IFAC CAMS 2024

CAMS 2024 Technical Program Tuesday September 3, 2024		
Track A	Track B	Track C
08:00-11:45 Assembly Hall Workshop TueMorningTutorial *Thor I. Fossen: 2-D and 3-D Line-Of-Sight Guidance Laws for Path Following: From Theory to Code Implementation*		
11:45-13:00 Latham Ballroom A TueEarly-AfternoonLunch-and-Welcome		
13:00-14:40 Assembly Hall Regular Session TueEarly-AfternoonA *GNC I*	13:00-14:40 Solitude Regular Session TueEarly-AfternoonB *Autonomous and Remotely Operated Vessels*	13:00-14:40 Cascades Regular Session TueEarly-AfternoonC *Maritime Robotics I*
14:40-15:00 Assembly Hall TueAfternoonCoffee-Break		
15:00-16:40 Assembly Hall Regular Session TueAfternoonA *Modeling, Simulation, Control*	15:00-16:40 Solitude Regular Session TueAfternoonB *Cooperative Navigation and Control*	15:00-16:40 Cascades Regular Session TueAfternoonC *Maritime Robotics II*

CAMS 2024 Technical Program Wednesday September 4, 2024		
Track A	Track B	Track C
08:30-09:30 Assembly Hall Plenary Talk WedMorningPlenary *Dr. Eva Kanso, University of Southern California*		
09:30-09:50 Assembly Hall WedMorningCoffee-Break		
09:50-11:30 Assembly Hall Regular Session WedMorningA *Adaptive Robust I*	09:50-11:30 Solitude Invited Session WedMorningB *GNC II*	09:50-11:30 Cascades Regular Session WedMorningC *Nonlinear and Optimal I*
11:45-13:00 Latham Ballroom A WedEarly-AfternoonLunch		
13:00-14:00 Assembly Hall Plenary Talk WedEarly-AfternoonPlenary *Towards Resident Autonomous Underwater Robotic Systems, Dr. Geoffrey Hollinger, Oregon State University*		
14:00-14:20 Assembly Hall WedAfternoonCoffee-Break		
14:20-16:00 Assembly Hall Regular Session WedAfternoonA *Intelligence and Autonomy*	14:20-16:00 Solitude Invited Session WedAfternoonB *GNC III*	14:20-16:00 Cascades Regular Session WedAfternoonC *Nonlinear and Optimal II*
18:00-22:00 German Club Manor WedEveningBanquet		

CAMS 2024 Technical Program Thursday September 5, 2024		
Track A	Track B	Track C
08:30-09:30 Assembly Hall Plenary Talk ThuMorningPlenary *Dr. Marty Irvine, U.S. Naval Surface Warfare Center and Naval Undersea Warfare Center*		
09:30-09:50 Assembly Hall ThuMorningCoffee-Break		
09:50-11:30 Assembly Hall Invited Session ThuMorningA *Renewable Energies I*	09:50-11:30 Solitude Regular Session ThuMorningB *Industry Talk*	09:50-11:30 Cascades Regular Session ThuMorningC *Maritime Safety and Decision Support*
11:45-13:00 Latham Ballroom A ThuEarly-AfternoonLunch		
13:00-14:00 Assembly Hall Plenary Talk ThuEarly-AfternoonPlenary *Dr. Nina Mahmoudian, Purdue University*		
14:00-14:20 Assembly Hall ThuAfternoonCoffee-Break		
14:20-16:00 Assembly Hall Invited Session ThuAfternoonA *Renewable Energies II*	14:20-16:00 Solitude Regular Session ThuAfternoonB *Maritime Robotics III*	14:20-16:00 Cascades Regular Session ThuAfternoonC *Adaptive Robust II*
16:00-17:30 Assembly Hall ThuAfternoonWalking-Tour		

TueEarly-AfternoonA	Assembly Hall
GNC I (Regular Session)	
Chair: Coates, Erlend M.	Norwegian University of Science and Technology
Co-Chair: Hopwood, Jeremy	Virginia Tech

13:00-13:20 TueEarly-AfternoonA.1

Enhancing Line-Of-Sight Guidance to Improve Path Following for Marine Surface Vessels, pp. 1-8

Kjerstad, Øivind Kåre — Norwegian University of Science and Technology
Coates, Erlend M. — Norwegian University of Science and Technology

This paper highlights and addresses several deficiencies with line-of-sight guidance not commonly discussed in the literature. We consider the path-following problem for marine surface vessels following smooth paths defined by a set of waypoints. Motivated by key shortcomings in state-of-the-art adaptive and integral line-of-sight guidance algorithms, we propose a novel guidance law with three main features. First, it incorporates a novel update law for the crab-angle estimate based on course error injection instead of cross-track error. Second, we add a feedforward signal for pivot point compensation. Last, the coupling with the underlying heading control system is properly treated by supplying acceleration, rate-of-turn, and heading setpoints derived from both the path formulation and the line-of-sight guidance scheme. A case study using a high-fidelity model of a research ship demonstrates the discussed deficiencies using popular line-of-sight formulations from the literature. It shows that the proposed design has marked improvements over these. We argue that the proposed design sets a benchmark for path-following performance for marine surface vessels.

13:20-13:40 TueEarly-AfternoonA.2

Combining Reinforcement Learning and in Situ Current Velocity Measurements for Efficient UUV Guidance, pp. 17-22

Greeley, Brian — DCS Corporation
Brandman, Jeremy — U.S. Naval Research Laboratory
Book, Jeffrey — U.S. Naval Research Laboratory
Barron, Charlie — U.S. Naval Research Laboratory
Landry, Blake — U.S. Naval Research Laboratory
Olson, Colin — U.S. Naval Research Laboratory

Conventional guidance algorithms for unmanned underwater vehicles commonly operate on geometric principles that do not directly take into account local environmental conditions. We describe here a deep reinforcement learning (RL) framework that partially addresses this issue by generating energy-minimizing guidance systems. Specifically, the proposed framework outputs trained policy networks (agents) capable of mapping histories of local current velocity measurements to heading and depth commands that yield nearly-optimal, minimum-energy transits through spatially varying current fields. Numerical experiments in three spatial dimensions on realistic ocean currents, where direction and speed vary non-monotonically in depth, demonstrate that trained agents reduce the energy costs of transits when compared against dead-reckoning, a common in-service guidance heuristic. In particular, numerical results suggest that trained agents learn an explore-exploit strategy according to which they initially execute an exploratory dive, followed by a return to a depth with optimally favorable currents, which they exploit for the remainder of the transit.

13:40-14:00 TueEarly-AfternoonA.3

Reducing Controller Effort in a Deep Reinforcement Learning-Based Autopilot for an Underactuated ASV, pp. 23-28

Jose, Joel — Norwegian University of Science and Technology
Ramkumar Sudha, Sanjeev Kumar — Norwegian University of Science and Technology
Coates, Erlend M. — Norwegian University of Science and Technology

With the growing interest in applications of Deep Reinforcement Learning for control of Autonomous Surface Vessels, it becomes vital that one ensures a smooth and efficient behavior of trained action policies. Excessive variation in control can lead to unnecessary wear and tear of actuators, passenger discomfort, inefficient and unstable vessel motions, and other complications. While several ways to handle this issue are documented in the literature, it is unclear how well these approaches can be tailored to applications in underactuated and fully actuated Autonomous Surface Vessels. In this study, we compare some of these methods in the task of Deep Reinforcement Learning-based rudder control of an underactuated vessel for path-following. The results indicate that introducing flexibility while enforcing controller smoothness yields a more stable behavior from the trained policy. In addition, we find that regularizing action policies yields a more efficient control behavior, but with a potential trade-off on smoothness and difficulties in implementation and analysis

14:00-14:20 TueEarly-AfternoonA.4

Deep Reinforcement Learning for Path-Following Control of an Autonomous Surface Vehicle Using Domain Randomization, pp. 29-34

Slawik, Tom — German Research Center for Artificial Intelligence (DFKI GmbH),
Wehbe, Bilal — German Research Center for Artificial Intelligence
Christensen, Leif — German Research Center for Artificial Intelligence
Kirchner, Frank — University of Bremen

In this paper, we propose a path-following controller for an autonomous surface vehicle (ASV) that is based on model-free deep reinforcement learning. To make the learning agent more robust, we investigate domain randomization for sim-to-real transfer. We provide a comparison between three different algorithms: Deep Deterministic Policy Gradient (DDPG), Soft Actor-Critic (SAC) and Proximal Policy

Optimization (PPO). The trained models are evaluated on the small-scale ASV Altus-LSA Niriis in the maritime test basin at DFKI RIC, Germany. Our results show that applying domain randomization leads to a significant performance improvement compared to no domain randomization, when tested on real hardware.

14:20-14:40 TueEarly-AfternoonA.5

Spatiotemporal Elastic Bands for Motion Planning in Highly Dynamic Environments, pp. 9-16

Amundsen, Herman Biørn — SINTEF Ocean
Xanthidis, Marios — SINTEF Ocean
Føre, Martin — NTNU
Kelasidi, Eleni — SINTEF Ocean

Robust motion planning in highly dynamic environments affected by challenging conditions remains an important task for autonomous robots, and an open problem for the robotics community. This paper proposes significant extensions to the elastic band method that gives more robustness to uncertainty in state and tracking performance, and a way to avoid fast-moving obstacles that may move multiple times faster than the vehicle in an efficient and non-conservative way. Particularly, we temporally enhance the algorithm, address future collisions spatiotemporally with continuous guarantees, and adapt the required safety clearance dynamically to address disturbances, control errors, and uncertainty. To validate the proposed method, results from a simulation study are presented, demonstrating the ability to safely plan trajectories in dynamic environments. The motion planner is lightweight and remarkably computationally efficient, with replanning orders of magnitudes faster than real-time needs by reaching and surpassing 1000Hz.

TueEarly-AfternoonB Solitude

Autonomous and Remotely Operated Vessels (Regular Session)

Chair: Indiveri, Giovanni — University of Genova
Co-Chair: Hasan, Agus — Norwegian University of Science and Technology

13:00-13:20 TueEarly-AfternoonB.1

Towards Autonomous Control System in Brazilian Navy's USV-Lab Using MOOS-IvP Framework, pp. 35-40

Lima, Douglas Silva de — Brazilian Navy
Carvalho, Pedro — University of São Paulo (USP)
Eiras, de Carvalho, Eduardo — Centro De Análise De Sistemas Navais (CASNAV, Marinha Do Brasil)
Tannuri, Eduardo Aoun — University of Sao Paulo USP
Coreixas de Moraes, Claudio — Universidade Federal Do Rio De Janeiro
Breitinger, Andre — CASNAV

This article aims to describe the implementation of an autonomous control system for the Brazilian Navy's Unmanned Surface Vehicle Laboratory (USV-Lab) using the MOOS-IvP framework. The main goal of this project is to enable an existing vehicle to be a laboratory for research of maritime autonomous systems, to perform unmanned maritime missions, following desired routes without human intervention or being remotely piloted. The paper starts with the importance of autonomous maritime vehicles and presents MOOS-IvP framework as a validated tool for autonomous maritime systems development. In succession, the main objectives are set, the physical system and components are shown and the proposed software and communication are structured. The work comprises the development of control interface, the integration of sensors and actuators, the tuning PID controllers, and specific software settings, along with several hardware modifications. The methodology consisted in progressive testing, from simulations to local operations as made in Guanabara Bay in Rio de Janeiro and Bay of All Saints in Bahia. Results revealed the system's effectiveness and robustness in maintaining configured routes, enabling its use in a Brazilian Navy military reconnaissance exercise, as well as serving as a laboratory for future research.

13:20-13:40 TueEarly-AfternoonB.2

Autonomous Marine Collision Avoidance with Sensor Fusion of AIS and Radar, pp. 41-46

Hem, Audun Gullikstad — Norwegian University of Science and Technology
Brekke, Edmund F. — Norwegian Univ. of Science and Tech
Kufoalor, Dzordzoenyenye Kwame Minde — Norwegian University of Science and Technology
Kingman, Ivan H. — Martime Robotics

We present the results of a series of autonomy experiments conducted to evaluate novel target tracking methods that use both exteroceptive sensors and messages from the Automatic identification system (AIS). The experiments used a 6-meter-long autonomous surface vehicle equipped with a radar and an AIS antenna, in combination with two target vessels. The tracker output informed a collision avoidance method about the surrounding targets, which allowed it to operate in the intended safe and regulations-abiding manner. The results show that the tracker provided target estimates of high enough quality to be used directly in the collision avoidance method without post-processing, and that the vehicle was able to navigate safely through the scenarios. The data collected during the experiments is made available.

