We use a new method to scale the controller gains based on the scalar dry mass of the individual bodies in the system. This scaling distributes the desired control forces and moments in a balanced way across the UVMSs.

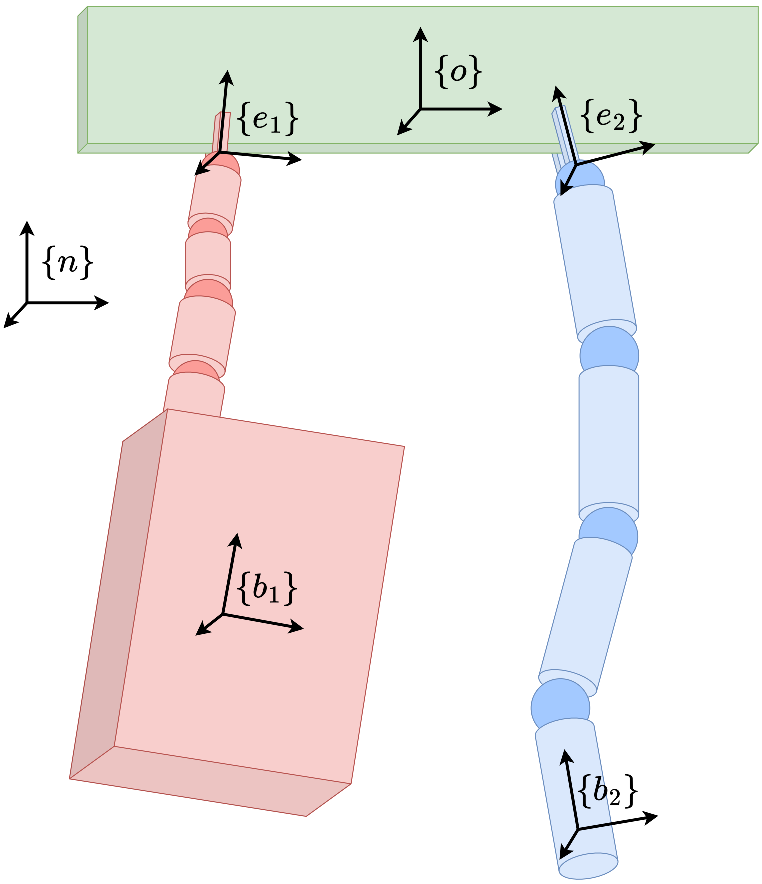


Figure 11: The cooperative system, the two UVMSs denoted {b1} and {b2}, along with the object denoted {o}. Notice that it resembles a two-arm UVMS, with the object as the base.

To show the efficacy of the proposed modelling and control method, we conducted a simulation study in which the UVMSs were to transport a long, rigid beam through a set of waypoints. During transit, the cooperative system was to avoid obstacles along the way. The system was given a prioritized set of tasks as follows:

1. Joint limit avoidance
2. Obstacle avoidance
3. Line-of-sight guidance
4. Keep object level
5. Specific configuration of the UVMSs
6. Optimal transit configuration

Importantly, the centralized control design let us safely navigate the obstacles along the path, as both UVMSs could move together in harmony.

