Vortex NTNU
Technical Design Report

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***Abstract*—This report is the technical design report of the AUV 'Beluga' made by Vortex NTNU. The report is to be submitted for the competition TAC Challenge 2023.**

I. INTRODUCTION

VORTEX NTNU is a non-profit student organization from the Norwegian University of Science and Technology in Trondheim, Norway. The focus of the organization is to introduce students to the field of marine robotics, a field which is of great importance to Trondheim, and Norway as a whole. 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 [8].

Vortex NTNU started work on a brand new AUV in 2020, specifically for the purpose of competing in various autonomous subsea competitions. Three years later, around 60 000 hours of design, development, and testing, has resulted in the latest iteration of the Beluga AUV.

The Beluga AUV, aptly named after the Beluga whale renowned for its robustness in the harsh Arctic conditions, represents the zenith of Vortex NTNU's engineering expertise and passion, harnessing innovative technologies to create a safe, efficient, and highly autonomous underwater vehicle. Beluga AUV is built around the idea of being adaptive to mission demands utilizing a modular hardware design and software pipeline architecture. A thorough testing program, comprising of rigorous pool and open-water tests, has helped us identify potential operational risks and mitigate them effectively.

II. COMPETITION STRATEGY

Generalization vs. Specialization

The design of an autonomous system needs to inherently have some level of compromise between generalized and specialized solutions[1]. This fact stems from the intrinsic challenge of developing a system that is robust enough to tackle a wide variety of tasks, while also being equipped with the capability to excel in specific scenarios. Generalization refers to the ability of an autonomous system to perform well across a wide variety of tasks or situations, which is crucial in environments that are dynamic and unpredictable. On the other hand, specialization refers to an autonomous system's ability to perform a specific task or a limited set of tasks extremely well. Specialized systems are often more efficient and reliable in their area of focus because they are finely tuned for that purpose.

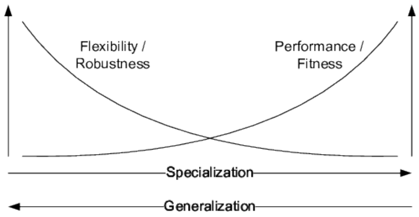

Fig. 1. System generalization versus specialization benefits [4]

The design of Beluga is threading a fine line between adaptability and specific task proficiency. This applies both for hardware and software solutions.

Solution Overview

When creating solutions to complete the tasks in TAC Challenge autonomously, an effective computer vision stack is a necessity to solve the majority of the tasks. Since the task descriptions provide a lot of prior information about object geometry and positioning, specialized approaches to tackle each task individually were developed. However, despite being tailored specifically for this year's competition, were created with an emphasis on straightforward and scientifically sound mathematical reasoning, based on principles from both target tracking and traditional estimation theory. Ultimately, this approach resulted in a simplified, task-oriented framework which has been easier to implement, adhering to the time-honored engineering principle that simple solutions are good solutions.

Task Prioritization

Equipped with a robust design, the Beluga AUV can operate as both an ROV and an AUV, allowing for superior dual-mode operations. Our strategy for competition emphasizes a minimax approach, prioritizing autonomous feature development for tasks that offer the highest bonus-points-to-complexity ratio, hence giving us a greater ’return on investment’ of effort. By concentrating our resources on selected tasks for superior autonomous execution and opting for manual mode for less beneficial ones, we balance overall competency and proficiency in key tasks.

Task Strategies

Subsea Docking: Subsea docking is a complex process that requires precision and accuracy, considering the limited Subsea Power Puck’s (SPP) area of effect. The key is to get precise estimate of the location of the SPP using image processing. For this we have decided to fully utilize the ArUco markers at the corners of the platform, as they allow for highly robust object triangulation and tracking with a camera. When the pose (position and orientation) of the SPP is estimated, the information is sent to the mission planner. The dynamic positioning (DP) system receives commands to gradually converge towards the SPP.

