Design of Affordable Hybrid Underwater Vehicle Platform using ArduSub & Robot Operating System (ROS) for Marine Robotics Research*

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***Abstract*— In the maritime world, operations are divided into two categories: inspection, and action. this paper discusses the development of a hybrid underwater vehicle (HUWV) that combines the features of autonomous under-water vehicles (AUV) and remotely operated vehicles (ROV) for inspection. The vehicle can be used for marine robotics research and is configured with multiple sensors and cameras to employ simultaneous localization and mapping (SLAM) technology. The vehicle is assembled from off-the-shelf components and fabricated using common machining methods. The vehicle is designed for use across several sectors, including underwater research, environmental assessment. When running the vehicle in autonomous mode, missions are operated using artificial intelligence (AI) control, taking feedback from available sensors on board. Additionally, the vehicle runs ArduSub linked to Robot Operating System (ROS) using MAVROS, enabling the vehicle to be piloted and tested using software-in-loop modelling with open-source software Gazebo & RViz. We provide the steps and design files required to manufacture, operate, and develop such vehicle.**

Keywords— Remotely Operated Underwater Vehicle ROV, Autonomous Underwater Vehicle AUV, Simultaneous Localization and Mapping, Pixhawk, ArduSub, MAVROS, MAVLink, Robot Operating System ROS, Thruster, Artificial Intelligence, BlueRobotics

I. Introduction

Underwater robotic vehicles play a major role in the environmental, commercial, military, and emergency operations. Underwater robotic vehicles can be divided into two groups: manually operated, and autonomous, both with their different applications [1]. In recent development, Robot Operating System (ROS) [2] expanded rapidly through community support to include software libraries, simulation platforms, and compatible hardware components to facilitate robotics development. However, the wide-reaching base of available ROS and similar software, in addition to the difficulties of developing underwater-compliant robotic systems, means that the barrier of entry into marine robotics needs reduced. This paper aims to propose a method that combine the advantages of the manual and autonomous vehicles with a low overhead, while applying the open-source ROS framework. This hybrid vehicle should be able to produce maps of maritime life underwater and analyze their ecological status using use visual-simultaneous localization and mapping (V-SLAM) technology [3], and other object detection technologies. The project also includes designing an integrated underwater vehicle simulation platform through which we can test command and control systems in various marine environments such as high currents and polluted environments to avoid the problems that the submarine may encounter in the working environment, and this feature is needed by everyone who works in the field of autonomous vehicles. On the commercial level, the hybrid underwater vehicle (HUWV) will be able to conduct survey patrols of the depths of water. The vehicle qualifies it to carry out industrial operations using the automatic or autonomous command system.

A. *Related work*

Creating an underwater robotics research platform involves significant overhead, works exist that aim to reverse engineer existing vehicles to support open-source software [4] [5] [6]. Additionally, some systems achieve autonomy but rely on expensive commercial platforms [7]. Open-source platforms are scarce and out-of-date or have incomplete instructions [8] [9]. Other open-source platforms are targeting low-cost without considering additional devices payload for underwater robotics research [10] [11] [12]. Manual-control only platforms offer additional examples of the mechanical and electrical design of underwater robotics [13].

B. *Contributions*

We contribute full design plans for a locally manufactured marine robotics research platform, excluding thrusters. The design uses readily available materials and manufacturing processes (wood routers, laser-cutters, metal work). Also included are the electrical system diagrams includes, and software tools used. To highlight we contribute the following:

- Mechanical system with body plans, insulation procedures, insight into design considerations; CAD drawings, assembly instructions, bill of materials and comparisons with commercial-off-the-shelf (COTs) items.
- Electrical system components, power circuit schematics, inter-system communication and tether.
- Software setup, ROS software libraries, documentation of hardware-software considerations.
- Documentation of helpful websites.
- Full project report.

The open-source documentation and files live *ad infinitum* at

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II. SYSTEM DESIGN

While designing the HUWV the main aim was to reach an underwater robotics research platform. The design is separated into three disciplines: mechanical, electrical, software. The mechanical design facilitated interlocking acetal sheets, and acrylic tubing for insulation. The electrical system consists of the power circuit, and the data circuit. Power is supplied via the tether with optional batteries on-board for verifying vehicle dynamics and software independent of the tether. The software is based on a collection of open-source libraries under the ROS framework with access to software-in-loop simulations in Gazebo.