13:40-14:00 TueEarly-AfternoonB.3

Model Based Navigation for a Twin Thruster Autonomous Surface Catamaran, pp. 47-52

Wanderlingh, Francesco — University of Genova
Simetti, Enrico — University of Genova
Indiveri, Giovanni — University of Genova

The paper describes the design, implementation, and performance assessment of a navigation system for a small-size robotic twin thruster

autonomous surface vessel (ASV). The navigation solution is designed building on a first principles maneuvering model that includes sources of nonlinearity and asymmetry of this class of catamaran robots. The paper illustrates how the proposed model is exploited in the navigation filter design and implementation and it discusses its impact on the overall navigation performance. Experimental results relative to the ULISSE ASV are included and illustrated.

14:00-14:20 TueEarly-AfternoonB.4

Joint Sensor and Actuator Fault Diagnosis for Autonomous Ships, pp. 53-58

Hasan, Agus — Norwegian University of Science and Technology
Salvo Rossi, Pierluigi — Norwegian University of Science and Technology

In this paper, we introduce an innovative approach for joint diagnosis of sensor and actuator faults in autonomous ships, leveraging an adaptive extended Kalman filter enriched with a forgetting factor. The fundamental concept involves filtering and augmenting measurements from the sensor systems into the ships' state space model. This method is designed to enhance the accuracy of the diagnostic process by dynamically adapting to changes in the sensor's behavior over time. To validate the efficacy of our proposed method, we conduct numerical simulations. Through these simulations, we aim to demonstrate the practical applicability and reliability of our approach in real-world scenarios, emphasizing its potential for enhancing the fault diagnosis capabilities of autonomous ships.

TueEarly-AfternoonC — Cascades

Maritime Robotics I (Regular Session)

Chair: Stilwell, Daniel J. — Virginia Polytechnic Inst. & State Univ
Co-Chair: Clement, Benoit — ENSTA Bretagne, CROSSING IRL CNRS 2010

13:00-13:20 TueEarly-AfternoonC.1

Hydraulic Volumetric Soft Everting Vine Robot Steering Mechanism for Underwater Exploration, pp. 59-64

Kaleel, Danyaal Mohamed — Queen Mary University of London
Clement, Benoit — ENSTA Bretagne, CROSSING IRL CNRS 2010
Althoefer, Kaspar — King's College London

Despite a significant proportion of the Earth being covered in water, exploration of what lies below has been limited due to the challenges and difficulties inherent in the process. Current state of the art robots such as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) are bulky, rigid and unable to conform to their environment. This makes certain underwater regions, especially those characterised by tight and narrow crevasses - as is the case for coral reefs - inaccessible to currently available exploratory tools. Soft robotics offers potential solutions to this issue. Fluid-actuated eversion or growing robots, in particular, are a good example. While current eversion robots have found many applications on land, their inherent properties make them particularly well suited to underwater environments. An important factor when considering underwater eversion robots is the establishment of a suitable steering mechanism that can enable the robot to change direction as required. This project proposes a design for an eversion robot that is capable of steering while underwater, through the use of bending pouches, a design commonly seen in the literature on land-based eversion robots. These bending pouches contract to enable directional change. Similar to their land-based counterparts, the underwater eversion robot uses the same fluid in the medium it operates in to achieve extension and bending but also to additionally aid in neutral buoyancy. The actuation method of bending pouches meant that robots needed to fully extend before steering was possible. Three robots, with the same design and dimensions were constructed from polyethylene tubes and tested. Our research shows that although the soft eversion robot design in this paper was not capable of consistently generating the same amounts of bending for the inflation volume, it still achieved suitable bending at a range of inflation volumes and was observed to bend to a maximum angle of 68 degrees at 2000 ml, which is in line with the bending angles reported for land-based eversion robots in the literature.

13:20-13:40 TueEarly-AfternoonC.2

Kinematic Task-Priority Path Following for Articulated Marine Vehicles, pp. 65-72

Sæbø, Bjørn Kåre — Norwegian University of Science and Technology (NTNU)
Pettersen, Kristin Y. — Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy — Norwegian University of Science and Technology (NTNU)

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 fit. 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. There has been some research on path following using a swimming gait, but this requires an undulating motion around the path and is less suited for articulated systems with external thrusters. In this paper a method for path following is developed where each link 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 stability properties of the proposed method will be examined theoretically, and validated in simulation.

13:40-14:00 TueEarly-AfternoonC.3

Experimental Study of a Preliminary Height Controller for a Small Autonomous Hydrofoil Craft, pp. 73-78

Moon, Heejip — Virginia Tech
Stilwell, Daniel J. — Virginia Polytechnic Inst. & State Univ
Brizzolara, Stefano — Virginia Tech

The development of an initial height controller for a small single-strut fully submerged hydrofoil craft is presented. The controller is designed using a dynamic model derived from the hydrodynamic forces measured during tow tank experiments. Field trials were conducted to tune the

controller until stable foiling state was achieved. We evaluate the field results and discuss the limitation of utilizing steady-state tow tank data in establishing the vehicle dynamic model.

14:00-14:20 TueEarly-AfternoonC.4

Unifying the Generalized Jacobian Matrix and Prioritized Task Hierarchies, with Application to Free-Floating VMSs, pp. 79-86

Wrzos-Kaminska, Marianna — Norwegian University of Science and Technology
Sæbø, Bjørn Kåre — Norwegian University of Science and Technology (NTNU)
Pettersen, Kristin Y. — Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy — Norwegian University of Science and Technology (NTNU)

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). In this work a control framework is 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 in order to reduce the need for counteracting disturbances while controlling the position of the manipulator workspace. 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.

14:20-14:40 TueEarly-AfternoonC.5

Low-Cost Sensor Technologies for Underwater Vehicle Navigation in Aquaculture Net Pens, pp. 87-94

Haugaløkken, Bent Oddvar Arnesen — SINTEF Ocean
Nissen, Oscar — Organization
Skaldebø, Martin — SINTEF Ocean
Ohrem, Sveinung Johan — SINTEF Ocean
Kelasidi, Eleni — SINTEF Ocean

This work presents a setup comprised of an underwater vehicle and various sensors that can be used for underwater navigation. The complete system is tested in an aquaculture fish farm, which features an environment that includes fish, deforming and flexible structures and highly variable environmental disturbances. The proposed approach integrates and provides software-based time-synchronization of data from external and on-board sensors to enable development and testing of multi-modal underwater navigation methods. All system components are low-cost, small-size and available off-the-shelf, motivated by the desire to collectively develop suitable underwater navigation methods that may be used in complex environments such as aquaculture fish farms, large tanks and underwater caves. Data captured through field trials in a fish farm show the potential of the proposed integrated system and the challenges related to underwater navigation in complex underwater environments such as fish farms.

TueAfternoonA Assembly Hall

Modeling, Simulation, Control (Regular Session)

Chair: Fossen, Thor I. — NTNU
Co-Chair: Mahmoudian, Nina — Purdue University

15:00-15:20 TueAfternoonA.1

Towards Online Data-Driven Discovery of Autonomous Ship Models for Digital Twins, pp. 95-100

Hasan, Agus — Norwegian University of Science and Technology
Coates, Erlend M. — Norwegian University of Science and Technology

In this paper, we introduce an innovative approach for discovering governing equations of autonomous ships from data, intended for integration into digital twins. Our method relies on an online adaptive observer comprising two interconnected exponential forgetting factor designs-one for the state and another for the parameters. With sufficient persistency of excitation, our method accurately identifies the underlying models. Numerical simulations demonstrate the effectiveness of our proposed approach, highlighting its potential for practical application in the development of digital twins for autonomous ships. The adaptive observer's dual design, for both state and parameter considerations, enhances its adaptability and robustness, making it a promising tool for accurate model discovery.

15:20-15:40 TueAfternoonA.2

Torque Reconstruction for Maritime Powertrains Using Trend Filtering, pp. 101-106

Hakonen, Urho — Aalto University
Manngård, Mikael — Åbo Akademi University
Laine, Sampo — Aalto University
Viitala, Raine — Aalto University

This paper presents a convex optimization approach for the simultaneous reconstruction of unknown input torque and torsional response in the driveline of an azimuth thruster. Accurate estimates of the shaft torque responses are necessary for condition monitoring purposes. Estimating torque responses also enables flexibility in the choice of sensor location, with subsequent potential savings in installation and maintenance costs. It is shown that the unknown inputs and states can be reconstructed using batch torque measurements from a single location in the propulsion line. The estimation problem is formulated as a trend-filtering problem, enforcing the smoothness of input estimates. The performance of the proposed method is evaluated by means of simulations and experiments on a small-scale testbench of a

maritime azimuthing thruster. The results show that the torsional response of the propeller shaft can be accurately reconstructed using torque measurements from sensors installed near the driving motor at the opposite end of the driveline.

15:40-16:00 TueAfternoonA.3

Performance of Ship Navigation Wave Filters with Low Encounter Frequency in Following Seas, pp. 107-114

Troye Røang, Simen — Norwegian University of Science and Technology
Fossen, Thor I. — NTNU
Johansen, Tor Arne — Norwegian University of Science and Technology

The effect of waves in the ship's autopilot is commonly considered as a part of the control system using a wave filter. The task of the wave filter is to remove the wave-induced motions from the measurements before they are used in the feedback control system. By not counteracting the wave-frequency motions when controlling course and speed, the autopilot avoids unnecessary wear and tear on the steering system. However, in following seas (with the wave direction being approximately in the same direction as the ship's course) the wave-frequency dynamics can be within the desired bandwidth of the course controller, since the wave encounter frequency can be very low. This paper compares the performance of different wave filters in following to quartering sea conditions, when considering different models, measurements and filtering techniques.

16:00-16:20 TueAfternoonA.4

Kinodynamic Motion Planning for a System with Squid Dynamics, pp. 115-120

Beaver, Logan — Old Dominion University
Wei, Cong — Old Dominion University
Yen, Wei-Kuo — University of Maryland

This paper introduces a path planning algorithm for a system with squid dynamics in a cluttered environment. We capture the complex interactions of fin, arms, and body patterning by analyzing experimental data collected from observing squid motion. We extract nine motion primitives to build the control sequence for a time-optimal trajectory. This task is formulated as a mixed-integer program, and we generate the minimum-time trajectory using a sample-based approach. Numerical simulations illustrate the efficacy of this strategy and motivate ongoing and future efforts to exploration of squid motion features, improvement of the modeling, and experimental demonstrations of the motion planning strategy.

16:20-16:40 TueAfternoonA.5

Gliding in Extreme Waters: Dynamic Modeling and Nonlinear Control of an Agile Underwater Glider, pp. 121-126

Yang, Hanzhi — Purdue University
Mahmoudian, Nina — Purdue University

This paper describes the modeling of a custom-made underwater glider capable of flexible maneuvers in constrained areas and proposes a control system. Due to the lack of external actuators, underwater gliders can be greatly influenced by environmental disturbance. In addition, the nonlinearity of the system affects the motions during the transition between each flight segment. Here, a data-driven parameter estimation experimental methodology is proposed to identify the nonlinear dynamics model for our underwater glider using an underwater motion capture system. Then, a nonlinear system controller is designed based on Lyapunov function to overcome environmental disturbance, potential modeling errors, and nonlinearity during flight state transitions. The capability of lowering the impact of environmental disturbance is validated in simulations. A hybrid control system applying PID controller to maintain steady state flights and the proposed controller to switch between states is also demonstrated by performing complex maneuvers in simulation. The proposed control system can be applied to gliders for reliable navigation in dynamic water areas such as fjords where the sea conditions may vary from calm to rough seasonally.

TueAfternoonB — Solitude

Cooperative Navigation and Control (Regular Session)

Chair: Clement, Benoit — ENSTA Bretagne, CROSSING IRL CNRS 2010
Co-Chair: Mwaffo, Violet — United States Naval Academy

15:00-15:20 TueAfternoonB.1

Time-Optimal Rendezvous for Cooperative UUV Swarms Using Hamilton-Jacobi Partial Differential Equations, pp. 127-132

Brandman, Jeremy — U.S. Naval Research Laboratory
Olson, Colin — U.S. Naval Research Laboratory

A new approach to time-optimal path planning for cooperative swarms of underwater vehicles in the presence of ocean currents is presented. Specifically, the determination of a time-optimal rendezvous among a swarm of vehicles is carried out by solving a family of Hamilton-Jacobi partial differential equations. The resulting algorithm is fast, globally time-optimal, and scales linearly with the number of vehicles. The method is validated through several examples for which optimal trajectories are known from the calculus of variations. Additional examples are also included.

