1. Abstract

Creating a complicated system such as an Autonomous Underwater Vehicle, is a task which requires both organizational and engineering skills. To be able to come up with proper requirements which describe the architecture of the robot, as well as specify how to achieve them, demands multidisciplinary knowledge and synergy between different teams. This paper describes our approach to the RoboSub competition and the design of our AUV. Requirements derived from the competition's tasks and our strategy, define the boundaries of all subsystems and their interfaces. It is an area where our infinite imagination can prove itself and come up with new innovative solutions and ideas. Thanks to our previous knowledge and know-how gained while working on our ROV project, we know the importance of experimental verification of the operation of our vehicle. None of the above could be achieved without proper systems engineering and utilization of mechatronic design which is our main field of study.

2. Competition strategy

List of tasks in the competition may seem to not be very long. Although, taking into consideration the complexity of the tasks for an autonomous vehicle and relatively short time for the robot to accomplish them, we decided to prioritize the tasks. The prioritization applies on two levels – one is the team effort in the design and development process and the second one is for the robot's AI algorithms. Each will be described separately.

2.1. The team effort

Our team works following a mechatronic design approach. This means that main parts of the AUV, like electric system, electronics, mechanics and software, are designed simultaneously, where none of these parts is an initial condition for another or fully dependent on another component's design. Different teams develop their part of the project in parallel but with high regard to other parts' progress. This approach requires strict systems engineering, defining the interfaces between subsystems, identifying overlapping responsibilities and extraordinary communication. This benefits in greatly reduced time spent on developing the project. The first thing to focus on during the design process for our team is to provide core functionalities. The following attributes are considered to be the basis for the vehicle from the hardware point of view:

- floating on its own,
- watertight,
- able to traverse with its thrusters mounted,
- having onboard computer with possibility to manually connect and control the robot,
- having the camera mounted,
- having basic sensors (like IMU) installed.

With these functionalities, the robot is ready for further improvements which will provide the ability to complete different tasks.

In parallel to hardware, the software is developed in simulation. Primary focus is put on control algorithms and image processing, which should provide the possibility to complete the first task, with passing through the gate in simulation.

Then, the work proceeds to merge software and hardware and start performing first physical trials, simultaneously developing next features.

It is important to notice that the robot's design, while iterative, has its initial assumptions about what hardware should be equipped in the final, most complex form. Thus, the team is aware of what modules will finally be placed there and can estimate how much space should be needed for improvements or how much power the vehicle should have in reserve for those modules. If the time runs out before developing the complete AUV, there will be a version which can – with reasonable certainty – complete prioritized tasks.

With the basis of the robot up and running, the team's effort is put primarily on the tasks which are directly related to those core functionalities. This means that the first efforts are put on the task of finding a path and making the grade. These tasks require no other hardware, than passing through the gate. As purely software tasks, these can be well developed and tested in the simulation.

Then, tasks which are more demanding in the field of hardware are taken into consideration. As the hardware works progress, the software team is obliged to work on the improvements concerning the first tasks that are the main focus. The example here is to work on the barrel roll during passing the gate. However, those improvement works will be paused, when some tasks with higher priority, for example fixing a major issue or bug, will appear.

From the tasks that are more complex and require additional effectors on robot, the torpedo launching will be preferred to take advantage of advanced propulsion system of the vehicle. Then, the manipulation tasks – collecting and cash or smash.

Acoustic pinger localization subsystem, both hardware and software, will be developed relatively independently and will be the primary and only task of a separate, acoustic team.

List of development priorities:

1) Working basic configuration of robot
2) Passing the starting gate task
3) Following the path to other tasks
4) Make the grade task
5) Starting gate style improvement
6) Acoustic pingers tracking
7) Torpedo launching platform
8) Survive the shootout task
9) Manipulation device
10) Collecting task

11) Cash or smash task

2.2. Robot's AI

The robot's AI will be programmed to focus on the tasks that will be on the highest level of development. It will have the priorities list with only one must–do point, which is the choose your side gate task. The other tasks will be put in order in which the robot should perform them but also with estimated limits of time. If the vehicle will be stuck for too long on one task, it will decide to ignore the task and proceed to another.

