Vortex NTNU's AUV Technical Design Report for RoboSub 2021

Børge Pahlm *(Hardware lead)*, Michael Hoyer *(Software lead)*, Christopher Strøm *(Software deputy lead)*, Jonas Fillan *(Electronics lead)*

***Abstract*—Vortex NTNU focused on modularity and testing potential when developing their new Autonomous Underwater Vehicle (AUV) *Beluga* for RoboSub 2021. This years project builds upon years of software development done entirely by students and the new AUV design allows the organization to broaden the possibilities of underwater observation and manipulation. Much of the time this past year has been spent digitally, and our hardware developers has been forced to be creative with their work due to pandemic restrictions. Some preceding solutions that have worked well are being re-used this year, but most of the designs are new. For the team to solve the RoboSub competition's challenging tasks they have spent time learning and using ROS, PCB design and manufacturing, mechanical design, simulation, machine learning, computer vision and much more. All of the researched and developed elements have been combined into a modular and fully autonomous AUV called Beluga.**

***Index Terms*—Vortex NTNU, AUV, NTNU, RoboSub, Marine Robotics, Autonomy, Product Development.**

I. Introduction

Vortex NTNU is a non-profit student organization from the Norwegian University of Science and Technology in Trondheim, Norway. They are developing Autonomous Underwater Vehicles (AUV) to compete in international competitions. Trondheim is home to many marine robotics companies and the fjord is important for Norway's technological development as the first "technological playground" for all kinds of unmanned and autonomous vessels [1]. Vortex NTNU was founded in 2015, and for their admission to RoboSub 2021 they have developed their fourth UUV, Beluga. This report covers their product development and thought process from the start of the 2020 fall semester until the RoboSub 2021 submission deadline.

Fig. 1. Render of AUV Beluga created in SolidWorks.

II. Competition Strategy

In 2019 our goal was to reach the finals of RoboSub, and since then we have spent a lot of time reviewing the design process and improving our codebase. To set the mood for this year's development we stated to the team that our Big Hairy Audacious Goal (BHAG) for this year was to win RoboSub 2021. To achieve this the organization focused on improving project management and technical design approaches among other things. This was the time to develop something new with the experiences we have gathered and passed on over the last few years. The organization decided to make a new AUV from scratch that could handle anything in the competition. The 2021 team had the keyword *modular* in mind during design, and from it emerged our AUV *Beluga.*

A. Hardware Adaptability

We created an AUV frame from the idea of having a platform that we can configure however we want whenever we want to. With the appropriate 3D-printed mounts we can test different propulsion configurations, sensor placements and buoyancy balancing. We went from constraining our adaptability with our preceding drone which was originally created as an ROV to expanding our possibilities with a more open frame. Our vision for this year was that functionality and ease of testing came first as the result of a modular design, and that adding a great visual look could come afterwards.

The basic frame allowed us to work independently on different parts of the drone without spending too much time on discussing cross-group integration. We completely changed out the actuator mechanism from servos to pneumatics to shift the problem from waterproofing electronic components to rather focusing on good pneumatically activated mechanical designs. The electrical system has been overhauled and standardized with the intention of having a good integration standard in the future. The overall strategy for the hardware group was to minimize any possible complication or fault so that the software group could more easily troubleshoot.

B. Software Quality

Improving our software quality was an important goal for this year. There were two main focus areas: 1) improving maintainability and making our codebase easier to learn, and 2) improving reusability allowing us to reuse more code between our Unmanned Underwater Vehicles (UUVs). The first focus area is important due to the high turnover rate student organizations experience. Vortex accepts many new members every year, and making our codebase easy to learn and work with is crucial to getting new project members quickly up to speed. The second focus area is important since Vortex has two operational UUVs, and being able to reuse code across them saves development time and reduces the maintenance overhead that would come with having two separate codebases for our drones.

C. Task Solutions

Under the competition our strategy is to search and hone in on objects using stereo vision and sonar. Stereo vision allows for depth estimation and object detection in the same package. With a 360° sonar we will do a crude search of our surroundings and detect clusters of points with higher intensities. High density clusters are potential points of interest and can be inspected more closely with the camera. If an object related to a task is detected a state machine for said task is executed.