15:20-15:40 TueAfternoonB.2

Path Planning for a Cooperative Navigation Aid Vehicle to Assist Multiple Agents Sequentially, pp. 133-138

Wolek, Artur — University of North Carolina at Charlotte

This paper considers planning a path for a single underwater cooperative navigation aid (CNA) vehicle to sequentially aid a set of N agents to minimize average navigation uncertainty. Both the CNA and agents are modeled as constant-velocity vehicles. The agents travel along known nominal trajectories and the CNA plans a path to sequentially intercept them. Navigation aiding is modeled by a scalar discrete time

Kalman filter. During path planning, the CNA considers surfacing to reduce its own navigation uncertainty. A greedy planning algorithm is proposed that uses a heuristic to schedule agents to the CNA that is based on the optimal time-to-aid, the overall navigation uncertainty reduction, and the transit time. The approach is compared to an optimal (exhaustive enumeration) algorithm through a Monte Carlo experiment with randomized agent trajectories and initial navigation uncertainty.

15:40-16:00 TueAfternoonB.3

Centralized Underwater Cooperative Transport with Safety Constraints, pp. 145-152

Iversflaten, Markus H. Norwegian University of Science and Technology
Schmidt-Didlaukies, Henrik M. Norwegian University of Science and Technology
Pettersen, Kristin Y. Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy Norwegian University of Science and Technology (NTNU)

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.

16:00-16:20 TueAfternoonB.4

COLSim, a Simulator for Hybrid Navigation Acceptability and Safety, pp. 139-144

Clement, Benoit ENSTA Bretagne, CROSSING IRL CNRS 2010
Chaffre, Thomas Flinders Unicersity
Sarhadi, Pouria University of Hertfordshire
Dubromel, Marie ENSTA Bretagne

Autonomous vessels have emerged as a prominent and accepted solution. However, achieving full autonomy for marine vessels requires the development of robust and reliable mission planning and control systems that can handle various encounters with manned and unmanned vessels while operating effectively in various weather and sea conditions. These algorithms need to account for various aspects of a mission like global/local planning, manoeuvrability limitations, external disturbances, Collision Avoidance (COLAV), motion regulations. A significant challenge in this pursuit is ensuring the autonomous vessels' compliance with the International Regulations for Preventing Collisions at Sea (COLREGs). This paper proposes a (prototypical) realisation of an open-source simulator including replay of AIS Data. The aim of this simulator is to provide fast simulation feeded with real data and including autonomous agents.

16:20-16:40 TueAfternoonB.5

Cooperative Control of Teams of Catamaran Surface Vessels with Noisy Dynamics, pp. 153-158

Mwaffo, Violet United States Naval Academy

This work investigates the cooperative control of teams of unmanned water surface vehicles (USVs) affected by maritime disturbances like water waves, currents, and wind encapsulated as stochastic noise. A distributed control strategy using local team communication is introduced to navigate the USVs through waypoints, maintaining desired formations and avoiding collisions. The control's bounded convergence is assessed using a Lyapunov-based approach adapted to stochastic systems. Numerical simulations are used to confirm the effectiveness of the control scheme, highlighting the balance between control parameters and noise intensity. Notably, the stochastic process is pivotal in replicating the noise observed in the USV kinematic variables while avoiding singularities caused by the collision avoidance forces.

TueAfternoonC Cascades

Maritime Robotics II (Regular Session)

Chair: Bibuli, Marco CNR-INM
Co-Chair: Mahmoudian, Nina Purdue University

15:00-15:20 TueAfternoonC.1

Heterogeneous Multi-Robot (UAV-USV-AUV) Collaborative Exploration with Energy Replenishment, pp. 159-164

Li-Fan, Wu Purdue University
Rastgaar, Mo Purdue University
Mahmoudian, Nina Purdue University

This work enables heterogeneous robot collaborative exploration using aerial (UAV), surface (USV), and underwater (AUV) vehicles. The approach employs dynamic programming to determine the optimal number of heterogeneous vehicles based on their characteristics and battery capacity of mobile charging stations. Collaborative Coverage Path Planning (CPP) execution, treated as a multi-traveling salesman problem, utilizes the Genetic Algorithm to get near-optimal solutions. Furthermore, Dijkstra's algorithm is integrated to address obstacles like islands and coral reefs, ensuring efficient energy replenishment for UAVs and AUVs. The strategy can be applied to short-term missions like rescue and delivery, as well as long-term operations like surveillance.

15:20-15:40 TueAfternoonC.2

Visual and Hydrodynamic Feedback Control of a Robotic Fish for Inline Swimming, pp. 165-170

Yen, Wei-Kuo — University of Maryland
Bhingradiya, Kruti — University of Maryland
Regli, Anthony — University of Maryland, College Park
Paley, Derek A. — University of Maryland

This paper develops a method to control the downstream position of the sensor-equipped follower in a pair of two robotic fish swimming in an inline configuration. To swim against the incoming flow, the follower estimates the relative flow velocity using a Bayesian filter with pressure measurements and sets it as the reference to control its flapping amplitude. To maintain its downstream position relative to the leader, the follower extracts the oscillation frequency, phase, and separation distance of the leader from onboard camera images. Water tunnel experiments confirm the feasibility of using hydrodynamic and visual measurements for swimming speed and downstream position control.

15:40-16:00 TueAfternoonC.3

Hybrid Cable Thruster Actuated Remotely Operated Underwater Vehicle, pp. 171-176

Attia, Youssef — Universit`a Degli Studi Di Genova
Simetti, Enrico — University of Genova
Gouttefarde, Marc — LIRMM, Univ. Montpellier, CNRS

This paper introduces a novel Hybrid Cable Thruster Actuated Remotely Operated Underwater Vehicle (HCT-ROV), merging the strengths of ROVs and Cable-Driven Parallel Robots for enhanced underwater capabilities. It presents the world's first HCT-ROV prototype, together with a control law using Quadratic Programming (QP) for efficient operation. Extensive MATLAB simulations and prototype tests demonstrate superior performance in tasks like object transportation. This research work paves the way for advanced underwater exploration and operations, emphasizing the need for further optimization in real-world applications.

16:00-16:20 TueAfternoonC.4

Virtual-Target Based Path-Following in the 3D Underwater Environment, pp. 177-182

Bibuli, Marco — CNR-INM

This work focuses on the design of a 3D path-following strategy for under-actuated underwater vehicles. The modeling of the problem relies on the Serret-Frenet apparatus, leading to the definition of the position error dynamics, with respect to a generic smooth curve in the operational 3D space. On the basis of such a model, a virtual-target based non-linear guidance law, derived by the exploitation of Lyapunov methodology, is designed. The theoretical proof and simulation results prove the functionality and reliability of the proposed approach.

16:20-16:40 TueAfternoonC.5

Path Following Model Predictive Control of a Coupled Autonomous Underwater Vehicle, pp. 183-188

Jimoh, Isah Abdulrasheed — University of Strathclyde
Yue, Hong — University of Strathclyde

The operation of an autonomous underwater vehicle (AUV) faces challenges in following predetermined waypoints due to coupled motions under environmental disturbances. To address this, a 3D path following guidance and control system is developed in this work based on the line-of-sight (LOS) guidance method. Conventionally, the 3D path following problem is transformed into heading and depth control problems, assuming that the motion of the vehicle is decoupled in horizontal and depth coordinates. The proposed control system design avoids this simplifying assumption by transforming the problem into a 3D position and orientation tracking problem. This design is achieved by computing a 2D horizontal coordinate based on the desired heading and then computing a corresponding LOS depth coordinate. A model predictive controller (MPC) is then implemented using the 3D LOS coordinate and the computed orientation vector. The MPC obtains a robust control by solving a minimax optimisation problem considering the effects of unknown ocean disturbances. The effectiveness of the proposed guidance and control system is demonstrated through the simulation of a prototype AUV system. Numerical results show that the AUV can follow predetermined waypoints in the presence of time-varying disturbances, and the system is steered at a constant surge speed that is proportional to the radius of the circle of acceptance used to implement the guidance system.

WedMorningA Assembly Hall

Adaptive Robust I (Regular Session)

Chair: Cichella, Venanzio — University of Iowa

Co-Chair: Mandić, Luka — Faculty of Electrical Engineering and Computing, University of Zagreb

09:50-10:10 WedMorningA.1

Adaptive Control of a Two-Zone Model of Electric Ship Power Electronics Power Distribution System, pp. 189-195

Alavi, Zahrasadat — California State University Chico

Kredo, Kurtis — California State University Chico

Mustafa, Hadil — California State University Chico

Zenor, John — California State University Chico

Crosbie, Roy — California State University Chico

Power system operations must be robust to unexpected non-ideal conditions. In an attempt to create more robust Power Electronic Power Distribution Systems in ships in the event of changes in the ambient characteristics such as temperature or load changes, a Model Reference Adaptive Control was implemented. Our approach was based on distributed control of the converters in a two-zone model and for the two types of converters present in the system. This work used adaptive law based on instantaneous cost to modify the existing control coefficients in an online mode. The result is that the designed adaptive control can readjust the transient and steady state responses of the converters when they deviate from their original forms in case of any of the unexpected conditions.

10:10-10:30 WedMorningA.2

Application of Modified Model Reference Adaptive Controller and Observer (MRACO) for Speed Control of an Unmanned Underwater Vehicle, pp. 196-202

Ohrem, Sveinung Johan — SINTEF Ocean

Haugaløkken, Bent Oddvar Arnesen — SINTEF Ocean

Holden, Christian — Norwegian University of Science and Technology

In this paper, a modified Model Reference Adaptive Controller and Observer (MRACO), including an integral term to handle external disturbances, is applied to control, independently, the surge and sway speeds of an unmanned underwater vehicle (UUV). The suitability of the method is shown in simulation and in an experiment on a real system where a use-case from aquaculture robotics is demonstrated. The results show that the modified MRACO method is capable of controlling the surge and sway speeds accurately despite being derived on a simplified model of the UUV system used.

10:30-10:50 WedMorningA.3

Adaptive and Robust Direct Data-Driven Controller for Surface Vessel Navigation, pp. 203-208

Mandić, Luka — Faculty of Electrical Engineering and Computing, University of Z

Nad, Dula — University of Zagreb

Miskovic, Nikola — University of Zagreb Faculty of Electrical Engineering and Compu

The challenging and unpredictable nature of the marine environment poses challenges for both human operators and non adaptive automatic controllers. This paper introduces and applies an extension of the DeePC algorithm as the vessel controller, aligning with the increasing trend of data-driven reference tracking in control system theory. The algorithm records input-output pairs during vessel operation, constructs a linear model that mimics the recorded system's trajectory and uses filtered and corrected trajectory required for the future behavior prediction in the direct data-driven scheme. The resulting controller is closed-loop stable, outperforms conventional control methods and is able to adapt to changing model parameters over time. The method is evaluated on a simulated Unmanned Surface Vehicle (USV), where it is initially used as a velocity controller and then extended to a dynamic positioning controller.

10:50-11:10 WedMorningA.4

Autopilot System for Depth and Pitch Control in Underwater Vehicles: Navigating Near-Surface Waves and Disturbances, pp. 209-214

Petrov, Vladimir — The University of Iowa

MacLin, Gage — The University of Iowa

Cichella, Venanzio — University of Iowa

This paper introduces a framework for depth and pitch control of underwater vehicles in near-surface wave conditions. By effectively managing tail, sail plane angles and hover tank operations utilizing a Linear Quadratic Regulator controller and (mathcal{L}_1) Adaptive Autopilot augmentation, the system ensures balanced control input distribution and significantly attenuates wave disturbances. This development in underwater vehicle control systems offers potential for improved functionality across a range of marine applications. The proposed framework is demonstrated to be robust in wave conditions, enabling more precise navigation and improved safety in operational scenario. The effectiveness of this control strategy is validated through extensive simulations using the Joubert BB2 model.

