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Design of an Autonomous ROV for Marine Growth Inspection and Cleaning

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***Abstract*—Marine growth affects offshore structures, causing additional weight and roughened surfaces, increasing wave load. In order to reduce these issues, regular inspection and cleaning can be carried out using various methods, of which one is Remotely Operated Vehicle-based (ROV) operations. In the work presented here, the design of a task-specific ROV for marine-growth cleaning is described, which is differentiated from the normal general-purpose ROVs currently used for this purpose by specialized construction and the use of a simple yet flexible framework. Compared to existing solutions, the proposed framework requires limited low-level programming, which heavily simplifies the implementation and thus reduces the associated practical overhead. The presented ROV prototype design has been demonstrated in a test tank facility and will be validated in an offshore scenario in a future offshore campaign.**

***Index Terms*—ROV, UUV, Underwater Robotics, Design, Construction, Marine Growth, Automation, Cleaning, Inspection**

I. INTRODUCTION

Marine growth (MG) on offshore underwater structures increases the hydrodynamic loads and consequently reduces the lifespan [1]. Therefore, operators have a significant operational expenditure annually to remove MG using manually operated commercially available Remotely Operated Vehicles (ROV), a sub-class of unmanned underwater vehicle (UUV), characterized by the use of a remote operator acting as pilot of the vehicle. Today, ROVs used for cleaning are based on general-purpose platforms with a plug-in module for cleaning, such as the widely used Ocean Modules ROVs. Such manually operated, general-purpose ROVs have significant operating expenditure due to the large vessels required to maintain them and poor cleaning efficiency, as they are difficult to manually control in the harsh, disturbance-heavy environment of the offshore scenario. Thus, automation of the ROVs can improve performance and reduce overall expenditure. More details on the current MG management process can be seen in [1].

Related works on the designs of unmanned underwater vehicles (UUVs) vary widely based on critical parameters such as operating depth, required maneuverability, and task-specific parameters such as sensor signal bandwidth or additional actuators. Examples of the design of two relatively lightweight, shallow-water ROVs are given in [2] and [3], wherein treatment of both mechanical and electrical designs have been considered, and where [2] pays special attention to drag, stability and symmetry concerns for the design. A deep-water design ROV design was presented in [4], where the operating range up to $3000\,\mathrm{m}$ depth is considered; in contrast to the shallow-water operating ROVs, the weight is increased, and additional design is necessary for the launch-and-recovery system including tether-management since higher weights and distance to topside are involved.

The main contribution of this paper is the collection of specifications and requirements for both the hardware and software needed for building an automated ROV for cleaning purposes. Specifically, the work presented here proposes and demonstrates the development of a task-specific, weight-reduced, automated UUV prototype (PT) designed to automatically remove MG from offshore structures in the Danish North Sea, intending to reduce the total operating expenditure. The reduced overhead is achieved by lowering the operating overhead significantly as it requires less staffing and machinery to launch, operate and retrieve and by reducing the necessary operating time through efficient cleaning operations [1]. In contrast to the low-cost ROV work in [3], which has a similar shallow operating depth, the power is supplied through the tether rather than onboard batteries, which allows for increased actuation and computational power used in prolonged autonomous operations, which is especially relevant during cleaning operations. Compared to the deep-water ROV design of [4], the overall system structure is very similar, but the proposed UUV solution is half the weight and has a lower power consumption; in addition, emphasis has been on onboard computation rather than multiplexing all signals to the topside system. Inspired by the work of [2], system requirements for symmetric shape, passive stability, and lightweight materials are considered for maneuverability, control authority, and performance.

In section II some initial feasibility investigations are presented. From these, in section III the mechanical, electrical and software requirements of the PT are outlined. From the requirements the PT is designed in section IV and implemented and tested in section V. Finally a concluding remark is given in section VI. It should be noted that this paper is intended to present the PT design considerations. The algorithms needed for localization and mapping and control are currently ongoing where preliminary results may be found in [5], [6]

II. FEASIBILITY STUDIES

Prior to the development of the prototype described in this work, several feasibility studies were performed to delimit the solutions, investigated through a rapid prototype (RPT) development, cleaning tool investigation, and sensor-technology review, which are summarized in the following sections.

