AGH MARINES

Technical Documentation

The AGH University of Krakow
Cracow, POLAND

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1. Abstract

This technical report describes the development and deployment of the ROV (Remotely Operated Vehicle) robot "Narwhal" by the AGH Marines team. Students from various engineering disciplines worked together, combining theoretical knowledge with practical skills. Inspired by the narwhal, a marine mammal known for its deep-diving abilities, the Narwhal robot features advanced sensors, strong control systems, and innovative propulsion, allowing it to handle complex underwater tasks.

Like narwhals navigating in Arctic waters, the Narwhal robot is designed for efficient and stable underwater movement. This report covers the technical challenges, solutions implemented, and robot performance in various underwater scenarios. The successful deployment of Narwhal shows the potential of student-led projects to advance marine technology and support underwater exploration.

The AGH Marines Scientific Club focuses on expanding members' knowledge and skills in mechatronic underwater systems, participating in competitions, and promoting technology and marine environment knowledge. This collaborative environment enhances technical and soft skills like communication, problem-solving, and project management. Students gain hands-on experience in mechanical design, electronics, software development, and system integration. The club also helps new members learn new skills in their areas of interest, such as mechanics, electronics, or programming.

2. Team Description

2.1. Overview

At AGH Marines, we specialize in underwater robotics, focusing on remotely operated (ROV) and autonomous (AUV) underwater vehicles. Our main goal is to expand our members' knowledge and skills through hands-on design and construction of robots and equipment. Founded on September 11, 2018, by four Mechanical Engineering and Robotics students—Filip Dudek, Patrycja Lisak, Tomasz Małachowski, and Mateusz Stemplewski—the club has grown and evolved.

In October 2022, the board and member structure changed, with a new board comprising students from various faculties: Malwina Cieśla, Michaela Murzyniec, Mikołaj Pasterz, and Piotr Wilkoń. We welcome both experienced individuals and newcomers to join our activities. We aim to continue previous projects while introducing new ones, offering new members a chance to integrate and start practical work quickly.

Our current focus remains on designing and building underwater robots (ROVs and AUVs). We also work on smaller mechatronic projects and provide training for members to learn independently in their areas of interest. Our activities cover various marine industry applications, such as inspecting, assembling, and maintaining underwater machinery, military uses, and seabed exploration for geological, biological, environmental, or archaeological research. These devices are crucial as they enable humans to reach inaccessible or dangerous places and perform complex operations.

2.2. Main Personnel of a team

We have 35 members organized into six teams, and here we primarily highlight the main personas in our group.

Dr. Ryszard Olszewski

The group's supervisor, an assistant professor at the Department of Mechanics and Vibroacoustics, WIMiR AGH. Areas of professional interest include mechanics, vibrations, theory of mechanisms, and numerical modeling.

Dr. Jędrzej Blaut

Club supervisor, assistant professor at KMiW, WIMiR AGH. Enthusiast of new technologies. His area of scientific interest is diagnostics based on non-linear phenomena in both technology and medicine.

Malwina Cieśla, BEng

Chairwoman of the group. 5th year student of Technical Informatics. This crazy soul loves dancing, she has been a member of the AZS AGH Cheerleaders section for 6 years, supporting our university colleagues. As if that wasn't enough, since the lockdown she has taken on the 24-hour duty of being a dog mom.

Mikołaj Pasterz

Vice-chairman, and leader of the electronics team.
4th year student of Electronics and Telecommunications.
In addition to a wide technical spectrum (from high voltage to robotics), he is passionate about film production, music, and playing the guitar. He also doesn't despise good coffee.

Michaela Murzyniec, BEng

Leader of the hydroacoustics team, specialist in acoustic localization algorithms. Member of the club's board. Second-year student of second-cycle Acoustic Engineering. Her passion is diving and freediving, which she has been training for two years. Additionally, she likes mountain trips.

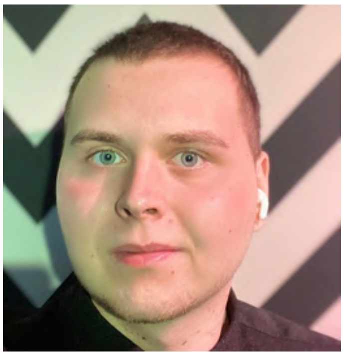
Piotr Wilkoń, BEng

Embedded and software team leader. Member of the club's board. Pursuing master’s degree in Electronics and Telecommunications. A fan of black tea and electronic music. Passionate about analog electronics, radio engineering, and DSP. Amateur radio operator with call signs SQ8L and AD2BZ.

Szymon Wojciula, BEng

Mechanics team leader. Electronics technician. 4th year student of Mechanics and Machine Construction. Passionate about adrenaline in extreme sports and pineapple on pizza.

Piotr Flak



AI team leader. Second-year student of Teleinformatics. By day, he is a front-end developer, in his free time he is passionate about shipping and analog photography.

3. Design Assumptions for the ROV Robot

The project will meet the following assumptions:

- **Innovative Design:** The modular construction of the underwater robot will allow for flexible expansion, adaptation to various tasks, and future modifications.
- **Multitasking Capability:** By adding or exchanging modules, the robot can be easily adapted to different areas, such as seabed exploration, underwater infrastructure inspection, or marine environment monitoring.
- **Educational Tool:** The project aims to use the robot as an educational tool, enabling students to gain practical experience in underwater technology, robotics, marine engineering, and natural sciences.
- **Promotion of Education and Innovation:** Participation in prestigious competitions like the MATE ROV COMPETITION will highlight the innovative nature of the project and contribute to the development of modern underwater technologies, promoting education and practical skills among future engineers and scientists.

4. Decision Making

4.1. Materials

The robot's structure is built around an aluminum frame, chosen for its cost-effectiveness, quick manufacturing, and the ability to outsource production. Aluminum was selected because it worked well in a previous project. The frame is designed to handle underwater pressure, provide space for components, and reduce drag during movement.

Key components, such as thrusters, lighting, and a watertight cylinder for electronics, are mounted on the frame. The cylinder is made from acrylic, chosen for its proven durability and clarity from past projects.

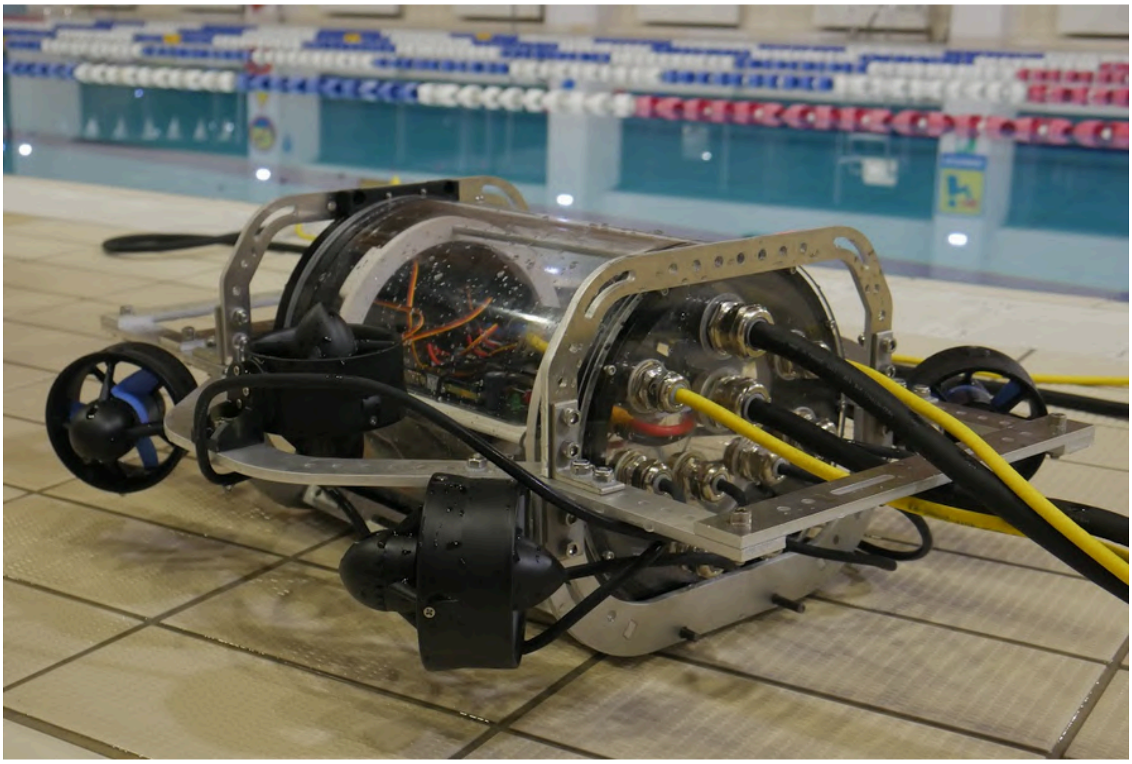
The thrusters were bought from Blue Robotics, known for their reliable and efficient products. Previous self-made thrusters did not perform well, so we opted for these trusted thrusters.

