RoboSub 2024 Technical Design Report

Tartan Autonomous Underwater Vehicle

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***Abstract*—In RoboSub 2024, TartanAUV[1] intends to deploy Kingfisher as a single robotic platform, capable of completing all competition tasks. We have sharpened our competitive focus by developing elegantly engineered solutions tested in simulation and in water. Kingfisher's sphincter intake mechanism displays our team's design creativity, while our updated torpedo, torpedo launcher, and dropper have been optimized for efficiency on the course. Rigorous stress-testing of acoustics, electrical, and software systems ensures their ongoing reliability. We thank our incredible sponsors and supporters and are eager to exhibit our engineering skills at this year's competition.**

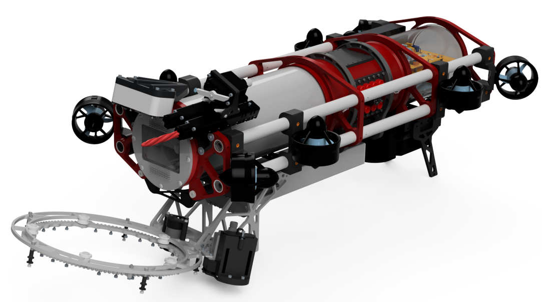

Fig. 1: 3D model of Kingfisher, 2024.

I. Competition Strategy

Over the past year, TartanAUV has re-evaluated our team strategy and engineering approach to better align with our educational and competition-based goals. In the past, our young team of curious and eager engineers has valued the exploratory development of new systems with great potential over tried-and-true solutions to the problems that the RoboSub competition presents. TartanAUV fielded two vehicles at RoboSub 2023: Kingfisher, our primary submarine equipped with a complete sensor and actuation suite that served us well as an all-in-one solution to many of the competition tasks in 2022, and Albatross, our debut submarine primed to focus on simpler vision tasks achievable with a reduced sensor payload while relying on Kingfisher for navigation and guidance. Our vision for this collaborative, two-vehicle approach to the RoboSub competition was novel in nature, and, as our educational goals prioritize innovative research and development, it was met with great excitement from our team. However, the RoboSub competition is an intensive survey of the robotic systems that competing teams build, and under-tested systems are a mismatch for multiple long days of practicing and competing in the water. We quickly realized that maintaining two robotic platforms increased our risks of mechanical failures while putting a strain on our team's resources, and that, if we want to succeed at competition, it is important that our team focuses its vision on simple solutions that are well-tested and whose successes are repeatable.

TartanAUV has thought carefully about how to better manage our limited engineering resources to maximize our competitive success, maintaining our excitement for innovation while prioritizing proven solutions. We aim in RoboSub 2024 to present refined and reliably engineered solutions, approaching all competition tasks with a single unified robotic platform. Several vehicle design decisions were made as a result of this overarching mission. First

[1]Authors presented in alphabetical order. For individual contributions and responsibilities, please visit our team website.

Fig. 2: Sphincter intake acquiring the coral game piece.

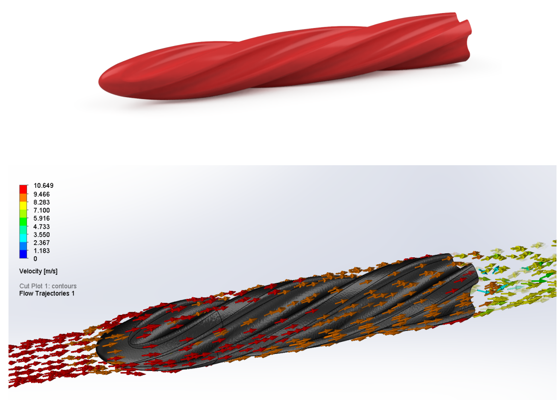

Fig. 3: Fluid dynamics of our torpedo.

and foremost, we have streamlined our strategy and decreased the margin for operational error by deploying only our main vehicle, Kingfisher. By concentrating on our flagship vehicle, we have aimed to enhance its software, mechanical, and electrical capabilities, ensuring more robust and consistent performance. Creative and elegantly designed solutions include our sphincter gripper, while our electrical and acoustics systems have undergone overhauls with rigorous testing to ensure stable performance. TartanAUV is excited to demonstrate Kingfisher's formidable engineering and reliability in all of this year's competition tasks.