A. *Hardware*

The system is designed from the ground-up for ease of manufacturing and modularity for research. The system considers local alternatives to importing systems from companies similar to BlueROV to reduce cost and decrease financial barrier of entry. Various make-or-buy decisions were made such as with manufacturing the main electronics insulated enclosure from acrylic tubing and metal flanges made at a metal workshop.

1) *Vehicle Frame*

Our mechanical team aimed to design a modular, durable, lightweight, and easy to manufacture frame. The result is using 8 mm thick sheet shape frame made of easy to machine plastic, high-density polyethylene (HDPE), which allowed fast manufacturing on a CNC router, and due to its low density to strength ratio, high-density polyethylene (HDPE) was used as it has a neutral-to-water density of 970 Kg/m3 (see “TABLE I”), and the most effective cost at $19/m2, in comparison to the other possible option; Aluminium-7075 which is 5mm sheets at $110/m2 [14].

TABLE I. DIFFERENT SPECIFIC GRAVITIES OF MATERIALS WE CONSIDERED.

Plastics - Metals	*Specific Gravity*
Acetal copolymer	1.41
High-impact ABS	1.03
Polyetherimide	1.27
Polymethyl pentene	0.83
Aluminum	2.55 – 2.80
Carbon Steel	7.8
Cast Iron	7.03 – 7.13
Copper	8.89
Stainless Steel	7.7

We aimed for the thrusters configuration in “Fig. 1” that allows more lift comparatively, while also allowing more usable work area for potential modules to be mounted centarally in the frame. The 4x4 thrusters configuration allows six-degrees of freedom, as well as being symmetrical. This reduces control software complexity and the need to compensate for inequal forward- and backward-thrust of the T200 thrusters.

After three iterations of the design following the VDI model of mechatronics systems development, we reached the design shown in “Fig. 2”. The vehicle is modular and allows for additional modules like 360° camera system, advanced sensors for SLAM, and marine life measurements and instrumentation.

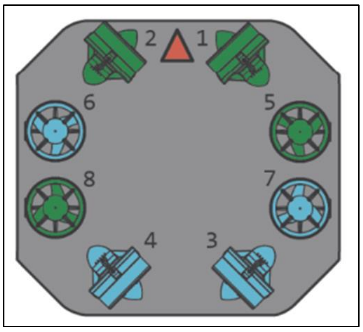

Fig. 1. Our chosen 4x4 thrusters configuration.

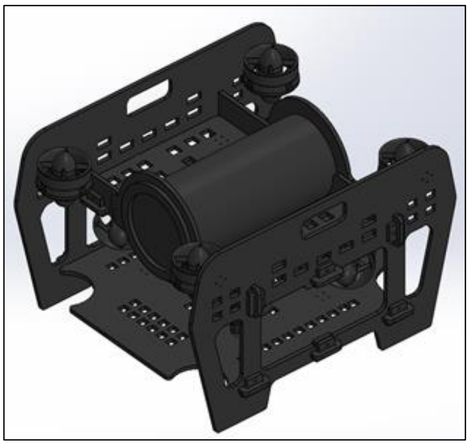

Fig. 2. Complete vehicle assembly in SOLIDWORKS.

2) *Sealed Electronics Enclosure*

The electrical system of the vehicle is necessarily insulated from water ingress. The ideal shape for an insulated is to be tube-shaped, as the pressure sustainable by tubes of the equivalent material is much greater due to the nature of opposing forces cancelling. “TABLE II” shows comparable commercial solutions compared to our developed acrylic tube with glands and O-rings. It consists of an acrylic tube with aluminum flanges.

TABLE II. COMPARISON OF COSTS OF ACRYLIC TUBES.

Product	Cost	Misc.	Lead-time	Rated depth
US Bluerobotics Ø4″ 298mm	$212	$90	1-3 weeks	100m
Our solution Ø14mm (5.5”) 325mm	$95 (EGP1450)	N/A	3 days	75m

3) *Electrical System*

We conform to the constraints of the MATE ROV competition [15]. The power source consists of a 48V 30A power source, and the voltage is stepped down to 12V via an ADQ700 quarter-brick telecom grade buck convertor [16] to accommodate the thrusters, with a secondary buck convertor to 5V for the control electronics. “Fig. 3” shows the quick-connect PCB, while “Fig. 4” shows the entire system.