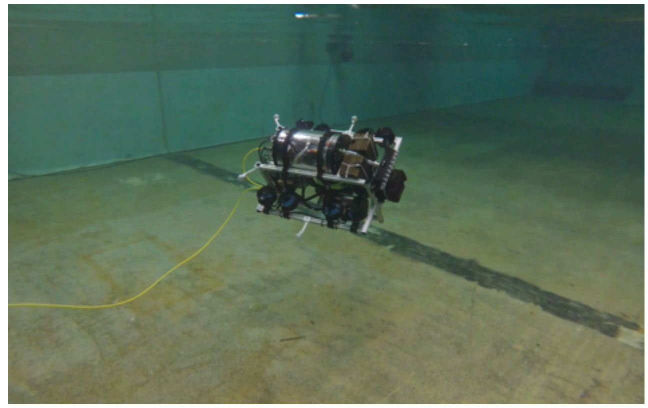

Fig. 2. AUV Beluga during propulsion testing at the Marine Cybernetics lab in Trondheim in March 2021.

We had existing solutions for some of the competition tasks, but those which needed new products were assigned small task forces within the organization. The tasks this year that got some extra attention were the further development of our pinger location system and the required actuator solutions to be able to manipulate the competition course.

Furthermore, testing was crucial for us to get an understanding of the AUV system as a whole. It was beneficial to split the entire product development in two parts over two semesters; planning and assembly. The entire first semester was spent creating concepts, designing and ordering the most important parts. The second semester was used to gradually assemble the parts and begin testing. We have a small tub in our workshop for small tests, but have to find other options when it comes to bigger tests. We planned to carry out larger pool tests once a month for the second semester as the bare minimum.

III. Design Creativity

The beginning of an academic year is always busy, so we had to kickstart the design process as hard as we could. For all the members to ease up and feel comfortable with the now twice as large organization counting 40 members, we spent the first weekend together engaging in creative activities. Our first internal competition consisted of making the best AUV concept based on a randomly selected adjective and noun. It let the team think outside the box before the real design process began.

A. *Mechanical*

The design of the frame was crucial for our sensors to be applicable for their purpose while still having room to reorganize. We made the frame from aluminium profiles and to not make it look too boxy it was given two *wings*. The wings came in handy for separating the thrusters from the sensors, and minimized any disturbances in sensor input. The inner frame was made open to give room for the rest of the equipment and making it a breeze to test different configurations. The frame has great reusability for future projects.

Our propulsion system consists of eight thrusters configured to prioritize maneuverability over speed. They are all in the same plane with the four pointing straight up controlling heave, pitch and roll, while the rest control yaw, sway and surge. The AUV can turn and adjust around the z-axis fast because of the 45° thruster placement related to direction of the vehicle. All of the thrusters are placed at the halfpoint of the height to not affect the sensors which are installed near the top or bottom.

Since not all components fits well in readily available waterproof containers we have made some ourselves to protect important equipment. Our new stereo camera requires a high bandwidth and a clear vision underwater. We needed it to have its own waterproof container for testing purposes and a faultless electrical connection. We created a custom POM housing to fit the camera shape with a thick and tightly secured translucent lens cover. The electrical connection was waterproofed with the simple solution of having a hose big enough to fit a USB connector through it secured by cable glands on both sides.

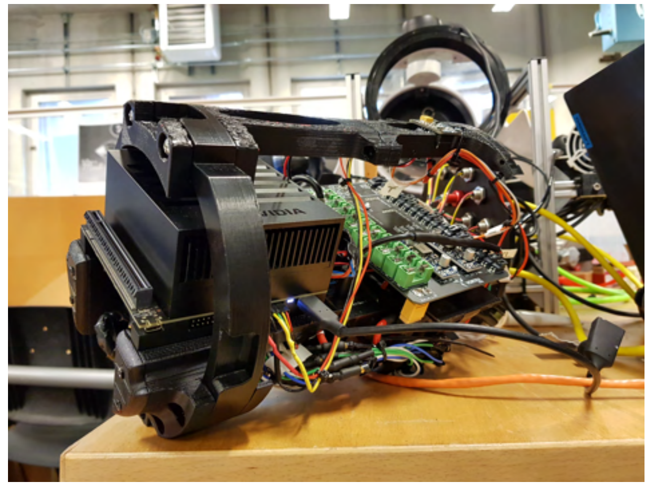

Fig. 3. The main electronic system slid out of the main housing for maintenance. The main Nvidia computer, PDB, ESCs, IMU and sensors are tightly packed.

B. *Electrical*

Most of the electrical components are installed in the main electronics housing in the top middle of the AUV. It is a commercially available product with an 8 inch diameter. From the start we began designing a way to pull out the electronics like a tray for maintenance and installation. This proved to be a logistically challenging task considering the amount of cables needed outside of the waterproof housing. The solution is a 3D printed sliding structure supporting all of the electronic components and keeping them in place. This application is something we are continuously improving and is great for small underwater vehicles due to the compactness, strength in the circular design and easier maintenance.