4.2. Build vs Buy, New vs Used Elements

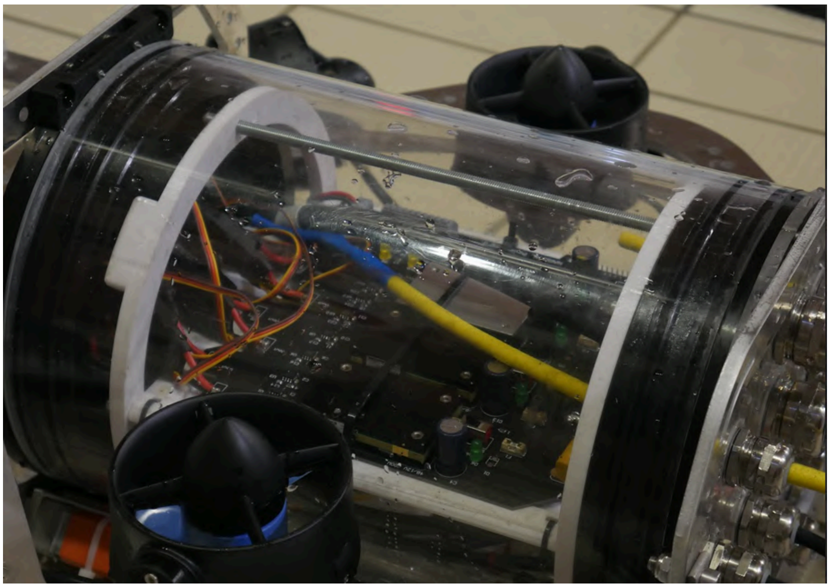
In developing the robot, we carefully considered whether to buy or build components and whether to use new or existing parts. We chose to build 3D-printed parts in-house for customization and quick design changes.
For electronics, we opted to buy most components to ensure high reliability and consistent quality.
The mechanical frame was custom-designed and newly cut to order, meeting our specific requirements for strength, space, and streamlined shape. Although we reused code from a previous project, we reimplemented most functions due to disorganized documentation from a management change, allowing us to clean up and improve the code.
The AI components were developed from scratch, as the new AI team wanted to incorporate the latest features.

5. ROV Design

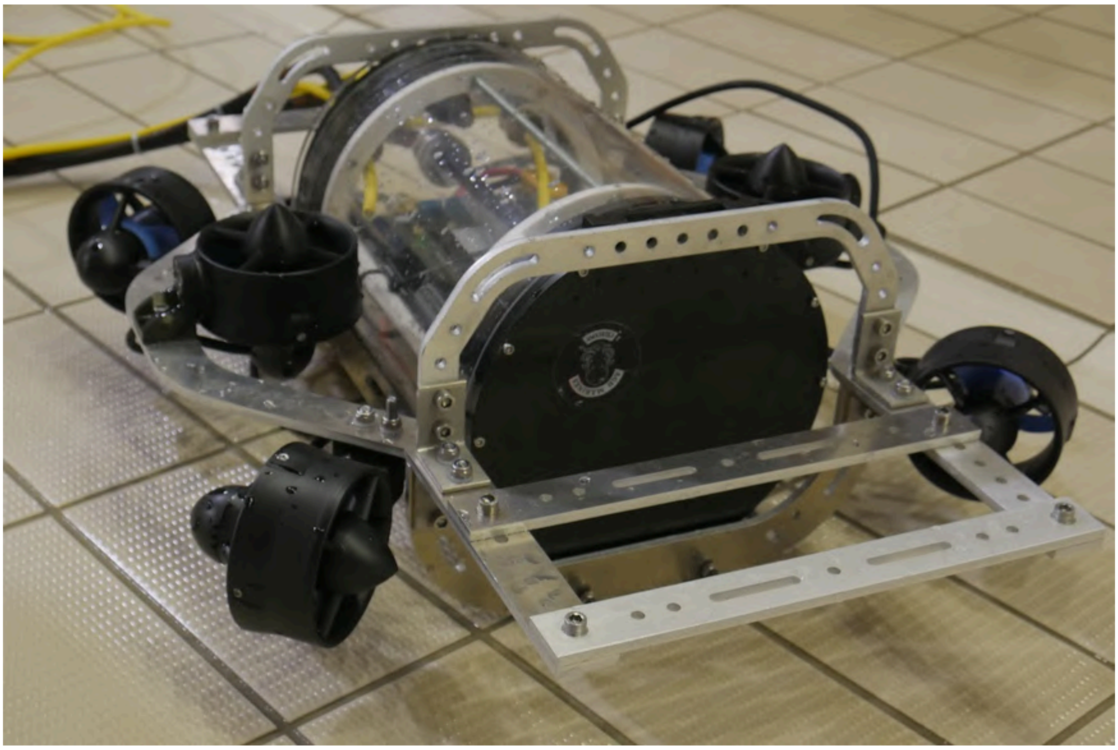
Here are the photos of the ROV design taken on the pool testing day:



Picture of the left and roof side of the Narwhal ROV



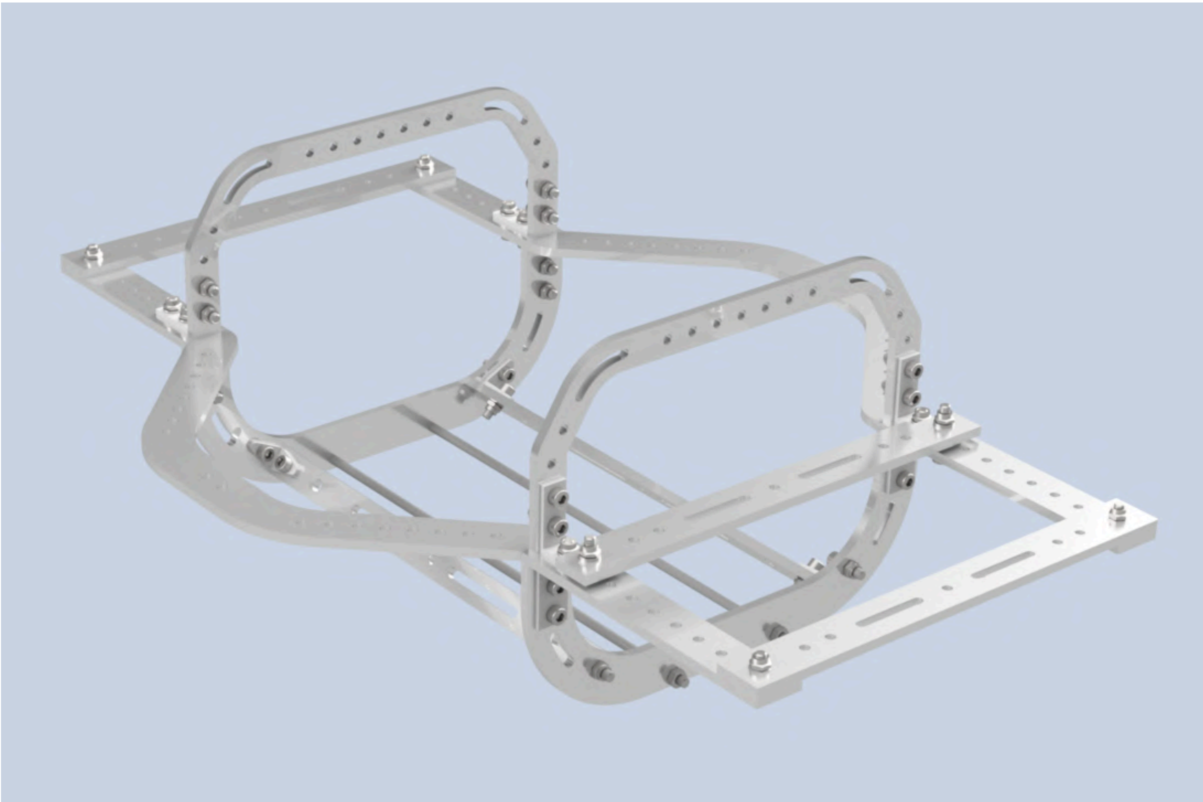
Inside the Narwhal ROV



Picture of the front and top of the Narwhal ROV

6. Mechanics

The underwater robot features a robust and symmetrical aluminum frame (PA11), consisting of two primary base elements, two upper, and two lower ribs which are secured with aluminum counters, bolts, washers, and self-locking nuts. The frame is reinforced with two additional ribs, between which an acrylic tube from Blue Robotics is mounted. These additional ribs are used to mount pre-selected ballast to balance the robot trim. The acrylic tube is equipped with aluminum flanges and one solid aluminum end cap, while the other end cap is made of acrylic, custom-manufactured by the team.



Narwhal frame render

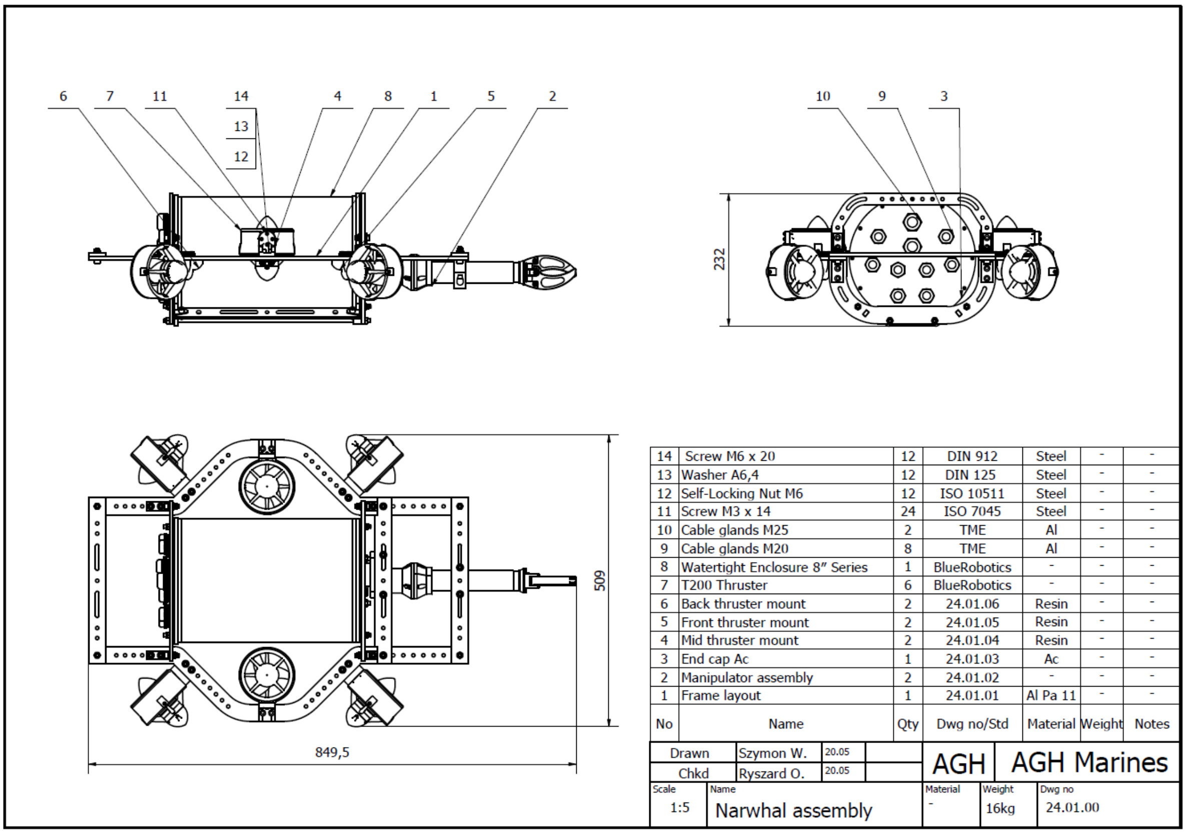
Six resin-printed supports are attached to the frame to hold the T200 thrusters to ensure stable propulsion. In addition to the ribs, there are three additional supports—one at the rear and two at the front. The front supports serve as mounting points for a manipulator and a camera.

Outside the acrylic end cap, there are ten cable glands made of nickel-plated brass. Eight with a diameter of twenty millimeters: six for motor control, one for camera, and one for robot control. In addition, two with a diameter of twenty-five millimeters, one of which powers the robot, and the other is designed to control the manipulator. All cable glands are IP68 certified up to 10 bar.

Cable glands and custom-manufactured acrylic end cap

At the front, a Blue Robotics manipulator is mounted on two custom-designed and 3D-printed connecting elements. These elements are secured to the front support and a servo basket, ensuring a stable and functional setup. The whole structure weighs about sixteen kilograms.

This mechanical structure provides a durable and flexible foundation for the underwater robot, allowing for various modifications and enhancements to suit future needs, such as different underwater tasks and research activities.



14	Screw M6 x 20	12	DIN 912	Steel	-	-
13	Washer A6,4	12	DIN 125	Steel	-	-
12	Self-Locking Nut M6	12	ISO 10511	Steel	-	-
11	Screw M3 x 14	24	ISO 7045	Steel	-	-
10	Cable glands M25	2	TME	Al	-	-
9	Cable glands M20	8	TME	Al	-	-
8	Watertight Enclosure 8" Series	1	BlueRobotics	-	-	-
7	T200 Thruster	6	BlueRobotics	-	-	-
6	Back thruster mount	2	24.01.06	Resin	-	-
5	Front thruster mount	2	24.01.05	Resin	-	-
4	Mid thruster mount	2	24.01.04	Resin	-	-
3	End cap Ac	1	24.01.03	Ac	-	-
2	Manipulator assembly	2	24.01.02	-	-	-
1	Frame layout	1	24.01.01	Al Pa 11	-	-
No	Name	Qty	Dwg no/Std	Material	Weight	Notes

Drawn	Szymon W.	20.05	AGH	AGH Marines
Chkd	Ryszard O.	20.05		
Scale 1:5	Name Narwhal assembly	Material -	Weight 16kg	Dwg no 24.01.00

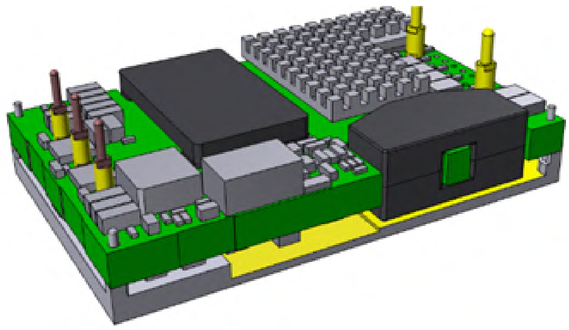
Technical drawing of the Narwhal ROV

7. Electronics

The electronics onboard the Narwhal can be divided into two main segments: power systems and control systems.