11:10-11:30 WedMorningA.5

Object Manipulation in Marine Environments Usin Reinforcement Learning, pp. 215-222

Ahmed, Ahmed — Khalifa University of Science and Technology

Ud Din, Muhayy — Universitat Politcnica De Catalunya (UPC)

Mohammed Abdul, Mughni Irfan — Khalifa University
Irfan, Hussain — Khalifa University of Science and Technology

Performing intervention tasks in the maritime domain are crucial for safety and operational efficiency. The unpredictable and dynamic marine environment makes the intervention tasks such as object manipulation extremely challenging. This study proposes a robust solution for object manipulation from a dock in the presence of disturbances caused by sea waves. To tackle this challenging problem, we apply a deep reinforcement learning (DRL) based algorithm called Soft Actor-Critic (SAC). SAC employs an actor-critic framework; the actors learn a policy that minimizes an objective function while the critic evaluates the learned policy and provides feedback to guide the actor-learning process. We trained the agent using the PyBullet dynamic simulator and tested it in a realistic simulation environment called MBZIRC maritime simulator. This simulator allows the simulation of different wave conditions according to the World Meteorological Organization (WMO) sea state code. Simulation results demonstrate a high success rate in retrieving the objects from the dock. The trained agent achieved an 80 percent success rate when applied in the simulation environment in the presence of waves characterized by sea state 2, according to the WMO sea state code.

WedMorningB — Solitude

GNC II (Invited Session)

Chair: Zhang, Yan-Yun — KU Leuven
Co-Chair: Verbeke, Mathias — KU Leuven
Organizer: Dhyani, Abhishek — Delft University of Technology
Organizer: Wang, Yunjia — KU Leuven
Organizer: Verbeke, Mathias — KU Leuven
Organizer: Reppa, Vasso — Delft University of Technology

09:50-10:10 — WedMorningB.1

Uncertainty-Aware Decision Making for Safe Navigation of Autonomous Ships (I), pp. 223-228

Hansen, Peter Nicholas — Technical University of Denmark
Prabowo, Yaqub Aris — Technical University of Denmark
Papageorgiou, Dimitrios — Technical University of Denmark - DTU
Galeazzi, Roberto — Technical University of Denmark

During ship encounters, uncertainty surrounding other vessels' intentions and future trajectories can complicate situation assessment. When encountering an erratic vessel, navigators will take precautionary actions to avoid any risk of collision. This paper introduces a new decision-making algorithm tailored to address uncertainty in vessel encounters at sea. The proposed method achieves this by defining the risk of a future scenario as the combination of two factors: the probability of collision and the magnitude of the uncertainty. As this method does not assume deterministic future trajectories for either of the vessels, it can therefore be applied to any pair of vessels, and it allows the use for anticipation of future behaviours of other vessels in a scene. The method is verified through a simulation study.

10:10-10:30 — WedMorningB.2

Experimental Identification of Decoupled Ship Dynamic Models for an Autonomous Catamaran Urban Cargo Vessel (I), pp. 229-234

Zhang, Yan-Yun — KU Leuven
Billet, Jef — KU Leuven
Slaets, Peter — KUleuven

KU Leuven developed and launched the Maverick catamaran in 2023, designed specifically for autonomous cargo transportation in narrow urban waterways. This vessel features a distinct actuation system utilizing two 360-degrees-steerable azimuth thrusters, positioned at the bow and stern. This study proposes and experimentally identifies decoupled ship dynamic models for the Maverick that concentrate on surge and yaw. The models aim to predict the vessel's speed and heading, particularly when steered by a bow thruster, sailing stably around service speed along the waterway. To do so, two sets of experiments were designed, each dedicated to collecting data for the individual identification of the decoupled models. These experiments deviate from the conventional use of standard maneuvers such as zigzag or turning, which are intended for maneuverability assessment of sea-going rudder-propeller vessels. Instead, sinusoidal excitation maneuvers were employed to better suit the dynamic system of the Maverick with its unique actuation system and operational strategy. Finally, a comparison is made between model predictions and a manually executed waterway-following maneuver recorded for reference. The results underline the suitability of the identified models for accurate trajectory prediction during the stable sailing scenario with small external disturbance and minor course curvature.

10:30-10:50 — WedMorningB.3

Uncertainty Aware Path Planning and Collision Avoidance for Marine Vehicles (I), pp. 235-240

Ahmadi Dastgerdi, Karim — Queen's University Belfast
Singh, Bhawana — Queen's University Belfast United Kingdom
Naeem, Wasif — Queen's University of Belfast
Athanasopoulos, Nikolaos — Queen's University Belfast
Lecallard, Benoit — Artemis Technologies Ltd

Motion planning, a challenging problem for any autonomous agent, becomes even more difficult for marine craft due to under-actuation, nonlinear and unmodelled kinematics, uncertainties and noise in sensor data, uncertain obstacles, wind and waves. We consider a marine

craft with unmodelled kinematics, subject to environmental disturbances and in the presence of moving obstacles with unknown kinematics. We utilise a Luenberger observer structure to estimate the marine craft and obstacles kinematics in real-time using sensor data. We furthermore bound the estimation error and subsequently use it explicitly in the determination of the guidance control laws. The modular nature of this algorithm enables integration with existing state-of-the-art path planning methods. The effectiveness of our proposed approach is illustrated and compared using Imazu benchmark scenarios and several existing planning methods, specifically, velocity obstacle method, geometric line-of-sight (LOS), time-critical LOS based guidance methods (finite-time), assuming unmodelled kinematics of the marine and obstacles craft, while being exposed to wind effects.

10:50-11:10 WedMorningB.4

Advancing Sparse Classical Scene Flow into the Maritime Domain (I), pp. 241-246

Dalhaug, Nicholas — Norwegian University of Science and Technology
Nygård, Trym Anthonsen — Norwegian University of Science and Technology
Stahl, Annette — Norwegian University of Science and Technology
Mester, Rudolf — Norwegian University of Science and Technology (NTNU)
Brekke, Edmund F. — Norwegian Univ. of Science and Tech

For Unmanned Surface Vehicles (USVs) to navigate safely without collisions, target tracking of other boats is essential. By utilizing stereo cameras, instead of for example time-of-flight sensors like lidar and radar, the frame-to-frame data association can be solved based on image patch similarity, and the frame rate is higher. In this paper we develop a method for sparse scene flow using a dual baseline stereo camera setup, propagating the short baseline disparity to see farther. By utilizing a dense disparity image and successively refining the depth using pyramidal Lucas-Kanade optical flow (pLK), the disparity of points across a wide baseline has been successfully estimated. An analysis of what parameters to use in the pLK, both for sparse stereo matching and in optical flow in the maritime domain, shows that too large window size makes pLK track the background. The parameters that are analyzed are the window size and the pyramid levels in pLK. We furthermore demonstrate the use of scene flow for tracking in the maritime domain. The methods have been tested on real data gathered during the summer of 2023 in Trondheim, Norway.

11:10-11:30 WedMorningB.5

Model-Based Reinforcement Learning for Ship Path Following with Disturbances (I), pp. 247-252

Dong, Zhengyang — Wuhan University of Technology
Chen, Linying — Delft University of Technology
Huang, Yamin — Delft University of Technology
Chen, Pengfei — Wuhan University of Technology
Mou, Junmin — Wuhan University of Technology

Modelling and control of ships is a challenging task due to their intrinsic nonlinearities and high uncertainty. In the complex and dynamic sea environment, the efficacy of well-designed motion controllers diminishes significantly. To achieve optimal performance, high-performance motion control systems must possess the ability to adapt to diverse working conditions, repel external disturbances, and incorporate learning capabilities. In addressing critical computational challenges encountered in the real-world deployment of autonomous driving agents, Reinforcement Learning (RL) methods have been effectively employed. This paper proposed a reinforcement learning control method for ship path following based on an environmental disturbance model. RL is utilized to learn the dynamic properties of the system to resist environmental disturbances. Experimental results show that the method can follow the path with acceptable accuracy and high robustness.

WedMorningC — Cascades

Nonlinear and Optimal I (Regular Session)

Chair: Coates, Erlend M. — Norwegian University of Science and Technology
Co-Chair: Woolsey, Craig — Virginia Tech

09:50-10:10 WedMorningC.1

Nonlinear Model Predictive Control for Sinusoidal Gait Tracking for an Underwater Snake Robot, pp. 253-258

Orucevic, Amer — Norwegian University of Science and Technology (NTNU)
Foseid, Eirik Lothe — Norwegian University of Science and Technology
Lysø, Mads Erlend Bøe — NTNU
Pettersen, Kristin Y. — Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy — Norwegian University of Science and Technology (NTNU)

Energy efficiency is crucial for the operational time and reach of autonomous underwater vehicles (AUVs). A new class of AUVs, underwater snake robots (USRs), has an articulated body that may be utilized to enhance propulsion efficiency and achieve energy autonomy. This paper applies nonlinear model predictive control (NMPC) to achieve sinusoidal gait tracking for underwater snake robots (USRs). We present a comprehensive simulation study that incorporates high-fidelity modeling of fluid-structure interaction, which validates the control design. Additionally, we showcase the potential for significant energy savings by fine-tuning the cost function, leading to reduced actuator power consumption.

10:10-10:30 WedMorningC.2

Surface Contour Following by an Underwater Vehicle with Integral Action, pp. 259-264

Willebeek-LeMair, Ian — Virginia Tech
Grant, Curtis — Virginia Tech

Lambert, William — Virginia Tech
Brizzolara, Stefano — Virginia Tech
Woolsey, Craig — Virginia Tech

This paper describes the modification and extension of an earlier nonlinear control method for near-surface contour following by an underactuated autonomous underwater vehicle (AUV). The slender AUV has direct control in yaw, pitch, roll, and surge, but cannot directly generate a heave or sway force. A potential energy shaping control law is used to track a reference attitude that is generated using proportional-integral-derivative action on depth relative to a desired contour that corresponds to the slowly varying part of the free surface height. In this application, the vehicle operates close enough to the surface that added mass and inertia vary with depth, memory effects are important, and surface wave effects cannot be ignored. Preliminary robustness results for the proposed contour following system are also presented.

10:30-10:50 — WedMorningC.3

Nonlinear PID Control for Automatic Docking of a Large Container Ship in Confined Waters under the Influence of Wind and Currents, pp. 265-272

Lexau, Simon J. N. — Norwegian University of Science and Technology (NTNU)
Lekkas, Anastasios M. — Norwegian University of Science and Technology
Breivik, Morten — Norwegian University of Science and Technology

This study addresses the challenges of maneuvering a large container ship in confined waters under the influence of wind and currents. The proposed guidance, navigation, and control system presents a novel combination of modeling methodologies, control allocation techniques, and nonlinear control systems theory. We consider a docking scenario through a simulation of a realistic, narrow harbor accommodating area-specific currents and global wind forces. Control allocation is solved by utilizing detailed models of the actuators and hydrodynamics in a mixed-integer-like solution for optimal thrust allocation, and an inverse mapping to the control inputs. Furthermore, our approach introduces a modified Wageningen B-Series model, that is capable of modeling propellers with negative pitch dynamics. The complexity of safely docking in environments like the Antwerp harbor, where wind and currents pose significant risks, is tackled using a nonlinear PID control system integrated with Line-Of-Sight (LOS) guidance. This enables precise maneuvering of a fully actuated Roll-On/Roll-Off vessel to its docking position and orientation. Given that few studies on automated docking holistically address the intricate challenges of complex harbor environments and the concurrent impact of multiple external forces, our work proposes a comprehensive solution based on an integrated combination of guidance, navigation, and control systems.

10:50-11:10 — WedMorningC.4

A Comparative Study of Control Laws for Maritime Surface Vessels Tracking an Underwater Vehicle, pp. 273-280

Frafjord, Aksel Trentemøller — Norwegian University of Science and Technology
Saksvik, Ivar — Oslo Metropolitan University
Kjerstad, Øivind Kåre — The University Centre in Svalbard
Coates, Erlend M. — Norwegian University of Science and Technology

This paper compares the tradeoffs between performance and implementation efforts of three pure pursuit control laws; a proportional-integral-derivative (PID), nonlinear model predictive (NMPC) and a deep reinforcement learning (DRL) trained neural network (NN). The control laws are employed on a target tracking problem where the issue is to keep an unmanned surface vessel (USV) within proximity to a submerged autonomous underwater vessel (AUV) for optical communication to operate. The results from a simulation case study, show that the PID settled with a steady error of 2 m from the target, the NMPC at 2.4 m and the NN at 2.3 m. The relative control effort is highest for the PID at 100%, the NMPC settled at 98% and the NN at 96%. The PID represents a methodology that has transparent and time-efficient tuning rules together with a high update rate of 11,5 kHz. The NMPC provides a flexible tuning method but requires an accurate dynamic model and has the slowest update rate of 5.2 Hz. The DRL stand as a viable solution to solve the control problem and has an update rate of 4,2 kHz, but it bears the most time-consuming implementation and tuning of the three alternatives presented here.