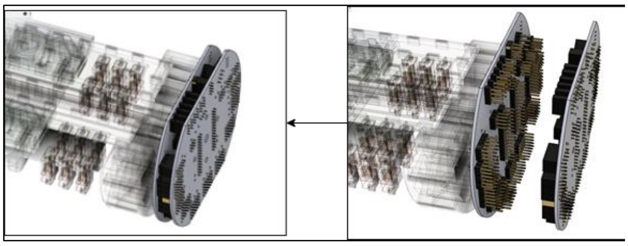

Fig. 3 Easy quick-connect PCB design.

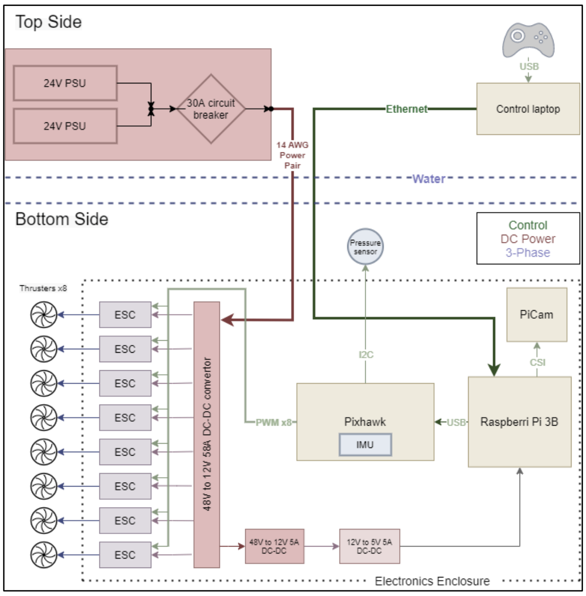

Fig. 4. Electrical circuit diagram of the vehicle.

The system uses a Raspberry Pi 3B for communication with top stations and providing on board compute and vision with the RPi Camera v2. A Pixhawk 2.4.8 is used to interface with the six thrusters' electronic speed controllers (ESCs), and the BlueRobotics Bar02. Additionally, the Pixhawk provides an onboard inertial measurement unit (IMU). The system is ready to be connected to an Nvidia Jetson Nano which has been selected for its AI processing capabilities.

4) Electrical Rack

For achieving a reliable underwater vehicle system, the electrical system must be well arranged to facilitate ease of maintenance, modularity, and reliability. From previous experience in building underwater vehicles systems, it was clear that tremendous time and effort were wasted on assembly and disassembly of the electrical system and insertion inside the insulated acrylic tube. Thus, to achieve good components density and ease of maintenance, we chose to design a rack for the electrical components.

Utilizing the free and well-supported software Autodesk Fusion 360 (chosen for its flexibility in prototyping creatively), we went through two iterations shown in "Fig. 5 **Error! Reference source not found.**" and "Fig. 6". The first was fully 3D printed. The entire assembly was designed in seven slices. While the second used aluminum extrusion 2020 as a spine for all components to mount on, reducing complexity and increasing modularity and ease of manufacturing, and later on maintainability.

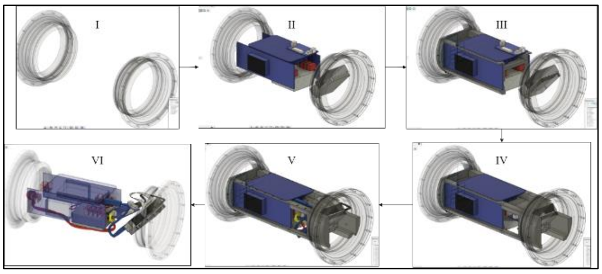

Fig. 6. Design process of first iteration rack. From I to VI: constraints, placement of components in space, sketches and extrusion of the first few 'slices', full design, wiring checks, wiring visible.