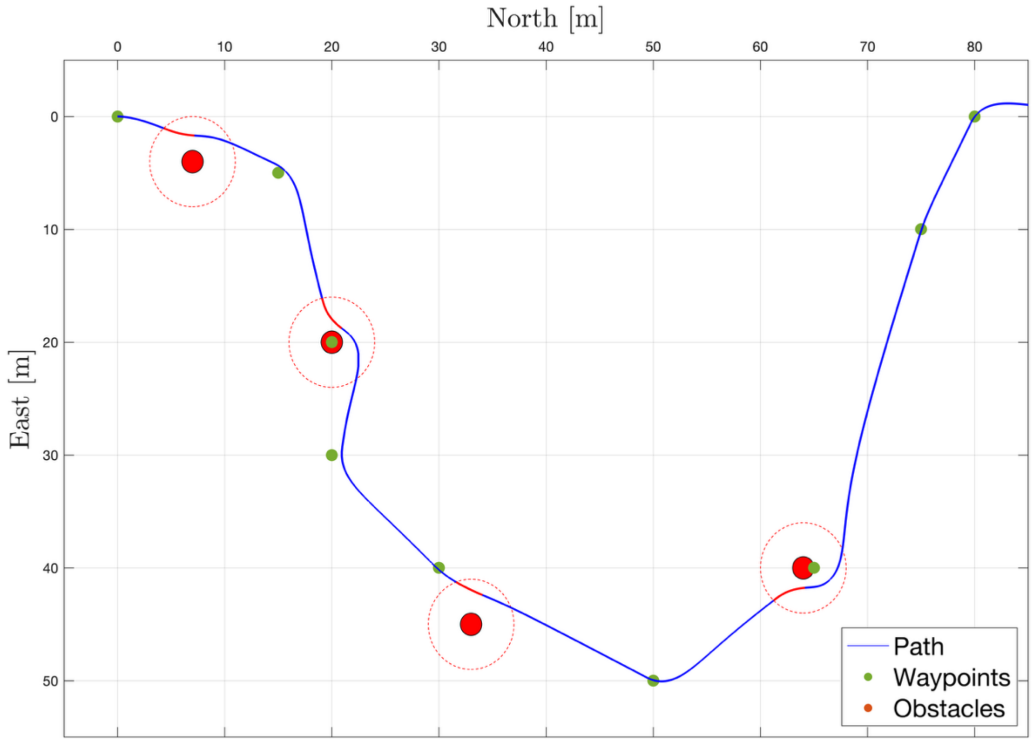


Figure 12: The trajectory of the cooperative system in a North-East grid. The system navigates through waypoints shown in green, whilst avoiding obstacles in red. Notice that some waypoints even overlap with the obstacles. The dotted red circles are activation zones for obstacle avoidance maneuvers.

Paper reference

Iversflaten, M. H., Schmidt-Didlaukies, H., Gravdahl, J. T., and Pettersen, K. Y. (2024) Centralized underwater cooperative transport with safety constraints. *IFAC-PapersOnline*, 58(20), 139-146. https://doi.org/10.1016/j.ifacol.2024.10.045

Selected VISTA CAROS Campaigns

Underwater Hyperspectral Imaging Using the Snake Robot Eely Revealed Potential Leakage from Dumped Munitions

Mjøsa is the largest lake in Norway with the cities Lillehammer, Gjøvik, and Hamar close by. Mjøsa is the drinking water for about 100 000 people in the region and is an identity builder for the region. Up to the beginning of the 1970s a huge amount of munitions, several hundred tons, was dumped in the lake at that time assuming safe displacement.

Mission Mjøsa is a research program managed by NTNU in partnership with local authorities, governmental agencies, and research institutes with the aim of facilitating value creation through sustainable use of Mjøsa's resources and ecosystem services while simultaneously maintaining the ecosystem's structure, functioning, productivity, critical infrastructure, and biodiversity. A clear objective is to act as a pilot for a larger national effort towards improved knowledge-based management of freshwater resources, both in Norway and globally.

The last two weeks of October a team of researchers from VISTA CAROS, SFI HARVEST and Mission Mjøsa carried out investigation of potential leakage from dumped munitions in the lake Mjøsa north of Oslo. The research hypothesis was to investigate if Underwater Hyperspectral Imaging (UHI) can be used as a remote sensing method to reveal potential leakage from the dumped munitions. The UHI sensor with integrated lightning was installed on the snake robot Eely as a payload sensor. The site was decided by earlier acoustical mapping in 2022 using the autonomous underwater vehicle HUGIN by the Norwegian Defence Research Establishment (FFI), which is also a partner in Mission Mjøsa.

Figure 13: UHI sensor on the snake robot Eely.