11:10-11:30 — WedMorningC.5

PID-Fixed Time Sliding Mode Control for Trajectory Tracking of AUVs under Disturbance, pp. 281-286

Close, Jack — Queen's University Belfast
Van, Mien — Queen's University Belfast
McIlvanna, Stephen — Queen's University Belfast

A novel approach is proposed for the trajectory tracking control of Autonomous Underwater Vehicles (AUVs). Firstly, previous implementations of Proportional-Integral-Derivative (PID) and Sliding Mode Control (SMC) are discussed and their disadvantages are highlighted in terms of fixed time convergence and the chattering phenomenon. Secondly, to improve the stability of the tracking performance and convergence of the system, a controller combining PID and Fixed Time SMC (FTSMC) is proposed for AUVs. The proposed controller is then applied to simulate a 6 Degrees-of-Freedom (6DOF) BlueRov2 underwater robot and the results are analytically discussed. The simulation results show that the proposed PID-FTSMC controller can accurately control the BlueRov2 in trajectory tracking operations with faster convergence and no oscillations around the set reference, even under disturbance

WedAfternoonA — Assembly Hall

Intelligence and Autonomy (Regular Session)

Chair: Saad, Aya — SINTEF Ocean AS
Co-Chair: Clement, Benoit — ENSTA Bretagne, CROSSING IRL CNRS 2010

14:20-14:40 — WedAfternoonA.1

Learning-Based Integrated Cooperative Motion Planning and Control of Multi-AUVs, pp. 295-300

Behnaz, Hadi	Babol Noshirvani University of Technology
Khosravi, Alireza	NoshirvaniUniversity of Technology
Sarhadi, Pouria	University of Hertfordshire
Clement, Benoit	ENSTA Bretagne, CROSSING IRL CNRS 2010
Ali, Memarzadeh	Babol Noshirvani University of Technology

This paper introduces a learning-based solution tailored for the integrated motion planning and control of Multiple Autonomous Underwater Vehicles (AUVs). Tackling the complexities of cooperative motion planning, encompassing tasks such as waypoint tracking and self/obstacle collision avoidance, becomes challenging in a rule-based algorithmic paradigm due to the diverse and unpredictable situations encountered, necessitating a proliferation of if-then conditions in the implementation. Recognizing the limitations of traditional approaches that are heavily dependent on models and geometry of the system, our solution offers an innovative paradigm shift. This study proposes an integrated motion planning and control strategy that leverages sensor and navigation outputs to generate longitudinal and lateral control outputs dynamically. At the heart of this cutting-edge methodology lies a continuous action Deep Reinforcement Learning (DRL) framework, specifically based on the Twin Delayed Deep Deterministic Policy Gradient (TD3). This algorithm surpasses traditional limitations by embodying an elaborated reward function, enabling the seamless execution of control actions essential for maneuvering multiple AUVs. Through simulation tests under both nominal and perturbed conditions, considering obstacles and underwater current disturbances, the obtained results demonstrate the feasibility and robustness of the proposed technique.

14:40-15:00 WedAfternoonA.2

Active Pose - Autonomous Hole-Filling Techniques for 3D Surface Reconstruction for Enhancing Underwater Exploration, pp. 287-294

Yip, Mau Hing	Department of Engineering Cybernetics, NTNU
Schellewald, Christian	Sintef Ocean
Gambin, Gambin	Heritage Malta/xlendi Archaeological Park
Stahl, Annette	Norwegian University of Science and Technology

Underwater exploration and research face significant challenges, including incomplete data collection and the high cost of operations. An underwater robot's capacity to independently identify, target, and address gaps in 3D surface data, termed as 'holes', during a mission has the potential to significantly lower the expenses associated with research endeavors, such as those in underwater archaeology, and to improve sea surface mapping for autonomous robots. This study introduces a novel approach that combines the boundary-edge of a triangle mesh with Principal Component Analysis (PCA) to actively gather incomplete data. We propose two distinct techniques for active hole-filling, as well as a method to determine the most appropriate strategy. We introduce the flying-over and following-rail approaches to automatically determine new sensor positions for collecting additional point cloud data, which are then used to reconstruct the surface and fill the gaps. Experiments were conducted using both simulated underwater images with ORB-SLAM3 (Campos et al. (2021)) and real-world Multibeam Echo Sounder data.

15:00-15:20 WedAfternoonA.3

Automation at Sea and Human Factors, pp. 301-306

Grosser, Linda	University of South Australia
Wilkinson, Chelsea	University of South Australia
Oppert, Michelle	University of South Australia
Banks, Siobhan	University of South Australia
Clement, Benoit	ENSTA Bretagne, CROSSING IRL CNRS 2010

Collisions at sea can have severe effects for humans and the environment, leading to costs for marine organisations. Human factors, particularly fatigue, contribute to more than 80% of maritime collisions. Ships and vessels have become increasingly sophisticated in design and more recently, autonomous navigation systems have been integrated to reduce human errors associated with collisions. The rise in maritime traffic makes these autonomous systems crucial for enhancing safety. A challenge for autonomous navigation systems, causing contention among mariners and within maritime literature, is compliance with COLREG (Convention on the International Regulations for Preventing Collisions at Sea). An emerging solution to this challenge involves the development of a light simulator (COLSim) that leverages historical AIS (Automatic Identification System) data to introduce multiple autonomous vehicles into real-world scenarios, while incorporating the COLREG rules to avoid collision. Acceptance of autonomous navigation systems is important for the future of transportation at sea and is the natural evolution of maritime traffic. As AI is still evolving, humans will continue to play a vital role in the operation of ships and vessels and interpretation of COLREGs. In the future, human-AI interactions will be important for work, health, and organisational safety, where both humans and AI can support each other. Finding a balance between human expertise and AI assistance is essential for the maritime industry's future safety and efficiency.

15:20-15:40 WedAfternoonA.4

Batch Estimation of a Steady, Uniform, Flow-Field from Ground Velocity and Heading Measurements, pp. 307-312

Wolek, Artur	University of North Carolina at Charlotte
McMahon, James	Naval Research Laboratory

This paper presents three batch estimation methods that use noisy ground velocity and heading measurements from a vehicle executing a circular orbit (or similar large heading change maneuver) to estimate the speed and direction of a steady, uniform, flow-field. The methods are based on a simple kinematic model of the vehicle's motion and use curve-fitting or nonlinear least-square optimization. A Monte Carlo simulation with randomized flow conditions is used to evaluate the batch estimation methods while varying the measurement noise of the data and the interval of unique heading traversed during the maneuver. The methods are also compared using experimental data obtained with a Bluefin-21 unmanned underwater vehicle performing a series of circular orbit maneuvers over a five hour period in a tide-driven flow.

15:40-16:00 WedAfternoonA.5

Mouth Opening Frequency of Salmon from Underwater Video Exploiting Computer Vision, pp. 313-318

Schellewald, Christian — Sintef Ocean
Saad, Aya — SINTEF Ocean AS
Stahl, Annette — Norwegian University of Science and Technology

Maintaining fish welfare is one of the most prevailing and challenging tasks in aquaculture production, in particular as there can be more than 200,000 fish present within a single sea cage. Observing this amount of individual animals is a very challenging task and requires a high degree of automated computer vision-based monitoring along with the use of advanced machine learning and AI algorithms. This paper introduces a computer vision based approach for determining the ventilation frequency in terms of the mouth opening frequency of salmon in aquaculture environments through underwater video analysis. We exploit an object detection network to detect specific salmon features including head, eye, snout, mouth and then apply optical flow analysis to the snout region to assess their ventilation rates, serving as a potential indicator of fish health and well-being. This aims towards analyzing salmon behavior on individual level in real-time, enabling an in-depth view of the population's status. Our methodology represents a significant progress towards a more automated salmon monitoring providing an objective measure to determine an important aspect of fish behaviour in an effective way which will subsequently help to enhance efficiency in aquaculture operations. The results, obtained from analyzing annotated videos are very promising and validate the usability of our approach. This study also paves the way for further exploration into utilizing computer vision and machine learning for comprehensive fish status assessment, contributing valuable insights into sustainable aquaculture practices.

WedAfternoonB Solitude

GNC III (Invited Session)

Chair: Dhyani, Abhishek — Delft University of Technology
Co-Chair: Verbeke, Mathias — KU Leuven
Organizer: Dhyani, Abhishek — Delft University of Technology
Organizer: Wang, Yunjia — KU Leuven
Organizer: Verbeke, Mathias — KU Leuven
Organizer: Reppa, Vasso — Delft University of Technology

14:20-14:40 WedAfternoonB.1

Who Performs Better? a Comparison between Backstepping and Model Predictive Control for Ship Trajectory Tracking (I), pp. 319-324

Qiu, Qianqian — Wuhan University of Technology
Chen, Linying — Delft University of Technology
Chen, Pengfei — Wuhan University of Technology
Huang, Yamin — Delft University of Technology
Li, Mengxia — Wuhan University of Technology
Mou, Junmin — Wuhan University of Technology

This paper aims to solve the trajectory tracking control problem for Autonomous Surface Vessels with nonlinear and cross-coupled models, system constraints, and unknown disturbances. Two advanced control methods, backstepping and model predictive control (MPC), are respectively applied to design controllers for the fully actuated surface vessels. The former represents the mainstream method to deal with nonlinear systems based on Lyapunov theory, and the designed backstepping controller ensures that all signals within the closed-loop trajectory tracking control system are globally uniformly ultimately bounded. The latter is an optimization-based time-domain control method with the distinct feature of systematically handling system constraints. MPC addresses the optimization problem to determine a sequence of actions that steer the autonomous vessel in the correct direction. Only the first action in this sequence is applied, and in the subsequent step, the optimization problem is resolved in a receding horizon fashion. Classical confront newly arising, who will perform better? A series of simulations are conducted to compare the results of the two methods regarding tracking speed, accuracy, constraints handling, and robustness. Consequently, a comprehensive analysis of the advantages and disadvantages of the two methods is provided.

14:40-15:00 WedAfternoonB.2

Research on ASV/ROV Cooperative System with AI for Seagrass Distribution Survey (I), pp. 325-328

Yamamoto, Ikuo — Nagasaki University
Akihiro, Morinaga — Nagasaki University
Oshino, Taishi — Nagasaki Univeisity
Kinoshita, Kyohei — Nagasaki University
Izumi, Yasunori — MUSOKAGAKU.inc

The authors developed the ASV/ROV cooperative system. The ASV has four thrusters located in a rhombus arrangement which enables omnidirectional movement. The developed ASV is equipped with GNSS, with such functions as dynamic positioning and automatic navigation by setting up route coordinate in advance. Moreover, it has a cable control device for linkage with ROV. A cable wound by drum is connected with a PC on the ASV through a slipring. In addition, a cage for ROV storage is set up between floating units of the ASV. The cage height is adjustable for the ROV to limit the hydrodynamic resistance during ASV cruising. It can take 3D underwater pictures and transmit images to land in real time. The ASV determines its movement from the relative position and azimuth of the ROV, as well as the cable length. The relative position of the ROV to the ASV is determined by an acoustic positioning system. Also, the ROV has AI system to catch images and grasp an image by DPS against current disturbance. The developed ASV/ROV cooperative mobility vehicle was

successfully tested in the ocean for monitoring seaweeds and useful for CO2 measurement in the sea.

15:00-15:20 WedAfternoonB.3

Autonomously Docking a Feeder Vessel; an Experimental Validation (I), pp. 329-334

de Kruif, Bas MARIN

Docking a ship is an integral part of sailing between ports. Due to the change in course and speed, the approach to the dock is considered a difficult part of this operation. In previous work, we applied the Guidance-Navigation-Control (GNC) framework to autonomously dock in a simulation. In this work we validate if this framework can dock a 1:17 scale-model of a 71~m feeder vessel and investigate when the controlled system has difficulties tracking its trajectory.

The test were performed in MARIN's Sea keeping and Manoeuvering Basin such that we could systematically test for wave and wind disturbances. The results show that the controlled system could dock the vessel while approaching from different angles and countering several disturbance levels. The position errors during the approach phase became larger if the guidance requested a large course change at low speed, or if a significant drift angle was needed just to sail straight due to wind and waves. The effect of these errors were mitigated by the bow thrusters when they became active in the final phase of the docking.