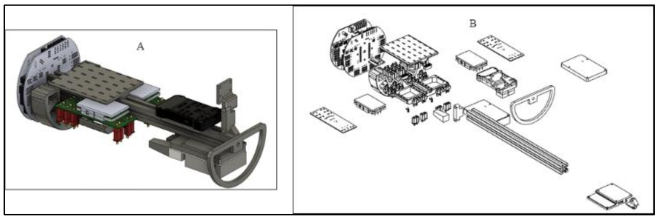

Fig. 7 The second iteration rack. (A) Assembled design. (B) Exploded view.

III. Autonomy & Control Software

A. *Software components*

The control system of the HUWV is ROS based, where the system consists of a set of "Nodes". Each node represents a single process that can then communicate with other nodes. Nodes are a convenient method to develop software for each subsystem in the vehicle.

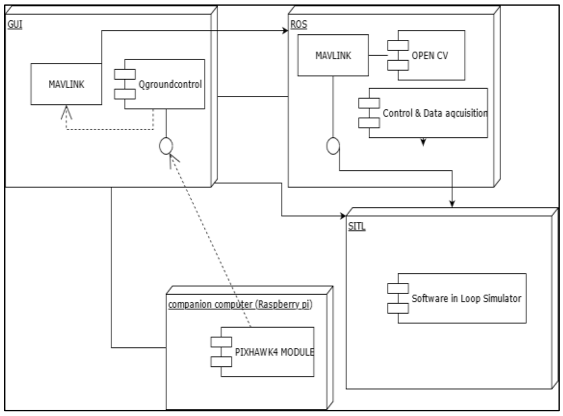

Fig. 8. Block Diagram for software elements.

As shown in "Fig. 7", the system is consisted of 4 Software nodes directed by the feedback taken from the Pixhawk through the companion raspberry pi computer. While the companion computer holds the ROS operations that is designed to include all elements of AUV and ROV control "Fig. 8".

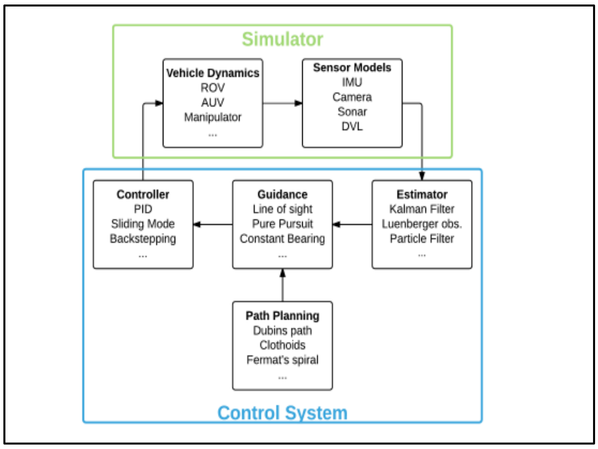

Fig. 8. Block Diagram for software elements.

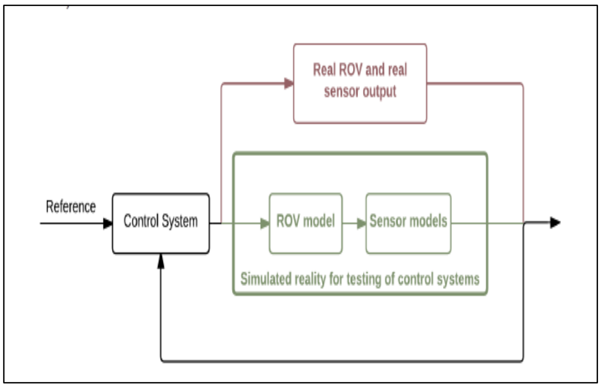

Fig. 9. Data flow diagrams for both simulation and real systems.

1) Companion computer

The companion computer is run by Ubuntu 18.04 operating system, this computer acts as a host for the Pixhawk 4 module which is connected to the top station computer through LAN network.

2) Graphical User Interface (GUI)

The Pixhawk is connected through ArduSub open-source platform runed on QGC software. Thanks to its user-friendly settings that enables the user to perform several tuning and calibration operations for the underwater vehicle. These operations include but not limited to:

- Thrusters' tunning
- Sensors Calibration
- Add-ons' installation
- PID auto tuning for system's 6 degrees of freedom

Furthermore, this GUI enables the user to connect the vehicle with other ROS nodes for data acquisition and other advanced operations such as autonomous ones. This is performed through MAVLINK with its open-source library for connection with ROS.