A. Rapid proto-type

Initially, the idea was to have an ROV that could attach to the structure while cleaning. This contact operating mode would make the ROV more robust to disturbances but limit its maneuverability. The RPT was constructed as free-floating to investigate whether a free-floating operating mode was suitable for cleaning a structure. The RPT was constructed based on a reconfigured BlueROV2. The reconfiguration included: Adding two additional thrusters to achieve 6 DOF control; mounting a water jet-nozzle (water provided from the topside); adding a relative distance measurement based on a camera and a laser; installing an underwater acoustic positioning system. The RPT was tested in an onshore test facility in steady water and was able to keep a constant distance to an underwater structure with the water jet turned on while following a trajectory; the tests are described in detail in [7]. The preliminary studies concluded that automation of the cleaning process is possible with a free-floating ROV. However, it was experienced; that the tether had a significant impact on the performance of the RPT, the sensors should be onboard/body-fixed since an acoustic positioning system requires too much external setup and calibration, and lastly, the RPT was sensitive to delays in the sensor measurements. The prototype will be constructed as free-floating due to the preliminary study, as it was not found to be necessary to attach the ROV to the structure.

B. Cleaning tooling

MG cleaning requires a tool, and several tools are available based on different technologies, most commonly hydraulic/mechanical, electrical/mechanical, and water jetting. All surveyed effective cleaning solutions require considerable power and energy density, more than 10kW, with cleaning operations lasting upwards of 10 hours; this makes onboard battery power infeasible. The cleaning tool, therefore, requires power from a topside unit, thus tethering the UUV to the topside. Aside from the cleaning tool, the thrusters and electronics also need power, which will simultaneously be provided from the topside.

Several commercially available cleaning tools based on mechanically/rotating tools or water jetting were investigated. Tests were performed on nine such cleaning tools (all commercially used for cleaning MG) to determine the effectiveness based on cleaning speed and cleaning results. This testing showed that none of the mechanical solutions effectively removed hard MG. The best performing tool was water jetting with a single rotating jet nozzle at a pressure of $500\,\mathrm{bar}$ with a flow of $30\,\mathrm{L/s}$.

C. Sensor Technologies

Several sensor technologies have been investigated for the measurement of both the UUV spatial position, detailed in [8], [9], and for the measurement of marine growth, detailed in [10]. This investigation has shown that several commercially available sensor technologies are relevant to the UUV, including sonar, vision-based sensors, inertial measurement units, and Doppler velocity logs. The electrical and software interfaces for these sensors influence the choice of the electrical hardware and software platform, particularly the need for onboard multiplexing or processing of the sensor data; this will later be used in defining the requirements for the UUV prototype. Fortunately, most of the sensors investigated thus far have at least partial openly accessible API support, and are available with modern communication interfaces such as Ethernet or CAN-Bus, thus limiting the need for specialized hardware/software design.

III. REQUIREMENTS

The PT will be designed for MG removal in the Danish North Sea where water depth is shallow, less than $100\,\mathrm{m}$. The maximum operational sea state is $3\,\mathrm{m}$ significant wave height and $0.5\,\frac{\mathrm{m}}{\mathrm{s}}$ of current. The PT should be able to clean tubular structures ranging from $0.32\,\mathrm{m}$ to $4.5\,\mathrm{m}$ in a diameter, jacket structures. The PT will be launched from either a support vessel or a fixed platform and is supplied with power, high-pressure water, and control signals from the topside through a tether.

A. Mechanical requirements

As noted in the introduction, due to the use of high-pressure water jetting, the UUV will be tethered to some topside structure, and given the desired operating depth, the tether will have a length of minimum $100\,\mathrm{m}$. The tether should have the smallest possible diameter to reduce the hydrodynamic drag and minimize the tether-management effort.

The main mechanical requirements are summarized below:

- $100\,\mathrm{m}$ depth operating rating
- Fully actuated (cardinal directions)
- Task-specific layout
- Center-attached tether
- Minimize tether diameter and stiffness
- Lightweight
- Compact

B. Electrical hardware requirements

The electrical systems onboard the UUV should be able to supply the thrusters, sensors, and control components with power while minimizing power loss. Minimizing power loss minimizes tether diameter and topside power requirements and provides for less thermal dissipation to be handled onboard the UUV. In addition to the power supply, there should be a communication link to the UUV to allow for logging and monitoring of the UUV operations for safety and performance-validation reasons, i.e., to allow the transfer of control signals and at least one high-quality video feed. The communication could allow some computations to be off-loaded to topside equipment; however, this induces some latency, which is a critical parameter for control-loop performance. For this reason, the choice is made to put sufficient computational resources onboard the UUV to handle at least the basic station-keeping and path control task, including the processing of associated sensors. The main electrical hardware requirements are summarized below:

- Minimum 6kW actuation power; minimized power-loss
- Communication connection to topside $>100\,\mathrm{Mbit}$
- Main-control computer onboard; sufficient computational resources to execute control-algorithms onboard

C. *Software requirements*

The software requirements are based on the core requirement that the UUV software should be easily maintainable and use as many off-the-shelf components as possible in order to speed the development time; while at the same time not precluding the ability to customize the behavior as required, as the development progresses. For this reason, modular and extensible software architecture is desired instead of a monolithic approach. Due to the use in an academic research project, an open-source approach is also desirable to allow the resulting developments to be shared. Additionally, as a minor requirement, the software should, where practical, not be tied to a specific hardware platform or operating-system version. In summary, the main software requirements are:

- Modular
- Extensible
- Open-source
- Platform-agnostic

IV. PROTOTYPE DESIGN

Based on the requirements and details given in section III, an overview of the system architecture is shown on fig. 1. This includes a support vessel providing electrical power and high-pressure water supply, a tether to carry these to the UUV, and the UUV itself, with the required onboard components integrated. The following sections detail the mechanical, electrical hardware, and software design applied to the UUV prototype (PT).

A. *Mechanical*

The design of the UUV, seen in Fig. 2, aims to rethink the design of a standard ROV to improve cleaning and inspection performance. A series of disturbances affect the operation of an ROV. The UUV design aims to minimize the effect of the significant disturbances: wave, current, and tether forces. The main objective of the operations is to keep stationery and move at low speeds. Therefore, the design aims to be independent of the direction of current and waves. The torus shape meets most of these criteria. By utilizing primarily round shapes, the drag of the ROV is kept low in all directions. The drag will be approximately identical for operation in the surge and sway and intermediate directions. The same is the case for movement in the heave direction, thus simplifying the control setup and design. The torus shape allows the tether to be attached as close to the center of mass (COM) as possible to minimize the torque created during operation. This effect is ensured by using a slightly positive buoyant tether, ensuring that the tether will always be placed over the UUV. Eight individual thruster groups control the UUV: Four for translatory movement and yaw; these are placed at a $45°$ angle compared with the forward direction to ensure the highest available thrust force. Another four thruster groups are placed for vertical movement, roll, and pitch. Place at the same angle as the translatory thrusters; these enable the ROV to utilize all thrusters for the pitch and roll motion. The UUV build aims to keep the construction price as low as possible. This goal is achieved by utilizing off-the-shelf parts whenever it is possible. The goal is to be able to do so without compromising the functionality of the UUV. Parts such as frame, shell, and electric pressure bottles are specially manufactured, but most other parts are off-the-shelf. For weight minimization, aluminum has been used for all structural parts.

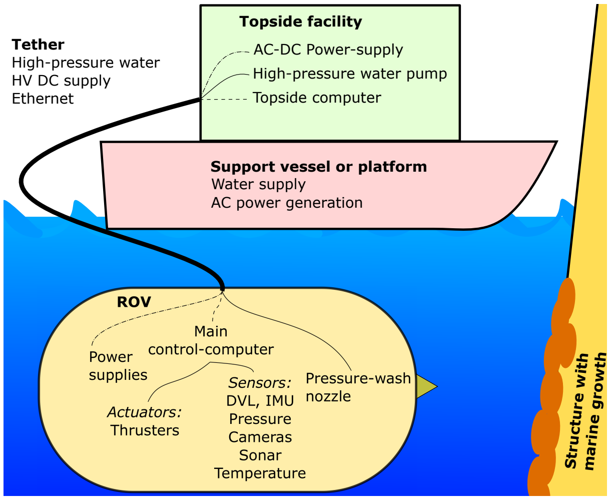

Fig. 1. Overview of UUV use case for marine-growth inspection and removal. Supporting systems within the support vessel are not considered further