Precise positioning of Eely with roll, pitch and altitude control provided excellent UHI data that is currently being analyzed.

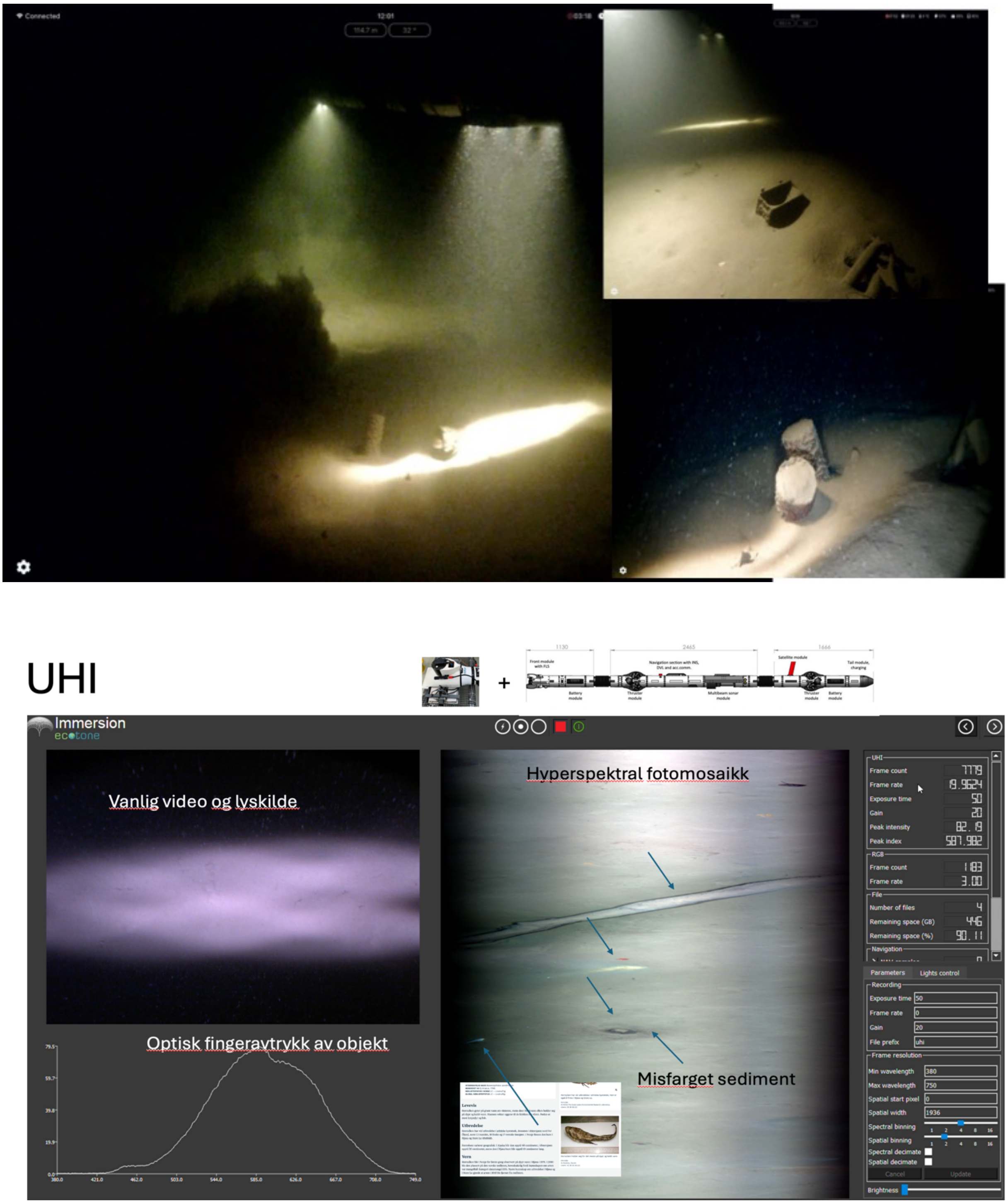


Figure 14: Top: Push broom imaging of the seabed using UHI. Bottom: Discolored UHI data indicating areas that are affected by potential leakage.