Pipeline Inspection: The pipeline inspection task requires real-time analysis of acquired images from a downwards-facing camera. To track the pipe, a contrast-based segmentation method together with adaptive thresholding detects the part of the image where the object is located. Subsequently, a RANSAC algorithm, detailed in section III, filters out outliers, unrelated to the pipeline. This process enables the creation of a vector towards the pipe. It serves as a reference for the Virtual Target Following (VTF) controller, elaborated in section III, guiding Beluga during the task. The implementation of ArUco detection from the docking task is repurposed to identify markers on the pipeline.

Visual Inspection: Given that bonus points are awarded only for automatic marker identification, there was no need to develop a specialized mission algorithm for autonomous scanning and navigation around the SDS. Instead, the strategy is to operate the drone in ROV mode, while the same ArUco detection algorithm scans the main camera view for potential marker detections.

Valve Intervention: Underwater valve intervention calls for precise and meticulous drone maneuvers to accurately rotate valves. Due to project time limitations, valve manipulation will be conducted in a piloted mode. To streamline operator control, a partial-control scheme has been devised, employing the Dynamic Positioning (DP) controller. This controller notably bolsters resistance to underwater currents and refines movement accuracy. Moreover, the use of the rotating gripper system removes the need to rotate the whole vehicle to turn the valve.

III. SYSTEM ARCHITECTURE

Mechanical Design

After researching different materials and methods it was decided to use 10mm Polyoxymethylene (POM) sheets for the frame. The plates were cut with a water jet cutter and assembled using angle brackets and machine screws. The choice of POM was due to its rigidity, weight and buoyancy, workability, corrosion resistance, and prior experience with the material. The process of water cutting the sheets meant that holes and cutouts for components had to be modelled before cutting, making it rigid but fixed with limited room for changes afterwards. Brackets and mounts for components and sensors were done mainly by 3D-printing with PET-G filament.

Gripper: To be able to manipulate the valves some form of actuator is needed. A pneumatic system is a great way to activate different actuators without having to deal with electrical actuators like servos underwater. We’ve experienced and learned how challenging it could be rotating the entire AUV to turn the valves, even in ROV mode. Therefore, a new actuator designed to rotate using the pneumatic system was made. There are two identical actuators made by 3D printing. One is mounted vertically and one horizontally, to use for each respective valve.

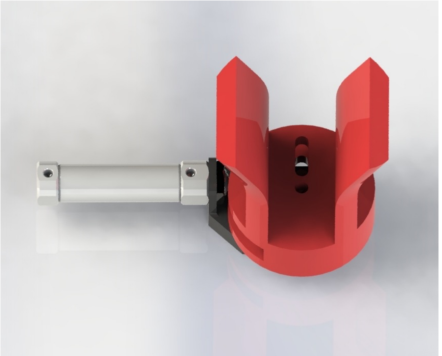

Fig. 2. Render of the pneumatic gripper made specifically for the valves.

Drone Shell: The white outer shell of the drone serves several purposes. The shell is made of white PET-G polymer, 3D printed in several pieces and fixed together with machine screws. The shell improves the hydrodynamic flow of the drone, while also completing the look. Making it more of a finished design. The design was inspired by the Beluga whale and its hump (called a melon, used to focus and modulate the frequency of its sound waves [5]), hence why it’s named Beluga AUV. The shell also provides a large area for sponsor logos.

Electronics Design

The focus for the electronics has been making the system more robust and reliable. As well as incorporating systems to solve new tasks, for example adding LED lights to indicate

Fig. 3. Render of the Beluga AUV with its shell.

when the batteries are charging from the power puck. The first step was to create a better internal structure for the electronics housing. The intention of this structure had always been for it to be able to slide in and out of the housing for easy access. What was dubbed *the pizza tray principle* was used. Which meant that you would have a plate with all the components fixed to it and that could slide in and out on tracks inside the housing, similar to a pizza tray in the oven. The redesign of this plate also has the added feature of having cable management inside of the plate.