3) Robot Operating System (ROS)

ROS is a set of "nodes" that are linked all together for one robot, these nodes include Open CV, Control, and Data acquisition for analysis [2]. These nodes acquire the data from system's GUI through MAVLINK using python scripts. Where these scripts are connected to system's Software In Loop Simulation (SITL).

4) SITL

This node includes all the processed data which is directed to the previously built environment using UUV Simulator open-source library, this library receives Data from the vehicle and translate it to predefined vehicle features included in the URDF file installed on the Simulation environment, "Fig. 9" Illustrates the data flow through both real and Simulation systems.

B. Vehicle Software Features

1) Depth hold

The aim of this function is to keep the vehicle vertically and horizontally stable as much as possible by using the Blue Robotics Bar02 pressure sensor that uses the pressure head principle in operation to calculate the, giving the pilot an advantage when doing several in the ROV mode - tasks on the same depth by controlling the setpoint on the QGC interface. Using the pressure Equation(2). pressure can be easily converted to a depth measurement.

$$P = \rho * g * h \tag{1}$$

For the orientation of the vehicle, the IMU onboard the Pixhawk provides clear data for the ArduSub system to identify the HAUV status underwater.

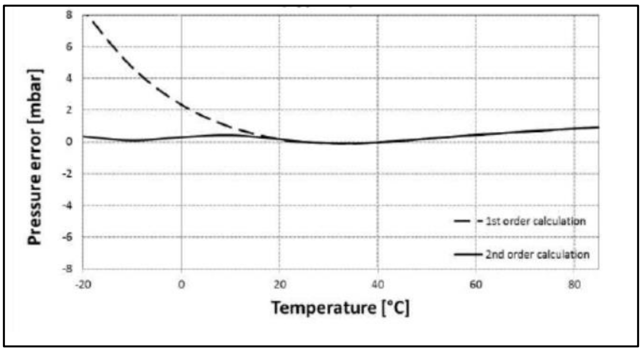

Fig. 10. Pressure error accuracy vs Temperature @850mbar (typical) retrieved from BAR02 datasheet.

Fig. 11. Representation of pressure, velocity & orientation captured from Ardusub-QGC software.

2) *Image processing of Coral Reefs using OpenCV*

OpenCV (Open-Source Computer Vision) is a computer vision software development library. If you want to do any real-time image processing with the companion camera, we strongly advise you to use OpenCV. Both Python 2 and Python 3 are supported. "Fig. 12" shows it in operation.

To capture video streams using the python script and QGC at the same time, it is needed to change the GStreamer settings:

$ *host=192.168.2.1 port=5600 to udpsink multiudpsink clients=192.168.2.1:5600,192.168.2.1:4777*

Then to add the new port option:

$ video (video = Video(port=4777))

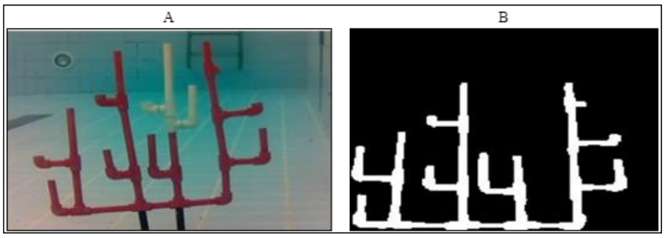

Fig. 12. OpenCV retreived Captured image (A) vs. masked image (B).

3) *SITL and Autonomous Motion*

A set of tools that operates together in the simulation of ROV operations would be the simulation framework. The aim is for developers to use this platform to test their algorithms, weather controller algorithms, sensor processing, guidance systems, or route planners. This will drastically help in optimizing the autonomous operations specially in training the vehicle. Based on modules and nodes built using the ROS, the simulation model was needed to be built. A module is a set of software generated to execute a specific purpose. A collection of data is processed using data analysis techniques made by python, and useful output is generated in each module. In another module, the output generated by one module will be used as the input, and the whole device will be a continuous information flow loop.