Assumed list of task priorities for robot:

1) Choose your side
2) Path to tasks
3) Make the grade
4) Collecting (reaching the bins at least)
5) Survive the shootout
6) Cash or smash

3. Design creativity

The team has great experience from development of ROV with autonomy elements for other competitions. Some of the key ideas were designed and tested during the realization of that project. The know-how and errata which are the results of that project are crucial for quick and successful completion of the RoboSub AUV project.

There are several fields, where our team is very experienced and implements their best knowledge to design and develop an extraordinary AUV.

3.1. Propulsion and control system

The propulsion subsystem providing 6 degrees of freedom with the use of only 5 thrusters is the trade mark of the team's projects. It is based on advanced and proven solutions in 2 major areas – custom thrusters and custom control system.

3.1.1. Custom thruster

The custom thrusters were designed as part of previous projects as well as the bachelor thesis of the mechanical team's leader. It was a process of designing the whole thruster from scratch, starting from choosing optimal airfoils for propellers' blades and thrusters' nozzles and dozens of numerical fluid flow simulations to empirical tests on custom test stands.

3.1.2. Control system

The control system for the 5-thruster system was a subject of the joint bachelor thesis and publication of the software team's leader and the electronics team's leader. It uses advanced control algorithms like LQR regulator and thrust allocation using quadratic programming to vectorize the thrust generated by 3 stationary and 2 azimuth thrusters which can provide desired force controlling the vehicle independently in all 6 degrees of freedom. What is worth mentioning, there are very few student constructions of underwater robots with complex thrust vectoring so it is believed to be very innovative.

Also, there is the possibility to achieve better forward speed by rotating one vertical thruster to aid the horizontal ones, increasing the possible thrust output by 33% but for now, this feature hasn't been tested yet.

The outstanding performance of this propulsion system should provide a decent advantage over other's team propulsion.

3.2. Image processing and AI algorithms

The team has experienced software developers, whose bachelor's theses were addressing the issue of underwater image processing and AI algorithms making decisions based on the image interpretation data. Using the stereoscopic camera on the vehicle, the software can build a local map of its surroundings and unambiguously detect, recognize, identify and label objects seen by the camera. Whole image processing system uses neural networks and image morphological algorithms for that purpose. The obtained data are sent to the main AI program unit, which is a custom implementation of a state machine. The vehicle decides what to do with regard to obtained information, its current state (for example what part of task it is performing) and time left for current activity. The commands are then sent to appropriate modules such as propulsion system, torpedo launcher, manipulator etc. This cutting edge software design is being thoroughly tested in simulations as it is purely experimental and designed from scratch.

3.3. Simulations and numerical models

For the simulations, the mathematical model of the robot was created. It is an accurate numerical description on how all internal and external forces will affect the vehicle, so the exact behaviour of the robot can be obtained. The model is constantly updated, considering the changes in

3.4. Hull design

Using the team's knowledge of numerical simulations it was decided to, in contrast to typical designs, equip the AUV's hull with highly streamlined external cover (or "shell") for drag reduction. Typical designs do not focus much on this subject but there are several reasons it may come out beneficial:

- drag reduction – less power and thrust is needed to obtain a certain speed and position shift,
- more predictable flow and drag forces – this means easier mathematical modelling and stability of the robot for control algorithms,
- all elements protruding from the main waterproof housings for electronics (like thruster power cables) are covered – this is beneficial for safety reasons,

- the outer “shell” provides additional cover which can save the robot from impact damage if it manages to hit an obstacle, pool side or bottom.

The inner hull, consisting of the electronics housings and some structural elements, will not be directly connected to the streamlined part. Both will be attached to the main frame independently.