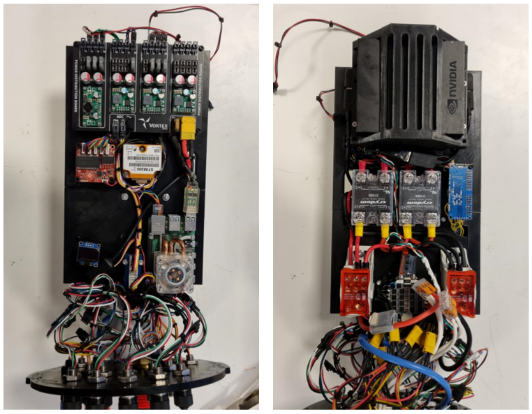

Fig. 4. Left: The electronic housing structure from above. Right: The structure from underneath.

Power Distribution: Designing a reliable and robust electronic system often begins with the source of power. With the newest edition of the Power Distribution Board (PDB), status lights were incorporated to indicate if fuses had been blown and if each of the DC-DC converters on the board are delivering the right voltage. The board is able to transform 14.8V battery voltage to 3.3V, 5V, 12V, and 24V to accommodate the different components of the drone. This PDB is also made to be used for other vessels as well, and as such has multiple exits for each voltage, to connect more units to power.

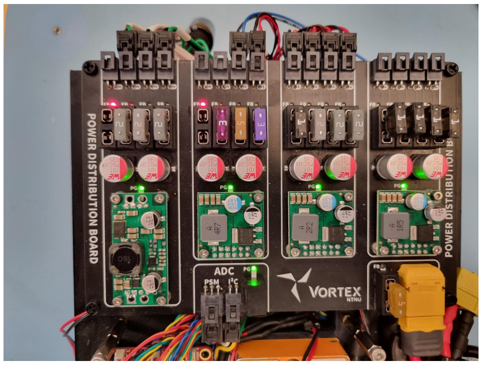

Fig. 5. The newest version of the PDB.

Super Capacitor Circuit: A reoccurring problem in our electrical system is supplying stable voltage to one of the processors, the Nvidia Xavier. It is extremely sensitive to the smallest power fluctuations, and tends to shut off when other parts of the system draws to much power. To solve this a super capacitor circuit has been implemented, also including a power resistor and other components for logic.

Connector Lid: The last step in making the system more robust and reliable was to make the electronics housing lid completely detachable from the drone. That is, by replacing all cable penetrators with detachable subsea connectors. To make sure that the correct connectors gets plugged into the correct sockets, the lid was laser engraved with labels by a local mechanical workshop.

Fig. 6. Laser engraved connector lid for the electronics housing.

Autonomous Systems

The hardware design of Beluga AUV has provided software team with a robust platform that, in theory, is equipped to tackle every one of the tasks outlined in the 2023 competition. Mission planning systems for strategic task execution, a dynamic positioning controller for precise navigation, and a virtual target following controller for complex maneuvers have been developed to optimize the AUV's performance in diverse sea conditions.

Mission Planning and Task Execution: Given the wide range of mission tasks and the unpredictable nature of the sea environment, we have developed specialized high-level task executors for each mission. These executors are designed to adapt and respond effectively to the diverse challenges presented in underwater exploration and competition. A novel approach to bridge control and perception, the *landmark server*, was developed in order to fully utilize this information. The landmark server holds data from each item that is expected to be in the pool like their last known position and orientation, as well as holding semantic information like if the pose estimate has converged or if an object is currently detected. Robustness is achieved by storing the starting position of the search and having a recovery state in case track of the object is lost or no object is found. Once an object is detected, however, the AUV prepares for execution of the task by slowing code and allowing computer vision algorithms to converge on the detected object pose. After converging, the drone enters execution state to perform the actual task.

