Blue Robotics Research:

Information: Hydrodynamic loads on a restrained ROV under waves and current - ScienceDirect

- **Hydrodynamic loads on a restrained ROV under waves and current**
- The study focuses on quantifying hydrodynamic loads on remotely operated underwater vehicles (ROVs), particularly the BlueROV2.
- The researchers approached the topic using eight tethers to restrain the ROV in the mid-depth of the FloWave wave and current test tank. This setup allowed the measurement of forces under realistic flow conditions around the ROV without significant interference.
- The paper presents the analysis of the load cell data as forces and moments in relation to the observed motion and rotation of the ROV.
- Quantified shadowing effects of cylinder in front of ROV.
- Validation experiment to support station keeping algorithms under realistic conditions
- Regular waves were tested as well as current speed coming from 4 directions.
- The paper provides insights into hydrodynamic loads on ROVs under various conditions, offering valuable information for design and control purposes.
- David M. Ingram
- 2021
- FloWave Ocean Energy Research Facility, School of Engineering, The University of Edinburgh
- Cited by 25
- 48 Citation

Information: JMSE | Free Full-Text | An Open-Source Benchmark Simulator: Control of a BlueROV2 Underwater Robot

- **An Open-Source Benchmark Simulator: Control of a BlueROV2 Underwater Robot**
- 2022
- Simon Pedersen
- AAU Energy, Aalborg University, 6700 Esbjerg, Denmark
- Department of Mechanical and Electrical Engineering, University of Southern Denmark, SDU, 6400 Sønderborg, Denmark
- 41 references
- Cited by 9

- This paper introduces a simulation model environment for the BlueROV2. The model is designed and experimentally validated to serve as a benchmark for control algorithms for underwater vehicles.
- It encompasses Fossen's equations, incorporating a kinematic model of the vehicle, hydrodynamics of vehicle-water interaction, dynamic thruster model, and gravitational/buoyant forces.
- Hydrodynamic parameters and thruster models are validated in a test facility, while ocean currents are modeled as constant velocity. The tether connecting the ROV to the top-site facility is modeled using the lumped mass method and implemented as a force input to the ROV model.
- A case study demonstrating the model's utility is presented, wherein a BlueROV2 inspects an offshore monopile structure using a sliding mode controller. The controller successfully meets the design criteria by accurately following the provided trajectory with minimal error.
- Overall, the simulator establishes a benchmark for future control schemes for position control and trajectory tracking, particularly under environmental disturbances.
- https://github.com/ROV-Simulator/ROV-Simulator
- The above github is a modular simulator fully implemented in MATLAB™ and Simulink™.
-

Information: Stabilization of a ROV in Three-dimensional Space Using an Underwater Acoustic Positioning System - ScienceDirect

- **Stabilization of a ROV in Three-dimensional Space Using an Underwater Acoustic Positioning System**
- Sigurd S. Klemmensen
- Department of Energy Technology, Aalborg University, Niels Bohrs Vej 8, 6700 Esbjerg, Denmark
- 2019
- Cited by 16
- 15 references
- This study investigates the feasibility of autonomous operation for the BlueROV2 inspection ROV prototype in three-dimensional space. The research involves modeling, identification, control development, and closed-loop simulations and experiments. The primary navigation system utilized is an Underwater Acoustic

Positioning System (UAPS), functioning as an underwater GPS unit. However, the UAPS introduces a significant output time delay, which is addressed using a Smith predictor.
- The study finds that the Smith predictor struggles to effectively handle the time delay, likely due to its time-variant nature.
- As a potential solution, the study proposes online identification of the time delay to minimize its impact as it varies over time.
- The LQRI controller with a Smith predictor fails to stabilize the ROV in two-dimensional space, likely due to the ineffective elimination of the negative impact of the UAPS time delay. Interestingly, employing alternative heave and yaw transmitters yields better performance in controlling the ROV.