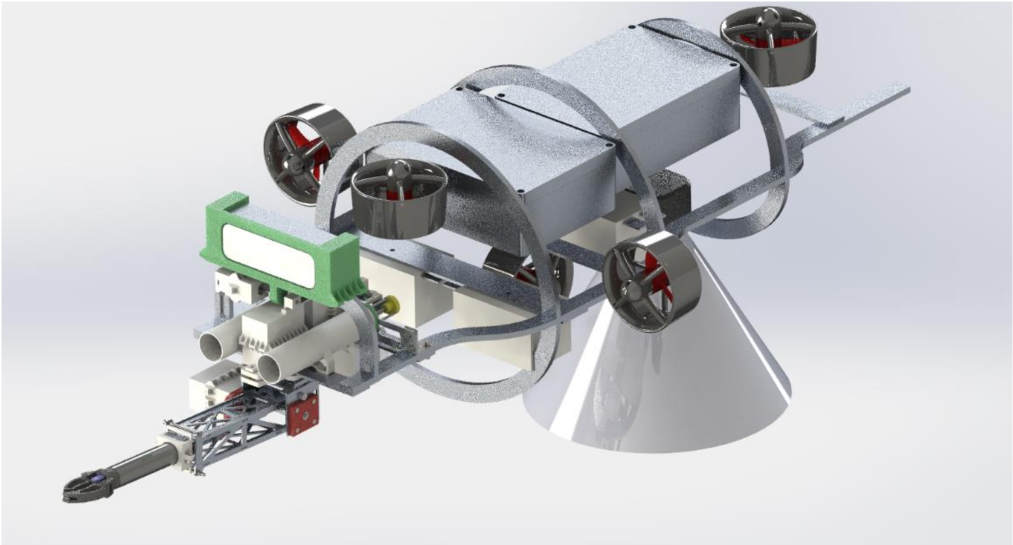

Figure 1 – Initial CAD design of AUV's hull and interior with mounting for the outer shell

3.5. Localization

The team’s solution is to combine four main sensors – DVL, IMU, stereoscopic camera and depth sensor.

The DVL will be responsible for the global localization, gyroscope on IMU for Euler angles of vehicle’s heading, the camera for local mapping and localization relative to detected objects and depth sensor obviously to obtain the current depth.

The main plan is to focus primarily on stereoscopic camera’s data and generated local map, supplementing it with global heading data from the gyroscope. While the local mapping is crucial for task completion, it is feasible to arrive at all the tasks’ locations with no regard to global position as the path to them is an outcome of visual recognition and interpretation of the path signs at the bottom of pool and acoustic pingers localization. However, there is one great benefit which justifies the use of DVL and global positioning. If the vehicle somehow gets lost and does not arrive in the desired location, it can relatively easily come back to the last known waypoint which cannot be done with such ease with only image recognition and gyroscope data.

Thus, the team’s decided to combine all those sensors for an optimal outcome.

3.6. Torpedo launching system

Prototype of a custom, double-barrel torpedo launcher was designed. It fits a smart solution for one servomechanism to launch both torpedoes independently which gives an opportunity to evaluate the effectiveness of first shot and make adjustments for the second to hit the target or, if the bigger target was successfully hit and aim for the smaller one.

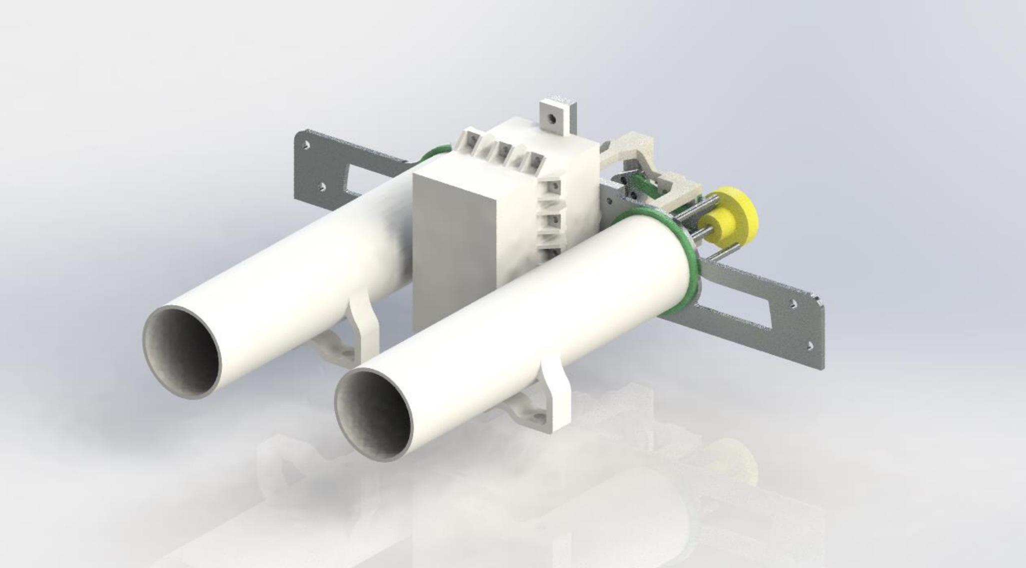

Figure 2 – Torpedo launcher prototype

Other subsystems are rather straightforward and are based on more standard solutions just like power and battery system and manipulator which will be an off-the-shelf product.