Virtual Target (Path) Following: To enhance controllability and resistance against potent sea currents, a novel 3D path following controller, known as the Virtual Target (Path) Following (VTF) controller, was implemented. This controller, based on a master thesis by a former Vortex member Kristoffersen [3], employs a control law derived from the reference model of a virtual target. This target is constrained to move along a given path, enabling the drone to approach the nominal trajectory with greater confidence than traditional path- and trajectory-following systems. The reference model is a simplification of the Fossen 6DOF-underwater-vehicle model [2], applicable for low-velocity maneuvers. The control law incorporates actuator constraints, allowing the algorithm to manage the along-track speed of the virtual target. This is achieved by formulating the inverse mapping of the control allocation as a quadratic program and solving it using a trust-region based optimizer.

Perception

The perception and robotic vision team aimed to construct a vision framework from the ground up, as much as possible. Minimizing reliance on external software has allowed the team to adapt and find innovative approaches for each task with our own design philosophy. The strategies we've developed serve as a foundation for any other detection and estimation scheme in the perception stack, drawing on creative applications of theory from various courses at NTNU.

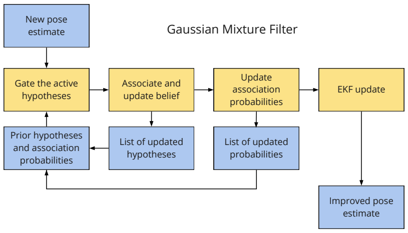

Fig. 7. The workflow of the Gaussian Mixture Filter.

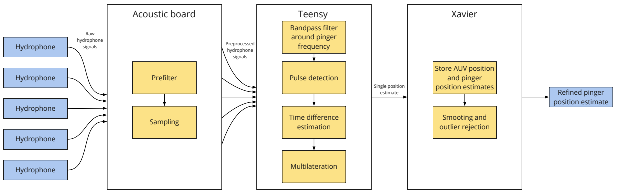

Fig. 8. The data flow and processing steps for the acoustic localization stack.

GMM: Increasing the robustness of pose estimates was tackled as a combined target tracking and existence detection problem. A novel algorithm, based on a Gaussian Mixture Model, was proposed and developed. This model allows for the simultaneous creation, termination, and probability evaluation of multiple tracks, based on the association of incoming pose measurements with active track hypotheses. The algorithm calculates probabilities, and a winning track can be declared as an existing object based on these probabilities. The aim of this solution is to unify a sensor fusion solution for robust search and final pose estimation, the workflow of which is depicted in Figure 7.

RANSAC: The pipe following task is addressed using classical estimation theory, with data gathered from a downward-facing camera while flying over the path. Detected pipe segment has a line fitted to it, defined by linear parameters α and β. The innovative aspect of our solution lies in a second stage of fit, utilizing a batch optimization algorithm based on RANSAC. This approach results in superior outlier rejection and more robust estimates of the line tracing the pipe.

Acoustic Localization: Vortex has developed a novel in-house solution for hyperbolic acoustic positioning. An array of five hydrophones is placed around the drone to receive the acoustic signals, maximizing the distance between them to increase the accuracy of the position estimates. The accuracy of positioning is highly dependent on the sampling frequency. Therefore, a specialized analog-to-digital converter (ADC) was utilized. This ADC has the capability to provide simultaneous multi-channel AD conversion at a high sampling rate of over 400 kHz. Teensy microcontroller then uses the digital signals to detect pinger pulses using dynamic thresholding. Once a pulse is detected, the time differences of the received pulses on each hydrophone are determined by cross-correlation. The pinger position relative to the AUV can then be calculated from the time differences using multilateration. These position estimates are accumulated over time, which allows for refinement through smoothing and outlier detection. The entire processing flow of this design can be seen in Figure 8.