The results so far indicate potential leakage from the munition. Fortunately, water samples indicate that the current level of leakage is below recommended thresholds for what is regarded as dangerous for humans. Further ground truthing with soil samplings for chemical analysis close to the detected areas is in the planning. The dumping areas will on regular basis be monitored for change detection in any unfavorable manner, where remote sensing capabilities using UHI will provide more effective coverage of the area of interest.

VISTA CAROS and SFI Autoship testing at MC-lab, Trondheim - Symbolic Control for Autonomous Docking of Marine Surface Vessels

Elizabeth Dietrich (UC Berkeley), Emir Cem Gezer, Bingzhuo Zhong (UC Berkeley), Murat Arcak (UC Berkeley), Majid Zaman (UC Boulder), Roger Skjetne, Asgeir Johan Sørensen

Docking of marine surface vessels and underwater vehicles is a demanding task due to its safety-critical nature. A team of researchers from VISTA CAROS, SFI Autoship, UC Berkeley, and University Colorado Boulder has developed a hierarchical symbolic control architecture for autonomous docking maneuvers of a dynamic positioning surface vessel, to provide formal safety guarantees. At the upper level, the vessel's desired surge, sway, and yaw velocities as control inputs and synthesize a symbolic controller in real-time.
The desired velocities are then transmitted to and executed by the vessel's low-level velocity feedback control loop. Given a synthesized symbolic controller, methods to optimize the performance of the proposed control scheme for the docking task are investigated. The efficacy of this methodology was evaluated on a low-fidelity simulation model of a marine surface vessel in the presence of static and dynamic obstacles and, for the first time, through physical experiments in June 2024 on a scaled model vessel in the NTNU Marine Cybernetics Laboratory (MC-Lab).