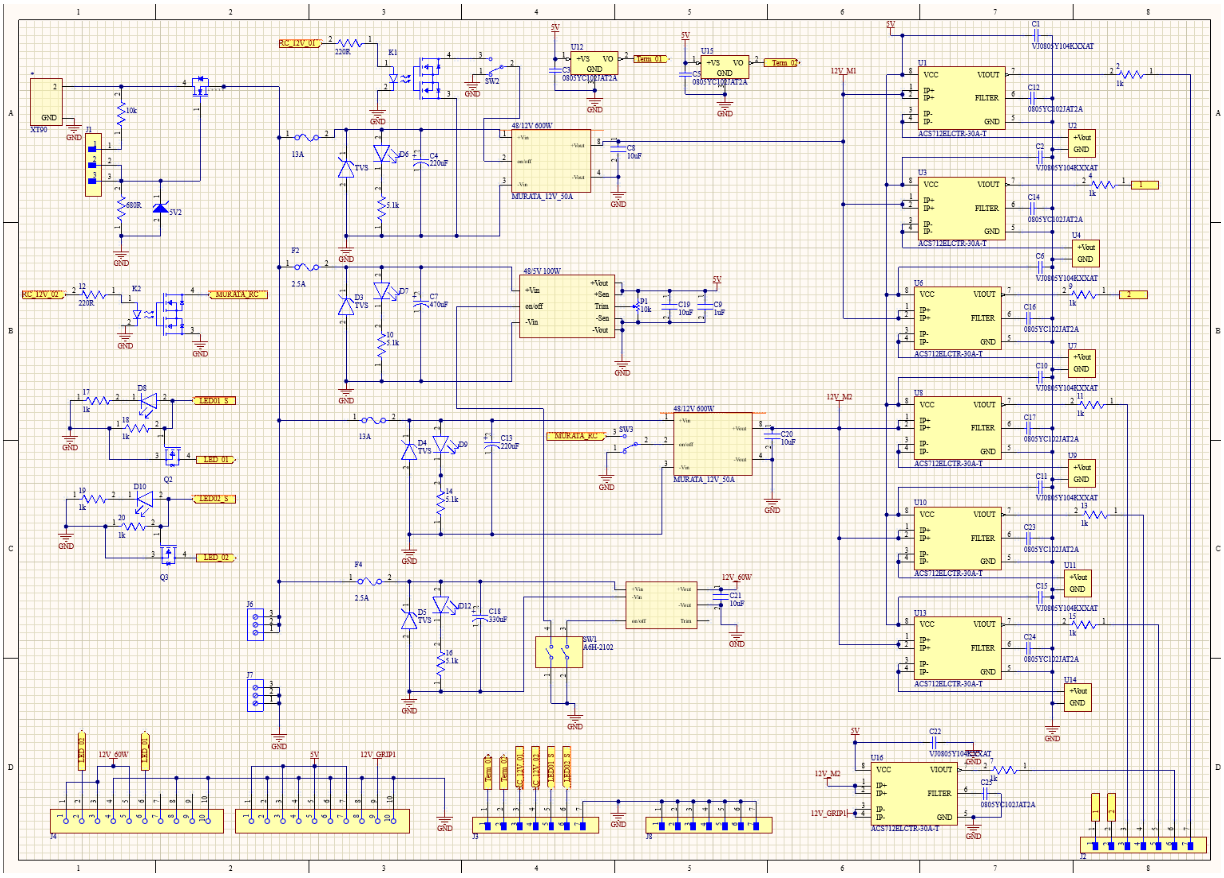
7.1. Power systems

The power system includes PCB1, which houses converters that transform the external supply voltage of 48V DC into the specific voltage levels needed for the robot's operation, namely 5V and 12V. This allows for maximum power usage (1360W) while maintaining compact size and high efficiency.



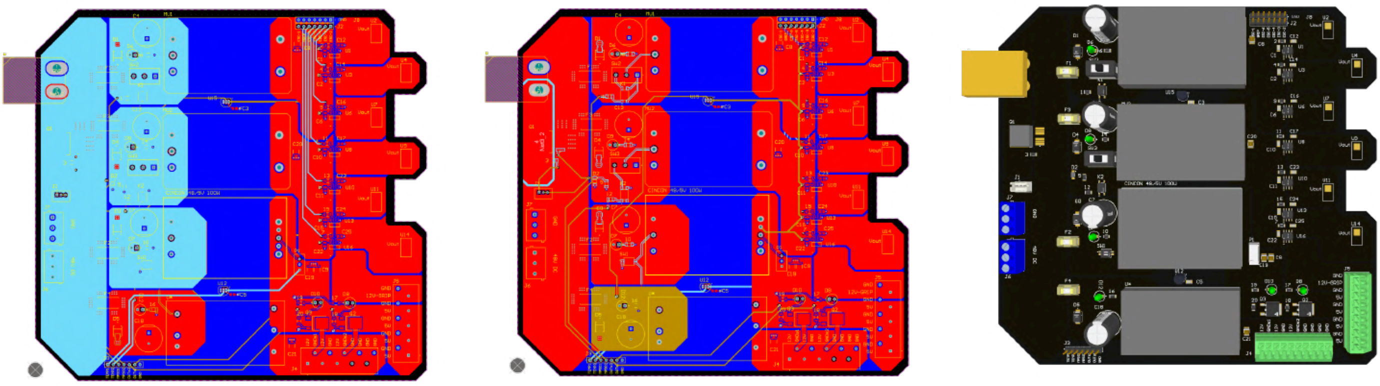
Used Power Converter Modules - 48/12V 600W DC/DC Converter

Additionally, the PCB contains filtering, protective, control, and measurement elements (sensors for measuring the current consumed by each of the six motors, as well as temperature sensors), and modules that enable remote switching on or off of individual converters. All the components used in the module are shown in the schematic below.



Schematic diagram of the power supply circuit

Additional layers on the PCB were used to allow higher currents to flow.

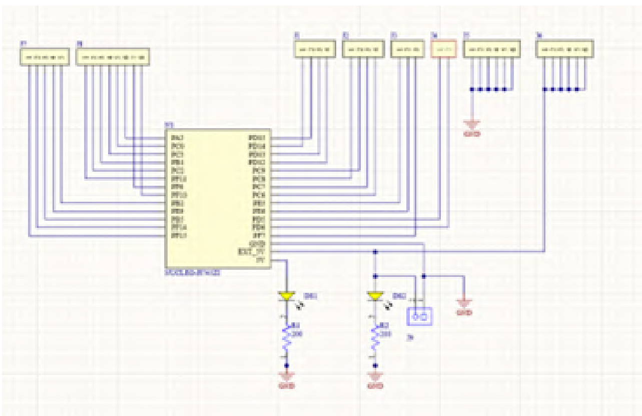


PCB layers and visualization - front view

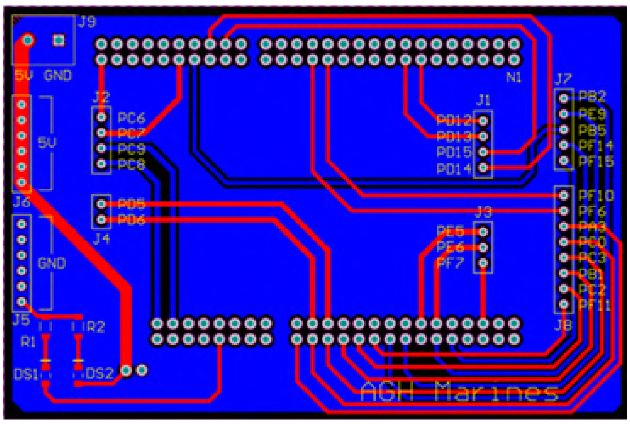
Bidirectional ESC speed controllers were used to control all six thrusters, which use a PWM signal from the microcontroller to regulate speed and direction. Each controller is powered by 12V, which it uses directly from the main power PCB.