Our core electrical system consists of a mix of off-the-shelf products and in-house developed PCBs. This year the electrical team focused on just getting all the basic required components to work, and in the center was our custom Power Distribution Board (PDB). It is the intermediary between the batteries and components offering all the necessary voltage levels. Every connected component has a replaceable fuse to isolate any potential power trouble in the system.

We also began developing circuit boards for controlling the Electronic Speed Controllers (ESCs) and the hydrophone input used to locate the pinger in the competition. Due to time constraints and insufficient testing we had to switch to readily available drivers and microcontrollers to solve these tasks this year.

C. Pneumatic System

This year we created a new actuator system based on pneumatics. It controls the manipulator, torpedo launch mechanism and the marker dropper. The pneumatic system consists of a 10 bar pressurized airtank, a pressure distribution system and relays for control. The distribution system has its own waterproof housing so that it can be placed optimally when we are iteratively exploring different actuator configurations. It is connected by tubes to the air tank and electronically to the relays inside the main electronics housing. The relay outputs is sent to the decentralized system to Normally Closed (NC) valves, and the loop is closed by a common ground back to the main housing.

D. Software

Code maintainability was improved by a) refactoring our codebase into a more modularized structure and b) improving our documentation. By creating a modular design we can also improve its extensibility. There is a tradeoff between modularity and performance. The modularization fits nicely with our existing use of ROS, which encourages a design based on nodes that communicate with each other. When writing documentation it is important to find the right balance between over- and underdocumenting code. Too much documentation creates unnecessary work and increases the risk of documentation becoming outdated. Too little documentation makes it difficult to get an overview of the codebase and to understand its individual parts.

Our strategy for improving reusability revolves around creating a good repository structure on Github on and gathering hardware dependent parameters in a central place. Hardware dependent code should be placed in separate repositories, while hardware independent code is gathered in our main repository. By gathering hardware dependent parameters in a central place, it gets easier to get an overview of the system. All of our code is open source and can be found on our Github page [2].

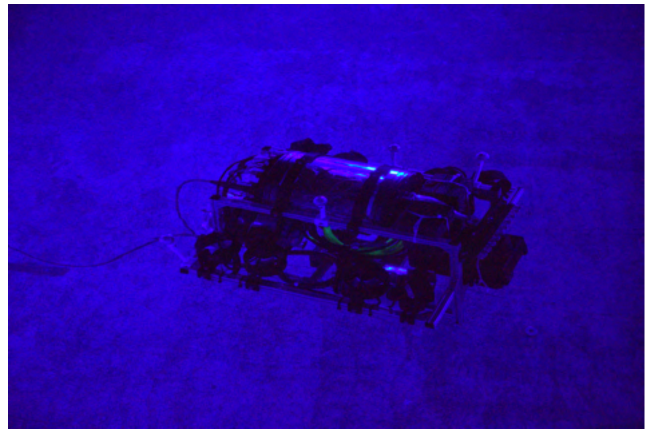

Fig. 4. Beluga in the pool at the Marine Cybernetics lab during calibration of the lab equipment.

This ties in with the organization now having several functioning UUVs making it more important to abstract the software to the point of hardware independency. Testing with our drones now means using a drone-specific configuration file rather than tailor-made control software for specific hardware. This sets up the possibility of cooperating AUVs in the future.

IV. Experimental Results

This years testing plan was heavily influenced by the creation of a new vehicle and pandemic restrictions. Our workshop has restrictive access and whenever campus is closed so does the doors to the workshop. Due to this a lot of our work has been shifted to digital platforms with frequent digital meetings and smaller task forces working on independent elements. The quality of work is great, but the systems integration has been affected by the less than frequent physical technical discussions and social activities.

Our workshop, which is located on our university campus, has the necessary facilities to test most general UUV applications. It has a 2 cubic meter tub filled with water for simple testing. For more sophisticated testing we use the Marine Cybernetics Laboratory in Trondheim [3]. The lab has a pool large enough for us to do whatever we need, and the only drawback is planning the tests months in advance to secure a spot.

A. Integration

The past year has contributed to many ”eureka” moments from working on general equipment since it has been a few years since we developed something entirely new. Members have had to contribute in many different areas outside their main responsibilities due to shifting of plans, restrictions and time constraints. This has led to a good understanding of the entire system but only for those few essential members.

During the beginning of March we spent a week at the Marine Cybernetics lab to continue our delayed testing from the last month. It became a week full of finding and solving bottle necks and faults in the system, but ended up with a well-functioning drone. We discovered that ESCs has a lot of firmware options potentially throttling the thruster output and tweaking them gave us fivefold the thrust from before.