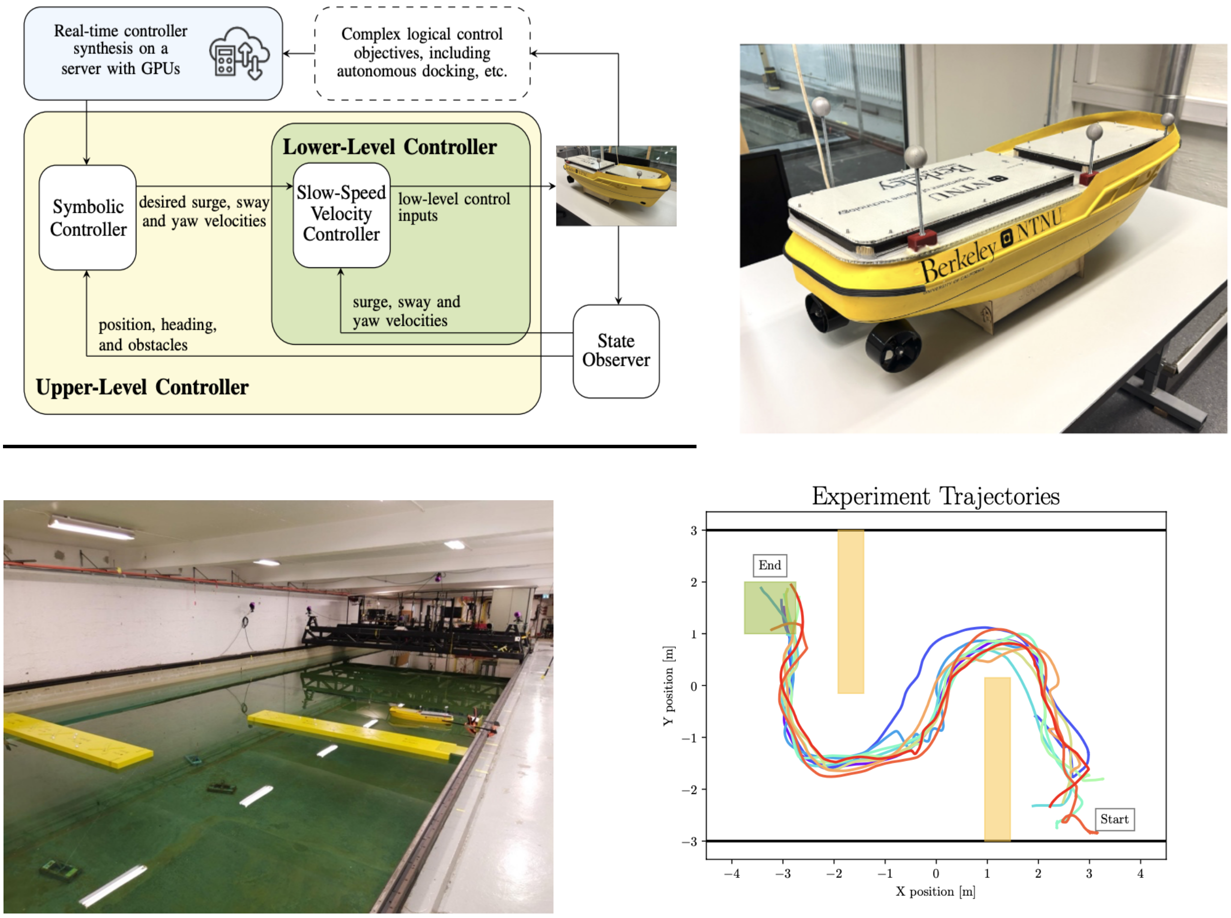


Figure 15: Successful demonstration of symbolic control for safe autonomous docking maneuvers of autonomous surface vehicles. The methodology is also applicable for docking of underwater vehicles.

VISTA CAROS Campaign at Trondheimsfjord

In June 2024, NTNU conducted a multi-day research cruise in Trondheimsfjorden. The cruise involved extensive testing of the work-class ROV Minerva, integration trials with the Eelume snake robot and BlueROV, and real-time 3D mapping experiments using a custom multi-camera and sensor rig.

Objectives and Activities

The campaign was structured around three central objectives:

- Collaborative operations between robots Eelume and BlueROV were deployed in tandem to investigate "flying third eye" capabilities, where the BlueROV shadows Eelume to provide visual support during missions. This setup enhances safety and mission capability by expanding visual perception and supporting collaborative navigation strategies.
- Advanced navigation and control with ROV Minerva. The Minerva ROV, a Sperre Sub-Fighter 100K operated by NTNU's AUR-Lab, was equipped with a custom navigation system developed in-house. This system fuses data from an IMU (STIM300), DVL, and compass using an extended state estimator. Together with a station-keeping controller, it enables high-precision underwater positioning and maneuvering, even in the absence of external GPS signals.
- 3D Perception and Real-Time Mapping. A multi-camera rig consisting of synchronized wide-angle cameras and inertial sensors was mounted on Minerva to collect data for high-resolution 3D reconstructions. These setups supported both geometric SLAM and learning-based visual odometry approaches. The datasets include surveys of the Hercules shipwreck and a Pig Loop Module (PLM) installation, with SLAM trajectories demonstrating closed loops and rich structure reconstructions under low-visibility conditions.

Figure 16: A) Preparation of ROV Minerva with a stereo camera setup. B) Vehicle tuning and control in the lab of RV Gunnerus.

Key Results

- Successfully demonstrated multi-robot collaboration between Eelume and BlueROV for joint inspection operations.
- Achieved station-keeping control and precise path following with Minerva using NTNU's custom navigation software stack.
- Collected high-quality, multi-sensor datasets of subsea targets under various environmental conditions, including feature-poor seabed and turbid water.

- Generated dense 3D maps of the Hercules shipwreck, with concentric survey trajectories and visual loop closure verified through SLAM pipelines.