7.2. Embedded Hardware

The second segment is the embedded hardware, which includes the NUCLEO H745ZI-Q STM32 and a shield that provides power to the Nucleo and outputs signal connections for the used modules. The supply voltage, delivered to the terminal block connector, is also routed to the goldpin connectors. The used Nucleo outputs are routed to the goldpin connectors. The system is equipped with two LEDs: one indicates external power, and the other indicates power to the Nucleo.



Schematic for Nucleo shield



PCB project

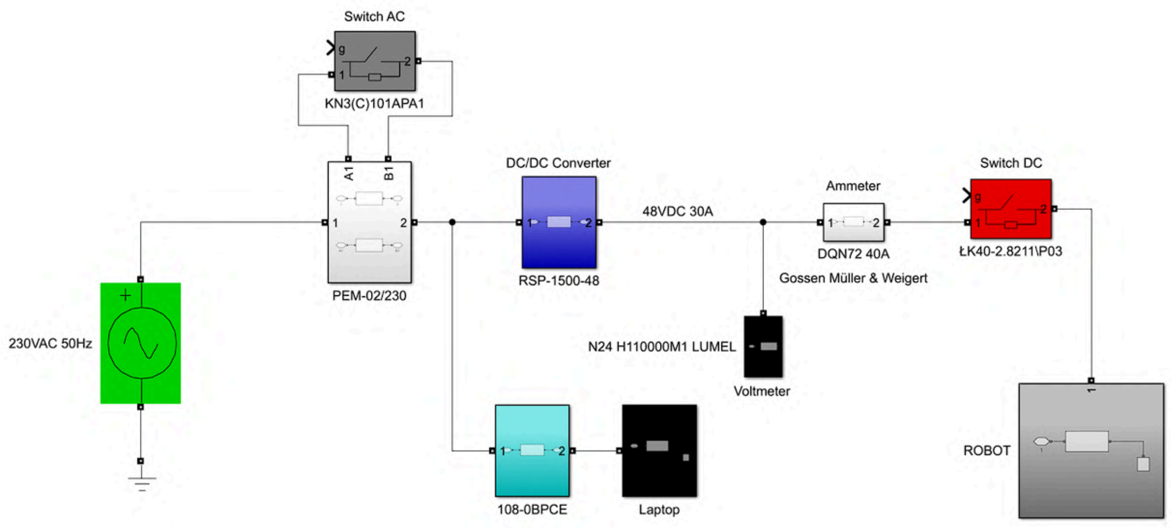
7.3. Main and position lighting

The main lighting control system for the ROV robot is based on the LT8391DJ Buck-Boost controller for LED lighting from Analog Devices and the high-power LED emitter CMB1825-R096-000N0B0A57E from CREE LED.

The LED lighting module is based on 2 high-power LED emitters from the CREE LED XLamp XE-G series with the ST1CC40PUR controller from STMicroelectronics.

7.5. Power supply station

To supply power for the underwater robot, a power supply station in the form of a chest was made. The station outputs 48V 30A DC. The chest itself was created using elements such as a 1500W AC/DC converter serving as the main source of power for the power supply station, power outlet, mainly used for powering a laptop, two switches, one used for turning on the DC/DC converter and the other used to enable the station’s output, ammeter and voltmeter used for controlling the exact values of power station’s output

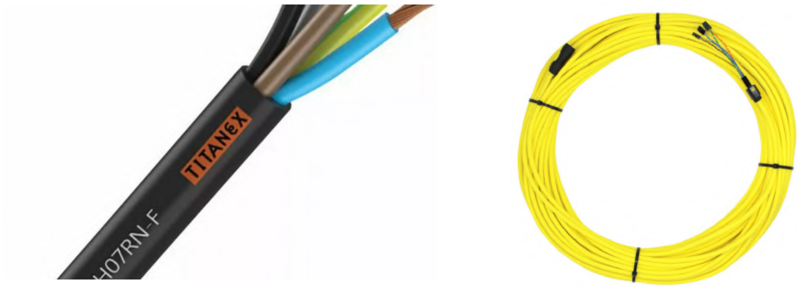


Schematic diagram of the power station

7.6. Wiring and electrical connection systems

The tether consists of two cables, 15 meters long each. A power cable H07RNF, TITANEX 2x6mm2 rubber-insulated cable is directly connected to the main power board to supply it with the needed amount of electrical power with a 30A fuse placed at a distance of

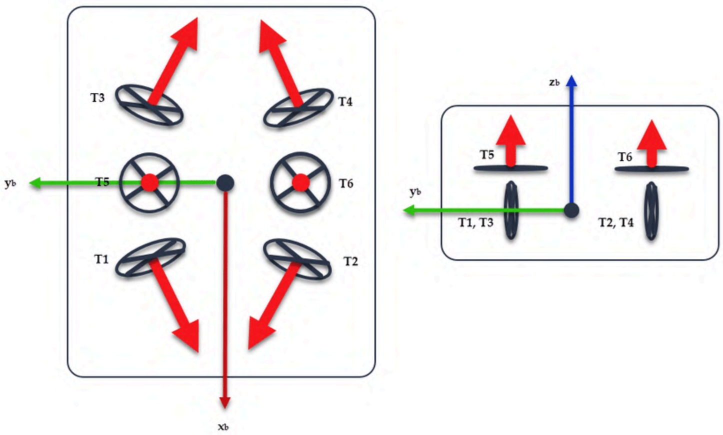
20 cm from the power station for protection. The communication cable is the ROV Ethernet Tether which is connected to the microcontroller and the computer.



The communication cable used in Narwhal ROV

8. Control system

The control system is a crucial component of the whole project, which enables the operator to control the robot in a uniform and intuitive manner. One of the main responsibilities of the control system is to translate the operator input to appropriate values that are used to control motors, servos, and other elements.



Thruster configuration [2]

The robot utilizes a standard vectored thruster configuration with six devices, as shown in the figure above. Such configuration allows for a linear movement in all axes (X, Y, Z), as well as rotations around the X and Z axes, called roll and yaw, respectively, thus ensuring five degrees of freedom.

Since the operator is responsible for controlling the robot movement, rather than setting power values for each thruster separately, an appropriate conversion process must take place. Such a process is known as *thrust allocation* and its role is the mathematical translation of the force and torque vector to a vector containing normalized power values for each motor. In general, thrust allocation can be described by the following equation [1]:

$$u = K^{-1}T^{-1}\tau,$$

where τ is the input vector, T is the thrust configuration matrix, and K is the control signal coefficients matrix.

Vector τ in our robot is defined as:

$$\tau = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_z \end{bmatrix},$$

where F_a is the force in axis a and M_a is the torque around axis a. M_y is not present, as no thruster allows for a rotational movement around the Y axis.

Matrix T is defined as:

$$T = \begin{bmatrix} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 \end{bmatrix},$$

where t_n are column vectors representing forces and torques contributed by the thruster n, with their elements in the same order as in the vector τ.