IV. TESTING AND VALIDATION

Pooltests Schedule and Strategy

Small scale pooltests were initially conducted on the weekends of October and November 2022, and were mainly used to verify that existing code worked as intended, and making every member familiar with their area of responsibility for the drone to be operational. The first of the spring pooltests was conducted at the end of January, after a week-long workshop - per Vortex tradition, to test the newest features. A few smaller tests followed before the major pooltest at a larger facility happened during Easter, where two full weeks were spent testing new algorithms and rapidly prototyping solutions for the competition. Later, a test at sea was also conducted to prepare for more realistic conditions.

Control and Localization

The virtual target path following was firstly tested in simulations. Results from this can be seen in Figure 9, which shows the reference model smoothly following the path of the virtual target in all three linear degrees of freedom, as well as for heading. The overshoots when turning are explained by the actuator constraints in the objective function for the control law. After tuning the controller for the simulator, it was used to maneuver the AUV during live tests at various indoor testing facilities, as well as in the sea.

Although the controller exhibits high performance in simulations, accurate localization is essential when following a path defined in the real world. The AUV's Extended Kalman Filter (EKF) integrates IMU, DVL, and pressure measurements. This fusion of sensor data generates a pose estimate of the AUV relative to its initialization point.

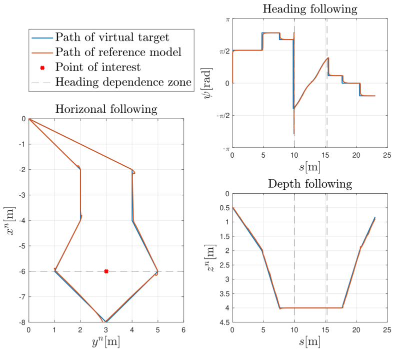

Fig. 9. Performance of the virtual target 3D path following algorithm in the simulator.

Perception

Throughout the spring semester, numerous innovative additions to the computer vision pipeline underwent rigorous testing. Figures 10 and 11 illustrate two preprocessing approaches. The first, based on contrast limited adaptive histogram equalization (CLAHE), enhances the visibility of brightly colored objects, like an underwater gate, which might otherwise appear washed out underwater. However, this stage also introduces background textures that could potentially cause issues for feature detection further down the pipeline. The second approach relies on the gray-world assumption, similarly enhancing the gate's visibility while preserving the original image's textures. The drawback of this method is the uncertainty of the gray-world assumption's validity underwater, as discussed in [6], which could also lead to issues with feature detection and outlier rejection.

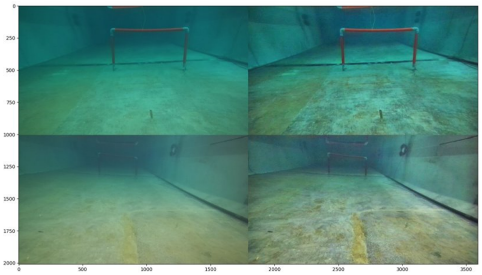

Fig. 10. Raw RGB image (left) compared to CLAHE preprocessing (right). CLAHE makes the gate stand out more compared to the background at both ranges, but also enhances textures in the background.

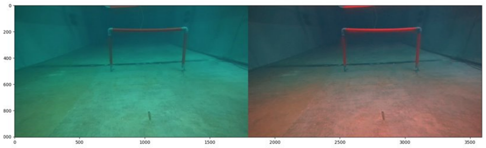

Fig. 11. Raw RGB image (left) compared to gray world preprocessing (right). Note that both the gate and parts of the pool floor is affected greatly by the preprocessing.

After preprocessing, the feature detection and segmentation algorithms can be applied. As an example, Figure 12 shows a ArUco detector using binary pattern identification process to locate potential markers, followed by a perspective transformation and error-checking to confirm valid markers. Output from the pipeline detection algorithms can be seen in figures 14 and 15, segmentation and RANSAC, respectively.

Acoustics

The estimation scheme defined in section III was implemented and tested using an in-house simulator which allows for arbitrary placement of hydrophones and sources in 3D space. Performance of the first two stages of the algorithm can be seen in Figure 16.