This campaign demonstrates the integration of real-time perception and control for autonomous operations in complex underwater environments. The results feed directly into ongoing research in multi-modal SLAM, semantic scene understanding, and mission-level autonomy. The field data supports several contributions, including an ICRA 2025 submission, and will serve as a benchmark dataset for the community. Furthermore, this deployment underscores the potential of robotic cooperation and real-time decision-making for future applications in environmental monitoring, infrastructure inspection, and marine archaeology.

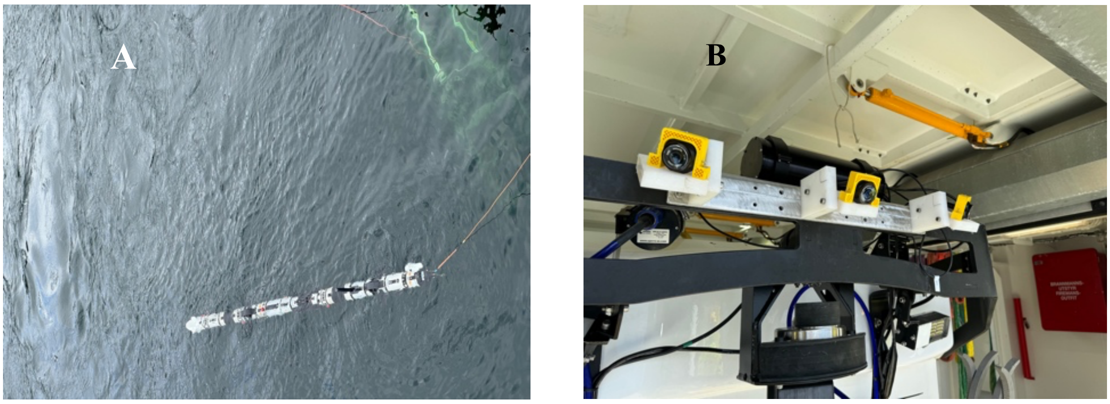


Figure 17: A) The Eelume underwater vehicle deployed from Gunnerus. B) The multi-camera rig on ROV Minerva

Key Economic Figures –2024

Revenue (Thousand NOK)

Cost:	
Personal cost:	7 464
Field trials:	1 080
Other cost	1 395
SUM:	**9 939**

Income:	
VISTA:	5 418
NTNU:	4 521
SUM:	**9 939**

Dissemination and Outreach 2024

Master Theses

1. Ivan Gushkov (KYP): Non-linear path following and data-driven applications in underwater snake robot control.
2. Alise Skaar (KYP): $\mathcal{L}$1 Adaptive Control of UUVs.
3. Oluwatobi Ojekanmi (OP): Neural Radiance Fields (NeRFs) for High Fidelity 3D Underwater Scene Reconstruction.
4. Andreas Sitorus (OP): Discrete Ballast Configuration Estimation for Underwater Vehicles.
5. Ramy Alham (OP): Enhancing Navigation and Fault Detection in Small Remotely Operated Vehicles.
6. Abdelhaleem Sadd (OP): Adaptive Control for Water-cleaning USVs.
7. Bjørn-Magnus Moslått (OP): Visual docking of small ROVs.
8. Ahmed Abdallah Abdelrehim Abdelgayed (ML): Adaptive Mission Planning for Water Column Investigations.
9. Isak Øvsthus Jordal (ML): Autonomous ROV Control in a Simulated Environment in Relation to a Docking Operation.
10. Nimra Jabeen (ML): Precise semantic segmentation from stereo-images for autonomous navigation
11. Md Raqibur Rahman (ML): Unsupervised Learning of Depth and Ego Motion of Underwater Robots from image sequences.