Information: Data | Free Full-Text | Experimental Force Data of a Restrained ROV under Waves and Current

- **Experimental Force Data of a Restrained ROV under Waves and Current**
- David M. Ingram
- 30 references
- Cited by 22
- 2020
- The experiment aimed to investigate the hydrodynamic forces exerted on a commercially available underwater Remotely Operated Vehicle (ROV), the BlueROV2, by currents and waves, along with the effects of a simplified cylindrical obstacle.
- The paper outlines the setup, input values (current speed and wave definitions), and initial data processing. Additionally, a processed dataset is provided, including forces in all three main coordinate directions, synchronized with 6 degrees of freedom (DoF) results and free surface elevations. This dataset can serve as a validation experiment and facilitate the testing and development of algorithms for position control in similar ROVs.

Information: https://ieeexplore.ieee.org/abstract/document/8626127

- **Autonomous Navigation for Unmanned Underwater Vehicles: Real-Time Experiments Using Computer Vision**

- A Manzanilla
- Cited by 72
- French Mexican Laboratory on Computer Science and Control LAFMIA-UMI 3175, CINVESTAV-IPN, Mexico City, Mexico
- This paper investigates autonomous navigation for unmanned underwater vehicles (UUVs) by leveraging computer vision for localization. The approach employs parallel tracking and mapping with a single camera to localize the vehicle relative to a visual map.
- An extended Kalman filter (EKF) integrates visual information with data from an inertial measurement unit (IMU) to improve pose estimation and recover map scale. To achieve trajectory tracking, a proportional integral derivative (PID) controller with compensation for restoring forces is proposed. Depth control is facilitated by a pressure sensor, while yaw control utilizes a magnetometer. The EKF provides feedback for the remaining states. Real-time experiments validate the navigation strategy using the BlueROV2.
- This work focuses on achieving fully autonomous trajectory tracking for underwater vehicles by integrating Parallel Tracking and Mapping (PTAM) with Inertial Measurement Unit (IMU) data through an Extended Kalman Filter (EKF).
- The primary contribution of this work lies in implementing the PTAM algorithm for autonomous navigation of underwater vehicles and validating it through real-time experiments. Future efforts aim to embed the algorithms directly into the vehicle, reducing reliance on long tethers and thereby enhancing autonomy and coverage.

Information: A Nonlinear Model Predictive Controller for Remotely Operated Underwater Vehicles With Disturbance Rejection | IEEE Journals & Magazine | IEEE Xplore

- **A Nonlinear Model Predictive Controller for Remotely Operated Underwater Vehicles with Disturbance Rejection**
- Aristides Kiprakis
- 2020
- School of Engineering, The University of Edinburgh, Edinburgh EH9 3FB, U.K
- The paper introduces a novel nonlinear model predictive dynamic positioning controller for Remotely Operated Underwater Vehicles (ROVs) used in challenging sea conditions with various disturbances from waves, currents, and turbulence.
- These disturbances are incorporated into the nonlinear ROV dynamic and propulsion model, enabling the proposed controller to effectively reject them. The

strategy is based on nonlinear model predictive control (NMPC) and is evaluated using hardware-in-the-loop simulation with a numerical water tank model.
- This study contributes an important insight on future theoretical design of model predictive disturbance rejection controllers and illustrates their practical implementation on real hardware.
- This controller utilizes 6 degrees of freedom nonlinear ROV dynamic and propulsion models, integrating external disturbances as forces and moments within the state space model.
- The dynamic positioning task is formulated as an optimal control problem and solved through numerical optimization with a receding time horizon approach.
- Tank tests and hardware-in-the-loop simulations demonstrate that the nonlinear MPC can effectively reject complex disturbances, enabling precise station-keeping around set-points with minimal control effort compared to baseline PID and LQR controllers.
- Overall, the design of this nonlinear controller and the study results hold significance for the future development of stable ROVs in observation and manipulation tasks.