15:20-15:40 WedAfternoonB.4

A POMDP Model-Based Online Risk Mitigation Method for Autonomous Inland Vessels (I), pp. 335-340

Dhyani, Abhishek Delft University of Technology
Wang, Yunjia KU Leuven
Verbeke, Mathias KU Leuven
Pissoort, Davy KU Leuven
Reppa, Vasso Delft University of Technology

Autonomous surface vessels (ASVs) increasingly gain appeal in the maritime industry for their high efficiency and improved navigational capabilities. However, risks originating from various internal and external factors such as faults, traffic, harsh weather conditions, etc., can affect their guidance and control capabilities and impact nominal vessel operations. The existing risk mitigation methods mainly focus on the vessel's guidance system and do not consider unsafe actions due to the control system. In this paper, we propose a new method based on a partially observable Markov decision process (POMDP) model for the online risk mitigation of autonomous inland vessels. The POMDP model-based method utilizes information about situational awareness to assist the vessel's planning and control system in real-time decision-making during hazardous situations, thereby ensuring that the vessel remains in a minimum-risk condition. Based on the identified risk-influencing factors (RIFs), the transition probabilities are updated by a Bayesian belief network (BBN). A case study of an autonomous inland vessel navigating in a confined waterway is presented to demonstrate the capability of the proposed method.

15:40-16:00 WedAfternoonB.5

Good Seamanship Score Quantification in Complex and Congested Waterways (I), pp. 341-346

Prabowo, Yaqub Aris Technical University of Denmark
Hansen, Peter Nicholas Technical University of Denmark
Papageorgiou, Dimitrios Technical University of Denmark - DTU
Galeazzi, Roberto Technical University of Denmark

This paper presents a novel method to quantify seafarers' good seamanship during navigation scenarios with multi-vessel encounters, in open and confined waters, and to compute COLREG's-compliant path deviations for avoiding collision and grounding. Accurate quantification of good seamanship necessitates comprehensive information about the vessels state and the surrounding environment, obtainable through the AIS system and electronic nautical charts. Our work advances the current state-of-the-art by: (1) incorporating a normalized grounding risk for navigating confined waters, (2) factoring in speed changes for a probabilistic assessment of collision risk, and (3) considering the minimum possible scenario risk based on vessel kinodynamic constraints. The proposed method is evaluated using historical AIS data and sea charts of Danish waters. The evaluation results demonstrate improved fairness scoring by acknowledging that navigators may lack risk-free options.

WedAfternoonC — Cascades

Nonlinear and Optimal II (Regular Session)

Chair: Skjetne, Roger — Norwegian Univ of Science and Technology
Co-Chair: Basso, Erlend A. — Norwegian University of Science and Technology

14:20-14:40 WedAfternoonC.1

Power-Based Safety Constraint for Redundant Robotic Manipulators, pp. 347-353

Tveter, Erling Norwegian University of Science and Technology
Pettersen, Kristin Y. Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy Norwegian University of Science and Technology (NTNU)

A robot making or losing contact with its environment will experience a sudden change in its dynamics. This may cause instability, possibly causing the robot to harm itself and its environment. To prevent this while not placing overly restrictive constraints on the energy generated by the controller, we place a time-varying constraint on the system's power. The power limit varies with a heuristic measure of a desired task trajectory's stability, which is based on the largest Lyapunov exponent. When the trajectory is deemed unstable, the controller is forced to dissipate energy, while it is allowed to generate energy when the trajectory is stable. The constraint is included in a strict task-priority framework, allowing a redundant robotic platform to perform several tasks simultaneously while ensuring that the performance of the

higher-priority tasks is not affected by the lower-priority tasks. The presented method is validated by simulation of an articulated intervention autonomous underwater vehicle (AIAUV).

14:40-15:00 WedAfternoonC.2

Learning Optimal Guidance Schemes with Safety Guarantees for Underactuated Marine Vehicles, pp. 354-359

Foseid, Eirik Lothe — Norwegian University of Science and Technology
Basso, Erlend A. — Norwegian University of Science and Technology
Schmidt-Didlaukies, Henrik M. — Norwegian University of Science and Technology
Marley, Mathias — Norwegian University of Science & Technology
Pettersen, Kristin Y. — Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy — Norwegian University of Science and Technology (NTNU)

In this paper, we propose a guidance scheme for underactuated marine vehicles with collision-avoidance guarantees. The guidance scheme is based on a line-of-sight approach and ensures path-following when safety allows it, but deviates from the desired path if safety mandates it. We provide formal safety guarantees by proving forward invariance of the collision-free safe set using a barrier function. However, while barrier-function-based control schemes provide formal safety guarantees, the real-life performance is often lacking due to the challenge of manually tuning such controllers. We demonstrate that the performance of the control law can be improved by replacing a part of the control law by a neural network, while retaining the same formal safety guarantees.

15:00-15:20 WedAfternoonC.3

Energy-Shaping Control for Swimming in Underwater Snake Robots, pp. 360-367

Lysø, Mads Erlend Bøe — NTNU
Pettersen, Kristin Y. — Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy — Norwegian University of Science and Technology (NTNU)

In this paper, we present a joint controller for stabilizing a swimming gait for underwater snake robots. The controller is based on energy-shaping control, and it is shown to render the gait exponentially orbitally stable for a range of control parameters. In addition to shaping the energy of each joint oscillation, the phase differences between them are stabilized to a desired phase shift. The result is a set of synchronized, shifted oscillations, constituting the swimming gait. Furthermore, a simulation study is conducted, in which the proposed controller is found to exhibit significantly greater robustness to disturbances than an existing joint controller from the literature.

15:20-15:40 WedAfternoonC.4

MPC Path Following with Macroscopic Shape Adjustment for AIAUVs, pp. 368-373

Gushkov, Ivan Ivanov — NTNU
Pettersen, Kristin Y. — Norwegian Univ. of Science and Tech
Gravdahl, Jan Tommy — Norwegian University of Science and Technology (NTNU)

This paper treats the problem of adjusting the macroscopic shape of an articulated robotic system following a path, such that the shape fits the path curve as closely as possible. We propose a way of quantifying the fit of the robot's shape to the path through the errors of the individual links, and investigate a kinematic MPC solution to the problem. The MPC generates position and velocity reference trajectories, which respect the constraints of the system, to be fed to a low-level controller. The scheme is evaluated in a kinematic level simulation study with constant irrotational ocean currents.

15:40-16:00 WedAfternoonC.5

Maneuvering-Based Dynamic Thrust Allocation for Fully-Actuated Vessels, pp. 374-379

Gezer, Emir Cem — Norwegian University of Science and Technology
Skjetne, Roger — Norwegian Univ of Science and Technology

This paper introduces a new approach to solving the thrust allocation problem using the maneuvering problem in the maritime domain for fully actuated vessels. The method uses a control Lyapunov function to create a nonlinear reference filter for the thruster forces. The filter ensures dynamic tracking of the optimal thrust allocation solution with rate limitation in the output thruster references. It further uses control barrier functions to ensure that the thruster force saturation limits are respected. The approach aims for simplicity and effectiveness, as well as smooth and dynamic thruster reference signals, in the implementation of thrust allocation for marine vessels.

ThuMorningA	Assembly Hall
Renewable Energies I (Invited Session)	
Chair: Ringwood, John	Maynooth University
Co-Chair: Coe, Ryan	Sandia National Laboratories
Organizer: Ringwood, John	Maynooth University

09:50-10:10 ThuMorningA.1

Exploiting Fano Resonance in Wave Energy Systems (I), pp. 380-385

Ermakov, Andrei — Maynooth University
Rose-Butcher, Jack — Hanze University of Applied Science
Stepanyants, Yury — University of Southern Queensland
Ringwood, John — Maynooth University

Energy maximising control of wave energy converters (WECs) typically results in exaggerated motion of the device, with consequent increases in mooring and other forces which can adversely affect WEC lifetime. In addition, the exaggerated motion typically increases the incidence of nonlinear hydrodynamic effects, confounding linear analysis upon which many WEC control design paradigms are based. This paper explores the potential to exploit Fano resonance in a wave energy context, where the WEC body remains relatively stationary, while the active power take-off elements are well exercised. Preliminary results suggest that significant WEC body motion reduction is possible, with a modest reduction in energy capture.

10:10-10:30 ThuMorningA.2

Accelerated MPC for Wave Energy Converters, Using Duality Techniques (I), pp. 386-391

Scruggs, Jeff — University of Michigan
Veurink, Madelyn — Michigan Technological University
Ligeikis, Connor — University of Michigan

In order to maximize power generation performance in stochastic response, the power generated by an ocean wave energy converter (WEC) must be controlled in real-time, based on feedback measurements of the dynamic response, as well as feed-forward measurements of the free-surface elevation. Even when the dynamics of the WEC are presumed to be linear, the existence of constraints on its admissible dynamic response result in a optimal nonlinear control problem. The principal constraints are the maximum allowable force and maximum allowable displacement of the power take-off (PTO) system. Model-predictive control (MPC) can be used to maximize power generation performance, subject to these constraints. MPC requires that an optimization problem be periodically solved in real-time, and the computational time associated with this algorithm increases with the length of the time horizon used in the algorithm. Performance also increases with the time horizon, motivating the use of the longest horizon that is computationally-feasible. In this paper we show preliminary results which indicate that, by using duality techniques, the computational time needed to solve the MPC optimization problem for WEC control problems can be reduced significantly, thereby enabling much longer time horizons to be used.

10:30-10:50 ThuMorningA.3

Nonlinear Control Design for a Spherical Wave Energy Converter (I), pp. 392-397

Abdulkadir, Habeebullah — IOwa State University
Abdelkhalik, Ossama — Iowa State University
Shabara, Mohamed — National Renewable Energy Laboratories

This paper discusses the development of two nonlinear controls for a nonlinear spherical wave energy converter (WEC) to maximize the energy it harvests from the waves. The first control is a simple nonlinear damping control, which is designed based on the hydrodynamic damping coefficients. These control coefficients are then optimized using a Genetic Algorithm. The second is a nonlinear optimal control derived analytically using the Pontryagin minimum principle for comparison. The study found that the nonlinear optimal control improves the device's performance by effectively leveraging the hydrodynamic nonlinearity from the floater's shape. The nonlinear bang-singular-bang (BSB) control showed an average 20% performance improvement over the nonlinear damping control (NLDC).

10:50-11:10 ThuMorningA.4

Constrained Pseudo-PI Linear Control of a Wave Energy Converter Via Model Predictive Control (I), pp. 398-403

Shifat, Tanvir Alam — Oregon State University
Coe, Ryan — Sandia National Laboratories
Bacelli, Giorgio — Sandia National Laboratories
Brekken, Ted — Oregon State University

Due to the inherent unpredictability of ocean waves, an advanced control technique is required to maximize power capture and improve the efficacy of wave energy converters (WECs). This paper investigates three different design approaches to find appropriate weight matrices for a model predictive controller (MPC) that mimics a proportional-integral (PI) controller under unconstrained operation. Later, the optimal design method is used to tune the MPC and implemented with a point absorber WEC model. The results were validated by comparing those with the previously determined linear feedback controller for maximum power capture. This approach enables the PI-emulating MPC to operate as a linear controller without constraints and revert to a conventional MPC under constraints, offering a flexible and effective control solution for WECs.

11:10-11:30 ThuMorningA.5

Fuzzy Logic Control of Wave Energy Converters (I), pp. 404-409

Shabara, Mohamed — National Renewable Energy Laboratories
Grasberger, Jeff — Sandia National Laboratories
Tom, Nathan — National Renewable Energy Laboratory
Abdelkhalik, Ossama — Iowa State University

This paper investigates the application of a fuzzy logic controller (FLC) to a nonlinear wave energy converter (WEC) system by comparing its performance with two linear controllers, proportional-integral (PI) and bang-singular-bang (BSB), as well as one nonlinear controller, sliding mode control (SMC). The study explores a trajectory derived under the linear assumption as the testing ground and applies a saturation limit on the control force. The linear controllers are evaluated based on their effectiveness within the linearized trajectory, while the nonlinear controllers, especially FLCs, are analyzed for their adaptability to the inherent complexities of nonlinear WEC systems. Through simulations, the paper quantifies the advantages and challenges of each controller type, shedding light on the potential of FLCs in enhancing the efficiency and adaptability of nonlinear WECs in real-world scenarios.