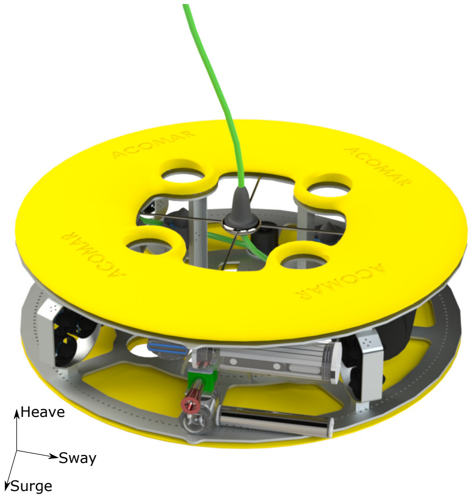

Fig. 2. Mechnical UUV design including attached tether

B. Electrical hardware

The electrical hardware design of the UUV prototype, illustrated on fig. 3, is separated into a high-power and low-power system, each housed in a separate subsea pressure enclosure. The separation into two enclosures has two reasons; the mechanical constraints on the size of the pressure enclosure, to be able to mount it within the robot chassis and improved electromagnetic compatibility (EMC) gained by separating the high-current and low-current components physically. The high-power system encompasses the power supply (DC/DC converters) and actuator drive electronics (ESCs) which drive the thrusters. The low-power system encompasses the main control board, low-voltage power supply, and Ethernet switches used for internal communication. Additionally, the sensors are included in the low-power system and are mounted within the low-power enclosure (pressure and temperature sensor) or in a separate enclosure (IMU and cameras). The communication between the high-power and low-power enclosures is achieved using a galvanically isolated bi-directional serial link, which prevents the formation of ground-loops and isolates the sensitive low-power system from noise arising in the high-power system.

1) Main control computer: The main-control computer used in the prototype is the Nvidia Jetson TX2i system-on-module, which has been chosen based on the requirements given in sections III-B and III-C. The Jetson module CPU fulfills the requirements for computational power; in addition, the possibility exists to use GPU accelerated algorithms using the onboard GPU, further extending and augmenting the computational power. The Jetson SoM is mounted on a suitable carrier board, which brings out the various communication interfaces needed for the actuation and sensing subsystems. Notable interfaces include: 6×CSI-2, 2×Gigabit Ethernet, CAN 2.0A/B, 2×Serial, I2C, SPI, GPIO etc. In addition to the external interfaces, an mSATA interface has a solid-state drive (SSD) attached to allow for onboard data recording. The use of the Jetson ecosystem also provides for up and downgrading depending on the computational load and required interfaces in the final UUV by replacing the Jetson TX2i SoM with an alternative such as the Jetson Nano, Xavier NX, or Xavier AGX [11]; or by replacing the carrier board to provide a different selection of interfaces.

2) Topside system: The topside system consists of a standard PC with Ubuntu Linux, which is attached via the tether to the UUV prototype and runs a remote connection via Ethernet to the onboard main control computer. For user (pilot) input, a joystick is connected, which is used with ROS teleoperation software to forward control signals to the UUV prototype. An adjustable DC power supply (10kW, 1000V) is utilized to supply the UUV prototype over the tether; for safety, the supply has built-in protection functions, including over/under-voltage and current-limiting.

C. Software

The central software chosen for the prototype is Robot Operating System (ROS) which is selected based on the requirements of section III-C, as well as compatibility with Ubuntu Linux, the default factory-supported operating system used on the main control computer in section IV-B1. The use of ROS allows for the following benefits; modularity, which allows the system software components to be easily replaced and modified individually; extensive ecosystem, meaning that many software components (packages) are already available for both actuation, sensing, and control functions; open-source, which is relevant for the possible sharing of academic results including developed software. ROS exists in many versions; for the UUV prototype, ROS1 Melodic [12] has been chosen for its maturity, extensive existing package repositories, and proven support on the Ubuntu Linux version and hardware platform of the Jetson TX2i SoM. This extensive ecosystem is exemplified in the UUV prototype's list of used software packages, given in table I. An overview of the system architecture of the UUV is shown on fig. 4.

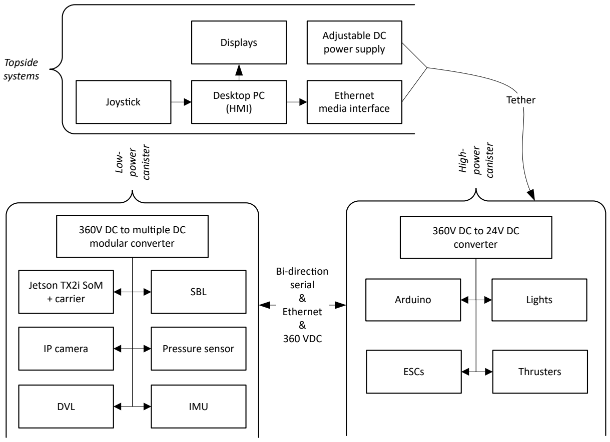

Fig. 3. Overview of the electrical system.