B. Environment Perception

We upgraded both acoustic and optical equipment this year to aid with perception. Earlier members had some experience with stereo vision and the theory behind it, and they encouraged the current team to pursue that technical aspect. We bought a camera with integrated tools for mesh and 3D world creation on live camera feeds, which is an exceptional addition to standard object detection with the same camera.

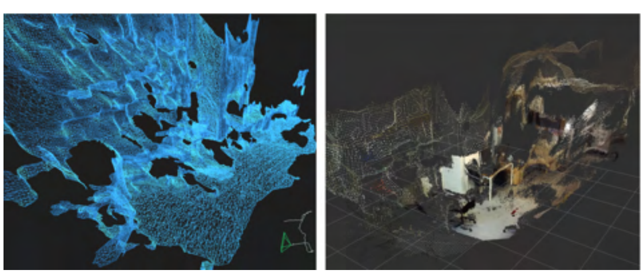

Fig. 5. 3D meshes of our offices in the workshop taken with the ZED2 stereo camera.

The new sonar is used to detect objects within a certain radius in all directions. Walls are presented as more densely packed points in a point cloud. There are a lot of phenomenon to take into account when dealing with sonars such as echoes of already detected objects and bending point clouds when turning the AUV while the sonar is scanning.

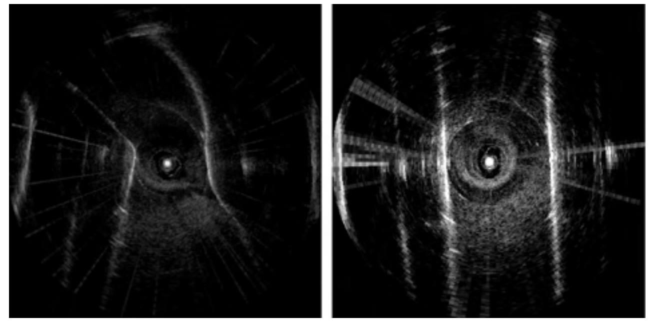

Fig. 6. Sonar images of the pool at the Marine Cybernetics lab. (*Left: bending walls while turning. Right: sonar image of long pool.*)

V. Conclusion

From fall 2020 to spring 2021 Vortex NTNU has designed and built the AUV Beluga. The main goals were to achieve a modular, future-proof design both in hardware and software. This resulted in a frame-based UUV and a refactoring of our codebase.

The year presented special challenges, as Covid-19 continued to affect all our lives. Vortex's offices had to be closed several times, and RobSub 2021 sadly had to go digital once again. The team nonetheless was able to adapt and continued much of its efforts digitally.

Vortex has grown a lot during the last year and is looking forward to continuing along this path next year.

Acknowledgment

Vortex NTNU would like to show their gratitude towards every member of the organization and all the time they have spent working on the project. It has truly been invaluable, and we hope the experiences they gathered and friends made will be cherished. Our mentors' and earlier members' work is still used today, and their foundation allows us to progress further in interesting subjects.

The creation of our AUVs have not been possible without the support of our sponsors allowing us to pursue world-class marine robotics. Our main sponsor, Equinor, has been with us for several years and is a cornerstone in our development. We would also like to thank Oceaneering, The Association for Remote Controlled Sub-Sea Technology (FFU), NTNU's Department of Engineering Cybernetics, SMC, Ocean Autonomy Cluster, NORTEK, Molex and Hydro for their sponsor- and partnerships [4].

Our motivation and drive has roots in the immense interest from the marine community and academia assuring us to continue with the work after six years. A huge thank you goes out to all our supervisors, friends, associates, competition organizers and competitors for their willingness to help, discuss and challenge us with challenging tasks.

REFERENCES

[1] G. Wolden, "Test site opens for unmanned vessels," Available at https://www.sintef.no/en/latest-news/2016/test-site-opens-for-unmanned-vessels/ (2021/05/04).
[2] "Vortex NTNU Github," Available at https://github.com/vortexntnu (2021/06/27).
[3] "Marine Cybernetics Laboratory," Available at https://www.ntnu.edu/imt/lab/cybernetics (2021/06/27).
[4] "Vortex NTNU's sponsor page." Available at https://www.vortexntnu.no/sponsor (2021/06/27).

APPENDIX A
COMPONENT LIST

Component list can be found on the report's last page.

APPENDIX B
OUTREACH ACTIVITIES

Vortex's motto is to *develop students on a deeper level*. Most of our members are from purely technical studies and from all over the country. Due to this, and restrictions, we have focused on developing our own members first, and secondly connect with local marine robotics industry to get a footing within the local robotics environment.