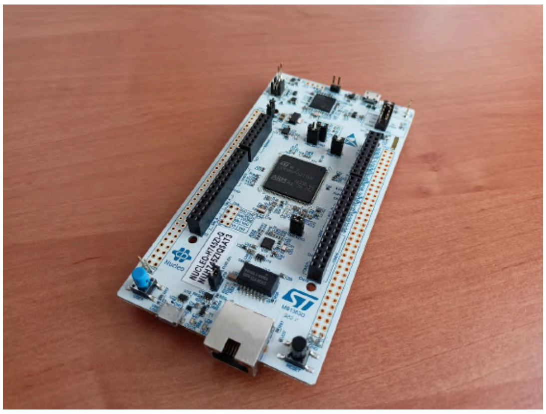
Since the actual force and torque values are irrelevant, all values are normalized, thus accepting the forces and torques in range -1 to 1 and producing motor control outputs in range -1 to 1. Then, the K matrix is an identity matrix.

Logitech F310 gamepad used as the control device

A standard gamepad (shown above), featuring five analog input axes and ten buttons, was used as the control device, due to its price, availability, and compatibility with most operating systems as a standard input device. The number of available analog inputs matches the number of degrees of freedom, thus making the gamepad suitable for controlling the robot. Additional buttons are used to control the elements that feature only two positions, such as opening and closing the gripper.

9. Embedded

One of the objectives when designing the robot was to limit the space utilization and heat generation on board. Such an objective required all possible systems to be moved to the surface, where heat dissipation and available space are no longer a problem. However, to provide a consistent interface between the control station and the actual hardware, the embedded subsystem had to be employed. Additionally, shifting software modules to the ground station simplifies the development process, as the frequency of microcontroller reprogramming, which requires the robot to be disassembled, is limited.
The main role of the embedded subsystem is to create a software-hardware abstraction layer, thus allowing the control station software to not care about the underlying hardware, such as electronic speed controllers or servos, making the solution more versatile.
The Gigabit Ethernet was chosen as the communication interface between the robot and the control station, as it provides very high throughput and excellent reliability, is easily extensible, and is available in most consumer devices and development platforms, thus notably simplifying the development and testing process.
The physical connection was realized using a waterproof twisted pair cable with standard modular 8P8C connectors.



Nucleo H745ZI board used as the embedded system base

The subsystem is based on the STMicroelectronics Nucleo H745ZI development board (shown above), which features a dual-core ARM microcontroller together with an Ethernet interface. An additional shield, described in the *Electronics* section, was designed and manufactured to facilitate access to necessary MCU pins. The MCU features multiple PWM outputs, ADC inputs, and GPIO outputs/inputs, which are used to control onboard hardware.
The communication is realized using the UDP protocol and a custom packet format. The packet consists of the module ID (e.g., 0x01 for motor control), data size, and payload, which is dependent on the underlying module, as shown in the figure below.

Command/response ID	Payload size	Payload
1 B	1 B	0-252 B
uint8_t	uint8_t	

The base communication packet format

The utilized TCP/IP stack, LwIP, calls the provided callback function, that parses the packet and passes it to the suitable module. The UDP protocol was chosen due to the small overhead and low latency, which is crucial for real-time control systems. Although packet losses can occur, they are insignificant in such systems due to periodic transmission of new control data.

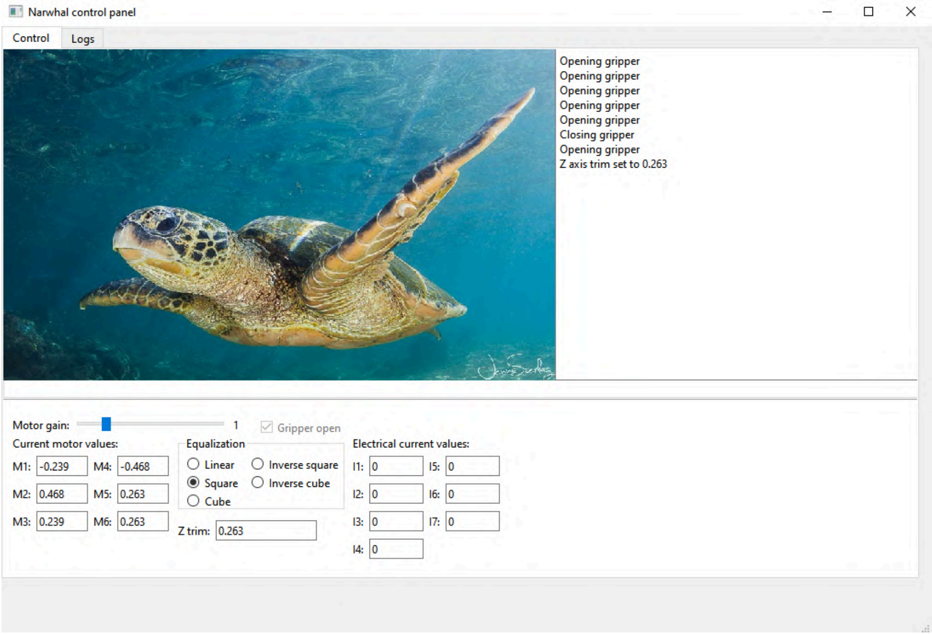
One of the most important functions of the embedded subsystems is to control motor power by driving the electronic speed controllers. The ESCs described in *Power systems* section utilize standard, servo-like PWM signals with a frequency of 50 Hz (20 ms period) and a variable duty cycle ranging from 5% to 10%, which proportionally controls the motor power. However, since the control software is not aware of the hardware, the normalized power values from -1 to 1 are issued for each motor and the embedded firmware is responsible for translating these values to PWM duty cycle values, based on the requirements of the ESCs. Similarly, the software issues the target angle in radians for servos, which is then recalculated to the duty cycle value appropriate for a given servo.

The firmware is designed to handle requests in a best-effort manner, thus maximizing the control data throughput. The proper operation of the embedded subsystem is ensured by the built-in watchdog.

The firmware was developed in STM32CubeIDE software using the provided HAL library and LwIP TCP/IP stack.

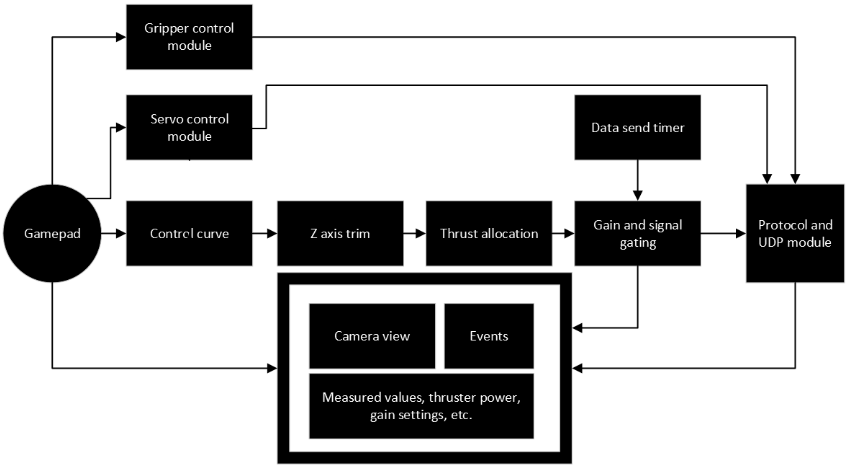
10. Software

The software is the topmost element in the operator-robot layer stack. It provides an intuitive, graphical interface for the ground team and exposes all robot control and maintenance routines through this interface. The main program window is shown below.