TABLE I
EXAMPLES OF ROS PACKAGES USED ON ACOMAR PROTOTYPE

Module	Pre-built	Sources	Interface
ESC	✓	[13]	CAN-bus, USB, Serial
DVL (Waterlinked)	✓	[14]	Ethernet
SBL (Waterlinked)	✓	[15]	Ethernet
Cameras	✓	[16]	Ethernet (GigE) etc.
Daughterboard (arduino)	✓	[17]	USB, Serial
Thruster control	✓	[18]	Internal (ROS)
Localization	✓	[19]	Internal (ROS)
CAN bus	✓	[20]	CAN
Pressure sensor	✓	[21]	CAN
HMI	×	[22]	ROS over ethernet
IMU	×		Serial, CAN-bus
High-level control	×	[23]	MathWorks ROS toolbox

Due to the use of ROS for the UUV, Gazebo can be used as a simulation environment, with UUV Simulator [24]. Gazebo is a robot simulator that provides realistic sensor feedback, and physical interaction between objects in a three-dimensional world [25]. Therefore, it is a good tool for simulating realistic control and filter algorithms behavior. Gazebo has the advantage of allowing user-defined plugins [24], such as the UUV

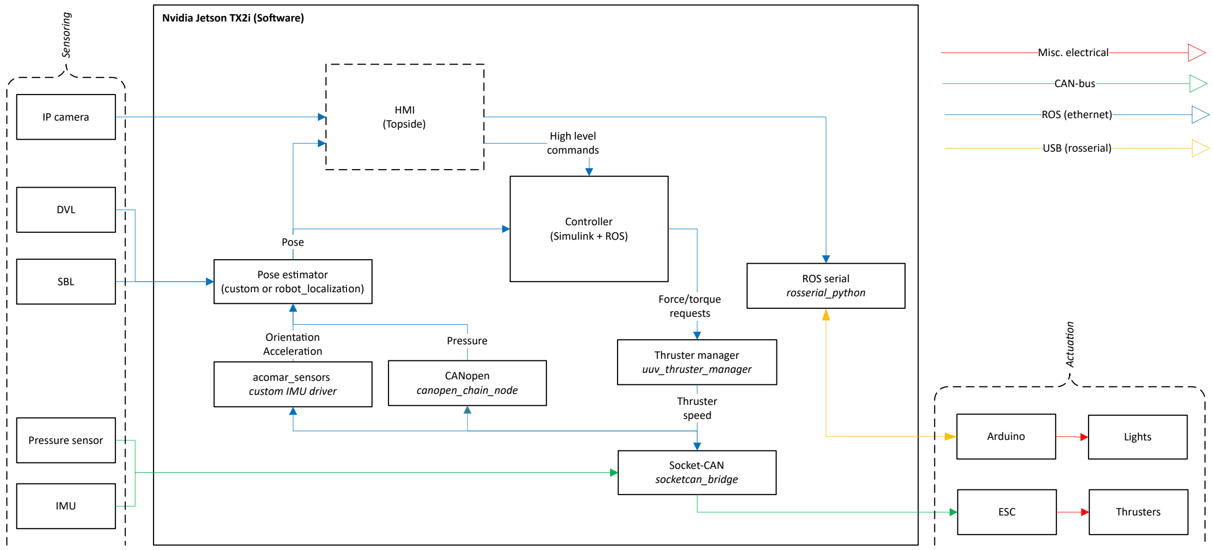

Fig. 4. Overview of software/hardware system. Note that the trial ESC's were connected to the Arduino rather than over CAN-bus due connectivity issues.