ThuMorningB Solitude

Industry Talk (Regular Session)

Chair: McCummins, Robert — Leidos
Co-Chair: de Kruif, Bas — MARIN

09:50-10:10 ThuMorningB.1

*Development of an Auto-Docking System for the Leisure Boat**

Kim, Surim — AVIKUS
Hujae, Choi — Avikus Co., Ltd
Kim, Inbeom — Avikus

Docking for leisure boat has required expert piloting due to the reduction of maneuvering performance caused by low speed. Docking piloting, in addition, requires considering the disturbance such as wind and current to be included in the docking process, and collision risk due to other boats or complex infrastructure of marina. Addressing these challenges, Avikus, a subsidiary of HD Hyundai, has developed the flagship model, “CoPilot” system-an autonomous leisure boat solution aimed at enhancing user experience and preventing accidents. CoPilot provides two main functions: auto pilot and auto docking. Auto pilot provides route planning, navigation, route tracking. While executing route tracking, the collision avoidance and adaptive cruise shall be activated considering relative distance and speed to other boats and obstacles which detected by sensor fusion. For user's comfort, auto heading and stay here function are also included. Auto docking provides adaptive docking guidance path, auto docking control which compensate disturbance. Auto docking also provides collision avoidance control which consider the obstacles and dock-able zone. In this study CoPilot-AutoDock, an autonomous docking solution is introduced. The system of CoPilot-AutoDock consisted of four distinct phases: approaching, dynamic positioning (DP), docking, and recovery. Entire docking process is designed to approach entrance of docking site(approaching phase), decelerate for stability(DP phase), and execute docking maneuvers to get into the target docking site applying disturbance(docking phase). Throughout the entire phase, real-time success rate is continuously computed to evaluate docking conditions, considering the control performance, safety envelope(the dock-able zone), the distance to dock and the obstacles such as other boats and infrastructure. When the success rate is lowered than the threshold value due to the disturbance or obstacles, the boat starts to restore its status to normal by switching to recovery phase. To verify the performance of the proposed docking algorithm, a series of docking tests were conducted using actual leisure boats.

10:10-10:30 ThuMorningB.2

*Automatic Docking Operation of a Leisure Boat Considering Discontinuous Thruster Allocation**

Hujae, Choi — Avikus Co., Ltd
Kim, Surim — AVIKUS
Kim, Inbeom — Avikus
Nam, Bo Woo — Seoul National University
Park, Jinmo — Avikus

The docking operation of a boat refers to a sequential procedure, including approaching, maneuvering, and final adjustment, that enables the boat to move smoothly close to the designated docking area, such as a quay wall. Generally, a high degree of skill is required to dock the boat without collision, as the boat docks at a low speed with reduced controllability, and considerable blind spots may exist at the side and rear areas. Additionally, unexpected ocean environmental disturbances, such as gusts or currents in the harbor, significantly impede safe docking operations. Therefore, for auto-docking operations, a highly accurate and robust control algorithm is necessary along with appropriate guidance and sensor systems. Another important technical issue arises from conventional engines used in boats, which maintain an idle rpm of around 600 rev/min, limiting the ability to command rpm below this threshold. This scenario resembles parking a car solely by shifting gears between Drive, Neutral, and Reverse without engaging the brake. Avikus, South Korea company that founded 2021, has been developing ADAS (Advanced Driver Assistance Systems) and autonomous navigation systems for leisure boats. Avikus is aimming of introducing our leisure boat ADAS products to the market starting next year. Our product range also includes a boat automatic docking system. As mentioned earlier, due to the absence of brakes in boats, achieving precise control while reducing speed during docking requires consideration of the discontinuous nature of thrusters. This ultimately poses a challenge in performing appropriate control allocation. In this presentation, it is represented that how we overcame these challenges to develop an automatic docking solution for boats. We introduced a control allocation technique utilizing by Fuzzy-style controller design or by optimization methods. Performance metrics for control allocation were introduced, and conducted performance comparison among the techniques through model simulations. Finally, the auto-docking controller was embedded into Avikus' testbed boat, the Quicksilver 29ft, and its performance was validated through field tests.

10:30-10:50 ThuMorningB.3

Autonomous Sailing System: Real-Ship Trial with Various Encountering Scenarios in the Port of Ghent, pp. 410-411

Miao, Tianlei RH Marine
el Amam, Ehab RH Marine

This presentation outlines a real-ship trial of our autonomous sailing system, carried out in the Grootdok area of the Port of Ghent, Belgium. Central to this system is the Collision Avoidance System (CAS), designed to generate a collision-free path for the ship in near to middle-range waters. Next to that, it is designed to execute this maneuver to avoid a potential collision and grounding. An advanced real-time collision avoidance algorithm, the improved hybrid A-star with finite control behaviors, stands as the cornerstone of the CAS. This algorithm has been developed as part of a PhD trajectory. The effectiveness of this algorithm has been thoroughly validated through massive simulations and real-ship experiments.

The system was installed on the 9 meters, Stan Patrol 900 vessel, refitted and enhanced with advanced sensors like Lidar and cameras by Damen to serve as an intelligent ship platform. The testing area is a harbor zone, approximately 144 m by 700 m, serving as a defined boundary for the navigable space. During the test, the harbor water was calm and the wind level was low. Vessels docked on both sides acted as static objects during the trial. Alongside the primary autonomous vessel, three other ships were involved in the trial as dynamic objects to assist. All ships are equipped with AIS transmitters and AIS data served as the source for object detection and measurement.

Throughout the trials, various encounter scenarios with one or more target vessels were tested in conjunction with port boundaries, including overtaking, head-on and crossing. The trials set different initial states that could lead to collision risk, such as approaching a target vessel with a lower speed sailing in the same lane from behind, heading to a target vessel with the overlapped planning trajectory, and encountering at the same position with a target vessel crossing from the right. For each vessel, one or two seafarers were onboard to maneuver the vessels to the initial state and take over the ship in any case of danger. During the trials, the autonomous vessel successfully adjusted its course, completed it safely and maintained a sufficient distance from these objects.

10:50-11:10 ThuMorningB.4

USV Behavior Advancements to Enhance Data Collection in the Surfzone, pp. 412-412

Bak, Andrew Spicer US Army Engineer Research and Development Center
Walls, Andrew US Army Engineer Research and Development Center
Glaspell, Garry P. US Army Engineer Research and Development Center
Conery, Ian W. US Army Engineer Research and Development Center

Very shallow water and surfzone environments are chal- lenging places to operate any type of vehicle which, natu- rally, lends itself to the usage of Uncrewed systems (UxS). For civilian operations, bathymetric data are often col- lected to help enable coastal management. The bathymet- ric profile controls wave energy dissipation and circulation patterns Anderson et al. (2021); Bak et al. (2019), and on sandy beaches can vary daily. Military operations, both offensive and humanitarian aid related, require traveling through the surfzone, which can be dangerous, particu- larly when bathymetry is unknown. Vehicle mobility in the surfzone is further complicated by the high hydrody- namic loading from breaking waves (initiated by shallow depths) which injects turbulence creating strong flows with high spatio-temporal variability, making a complex 4-D problem. These problems are compounded as wave height grows and vessel size is reduced. The constant change drives uncertainty in way-point based mission planning. If unaccounted for, this often results in coverage gaps or hazard (beachface/sandbar) interaction. Our work aims to develop adaptive behaviors to these existing environmental considerations.

11:10-11:30 ThuMorningB.5

Identify, Evaluate, and Reduce Uncertainty Margins in Maritime Situational Awareness, pp. 413-413

Hem, Audun Gullikstad Norwegian University of Science and Technology

Maritime Robotics develops unmanned surface vessels (USVs), and situational awareness is an important aspect of their functionality. Easy and safe remote operation requires a precise and easily managed overview of the surrounding area, and this becomes even more important when autonomy is involved. For the USV to make correct decisions it must know its environment.

One of the primary tasks when creating a system for situational awareness is to identify, evaluate, and if needed reduce the uncertainty margins. To do this, we need to know how these uncertainties are introduced, and how these impact different parts of the wider system. To ensure safe operation, the safety margins in the system will have to be conservative, and they will ultimately dictate what areas a vessel can safely operate in.

When an autonomous system only has uncertain information available, its functionality will be restricted. Say, for example, that any target estimate can be expected to have a course estimate standard deviation of 25 degrees. If its position has to be predicted 60 seconds in the future, this uncertainty will result in a large area where the target may be located. Any maneuvers to avoid the target will then have to account for this. The same problem applies to all kinds of obstacles, and it may render the USV unable to operate in an area with limited space for maneuvering. As such, better situational awareness with a more precise picture of the surrounding area will open new areas of operation, both literally and figuratively.

ThuMorningC — Cascades

Maritime Safety and Decision Support (Regular Session)

Chair: Hasan, Agus Norwegian University of Science and Technology
Co-Chair: Hahn, Axel Carl Von Ossietzky Universität Oldenburg

09:50-10:10 ThuMorningC.1

Experimental Validation of an Intent-Inference-Based Ship Collision Avoidance Algorithm, pp. 414-418

Park, Jinwook KAIST

Choi, Jiyong — Korea Advanced Institute of Science and Technology
Kim, Jinwhan — KAIST
Park, Jeonghong — KRISO (KOREA Research Institute of Ships and Ocean Engineering)
Yeo, Dong Jin — Korea Research Institute of Ships & Ocean Engineering

In this paper, we present an experimental study and analysis of an algorithm that infers the maneuver intentions of encountered ships and incorporates them into ship collision avoidance. Since not all ships strictly adhere to the collision avoidance regulations outlined by the International Maritime Organization, inferring the intent of encountered ships and integrating them into collision avoidance is crucial. We conducted experiments using physical scale model ship tests to validate the performance of the proposed intent-inference-based collision avoidance algorithm.

10:10-10:30 ThuMorningC.2

A Conceptual Approach to Harbor Object Detection: The Potential of 3D-LiDAR-Based Sensor Fusion for High Precision ENC, pp. 419-424

Pieper, Fynn — German Aerospace Center (DLR)
Hahn, Axel — Carl Von Ossietzky Universität Oldenburg

In the advancing era of autonomous maritime navigation, the precision of Electronic Nautical Charts (ENCs) is critical. This study conceptualizes a framework to validate and rectify ENCs in real-time, leveraging high-resolution 3D LiDAR, DGPS, and IMU data. The approach of this study includes a domain-specific point cloud filtering, object segmentation, classification in compliance with the S-101 standard classes and a georeferencing strategy. By comparing identified objects against ENC data, this study pinpoints discrepancies and augments the ENCs with up-to-date object information. An evaluation through field tests is proposed, complemented by Traffic Sequence Charts and reference calibration via Realtime Kinematic GPS, ensuring practical relevance of our framework to real-world conditions. The contribution of this paper lies in offering a comprehensive solution for real-time ENC refinement, thereby facilitating safer autonomous navigation by verifying that ENCs are reflective of current environmental conditions.

10:30-10:50 ThuMorningC.3

Vision-Driven UAV River Following: Benchmarking with Safe Reinforcement Learning, pp. 425-431

Zihan, Wang — Purdue University
Mahmoudian, Nina — Purdue University

In this study, we conduct a comprehensive benchmark of the Safe Reinforcement Learning (Safe RL) algorithms for the task of vision-driven river following of Unmanned Aerial Vehicle (UAV) in a Unity-based photo-realistic simulation environment. We empirically validate the effectiveness of semantic-augmented image encoding method, assessing its superiority based on Relative Entropy and the quality of water pixel reconstruction. The determination of the encoding dimension, guided by reconstruction loss, contributes to a more compact state representation, facilitating the training of Safe RL policies. Across all benchmarked Safe RL algorithms, we find that First Order Constrained Optimization in Policy Space achieves the optimal balance between reward acquisition and safety compliance. Notably, our results reveal that on-policy algorithms consistently outperform both off-policy and model-based counterparts in both training and testing environments. Importantly, the benchmarking outcomes and the vision encoding methodology extend beyond UAVs, and are applicable to Autonomous Surface Vehicles (ASVs) engaged in autonomous navigation in confined waters.