Control software main window (turtle picture being the placeholder when the camera is not connected)

The software seamlessly integrates with the connected gamepad and uses it as the input device. The software allows for monitoring instantaneous normalized thruster power values, as well as the measured electrical current values.
Additionally, a control curve selection allows for the selection of five different modes to facilitate steering depending on the environment, the type of thrusters and controllers used, and operator preferences.
A software-implemented Z-axis trimming option lets the operator set the constant up-down axis force offset to keep the robot immersed, omitting the need of holding the knob. The trim is set using the gamepad. The current offset value is shown in the appropriate field.
The events, such as opening and closing the gripper or setting the trim, are reported in the event window. The gripper state is also shown using the checkbox.
Internally, the software is responsible for all calculations required to keep the robot moving, most importantly the thrust allocation, which was described in the *Control system* section. These calculations are done utilizing the Eigen linear algebra library.
The software includes the UDP module, which is built around the Qt library, and the protocol parser and encoder which is required to communicate with the embedded system. The gamepad input values are continuously probed and sent periodically, at the frequency of 20 Hz, to the robot. The tests prove the frequency to be high enough to control the robot without significant delays, while not putting much stress on the embedded system or the network.
Moreover, the main window features the view from the onboard camera, which is replaced with a picture when the camera is not connected.
The software was written in C++ using Qt library and environment for GUI and network connection, as well as the SFML library for handling joystick inputs.
The block diagram of the software is shown below.

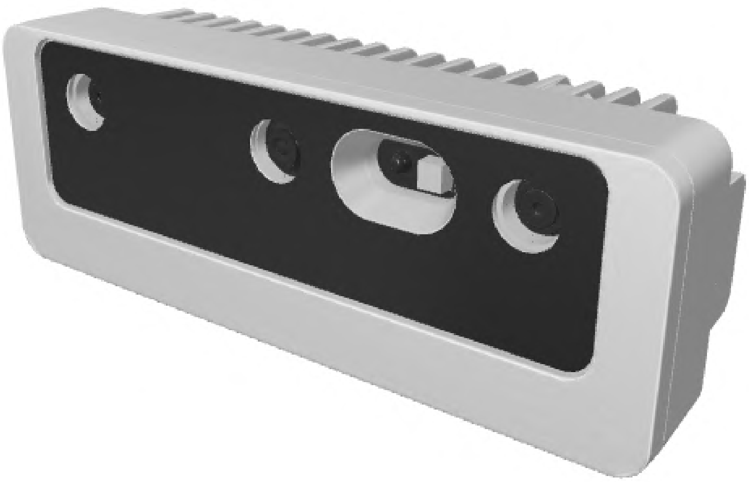


General block diagram of the software

11. AI

Device

Artificial intelligence solutions are being developed with the Oak D Pro POE stereoscopic camera providing deep vision, an integrated IMU, and a built-in processor for running custom AI models. The tool allows us to develop the functionalities of our underwater robot and is a prelude to the implementation of the autonomous mode in the future.



Oak D Pro POE Camera

Computer Vision

In addition to the standard camera usage, the AI team puts effort into developing neural networks for recognizing underwater objects both for competitions and useful in real-world scenarios. Computer vision neural networks are based on the YOLO framework, which produces satisfactory results with low consumption of CPU resources. An additional advantage of using a stereoscopic camera is the accurate localization in space of the detected object relative to the camera.

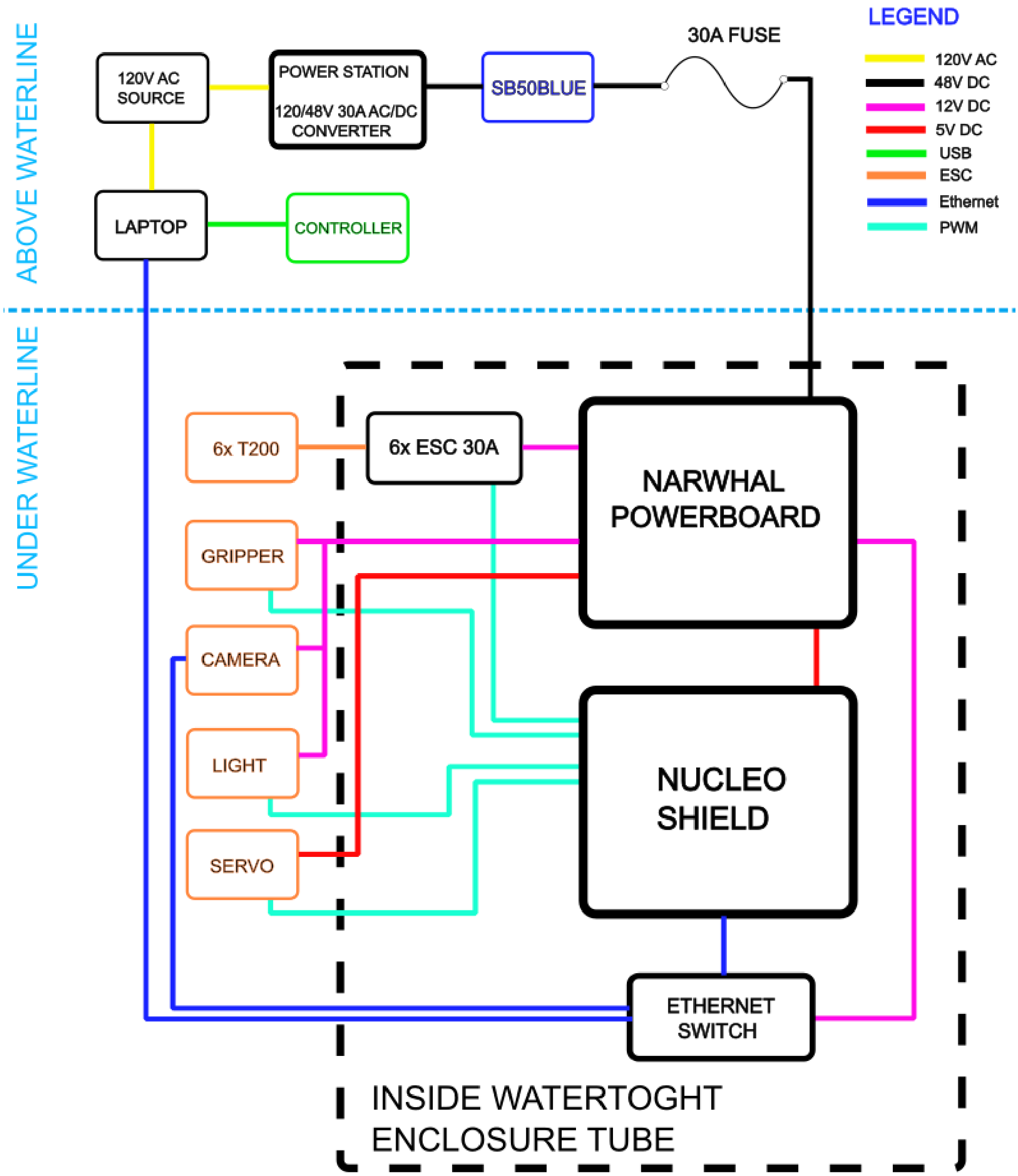
Depth Vision Extensions

Thanks to the integrated 9-axis IMU, it is possible to implement SLAM (visual simultaneous localization and mapping) technology combining accurate localization and depth vision which in effect allows scanning space in 3 dimensions. The spectacular AI API and nerfstudio are used for implementation.

12. Marketing

Our marketing efforts are led by a dedicated team of three, including a marketing specialist who also handles photography and video creation. This team ensures regular posts on our Facebook fanpage and LinkedIn profile, keeping our audience engaged and informed. They also produce marketing and promotional materials such as business cards, pens, and stickers, which are used to represent and promote our group at various events and exhibitions.