Simulator which is a plugin, that adds hydrodynamic and hydrostatic forces and moments into the physical engine, together with sensor models for underwater sensors and actuator models such as thrusters [24]. Furthermore, the UUV Simulator has some limitations concerning implementing forces generated by the tether. In the prototyping of the UUV, Gazebo is used in the initial design phase of different sensor algorithms due to its extensive support of commonly used sensors, such as Doppler Velocity Log (DVL), sonar, IMU, and cameras. For control development, MATLAB & Simulink can be connected using Robot Operating System toolbox [23]. This capability is used for fast prototyping in filter and control design and tuning as hardware-in-the-loop testing. The toolbox can also be used with dynamic models designed in MATLAB and Simulink, which are then used for testing in a fully simulated world, similar to Gazebo. Matlab and Simulink have the advantages of providing practical toolboxes concerning control and filter design.

V. PROTOTYPE IMPLEMENTATION & TESTING

After assembly of the UUV PT, shown on fig. 5, initial functional verification was performed on the complete system, first on the bench-top, then in a large test tank at the project partner. This testing showed that all actuation functions and sensor signals were functioning correctly and that the topside connection using Ethernet and ROS was functioning as expected.

In the initial prototype tests, a separate direct Ethernet cable connection was used rather than the tether to allow for gigabit transmission speed; this allows for initial work on the prototype without the constraints imposed by the slower tether-based connection; for later tether-based connections, the data may need to be compressed, using resources on the main control computer. For the topside system, a commercial joystick and standard displays, shown on fig. 6, were implemented as a

Fig. 5. UUV Prototype cleaning robot, note the placement of the vertical thrusters represents a previous design change.

Fig. 6. Topside control system with pilot joystick.

user interface within the ROS system using the standard ROS packages and used to control the attitude and position of the UUV prototype. On the initial prototypes, simple high-thrust testing showed increased temperatures within the high-power system when operating for extended periods. The thermal resistance within the high-power enclosure must be decreased in future work.

VI. CONCLUDING REMARKS

Building on a series of feasibility studies, a prototype UUV for marine growth removal was developed, focusing on specialized construction and system architecture for the specific application rather than an adapted off-the-shelf ROV. The development of the custom construction allows adapting of the UUV towards the application concerning; reduced weight, suitable size, actuation performance, and relevant sensor packages; while retaining system simplicity and the possibility of upgrades. The mechanical construction in the shape of a toroid has been selected to have low, symmetric drag, and minimum torque from tether forces, aiming to reduce the disturbances and thereby improve positioning control performance and reduce necessary actuation power. An open-source, modular, ROS-based approach has been chosen on the software side, which benefits from extensive software and hardware support from a large online community. ROS has reduced development time on the prototype and allowed for off-the-shelf and custom hardware to be integrated with little programming overhead. The electrical system has been designed to minimize power loss and tether diameter, using mature components and architectures, such as the Nvidia Jetson TX2i industrial system-on-module; thus, the reliability and availability of the system components are ensured. In future work, various control algorithms will be developed for the prototype UUV and tested in both on-shore test facilities and a designated offshore campaign to validate the performance and compare the developed solution to existing ROVs. This includes the validation of performance under various adverse scenarios such as intermittent sensor faults or performance degradation.

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REFERENCES

[1] S. Pedersen, J. Liniger, F. F. Sørensen, and M. v. Benzon, "On Marine Growth Removal on Offshore Structures," *Aalborg University*, 2022. [Online]. Available: https://vbn.aau.dk/en/publications/on-marine-growth-removal-on-offshore-structures

[2] R. M. Gomes, A. Sousa, S. L. Fraga, A. Martins, J. B. Sousa, and F. L. Pereira, "A new ROV design: Issues on low drag and mechanical symmetry," *Oceans 2005 - Europe*, vol. 2, pp. 957–962, 2005.

[3] O. A. Aguirre-Castro, E. Inzunza-González, E. E. García-Guerrero, E. Tlelo-Cuautle, O. R. López-Bonilla, J. E. Olguín-Tiznado, and J. R. Cárdenas-Valdez, "Design and Construction of an ROV for Underwater Exploration," *Sensors 2019, Vol. 19, Page 5387*, vol. 19, no. 24, p. 5387, 12 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/24/5387/htmhttps://www.mdpi.com/1424-8220/19/24/5387

[4] T. Salgado-Jimenez, J. L. Gonzalez-Lopez, L. F. Martinez-Soto, E. Olguin-Lopez, P. A. Resendiz-Gonzalez, and M. Bandala-Sanchez, "Deep water ROV design for the Mexican oil industry," *OCEANS'10 IEEE Sydney, OCEANSSYD 2010*, 2010.