TABLE III. LIST OF PARAMETERS FOR VEHICLE SIMULATION.

Dynamics of Vehicle	The target RPM is used as the input for each thruster and the resultant ROV movement is calculated. The dynamics of the vehicle can be generalized to include, for example, the dynamics of the manipulator, which would require another input form to control the joints.
Sensor Model	As an input, ROV simulated motion and location is used, and simulated sensor output is generated based on sensor type and acceptable noise and bias. This category also includes navigation systems, indicating systems that integrate outputs from various sensors.
Estimator	Detects system status upon data received
Guidance	Decides desired system states based current and desired motions of the vehicle.
Path Planning	Draws a path for the vehicle to move on using control algorithms
Controller	Uses information about current ROV states and desired states. to calculate RPM for each thruster such that the ROV will operate as planned.

The system was attempted using UUV simulation platform using BlueROV2 model which is equipped with parameters that are similar to our vehicle.

IV. CONCLUSION & FUTURE RESEARCH

We achieve the design of a modular and easy to produce HUWV with a focus on manufacturability in Egypt. We provide documentation for ease of development for interested researchers. Additionally, we give a brief overview of the system in this paper and showcase our contributions and key design considerations. Overall, the vehicle platform gives a ready design for testing by software & computer engineers to implement smart algorithms on and do marine robotics research.

A. *Future Research*

As the vehicle is intended as a marine robotics research platform, we propose some improvements and fields of interest below.

1) *V-SLAM Technology*

The SLAM can be defined as follows: given the robot's controls U, the observations of the world Z determine the map of the environment M, and the robot's pose X.

And in the probabilistic world as every element exhibits some errors, it can be expressed as:

$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T}) \tag{2}$$

Another important aspect of SLAM is that filters ought to be used since the robot is always operating under the assumption of being inside a distribution of errors. Kalman filters are used here as the error distribution can be Gaussian, particularly the Extended Kalman Filter as underwater robotics often experience non-linear motion models.

Upon the general idea of SLAM technology, ZED 2K Stereoscopic Camera convert the visual data into laser-based chart. Which could be identified by its node in the ROS network. Adding this to our vehicle would help achieve autonomy in good-visibility close-quarters marine environments.

2) *Advanced Sensors*

For future work we propose the following. Using state-of-art components for the autonomous navigation of the vehicle is the sensor based on Doppler velocity logs (DVL) [17] [18] [19], Additional sensor modules are possible such as sonar, global navigation system, and light-based data links.

3) *Battery system*

The battery system would help researchers work with no connection to the top station, giving the opportunity for more data acquisition from the seabed, and then receiving the data logs after the ending of the operation. The vehicle is ready for the battery system to be implemented on, by providing the needed space and connection for the batteries to be implemented.

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REFERENCES

[1] A. Tahir and J. Iqbal, "Underwater robotic vehicles: Latest development trends and potential challenges," *Science International*, vol. 26, pp. 1111-1117, 2014.

[2] M. Quigley, K. Conley, B. Gerkey, T. F. J. Faust and J. Leibs, "Ros: an open-source robot operating system," in *ICRA workshop on open source software, vol. 3, no. 3.2.*, Kobe,Japan, 2009.

[3] Manzanilla.A, Reyes.S, M. Garcia, Mercado.D and L. R., "Autonomous navigation for unmanned underwater vehicles: Real-time," *IEEE Robotics and Automation letters*, vol. 4, p. 1351–1356, 2019.

[4] Terrill, E. Gallimore, R. Stokey and E., "Robot Operating System (ROS) on the REMUS AUV using RECON," *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*, pp. 1-6, 2018.

[5] K. DeMarco, M. E. West and T. R. Collins, "An implementation of ros on the yellowfin autonomous underwater vehicle (auv)," *OCEANS IEEE*, pp. 1-7, 2011.

[6] N. Lawrance, R. DeBortoli, D. Jones, S. McCammon, L. Milliken, A. Nicolai, T. Somers and G. Hollinger, "Shared autonomy for lowcost underwater vehicles," *Field Robotics*, vol. 36, no. 3, pp. 495-516, 2019.