13. S I D



	Current [A]
6x T200	16,8
SERVO	0,52
Lights	0,83
Gripper	1,25
Camera	0,31
Total current	19,81
19,81 × 150% = 29,72A	
30 AMP FUSE	

SID documentation for Narwhal ROV

14. Budget

The budget for this project comes from a dedicated university's grant, which covers both the construction of the robot and the expenses for participating in competitions. Additionally, we utilize available equipment at the university, allowing us to perform many tasks in-house, purchasing only the necessary materials. The following tables present the budget and project costing, where all listed items are purchased to ensure a long-term, sustainable outcome for the new project.

				Reporting period
School Name:	The AGH University of Krakow			From: 1 Oct 2023
Instructor/Sponsor:	Ryszard Olszewski (supervisor of the science club), Malwina Cieśla (president)			To: 30 Sept 2024
		Income		
		Income at starts of the project		
Source				**Amount**
AGH UST GRANT				14500$
		Expenses		
Category	**Type**	**Description**	**Projected Cost**	**Budgeted Value**
Hardware	Purchased	Elements used for mechanical part	2300$	2300$
Electronics	Purchased	Electronic elements	800$	800$
Software	Purchased	Communiction cables and embedded devices	200$	200$
Travel	Purchased	Costs connected with team and robot transport	12000$	12000$
Marketing	Purchased	General marketing materials	150$	150$
			Total Income	14500$
			Total Exenses	12990$
			Total Re-used/Donations	0$
			Total Fundrasing Needed	950$

Project Budget Table

						Reporting period	
School Name:		The AGH University of Krakow				From: 1 Oct 2023	
Instructor/Sponsor:		Ryszard Olszewski (supervisor of the science club), Malwina Cieśla (president)				To: 30 Sept 2024	
Funds							
Date	**Type**	**Category**	**Expense**	**Desription**	**Sources/Notes**	**Amount**	**Running Balance**
16th April	Purchased	Mechanic	Tube	Watertight Enclosure for ROV/AUV (8" series) Plus Acrylic Tube	Used for preventing electronics and cabel from water	1	280.50$
16th April	Purchased	Mechanic	Tube	O-Ring Flange	O-Ring Flange and O-Ring Pick	1	204,00$
16th April	Purchased	Mechanic	Tube	End Cap	Watertight Enclosure End Caps	2	74.80$
16th April	Purchased	Mechanic	Thrusters	Thrusters	T200 Thrusters	6	1020.00$
03rd April	Purchased	Mechanic	Frame	Laser Cuting Frame	Laser cuting frame with PA11 #6mm element	1	259.80$
22nd April	Purchased	Electronic	Cables	TME Cables	Cables: 5M H07RN-F,TITANEX®;7G1,5mm2; 15M H07RN-F,TITANEX;2x6mm2; 5M H07RN-F,TITANEX;3G2,5mm2; 5M H07RN-F;7G2,5mm2; 2x Power connetor 10A;250VAC;IEC 60320; 2x Power connector AC;2P+PE;250VAC;16A	1	285.82$
22nd April	Purchased	Electronic	Measuring Equipement	Voltometer, Aperometer, Mutimeter	Voltmeter; digital, mounting; -100÷100V; LED; 4 Ammeter;on panel;I DC:0÷40A;Class:1.5;DQN;72x72x58.5mm Digital multimeter;LCD;(6000);5x/s;VAC:6V,60V,600V,1kV Digital multimeter;LCD;(4000);VDC:400mV,4V,40V,400V,1kV	4	321,20$
22nd April	Purchased	Electronic	Electronic Elements	Ceramic Condensators and Resistors	Elements to create electronic for rorbot	331	32,37 $
22nd April	Purchased	Electronic	Electronic Elements	Condensator, Solid Relays, Diodes	Elements to create electronic for rorbot	227	90,87$
23rd April	Purchased	Embedded	Embedded devices	Embeded Microcontrollers	STM32 Nucleo -H745ZI-Q devizes	3	139,00$
23rd April	Purchased	Software	Telecomunication tools	Switch and Cables	TP-Link Switch and telecommunication cables for cmmunication in robot	10	51,80$
23rd April	Purchased	General	MATE Registration	2024 MATE ROV World Championship Registration	Regstration for PIONEER category	1	350$
					Total Raised	0	
					Total Spent	3110,16$	
					Final Balance	3110,16$	

Project Costing Table

15. Benefits

In the context of contemporary challenges related to underwater environment exploration and the growing demand for innovative solutions in underwater technology, this modular underwater robot project represents a significant step towards the effective and versatile use of exploration tools in these areas. The expected outcome of the grant will be the development and deployment of a modular underwater robot. This design will allow for easy future modifications and expansions by adding or exchanging modules.

The robot, built with grant support, will enable various applications such as seabed research, underwater infrastructure inspection, and marine environment monitoring. The outcome of the project also includes using the robot as an educational tool for learning about robotics, marine engineering, and natural sciences. This will significantly contribute to students acquiring practical experience in underwater technology.

Additionally, the benefits of implementing our software include:

- **Monitoring Water and Seafloor Conditions Without Risk to Humans:** The underwater robot will enable monitoring of water and seafloor conditions in areas difficult for humans to access, eliminating the risk to human health and life.
- **Observing Underwater Infrastructure Using Artificial Intelligence and Machine Learning:** With advanced functions, the robot can analyze and report the condition of underwater infrastructure, contributing to safety maintenance and environmental monitoring.
- **Exploring Hard-to-Reach Caves and Marine Life:** The robot will facilitate the exploration of underwater areas such as caves and deep ocean zones, allowing for research that was previously inaccessible to humans.

16. Testing

The testing of the robot was conducted in three stages. Initially, dry tests were carried out in our workshop to verify the functionality of individual components and ensure all connections were correctly made. During this phase, we assembled the robot and ran preliminary checks on all electronic and mechanical parts to confirm they were working as expected.

The second stage involved water tests in a small pool within our lab. The purpose was to test the watertightness of various elements and perform initial operational tests of the robot. We submerged the robot to check for leaks and ensure the integrity of the seals. Additionally, we conducted initial functionality tests, including basic movement and control using the controller pad, and assessed the overall stability and buoyancy of the robot in water.

The final stage of testing took place in AGH University’s 25-meter sports pool after hours. This phase aimed to evaluate the robot's performance in a deeper and more extensive environment. We tested the robot's resistance to greater depths, specifically beyond the 45 cm depth of the small lab pool. The robot's maneuverability was assessed, including its ability to make tight turns and navigate efficiently. We also measured the maximum speed of the robot in the water to determine its operational capabilities in real-world scenarios and conducted endurance tests to ensure the robot could operate for extended periods without issues.

17. References

a. Links

Main AGH Marines page: http://aghmarines.agh.edu.pl/
Faculty of Mechanical Engineering and Robotics page: https://imir.agh.edu.pl/
Facebook Fanpage: https://www.facebook.com/aghmarines
BlueRobotics page: https://bluerobotics.com/
TME page: https://www.tme.eu/pl/
Ansys page: https://www.ansys.com/
Botland page: https://botland.com.pl/
MESco page: https://mesco.com.pl/
Solidworks page: https://www.solidworks.com/

b. Bibliography

[1] Filip Dudek, Tomasz Małachowski, “Analysis of the implementation possibility of a linear-quadratic regulator in the ROV propulsion system with azimuth thrusters”, engineering thesis, AGH University of Krakow, Krakow, 2021.
[2] González-García, Josué & Gómez-Espinosa, Alfonso & Garcia-Valdovinos, Luis & Tomas, Salgado & Cuan-Urquizo, Enrique & Escobedo Cabello, Jesús. (2022). Experimental Validation of a Model-Free High-Order Sliding Mode Controller with Finite-Time Convergence for Trajectory Tracking of Autonomous Underwater Vehicles. Sensors. 22. 488. 10.3390/s22020488.
[*] Guido Schillaci, Fabio Schillaci, Verena V. Hafner “A Customisable Underwater Robot”, 2017