[5] F. F. Sørensen, M. von Benzon, J. Liniger, and S. Pedersen, "A quantitative parametric study on output time delays for autonomous underwater cleaning operations," *Journal of Marine Science and Engineering*, vol. 10, p. 815, 6 2022.

[6] M. Benzon, F. Sørensen, J. Liniger, S. Pedersen, S. Klemmensen, and K. Schmidt, "Sliding mode control for a marine growth removing rov with water jet disturbance." IEEE, 2021, European Control Conference, Rotterdam, Netherlands.

[7] M. Von Benzon, F. Sorensen, J. Liniger, S. Pedersen, S. Klemmensen, and K. Schmidt, "Integral Sliding Mode Control for a Marine Growth Removing ROV with Water Jet Disturbance," in *2021 European Control Conference, ECC 2021*. Institute of Electrical and Electronics Engineers Inc., 2021, pp. 2265–2270.

[8] J. C. Kinsey, R. M. Eustice, and L. L. Whitcomb, "A survey of underwater vehicle navigation : Recent advances and new challenges," *IFAC Conference of Manoeuvering and Control of Marine Craft*, vol. 88, pp. 1–12, 20/09/ 2006. [Online]. Available: https://www.whoi.edu/cms/files/jkinsey-2006a_20090.pdf

[9] L. Paull, S. Saeedi, M. Seto, and H. Li, "Auv navigation and localization: A review," *IEEE Journal of Oceanic Engineering*, vol. 39, no. 1, pp. 131–149, 01 2014. [Online]. Available: https://ieeexplore.ieee.org/document/6678293

[10] J. Liniger, A. L. Jensen, S. Pedersen, H. Sørensen, and C. Mai, "On the Autonomous Inspection and Classification of Marine Growth on Subsea Structures," in *Proceedings of the IEEE OCEANS 2022 conference*, Chennai, 2022, pp. 1–6.

[11] "Jetson Modules — NVIDIA Developer." [Online]. Available: https://developer.nvidia.com/embedded/jetson-modules

[12] Stanford Artificial Intelligence Laboratory et al., "Robotic operating system." [Online]. Available: https://www.ros.org

[13] "GitHub - smarc-project/uavcan_ros_bridge: ? Bridge for communication between ROS and the uavcan CAN-bus protocol." [Online]. Available: https://github.com/smarc-project/uavcan_ros_bridge

[14] "GitHub - waterlinked/dvl-a50-ros-driver: Water Linked DVL A50 ROS driver." [Online]. Available: https://github.com/waterlinked/dvl-a50-ros-driver

[15] "GitHub - mkran/waterlinked_ros_driver: ROS driver for the Waterlinked SBL Positioning System." [Online]. Available: https://github.com/mkran/waterlinked_ros_driver

[16] "video_stream_opencv - ROS Wiki." [Online]. Available: http://wiki.ros.org/video_stream_opencv

[17] "rosserial - ROS Wiki." [Online]. Available: http://wiki.ros.org/rosserial?distro=melodic

[18] "GitHub - uuvsimulator/uuv_simulator: Gazebo/ROS packages for underwater robotics simulation." [Online]. Available: https://github.com/uuvsimulator/uuv_simulator

[19] "robot_localization wiki — robot_localization 2.6.11 documentation." [Online]. Available: http://docs.ros.org/en/melodic/api/robot_localization/html/index.html

[20] "socketcan_bridge - ROS Wiki." [Online]. Available: http://wiki.ros.org/socketcan_bridge

[21] "canopen_chain_node - ROS Wiki." [Online]. Available: http://wiki.ros.org/canopen_chain_node

[22] "rqt - ROS Wiki." [Online]. Available: http://wiki.ros.org/rqt

[23] MathWorks, *ROS Toolbox: For Use with MATLAB and Simulink*. MathWorks, 2019. [Online]. Available: https://mathworks.com/products/ros.html

[24] M. M. M. Manhães, S. A. Scherer, M. Voss, L. R. Douat, and T. Rauschenbach, "UUV Simulator: A Gazebo-based package for underwater intervention and multi-robot simulation," *OCEANS 2016 MTS/IEEE Monterey, OCE 2016*, 11 2016.

[25] W. Qian, Z. Xia, J. Xiong, Y. Gan, Y. Guo, S. Weng, H. Deng, Y. Hu, and J. Zhang, "Manipulation task simulation using ros and gazebo," in *2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014)*, 2014, pp. 2594–2598.