V. CONCLUSION

The Beluga AUV treads a thin line between being specialized and modular. It functions both as an AUV and ROV, being able to easily switch between. With our strategy of gathering extra points for autonomous solutions and just the right balance in specialization, we believe it will excel at this year's competition.

Fig. 12. ArUco detection and identification

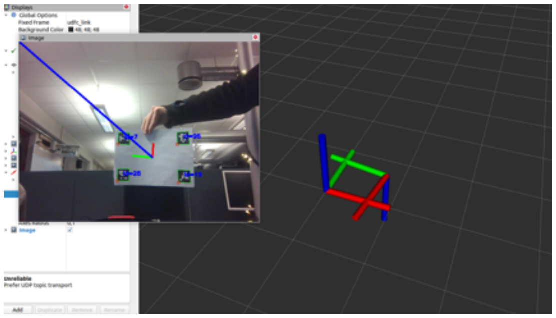

Fig. 13. ArUco pose tracking and dual-orientation problem

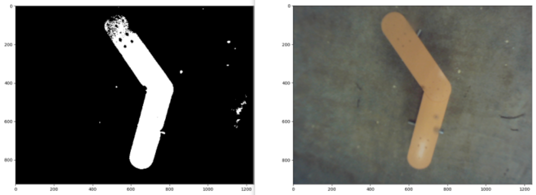

Fig. 14. Contrast-based segmentation of a test path

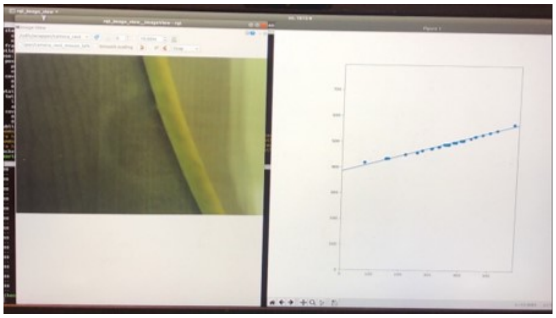

Fig. 15. RANSAC of a test pipe

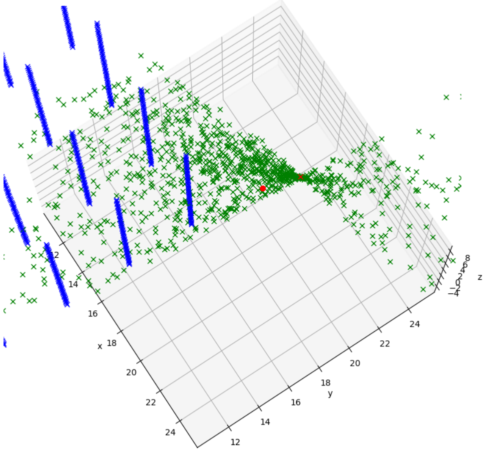

Fig. 16. Estimates of the pinger source position in 3D for sampling rate of 500kHz. The red dot shows the mean of distance gated estimates

ACKNOWLEDGMENTS

Vortex NTNU would like to show gratitude towards all members and alumni that have been a part of the project. Our members have sacrificed a lot of time and energy from their studies for this project and the results would not be possible without their dedication. The results of the work done by our members will be used for years to come and we hope the experiences and interest for marine robotics will be of use in future jobs and hobbies.

Without our sponsors, none of this would be possible. Our main sponsor, Kongsberg Maritime, has backed our project greatly, not just by providing us with financial and expertise support, but also by providing us motivation and encouragement to reach for the best technical solutions. This project would also not be possible without the support from the Norwegian University of Science and Technology (NTNU), and specifically the Department of Engineering Cybernetics, for providing our office and workshop facilities. Other sponsors and partners we want to thank are Nortek, Oceaneering, Mechman, FFU, 3DNet, and Bossard Norway [7].

Much of our motivation and for what we do has roots in the immense interest from the Norwegian marine community and academia. 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.

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