Publications at Conferences

1. E.A. Basso and H.M. Schmidt-Didlaukies, and K.Y. Pettersen, "Adaptive Line-of-Sight Path Following for Curved Paths as a Maneuvering Problem", *Proc. 63^{rd} Conference on Decision and Control,* Milano, Italy, Dec. 16-19, 2024.
2. M. Fossdal, A. H. Brodtkorb, M. Arcak, and A. J. Sørensen, "Past-Time Signal Temporal Logic Hybrid Switching Control for Underwater Vehicles". In: IEEE AUV2024 Symposium, Boston, US, Sept.18-20, 2024.
3. M.E.B. Lysø, E. Panteley, K.Y. Pettersen, and J.T. Gravdahl, "Orbital Control for Swimming in Underwater Snake Robots using Energy-shaping and Consensus Control", *Proc. 63^{rd} Conference on Decision and Control,* Milano, Italy, Dec. 16-19, 2024.
4. J.I. Dyrhaug, E.L. Foseid, H.M. Schmidt-Didlaukies, E.A. Basso, K.Y. Pettersen, and J.T. Gravdahl, "Super-Twisting Impedance Control for Robust and Compliant Intervention using a Redundant Robot Manipulator", *Proc. 4th Modeling, Estimation, and Control Conference*, Chicago, Illinois, Oct. 27-30, 2024.
5. S. Hoff, H.M. Schmidt-Didlaukies, E.A. Basso, D. Varagnolo, and K.Y. Pettersen, "Underwater vehicle navigation using bearing measurements from a mobile beacon", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
6. M.E.B. Lysø, K.Y. Pettersen, and J.T. Gravdahl, "Energy-Shaping Control for Swimming in Underwater Snake Robots", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.

7. J.I. Dyrhaug, K.Y. Pettersen, and J.T. Gravdahl, "Robust Interaction using Generalized Super-Twisting Impedance Control", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
8. E.L. Foseid, E.A. Basso, H.M. Schmidt-Didlaukies, M. Marley, K.Y. Pettersen, and J.T. Gravdahl, "Learning Optimal Guidance Schemes with Safety Guarantees for Underactuated Marine Vehicles", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
9. B. K. Sæbø, K.Y. Pettersen, and J.T. Gravdahl, "Kinematic Task-Priority Path Following for Articulated Marine Vehicles", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
10. E. Tveter, K.Y. Pettersen, and J.T. Gravdahl, "Power-Based Safety Constraint for Redundant Robotic Manipulators", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
11. I. Gushkov, K.Y. Pettersen, and J.T. Gravdahl, "MPC Path Following with Macroscopic Shape Adjustment for AIAUVs", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
12. A. Orucevic, E.L. Foseid, M.E.B. Lysø, K.Y. Pettersen, and J.T. Gravdahl, "Nonlinear model predictive control for sinusoidal gait tracking for an underwater snake robot", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
13. M. Wrzos-Kaminska, B.K. Sæbø, K.Y. Pettersen, and J.T. Gravdahl, "Unifying the Generalized Jacobian Matrix and prioritized task hierarchies, with application to free-floating VMSs", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
14. M.H. Iversflaten, H.M. Schmidt-Didlaukies, K.Y. Pettersen, and J.T. Gravdahl, "Centralized Underwater Cooperative Transport with Safety Constraints", *Proc. 15th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, Blacksburg, Virginia, USA, Sep. 3-5, 2024.
15. A. Haraldsen, M.S. Wiig, and K.Y. Pettersen, "Safety-critical Guidance of Underactuated Marine Vehicles in Dynamic Environments using Velocity Obstacles", *Proc. 8th IEEE Conference on Control Technology and Applications,* Newcastle upon Tyne, UK, Aug. 21-23, 2024.
16. A. Haraldsen, M.S. Wiig, A.D. Ames, and K.Y. Pettersen, "Safety-Critical Control of Nonholonomic Vehicles in Dynamic Environments using Velocity Obstacles", *Proc. 2024 American Control Conference,* Toronto, Canada, July 8-12, 2024.
17. E.L. Foseid, E.A. Basso, H. Schmidt-Didlaukies, K.Y. Pettersen, and J.T. Gravdahl, "Model Predictive Task-Priority Control using Control Lyapunov Functions", *Proc. 22nd European Control Conference,* Stockholm, Sweden, June 24-28, 2024.
18. P. Kaveti, A. Grimsrud Waldum, O. Pizarro, H. Singh, and M. Ludvigsen, "Enhancing Situational Awareness in Underwater Robotics with Real-Time Multi-Camera Mapping", IEEE Marine Imaging Workshop 2024, Monterey, California, US, 7-10 October 2024.