Information: https://www.mdpi.com/2504-446X/5/4/113

- **Design and Modeling of an Experimental ROV with Six Degrees of Freedom**
- Dr. Aleksey Kabanov
- 2021
- 25 references
- Cited by 25
- The article discusses the design and modeling of an experimental remotely operated underwater vehicle (ROV) with six degrees of freedom.
- It addresses the need for developing a range of autonomous and remotely operated underwater vehicles for various tasks, emphasizing cost reduction and increased functionality. The focus is on inspection class ROVs for coastal underwater inspection operations.
- The proposed ROV design achieves controllability in six degrees of freedom using six thrusters, which is fewer than the traditional eight-thruster layout. The article describes the ROV's design, presents the mathematical model, and discusses the results of modeling and experimental tests conducted on the developed ROVs.
- This work's purpose was to develop a new design of an inspection-class ROV, with minimal thrusters to achieve controllability in six degrees of freedom.

Information: https://flex.flinders.edu.au/file/27aa0064-9de2-441c-8a17-655405d5fc2e/1/ThesisWu2018.pdf

- **6-DoF Modelling and Control of a Remotely Operated Vehicle**
- Chu-Jou Wu, B.Eng
- 2018
- Flinders University
- Cited by 42
- Focuses on the modeling, system identification, and control system design for an observation class BlueROV2 Heavy.
- The first phase involves developing mathematical models and identifying relevant parameters for the vehicle. Modeling includes creating a 6-degree-of-freedom (6-DoF) model that encompasses thruster dynamics and vehicle motion dynamics.
- However, due to delays in receiving the BlueROV2 Heavy, experimental parameter estimation using immersion tank testing with onboard sensors could not be conducted. Instead, parameters were determined using technical specifications and published data.
- The identified model was then used to design a 6-DoF control system for the BlueROV2 Heavy, employing both conventional PID control and nonlinear model-based PID control. Simulation results showed that the nonlinear model-based control system outperformed the conventional PID controller, especially in handling external disturbances and executing complex movements or rotations. Robustness analysis using the Monte Carlo method demonstrated the feasibility of implementing the designed control system on the BlueROV2 Heavy, considering random disturbances and uncertainties in the model.
- The developed 6-DoF nonlinear model-based PID control system demonstrates superior control performance compared to the linear conventional controller. Simulation results indicate significant improvements in settling time and overshoot reduction, with at least a 42% decrease in settling time and a 62% reduction in overshoot. Despite requiring 138% more processing time, the nonlinear model-based control efficiently responds to dynamic disturbances and extends the operational range, accommodating current speeds up to 1.1 m/s compared to 0.4 m/s for the model-less control.
- Overall, the thesis concludes that the 6-DoF nonlinear model-based PID control system is viable for implementing precise position control of the BlueROV2 Heavy across all six degrees of freedom.

Information: https://www.frontiersin.org/articles/10.3389/fnbot.2021.801956/full

- **Underwater Localization and Mapping Based on Multi-Beam Forward Looking Sonar**
- Feihu Zhang
- School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an, China
- 2022
- 23 references
- Cited by 11
- This paper introduces a filter-based methodology for real-time underwater SLAM (Simultaneous Localization and Mapping) on small AUVs. It addresses challenges related to the vast amount of image sonar data and high latency of acoustic equipment.
- The methodology involves using a multi-beam forward-looking sonar (MFLS) to extract environmental features, followed by converting sonar images into sparse point cloud format (is a file format for storing 3D point cloud data) to manage data volume effectively. The DVL (Doppler Velocity Log), IMU, and sonar data are fused, and a Rao-Blackwellized particle filter (RBPF)-based SLAM method is employed to estimate AUV pose and generate an occupancy grid map.
- Experimental validation conducted in both controlled pool and real-world lake environments demonstrates the effectiveness of the proposed approach, showing improved performance in state estimation and divergence suppression compared to existing methods.
- "Two problems are solved: Aiming at the slow processing speed caused by a large amount of MFLS image data, and a method is proposed to convert the collected sonar image into sparse point cloud format data through threshold segmentation and distance-constrained filtering; Based on the proposed method, the DVL, IMU, and MFLS data are fused, and then the RBPF-based SLAM method is used to suppress the accumulation of errors of the inertial unit and generate an accurate occupancy grid map."