[7] Wilby, Antonella and E. Lo, "Low-Cost, Open-Source Hovering Autonomous Underwater Vehicle (HAUV) for Marine Robotics based on BlueROV2," in *OES Autonomous Underwater Vehicles Symposium (AUV)(50043)*, San Diego, California, 2020.

[8] M. Dunbabin, J. Roberts, K. Usher, G. Winstanley and P. Corke, "A Hybrid AUV Design for Shallow Water Reef Navigation," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, pp. 2105-2110, 2005.

[9] Prats, Mario, Romagós, D. Palomeras, N. Sánchez, J. Carlos, Nannen, V. Wirth, S. Fernandez, J. Beltrán, J. Campos, R. Rida, P. S. P. Oliver, G. Carreras, M. Gracias and N. M. Pra, "Reconfigurable AUV for intervention missions: A case study on underwater object recovery," *Intelligent Service Robotics*, vol. 5, pp. 19-31, 2012.

[10] R. Codd-Downey, M. Jenkin and K. Allison, "Milton: An open hardware underwater autonomous vehicle," 2017.

[11] Joordens and Matthew, "Design of a low cost underwater robotic research platform," *2008 IEEE International Conference on System of Systems Engineering, SoSE 2008*, pp. 1-6, 2008.

[12] Hostler, A. a. Benson, B. a. Warner and Joshua, "BudgetROV: An ultra low cost robotics platform for education and research," *OCEANS*, pp. 1-4, 2017.

[13] B. M. M. Anwar, M. A. Ajim and S. Alam, "Remotely operated underwater vehicle with surveillance system," *2015 International Conference on Advances in Electrical Engineering (ICAEE)*, pp. 255-258, 2015.

[14] PlasticsMakeItPossible. [Online].

[15] MATE Inspiration for Innovation, "2021 EXPLORER COMPETITION MANUAL," 10 May 2021. [Online]. Available: https://files.materovcompetition.org/2021/2021_EXPLORER_Manual_10May2021.pdf. [Accessed 19 July 2021].

[16] ARTESYN, "adq700_ds_29sep2016_1476689627-1036092," [Online]. Available: https://www.mouser.com/datasheet/2/633/adq700_ds_29sep2016_1476689627-1036092.pdf.

[17] Vortex NTNU, "Vortex NTNU - Robosub 2020," 2020. [Online]. Available: https://robonation.org/app/uploads/sites/4/2020/08/RS20_TDR_NTNU.pdf. [Accessed 19 July 2021].

[18] M. M. E. L. R. W. N. A. e. a. Irene Crowell, "California Institute of Technology RoboSub Technical Design Report," 2020. [Online]. Available: https://robonation.org/app/uploads/sites/4/2020/08/RS20_TDR_Caltech.pdf. [Accessed 19 July 2021].

[19] A. H. G. I. H. Z. M. B. A. H. A. N. e. a. Samer A. Mohamed, "Design and Implementation of Task-Oriented Autonomous Underwater Vehicle: Feryal," 2020. [Online]. Available: https://robonation.org/app/uploads/sites/4/2020/08/RS20_TDR_AinShams.pdf. [Accessed 19 July 2021].

[20] F. Eren, "Pose Detection and control of unmanned underwater vehicles -utilizing an optical detector array," University of New Hampshire, Durham, 2015.

[21] M. M. M. Manhães, S. A. Scherer, M. Voss, L. Douat and T. Rauschenbach, "UUV Simulator: A Gazebo-based Package for Underwater Intervention and Multi-Robot Simulation," OCEANS'16 MTS/IEEE Monterey, Monterey, 2016.

[22] A. K. Osman, A. M. Abdelghany, A. A. Salah, P. Y. Yasser, S. A. Adel, S. M. M. ElBaroudy, Y. J. Mohamed, Y. O. A. Elmansy and Z. M. Hassan, "Building ROS-based Software for an Autonomous Underwater Vehicle (AUV)," Ain Shams University (Unpublished), Cairo, Egypt, 2019.

[23] S. M. Mo, "Development of a simulation platform for ROV systems," NTNU, Trondheim, 2015.

[24] Bluerobotics, "rb-blu-27_-_documentation," [Online]. Available: https://www.robotshop.com/media/files/rb-blu-27_-_documentation.pdf.