Plenary Lectures

1. K. Y. Pettersen. Autonomous Robots for exploring the vast ocean space. Plenary lecture at the 8th *IEEE Conference on Control Technology and Applications*, August 21-23, 2024, Newcastle upon Tyne, UK.

2. K. Y. Pettersen. Autonomous Marine Robots. Plenary lecture at the 28th International Conference on System Theory, Control and Computing (ICSTCC 2024), Sinaia, Romania, October 10-12, 2024.
3. K. Y. Pettersen. All-Terrain AUVs: A New Class of Marine Robots, International Conference on Control, Automation, Robotics and Vision (ICARCV), Dubai, UAE, December 12-15, 2024.
4. K. Skaugset. Autonomous Robotic Organizations, keynote lecture at the Air Power Conference 2024, Royal Norwegian Air Force, Trondheim, Norway, February 7-8, 2024.

Journal Publications

1. J. E. Bremnes, I. B. Utne, T. R. Krogstad, and A. J. Sørensen, "Holistic Risk Modeling and Path Planning for Marine Robotics". In IEEE Journal of Oceanic Engineering.
2. J. E. Bremnes, T. Reitan Fyrvik, T. Røbekk Krogstad, and A. J. Sørensen, "Design of a Switching Controller for Tracking AUVs With an ASV". In IEEE Transactions on Control Systems Technology, vol. 32, no. 5, pp. 1785-1800, Sept. 2024.
3. A. Haraldsen, M. S. Wiig, and K.Y. Pettersen, "A Theoretical Analysis of the Velocity Obstacle Method for Nonholonomic Vehicles and Underactuated Surface Vessels", *IEEE Transactions on Control Systems Technology,* Vol. 32, No. 5, 2024, pp. 1801-1816.
4. S.A. Hoff, J. Matouš. D. Varagnolo, and K.Y. Pettersen, "Communication-aware NSB formation control for networks of AUVs", *European Journal of Control*, Vol. 80, Part A, Nov. 2024, 101062.
5. J. Matouš, C. Paliotta, K.Y. Pettersen, and D. Varagnolo, "The Hand Position Concept for Control of Underactuated Underwater Vehicles", *IEEE Transactions on Control Systems Technology,* Vol. 32, No. 6, 2024, pp. 2223 – 2239.
6. A. Orucevic, M. Wrzos-Kaminska, M.E.B. Lysø, K.Y. Pettersen, and J.T. Gravdahl, "Automatic Alignment of Underwater Snake Robots Operating in Wakes of Bluff Bodies", *Control Engineering Practice,* Vol. 147, 105904, 2024.
7. 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,* Vol. 32, No. 5, 2024, pp. 1631 – 1646.
8. E. Restrepo, J. Matouš, and K.Y. Pettersen, "Tracking Control of Cooperative Marine Vehicles under Hard and Soft Constraints", *IEEE Transactions on Control of Network Systems,* Vol. 11, No. 4, 2024, pp. 2126-2138.
9. H.M. Schmidt-Didlaukies, E.A. Basso, and K.Y. Pettersen, "Input-to-State Stable Integral Line-of-Sight Guidance for Curved Paths with Anti-Windup Guarantees", *IEEE Control Systems Letters,* Vol. 8, 2024, pp. 730 – 735.

International Guest Lectures

1. Sørensen, A. J. (2024). Robotic organizations and the observation pyramid for mapping and monitoring of the oceans. 9 December. DTU, Denmark