It is strongly believed that this combination of the creative design and development with off-the-shelf solutions and products will provide the robot with certain advantages.

Products bought from the market will provide us with reliable components which would be too complex or time-consuming for the team to design and manufacture. The saved time and resources can be spent on designing, testing and implementing the described innovations and techniques which are believed to be the strongest points of the team and can provide the biggest advantage over other teams compared to the effort put in them.

4. Experimental results

As previously mentioned, part of the subsystems were fully or partially tested and implemented during works on previous project and team members' bachelor theses.

Two independent simulation environments were created in several forms to provide different possibilities.

4.1. Control and propulsion systems simulation

This simulation was completed in two different variants.

First step was to combine Matlab and Gazebo environments to provide quick and handy prototyping of correctness and behavior of the mathematical model and thrust vectoring algorithms.

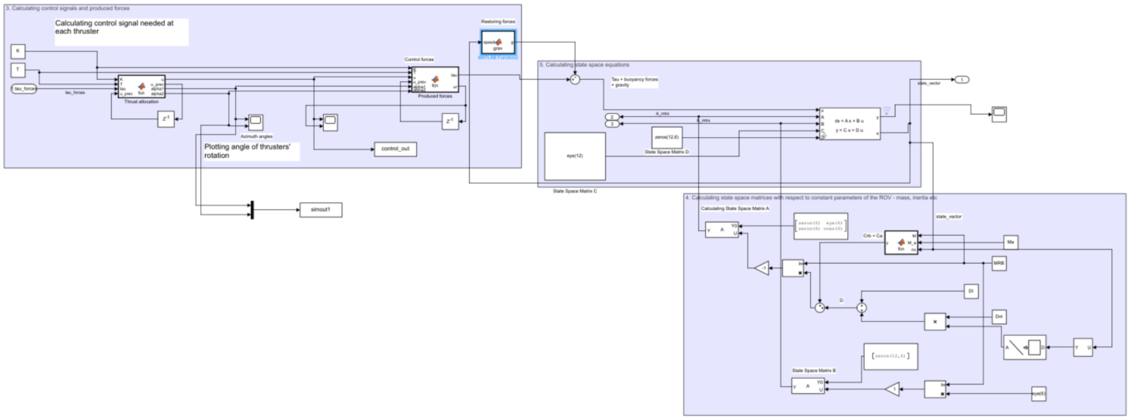

Figure 3 – Overview of simulation system in Matlab/Simulink

Second version was designed to overcome the long waiting times in Matlab, which gave no real time perspective on how the robot behaves. The algorithms were rewritten from Matlab to C++ which gave a significant boost in speed of the simulation and provided a nearly real time experience and ability to control the robot manually in this real time.