Information: https://www.mdpi.com/2073-4441/12/4/1196

- **Innovative Water Quality and Ecology Monitoring Using Underwater Unmanned Vehicles: Field Applications, Challenges and Feedback from Water Managers**
- Floris C. Boogaard
- 2020
- Cited by 34
- 36 References

- This paper highlights the increasing need for dynamic monitoring methods in water management due to climate change and urban development. It discusses the potential of aquatic drones equipped with sensors and cameras in addressing this need.
- The study, conducted in collaboration with local water managers in The Netherlands, presents outcomes, field experiences, and feedback from pilot applications.
- The use of underwater drones was found to provide valuable and cost-effective information that would be difficult to obtain using traditional methods.
- Key findings include the ability to capture three-dimensional data and underwater footage, map areas with varying vegetation, establish links between fauna/flora species and water quality, and observe variations in water quality parameters with depth.
- The paper also identifies opportunities for further application of this technology, discusses limitations and challenges, and proposes recommendations for future technical designs.

Information: https://www.sciencedirect.com/science/article/pii/S002980181831014X

- **Finite element cable-model for Remotely Operated Vehicles (ROVs) by application of beam theory**
- Ingrid Schjølberg
- Center for Autonomous Marine Operations and Systems, Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway
- 2018
- Cited by 45
- This paper introduces a novel three-dimensional cable model for Remotely Operated Vehicles (ROVs) using Euler-Bernoulli beam theory, aimed at enhancing autonomy, efficiency, and safety in subsea operations. Implemented in Matlab, the model accounts for various factors affecting underwater cables and ROV responses, including bending stiffness and cable compression. The non-linear equations resulting from the model are solved using the Galerkin finite element method for spatial discretization and the Newmark-β time integration scheme for temporal solution.
- Experimental verification of the model is conducted in ocean tank experiments with a real ROV system, demonstrating its accuracy and applicability. Additionally, a numerical example is provided, and the results are compared with previous findings. Finally, a sensitivity analysis for hydrodynamic parameters is presented,

further validating the model's robustness and utility in optimizing ROV control, operations, and design.
- Overall, the model accurately estimates cable response and tension forces in ROV-systems, validated experimentally and suitable for real-world applications. It can enhance numerical tools, simulators, and operator training and inform ROV design considerations such as maximum working depth and thrust requirements.
- Additionally, the model holds potential for state estimation, particularly in scenarios involving loss of acoustic positioning during deep-water operations. Its versatility makes it a valuable tool across various domains within underwater robotics and operations.

Information: https://www.sciencedirect.com/science/article/pii/S0022098119301868

- **Remotely operated vehicles as alternatives to snorkellers for video-based marine research**
- Vincent Raoult
- School of Environmental and Life Sciences, University of Newcastle, Ourimbah, NSW 2250, Australia
- 2019
- Cited by 27
- This is about marine research. Look more into it if needed.
- BlueROV2 heavy kit
- The passage discusses a study comparing the effectiveness of using mini-ROVs versus snorkelers for visual research in shallow marine environments, focusing on fish community sampling and behavior observation. It finds that mini-ROVs detect more fish and greater diversity compared to snorkelers, while being equally efficient in tracking fish behavior. Although responses differ slightly between the methods, the study concludes that mini-ROVs are a valuable tool for shallow marine research, offering logistical, financial, and experimental advantages. It predicts increased usage of mini-ROVs for marine research in the future.

Information: https://ieeexplore.ieee.org/abstract/document/10335654

- **Development and High-Fidelity Simulation of Trajectory Tracking Control Schemes of a UUV for Fish Net-Pen Visual Inspection in Offshore Aquaculture**
- Thein Than Tun
- 2023

- 65 references
- Three controllers, namely 1) Proportional-Derivative control with restoring force & moment compensation (Compensated-PD), 2) Proportional-Integral-Derivative control with restoring force & moment compensation (Compensated-PID), and 3) computed torque (or) inverse dynamics control (CTC/IDC) were conducted on a 6 degrees-of-freedom (DoF) BlueROV2 Heavy Configuration dealing with 12 error states (pose and twist).
- Results show that while utilizing the minimum thrust, CTC/IDC outperforms Compensated-PID and Compensated-PD in overall trajectory tracking under different underwater current disturbances.
- Numerical results measured with root-mean-square-error (RMSE), mean-absolute-error (MAE) and root-sum-squared (RSS) are reported for comparison, and simulation results in the form of histograms, bar charts, plots, and video recordings are provided.
- Future work will explore advanced controllers, with a specific emphasis on energy-optimal control schemes, accompanied by comprehensive stability and robustness analyses applied to linear and nonlinear UUV models.