Our group leaders are highly encouraged to participate in leadership and management courses. This year we joined a workshop hosted by another student organization with a background in business psychology, and also courses hosted by other companies. This has helped with productivity and efficiency in an otherwise busy study week all while preparing enthusiastic members to pursue higher quality of work.

As one of many technical student organizations at NTNU Trondheim, we often cooperate with common goals through meetings between our project managers every month. The other nearby organizations develop aerial drones, space rockets, satellites, hyperloops and race cars. A long awaited case has been to have the work done within a technical student organization recognized as a subject at the university due to the huge amount of time some students spend on extracurricular activities. These kind of cases take time and requires a lot of teamwork between the organizations.

We also encourage our members, or other interested students, to write their Master's or Bachelor's thesis with Vortex NTNU. Over the last two years we have provided equipment and supervision for six students writing their theses. This year's theses focused on 1) parameter estimation of AUVs and 2) cooperation between ASVs and UUVs. We also try to help other students with inquiries about underwater robotics to strengthen the community.

In April we visited the offices to Eelume, the company developing the unique autonomous underwater snake robot. Their CTO showed us their robots, earlier prototypes, and we exchanged our experiences and solutions for several hours longer than initially expected. We appreciate the continuous interest from the industry and will use the experience to enhance our own drones.

And lastly we are incredibly enthusiastic about strengthening the Norwegian student robotics environment by helping Tau Autonomy Center in Stavanger to create a new underwater and aerial robotics competition called the *TAC Challenge* for students. This July they are hosting their first annual event, and we will travel there to help set the guidelines for an international event next year.

Fig. 7. Ten of the members visiting Eelume.

Component	Vendor	Model/Type	Specs	Cost
Buoyancy Control			Buoyancy foam	Legacy
Frame	Rollco	Aluminum extrusions		Sponsored
Waterproof Housing	Blue Robotics	8" series enclosure	8" diameter 12.7" length	$343.00
Waterproof Connectors	Blue Trail MacArtney	Cobalt Series SubConn®Ethernet	Connectors and Bulkhead	$1,300.00 $280.00
Thrusters	Blue Robotics	T200 thrusters	5.25/4.1 kgf FWD/REV Thrust@16V	8 x NOK 1790 = NOK 14320 $\approx$ $1,700
Motor Control	iFlight	SucceX ESC	50A 4-in-1 BLHeli_32	2 x $78.99 = $157.98
High Level Control	Adafruit	PCA9685	PWM/Servo Driver 16-Channel, 12-bit, I^2C	$14.95
Actuators	SMC Corporation	Pneumatics		Sponsored
Propellers	Blue Robotics	T200 propellers	Clockwise and counter-clockwise	Included with thrusters
Battery	Gens Ace	Tattu	4S - 6750mAh 25C, XT90 connector	4x NOK 1125 = NOK 4500 $\approx$ $530
Regulator	In-house	Custom regulator PCB	$V_{battery}$ to 3.3V, 5V, 9V, 12V and 24V	
CPU	Nvidia	Jetson AGX Xavier Developer Kit	8-core 64-bit CPU 512-core GPU, 32GB RAM	$700
Internal Comm Network		Ethernet, Serial, i2c		
External Comm Interface		Ethernet		
Programming Language 1		Python		
Programming Language 2		C++		
Inertial Measurement Unit (IMU)	Sensonor	STIM300	Gyro: $\pm 400°/s$ Accelerometer: $\pm 10g$	NOK 10 000 $\approx$ $1,100
Doppler Velocity Log (DVL)	Nortek	DVL 1000	0.2-75m range, 300m depth 100Mbit Ethernet	Borrowed
Camera	Stereolabs	ZED2	Dual 4MP sensors 1080p 30fps, USB 3.0	$449.00
Sonar	Blue Robotics	Ping360	Scanning Imaging Sonar 50m range, 300m depth	$1,975.00
Hydrophones	Benthowave Instrument Inc.	BII-7014FG	1Hz 300kHz @ ±3dB V/μPa.	Legacy
Manipulator	In-house	Custom	Pneumatic gripper arm	
Algorithms: vision		Darknet_ros, YOLO		
Algorithms: acoustics				
Algorithms: localization and mapping		EKF, ESKF		
Algorithms: autonomy		State Machine		
Open source software		ROS, Linux		
Team size (number of people)		40		
HW/SW expertise ratio		0.49		
Testing time: simulation		50 hours		
Testing time: in-water		70 hours		