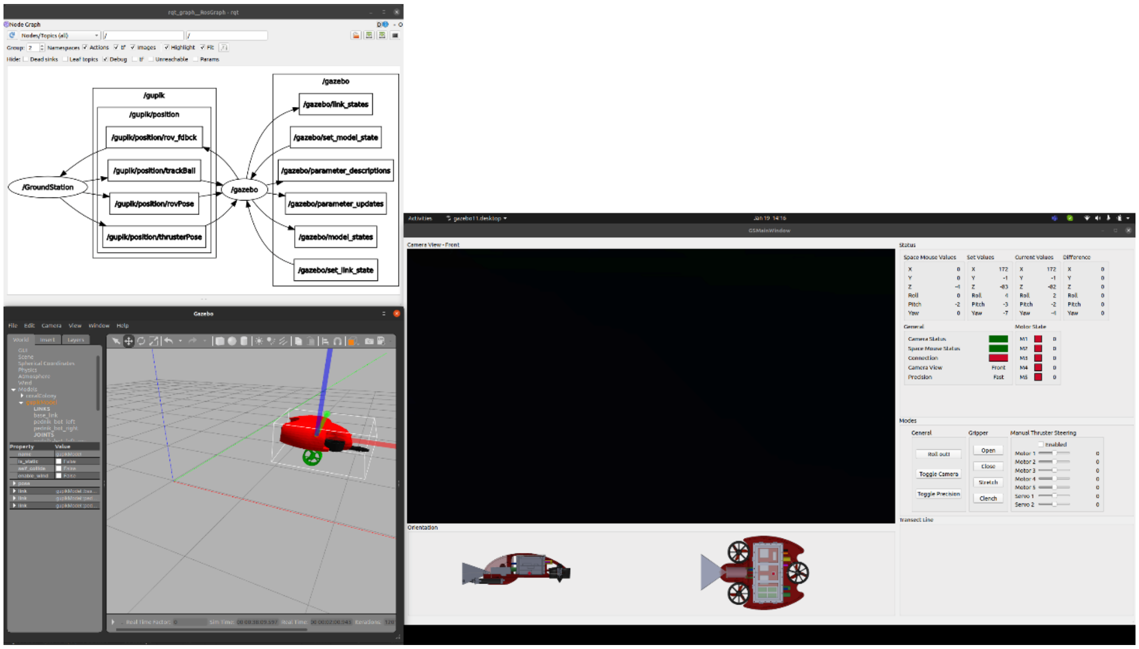

Figure 4 – Simulation environment in C++ and Gazebo

Both simulations provided the team with the knowledge and overview of how the system works and proved the concept of the propulsion system to be possible to implement in the real world and be efficient.

4.2. Vision algorithms

The second major simulation combines the C++ – Gazebo part, where the robot and propulsion system are mathematically modeled and the Unity graphics engine. Unity provides excellent tools to recreate the working environment of the robot, which is highly realistic for the visual perspective and thus is more suitable for image processing and recognition works. It can deliver thousands of realistic images needed for the neural networks machine learning. Both parts have the same, virtual environment modelled and are coupled via SQL database which gives the opportunity to recreate the exact same movements in both simulations.