Information: https://ieeexplore.ieee.org/abstract/document/9568805

- **Design and Fabrication of a Low-Cost 6 DoF Underwater Vehicle**
- Francesco Maurelli
- Jacobs University Bremen gGmbH, Bremen, Germany
- University of Central Punjab, Lahore, Pakistan
- 9 references
- This paper discusses the design and fabrication of such a vehicle to have a low-cost tag than its contemporary counterparts available in the market. Off-the-shelf thrusters are used to control the vehicle in 6 Degrees of Freedom.

Information: https://ieeexplore.ieee.org/abstract/document/9655050

- **Integral Sliding Mode Control for a Marine Growth Removing ROV with Water Jet Disturbance**
- Malte von Benzon
- Department of Energy Technology, Aalborg Univerity, Esbjerg, Denmark
- 21 references
- Cited by 12
- This study investigates the benefits of automating the ROV used for cleaning by demonstrating a sliding mode control (SMC) algorithm on a reconfigured BlueROV2 with an attached water jet.

- A nonlinear SMC was designed for the cleaning task. SMC stabilized the ROV's orientation while following a depth trajectory. Regular SMC could not stabilize the ROV in front of the member, with the water jet activated. To accommodate for the delay, integral action was added to the SMC (IxSMC) in the surge direction, which stabilized the ROV. From the research presented in this paper, it can be concluded that automation of a marine growth removing ROV can be achieved by applying IxSMC.
- This is for marine growth removal so it may not be relevant, but information could be useful.

Fusing Concurrent Orthogonal Wide-aperture Sonar Images for Dense Underwater 3D Reconstruction

Information: https://ieeexplore.ieee.org/document/9340995

- Claims to handle the ambiguity in elevation angle associated with the observations of a forward-looking multi-beam imaging sonar, and the challenges it poses for performing an accurate 3D reconstruction.
- 2021

ROVS:

https://www.mdpi.com/1424-8220/19/24/5387

Information: https://www.mdpi.com/1424-8220/19/24/5387

- **Design and Construction of an ROV for Underwater Exploration**
- Jose Ricardo Cardenas-Valdez
- 2019
- Cited by 64
- 48 references
- The article presents the design of a remotely operated vehicle (ROV) optimized for capturing underwater video in real-time via remote control communication using the Ethernet protocol. The ROV is compact, measuring 18.41 cm × 29.50 cm × 33.50 cm and weighing 15.64 kg. It is equipped with six brushless motors controlled by a smart PID controller and pulse-width modulation for improved stability during translational, ascent or descent, and rotational movements along three axes. The ROV captures video at a resolution of 800 × 640 pixels using motion control, 3D positioning, temperature sensing, and video capture simultaneously, utilizing the computational power of a Raspberry Pi 3 with four cores and the threading library for parallel computing. Experimental results demonstrate that the video capture

stage can process up to 42 frames per second. Remote control of the ROV is facilitated by a Python-based graphical user interface compatible with various operating systems, including GNU/Linux, Windows, Android, and OS X. The ROV has a maximum operating depth of 100 m (about 328.08 ft), surpassing the limitations of human divers who can typically reach depths of only 30 m. The proposed ROV is versatile and applicable in various underwater tasks such as surveillance, operations, maintenance, and measurement.