10:50-11:10 ThuMorningC.4

Safeguarding Autonomous Surface Vessels against Cyber-Attacks on Sensor Systems, pp. 432-437

Kuncara, Ivan Adi — Chonnam National University
Widyotriatmo, Augie — Bandung Institute of Technology
Hasan, Agus — Norwegian University of Science and Technology

This paper presents a novel approach to enhance the cybersecurity of autonomous surface vessels (ASVs) by introducing a secure state estimation framework. The proposed methodology focuses on detecting and estimating the magnitude of sensor attacks through the utilization of an adaptive observer. The process involves filtering measurement signals and integrating them into the ASV's state space model. The adaptive observer is then applied to accurately estimate the magnitude of potential attacks. Simulation results illustrate the high accuracy of the proposed observer in both detecting and estimating the attack magnitude. This innovative approach contributes significantly to fortifying the resilience of ASVs against sensor threats, ultimately enhancing their reliability and security in operational scenarios.

11:10-11:30 ThuMorningC.5

Analysis of LiDAR-Camera Fusion for Marine Situational Awareness with Emphasis on Cluster Selection in Camera Frustum, pp. 438-443

Obradovic, Juraj — FER, University of Zagreb
Fabijanic, Matej — Faculty of Electrical Engineering and Computing Zagreb
Batos, Matko — Faculty of Electrical Engineering and Computing
Miskovic, Nikola — University of Zagreb Faculty of Electrical Engineering and Compu

Providing accurate information about all objects in the environment surrounding an autonomous vehicle is essential for the development of a maritime navigation system used on board autonomous and unmanned vessels. In this paper, we introduce a method that integrates LIDAR and camera data for precise 3D object detection and tracking. The approach utilizes LiDAR for acquiring object position information and ensures accurate object classification through data from the camera. The proposed architecture is presented with a detailed explanation of all algorithms used. Several scenarios have been created in a simulated environment to compare three approaches for the selection of target object in the camera frustum: the Nearest Center, Gaussian Likelihood, and Intersection-Over-Union). Finally, the full algorithm setup is tested in a simulator environment with multiple vessels and a background coast. Additionally, three proposed methods for selecting the target object in the camera frustum are compared.

ThuAfternoonA	Assembly Hall
Renewable Energies II (Invited Session)	
Chair: Ringwood, John	Maynooth University
Co-Chair: Sun, Jing	Univ of Michigan
Organizer: Ringwood, John	Maynooth University

14:20-14:40 ThuAfternoonA.1

Force-Limited Control of Wave Energy Converters Using a Describing Function Linearization (I), pp. 444-449

McCabe, Rebecca — Cornell University
Haji, Maha — Cornell University

Actuator saturation is a common nonlinearity. In wave energy conversion, force saturation conveniently limits drivetrain size and cost with minimal impact on energy generation. However, such nonlinear dynamics typically demand numerical simulation, which increases computational cost and diminishes intuition. This paper instead uses describing functions to approximate a force saturation nonlinearity as a linear impedance mismatch. In the frequency domain, the impact of controller impedance mismatch (such as force limit, finite bandwidth, or parameter error) on electrical power production is shown analytically and graphically for a generic nondimensionalized single degree of freedom wave energy converter in regular waves. Results are visualized with Smith charts. Notably, systems with a specific ratio of reactive to real mechanical impedance are least sensitive to force limits, a criteria which conflicts with resonance and bandwidth considerations. The describing function method shows promise to enable future studies such as large-scale design optimization and co-design.

14:40-15:00 ThuAfternoonA.2

Co-Design of a Wave Energy Converter for Autonomous Power (I), pp. 450-455

Coe, Ryan — Sandia National Laboratories
Devin, Michael — Sandia National Laboratories
Michelén, Carlos — Sandia National Laboratories
Lee, Jantzen — Sandia National Laboratories
Bacelli, Giorgio — Sandia National Laboratories
Keow, Alicia — Sandia National Lab
Gaebele, Daniel Tim — Oregon State University
Grasberger, Jeff — Sandia National Laboratories
Spencer, Steven — Sandia National Laboratories
Spinneken, Johannes — Evergreen Innovations
Neary, Vincent — Sandia National Laboratories
Meuris, Brek — Sandia National Laboratories

A "bolt-on" wave energy converter is designed to provide power for sensors on an existing oceanographic buoy. The narrow-banded pitch/roll response of the target oceanographic buoy lends itself to a tuned-resonator design, for which we suggest a novel "pitch resonator" wave energy converter concept. Using a pseudo-spectral method, the performance of the proposed wave energy converter is modeled in the range of sea states expected to be present at the target deployment location to study the effect of flywheel inertia on performance. The results show that the system can marginally meet the desired power demands, but suggest that related design concepts may be worth consideration.

15:00-15:20 ThuAfternoonA.3

Robust Power Peak Seeking Control of Hydrokinetic Turbines, pp. 456-461

Naik, Kartik Praful — University of Michigan
Valachovic, Henry — University of Michigan
Sun, Jing — Univ of Michigan

Focusing on a hydrokinetic turbine application, this work presents a control strategy that is robust to changes in both flow speed and the turbine state-of-health (SOH). The proposed control strategy, namely Robust Power Peak Seeking, achieves maximum power point tracking through a line search triggered by real-time measurements. The developed control strategy is able to match the ceiling control performance of a nonlinear feedback controller with perfect knowledge of SOH and flow. This study also outlines the complexities associated with flow and SOH estimation while deriving detection strategies for each scenario. Finally, the benefits of the proposed formulation are demonstrated through improved flow and SOH estimation when compared to the standard quadratic speed feedback control strategy.

15:20-15:40 ThuAfternoonA.4

Waves Filtering in Heading Controllers: Impact on the Power Production of an Energy Ship, pp. 462-467

Juin-Gauthier, Giovanni — Nantes Université, Ecole Centrale De Nantes, LS2N
Babarit, Aurélien — Nantes Université, Ecole Centrale De Nantes
Elie, Baptiste — Farwind Energy
Kermorgant, Olivier — École Centrale De Nantes
Fremont, Vincent — Ecole Centrale De Nantes

This article investigates the impact on power production of an energy ship of two types of heading controllers. The first controller includes a

filter which eliminates the wave-frequency dependent motion of the ship, while the other aims at compensating the effects of waves on the motion of the ship. The study is based on a numerical model of the energy ship which is presented in the paper. Results show that waves compensation reduces the generated power variation but increases rudder oscillations. In the opposite, the waves filtering controller allows for a slightly greater power production at the expense of greater power variations.

ThuAfternoonB Solitude

Maritime Robotics III (Regular Session)

Chair: Schmidt-Didlaukies, Henrik M. Norwegian University of Science and Technology

Co-Chair: Hopwood, Jeremy Virginia Tech

14:20-14:40 ThuAfternoonB.1

Underwater Vehicle Navigation Using Bearing Measurements from a Mobile Beacon, pp. 468-473

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Autonomous underwater vehicles enable efficient underwater operations such as mapping, surveillance, and inspection. However, due to the lack of global navigation satellite systems (GNSS) signals, drift in pose estimates will occur over time. Common solutions to this issue are using either stationary or mobile beacons to provide range and possibly bearing measurements to bound the navigation error over time. However, this requires occupying communication bandwidth to get reliable round-trip range measurements. In this paper, we propose a system where a mobile beacon passively listens to communications from the underwater vehicle to estimate the position of the vehicle. We show that the estimation error is bounded over time through strategic movement of the mobile beacon.

14:40-15:00 ThuAfternoonB.2

A BlueROV2-Based Platform for Underwater Mapping Experiments, pp. 474-479

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We propose a low-cost laboratory platform for development and validation of underwater mapping techniques, using the BlueROV2 Remotely Operated Vehicle (ROV). Both the ROV and the objects to be mapped are placed in a pool that is imaged via an overhead camera. In our prototype mapping application, the ROV's pose is found using extended Kalman filtering on measurements from the overhead camera, inertial, and pressure sensors; while objects are detected with a deep neural network in the ROV camera stream. Validation experiments are performed for pose estimation, detection, and mapping. The litter detection dataset and code are made publicly available.

15:00-15:20 ThuAfternoonB.3

A Low-Cost 4K Video Streaming Underwater Observatory for Coastal Oceans, pp. 480-484

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Abstract: This paper presents an open-source underwater observatory for coastal data acquisition. The observatory combines a 4K underwater camera, an acoustic hydrophone, and auxiliary water quality sensors, linked by a tethered connection to a surface hub for remote data transmission. Due to the accumulation of microorganisms (biofouling) during long-time deployments, a magnetic wiper mechanism is integrated into the camera housing to clear the view. An open-source repository of the underwater observatory is made publicly available: https://github.com/OsloMet-OceanLab/aneris Keywords: Underwater Monitoring, Low-Cost System, Tethered Sensor Station

15:20-15:40 ThuAfternoonB.4

A High-Fidelity Unity Simulator for ROV Pilot Training, pp. 485-490

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Work-class ROVs are essential vehicles for subsea inspection, maintenance, and repair tasks. To improve ROV piloting skills, a virtual environment can be exploited to train pilots in underwater operations without the logistical and financial expenses of actual sea deployments. This paper presents a high-fidelity ROV simulator for pilot training, utilizing the Unity framework for photorealistic scene rendering. The simulator integrates with ROS for control tasks and is accessible via a WebSocket TCP/IP package, enabling remote user access. A practical application is demonstrated, where a simulated work-class ROV (Merlin ROV) engages with a visually rendered scene of a subsea installation in the North Sea. The simulation framework aims to bridge the gap between virtual training and real-world operations by providing

realistic graphics and accurate control dynamics. This work highlights the potential of game engine-based simulators in advancing the capabilities and efficiency of ROV pilot training.

ThuAfternoonC	Cascades
Adaptive Robust II (Regular Session)	
Chair: Monteriù, Andrea	Università Politecnica Delle Marche
Co-Chair: Jeinsch, Torsten	University of Rostock

14:20-14:40 ThuAfternoonC.1

Disturbance Observer Based Control for a Remotely Operated Vehicle, pp. 491-496

Baldini, Alessandro — Università Politecnica Delle Marche
Felicetti, Riccardo — Università Politecnica Delle Marche
Freddi, Alessandro — Universita' Politecnica Delle Marche
Monteriù, Andrea — Università Politecnica Delle Marche

This paper presents a Disturbance Observer Based Control scheme which deals with the full pose tracking control problem of a Remotely Operated Vehicle. The uncertainties are lumped, estimated by a Nonlinear Disturbance Observer and feed-forwarded in a tracking controller. The solutions only relies on known quantities, providing a dynamic disturbance compensation and ultimately bounded errors. The order of the disturbance observer is a design parameter, which is able to provide additional integral actions. Finally, numerical simulations test the proposed technique.

14:40-15:00 ThuAfternoonC.2

Adaptive Observer-Based Funnel Heading Control of Surface Vessels with Rudder Actuator Nonlinearity, pp. 497-502

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Poursadegh, Adeleh — Isfahan University of Technology , University of Guilan
Kurowski, Martin — University of Rostock
Jeinsch, Torsten — University of Rostock

In this work, an adaptive state observer based on the strictly positive real (SPR) theory in combination with funnel control is proposed for heading control of surface vessels with uncertainty in the model and subject to rudder dead-zone actuator nonlinearity. The rudder command is designed to guarantee predetermined transient and steady-state tracking performances for both heading angle and filtered virtual control tracking errors. The unknown nonlinear function in the model is tackled using an adaptive neural network and an adaptive mechanism is proposed to cope with the unknown control gain. To further improve the performance, an adaptive continuous chattering-free robust structure is considered. Using SPR Lyapunov synthesis approach, not only all the adaptive laws are derived but also it is proved that all the closed-loop signals are semi-globally uniformly ultimately bounded (SGUUB). Simulation results validate the efficiency and applicability of the proposed method.

15:00-15:20 ThuAfternoonC.3

Robust Interaction Using Generalized Super-Twisting Impedance Control, pp. 503-509

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With the goal of performing robotic intervention tasks reliably with high accuracy under uncertainty and unknown disturbances, robust control methods such as sliding mode are appealing. However, contact forces cannot be considered as disturbances in this setting and compliance to the unknown contact geometry and forces is crucial. Impedance control and passivity-based techniques can guarantee closed-loop stability when interacting with passive environments, but at the loss of precision. In this paper, we use the generalized super-twisting algorithm to obtain a controller which achieves the desired impedance even with disturbances like ocean currents and model errors. Global asymptotic stability is proved under perturbations with a bounded time derivative. The performance of the proposed super-twisting impedance control law is demonstrated in simulations of an underwater vehicle. It is compared with pure impedance control and first-order sliding mode and achieves the desired impedance with respect to the contact force despite model errors and ocean currents, with a continuous control input.