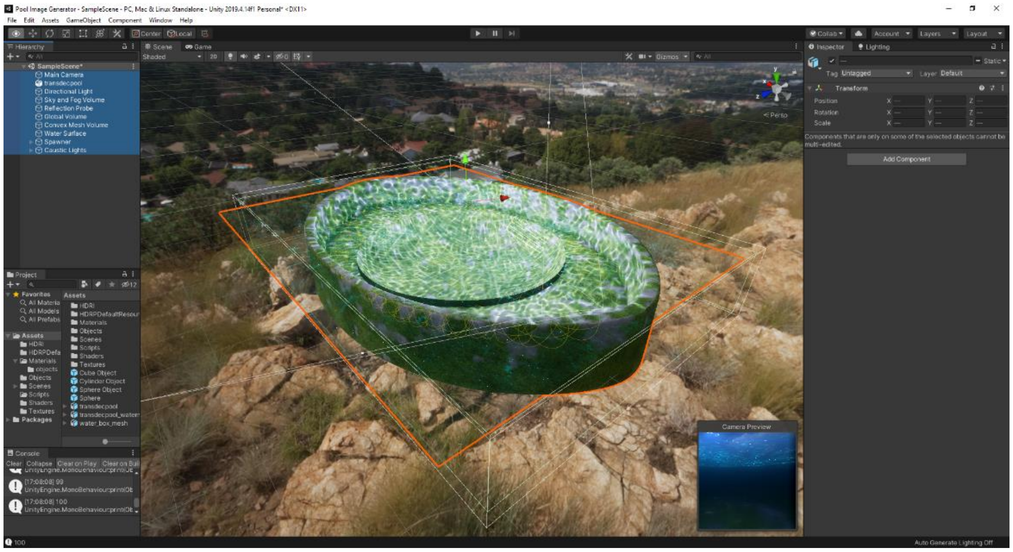

Figure 5 – The compettition pool model in Unity

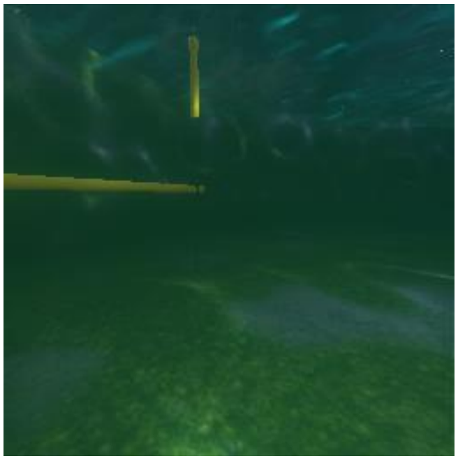

Figure 6 – Image generated for machine learning. Poor water and pool quality for a critical scenario testing

4.3. CFD simulations and test stand results of custom thruster

Dozens of CFD simulations were carried out in the process of designing the custom thruster.

After positive simulation results, a thruster prototype was 3D printed and tested on a custom test stand, which measured its parameters, including the most important – thrust force, rotational speed, power and current consumption. Tests proved empirically the results of simulation and the team has a proven design of a thruster outperforming the commercially available counterparts.

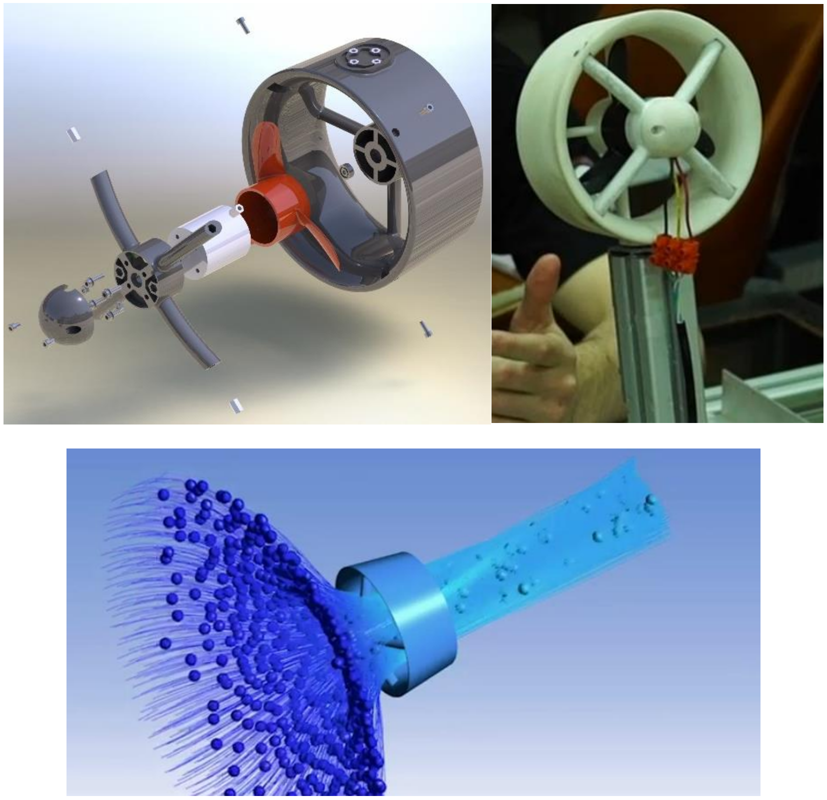

Figure 7 – Custom thruster in both virtual and real form

The prototype visions of a streamlined outer hull were also simulated in CFD software. While it was too early for even an estimation of the final form of the outer hull, the significant reduction of drag was obtained.

4.4. ROV project

Major part of the proposed solutions were applied and tested in the previously mentioned project of ROV. It also featured a propulsion system consisting of 5 thrusters from which 2 were azimuthal. The ROV also had to implement image processing algorithm capable of autonomous detection of changes in coral reef, creating a photomosaic from 5 photos taken by the robot and detecting as well as tracking the edges of a test track while following it. Many similarities between the robots mean that previously made code or hardware can be reused, while also upgraded, since now the team has the knowledge of its problems and shortcomings. This gives more time to spend on further testing the AUV, fine tuning its localization and AI algorithms and improve the design.