Information: https://ieeexplore.ieee.org/abstract/document/9977203

- **Blue Crawfish Goes Swimming: Hardware Architecture of a Crawling Skid for Underwater Maintenance with a BlueROV2**
- Helge Renkewitz
- 2022
- Cited by 2...
- Fraunhofer IOSB, IOSB-AST Ilmenau, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation, Ilmenau, Germany
- Fraunhofer SOT presents a solution for dealing with niche areas and small curvature radii, addressing the need for more agile and versatile underwater intervention systems. As the demand for such systems increases with expanding marine activities, crawlers have the potential to replace divers in various tasks, including cleaning ship hulls and repairing anti-corrosion coatings, thereby expanding the scope of underwater operations.

Information: https://www.mdpi.com/2077-1312/5/1/13

- **Inspection-Class Remotely Operated Vehicles—A Review**
- Daniel Toal
- 2017
- Cited by 209
- 179 References
- This paper presents a review of inspection- class ROVs, it is divided size and capability.
- This is for personal learning.
- The author also included several comparison tables throughout the review, including comparison of wired data transmission technology, comparison of common ROV communication protocols and comparisons of various inertial navigation systems.

Information:
https://rex.libraries.wsu.edu/view/pdfCoverPage?instCode=01ALLIANCE_WSU&filePid=13354074960001842&download=true

- Autonomous Water Quality Monitoring System
- Aljon Salalila, M.S
- (I think this is interesting, I'm not sure how helpful the information is though.)
- Washington State University
- 2021
- An autonomous water quality monitoring system has been developed to address limitations of existing systems near hydropower facilities. It employs a remotely operated vehicle (ROV) for mobility, overcoming safety risks and allowing monitoring in dangerous water environments. Key components include a dissolved oxygen sensor, tether management system, solar docking platform for power, and a web-based interface for data analysis. Field tests at McNary Dam and High Rock Dam demonstrate its effectiveness. The system aims to improve data collection, optimize hydropower generation, and reduce regulatory compliance costs.
- The usage of the BlueROV.

The Control Toolbox:

https://ar5iv.labs.arxiv.org/html/1801.04290

- Control Toolbox (CT), an open-source C++ library for efficient modeling, control, estimation, trajectory optimization and Model Predictive Control.
- Github: https://github.com/ethz-adrl/control-toolbox
- The CT can be applied to many dynamic systems but features additional modelling tools specially designed for robotics.
- From github: Slightly more complex optimization examples, including gait optimization for a quadruped, are availabe in ct_ros
- https://ieeexplore.ieee.org/document/8376281
- Was referenced in https://ieeexplore.ieee.org/abstract/document/9180253 “A Nonlinear Model Predictive Controller for Remotely Operated Underwater Vehicles with Disturbance Rejection”, this was mentioned earlier in this paper. They implemented the core optimization algorithm with the control toolbox. This allowed for better performance.

Vison:

https://www.mdpi.com/2072-4292/13/24/5075

https://journals.sagepub.com/doi/10.1177/0278364907074473

https://www.sciencedirect.com/science/article/pii/S0967064513000647

Personal Notes:

Definitions:

- DVL (Doppler Velocity Log): The Doppler-velocity-log sonar measures the relative velocity between an instrument and the bottom of a body of water by estimating the Doppler shift of back-scattered sound in multiple beams that point in different directions.
- pose (position and orientation)
- Rao-Blackwellized Particle Filter (RBPF) is an extension of the standard particle filter used in the context of Simultaneous Localization and Mapping (SLAM)
- A load cell is a transducer that converts force or weight into an electrical signal.
- The lumped mass method is a technique used in structural dynamics and mechanical engineering to simplify the modeling of complex structures by approximating their behavior as discrete masses connected by springs and dampers.
- PTAM stands for "Parallel Tracking and Mapping," and it's an algorithm used in computer vision and robotics for Simultaneous Localization and Mapping (SLAM).

Githubs:

- The Control Toolbox:https://github.com/ethz-adrl/control-toolbox
- ROV Simulator is a modular simulator: https://github.com/ROV-Simulator/ROV-Simulator
- Fusing Concurrent Orthogonal Wide-aperture Sonar Images for Dense Underwater 3D Reconstruction: https://github.com/jake3991/Argonaut
- Keep an eye on: Image-Based Visual Servoing Control (IBVS): https://github.com/abhimanyubhowmik/Visual_Servoing