Figure 8 – ROV "Guppy"

5. Acknowledgements

We would like to thank AGH University of Science and Technology in Cracow and especially Faculty of Mechanical Engineering and Robotics for the financial aid, and all merit support that we have received. Many thanks to our sponsors which provide us with 3D printing filament, tech support with advanced software, certified courses which allow us to expand our competences. Last but not least we would like to thank Polish Ministry of Education for financial aid granted as a part of the programme "Students' Science Clubs create innovations".

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Appendix A

Component	**Vendor**	**Model/Type**	**Cost**	**Status**
Frame	–	Custom		Manufacturing
Waterproof housing			Estimated	Modifying
Waterproof connectors	Bulgin	Various	Varying	Partially ordered
Thrusters	–	Custom, based on SW 2820 BLDC motor	Estimated $500 for all	Manufactured and ready
Motor Control	STMicroelectronics	5x STEVAL-ESC001V1	$165 for all	Ready
High Level Control	STMicroelectronics	Nucleo-F767ZI	$23	Ready
Servos	Feetech	4x FI7635M	$100 for all	Ready
Propellers	–	Custom	–	Ready
Battery	–	–	–	Yet to be chosen
Converter	–	–	–	Yet to be chosen
Regulator	–	–	–	Yet to be chosen
Onboard computer	NVIDIA	Jetson Xavier AGX	$700	Ready
IMU	Redshift Labs	UM7-LT	$150	Ready
DVL	Teledyne	Wayfinder	$7500	Ordered
Camera	Stereolabs	ZED 2i	$500	Ready
Hydrophone	Aquarian Audio	2x H1C	$280 for all	Ordered
Manipulator	Blue Robotics	Newton Subsea Gripper	$450	Ready
Algorithms: vision	OpenCV library	Various morphological operations, neural networks	–	Under development
Algorithms: acoustics	Interaural level difference, Time delay difference	–	–	Under development
Algorithms: localization and mapping	Custom SLAM algorithms	–	–	Under development

Algorithms: autonomy	Custom algorithms based on state machine	–	–	Under development
Open source software	Gazebo, Unity, C++ Standard Libraries, OpenCV, OpenAL, OpenCL, CUDA, Python modules, other libraries	–	–	–
Team size	10	–	–	–
Expertise ratio hardware vs software	3:7	–	–	–
Testing time: simulation	All simulations excluding CFD and other CAE	Over 500 hrs	–	Under development
Testing time: in-water	None yet as whole system due to pandemic. Some components tested individually	About 100 hrs as subsystems	–	Under developments

All costs are orientational.

Appendix B

Since its establishment, AGH Marines took part in many activities whose purpose was to popularize science, robotics or to present our accomplishments in the scientific environment. We participated in the creation of a popular science YouTube video about exploring Vostok Lake, which reached 42 800 views. Members of AGH Marines took part in the Festival of Science and Art in 2019, on the Main Square in Cracow, where different scientific organizations showed interesting experiments and popularized different disciplines of science. Huge crowds were able to see our projects, which at that time were the test stand for testing underwater thrusters and a prototype of a propulsion system. One of our female members took part in Women in Tech Summit 2019, where she represented our organization and took part in inspiring speeches about enabling more women into the field of engineering and science. Since 2018, we took part in many scientific conferences, where our members have been able to achieve many successes, while discussing our research and findings. Many of them include: yearly conferences of Science Clubs on AGH UST in Cracow, STUKNUT'19 where many students and PhDs presented their papers about marine technology and environment, OCEANS 2020 which is the biggest conference about topics such as marine technology, engineering, science, research, and education. Moreover we took part in Open Days of AGH UST, where we presented our projects to high school students interested in studying at our University in the future. Additionally we conducted lectures in local high school about engineering, marine environment and underwater robotics. Exactly like RoboSub’s, our foundational purpose was also to reach to the community, and enrich it with any knowledge that we have. That is why in the beginning phase of our Facebook page, we conducted a series of short posts regarding the underwater environment, robotics, engineering as well as trivia about underwater animals and mythic creatures and much more. We believe that it is very inspiring to spark the interest in younger, ‘future engineers’, who may be curious about anything we do. For this reason we consider our educational goals just as important as creating and maintaining the underwater vehicle.