II. Design Strategy

A. Design of Sphincter Intake

When tackling the task of sample collection, we iterated over various intake designs to optimize grasp stability and robustness. Our initial design, featuring a classic compliant claw, faced significant challenges with pose estimation. We then moved to a dual-powered, street-sweeper-inspired design, equipped with two sets of concrete roller spikes to better grip the PVC samples. However, the diversity in diameter of the samples along with the asymmetry of the coral object led us to our final design.

Inspired by the bio-robotics department at our university, this design is an adaptation of a flexible iris valve. The circularly symmetric design requires minimal pose estimation and provides a wider grasping zone. Furthermore, the large open area allows our downwards-facing camera to see through the module while it's not in use, thus allowing other tasks to be completed without impact.

The gripping portion of our intake is composed of five elastic latex cords, an addition we made after our tests reflected that latex cords offered the best grip strength. A custom machined ring gear and mounting plate are attached with five roller bushings. Rotating the gear stretches the cords from a position tangent to the circular grip area towards the center. For simplicity, an m200 motor is used to power the mechanism via a 1:10 gear ratio, optimizing for torque. No sensors are required, as the mechanism is controlled based on timing with physical hard-stop endpoints. To handle the forces that accompany the high closing speeds, a pinion gear made of polyurethane rubber drives the larger ring mechanism, absorbing the high shock loads to protect other parts of the system.

Kingfisher has had a significant software upgrade to its controls this year, allowing accurate tracking while the vehicle is pitched downwards 15 degrees. The cantilever design of the module works in combination with these software upgrades, allowing it to elastically deform towards the target when it contacts a task's protective railing. This allows the vehicle to have maximum manipulability while maintaining the ability to navigate the course freely. Further, the sphincter has proved very effective at gripping the competition's game pieces because of their height.

B. Design of Torpedoes

To meet the increased accuracy requirement of this year's competition, we have machined rifling

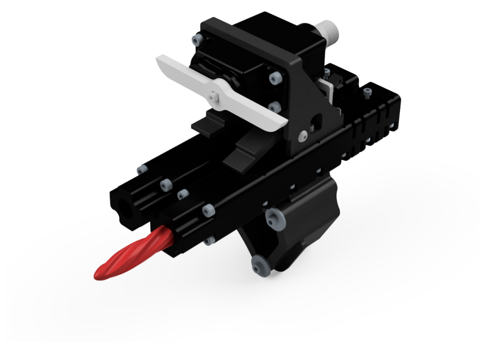

Fig. 4: The torpedo launcher firing a torpedo.

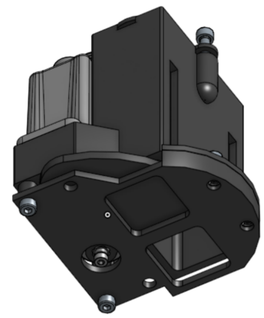

Fig. 5: The dropper mechanism.

into our torpedoes. Similar to a traditional firearm, four spiral slots have been machined into the external body of each torpedo in a polygonal pattern. These slots induce a spin onto the torpedoes as they exit the barrel of our launcher [1]. This spin minimizes the variability of the mechanism and allows for a more accurate shot [2]. The torpedoes are made of a UHMW material with a density of 97% of water, allowing for easy retrieval while testing. A decreased outer diameter from earlier prototypes was chosen to increase the accuracy of the larger spread of targets.

C. Design of Torpedo Launcher

The launcher itself utilizes a 7” compression spring with square slider blocks to launch the torpedoes. The springs are held in tension via a rectangular pin that slots into the slider blocks, where the torpedoes are then placed resting against the blocks. The pins are released via a lever mechanism driven by a Blue Trail servo, and held in place via a small extension spring. Upon release, the round torpedoes are driven forward through the barrel, whereas the slider block’s square corners keep it inside the mechanism. Pressure slots are cut behind the locking position of the torpedo, allowing for maximum power to be transferred to the mechanism, without the fluid dynamics of kingfishers movement interfering with the starting conditions of the torpedo.

D. Design of Dropper

Our new dropper mechanism has a much smaller footprint than the previous iteration, allowing us to attach more peripheral devices to the sub without significantly obfuscating our camera’s field of view. The dropper uses a single servo motor to open one chamber at a time, giving us precise control over when and which ball we drop into the target area. The pivoting lid with the handle not only allows for quick reloading but also keeps the projectiles secured while the sub performs its iconic barrel roll.

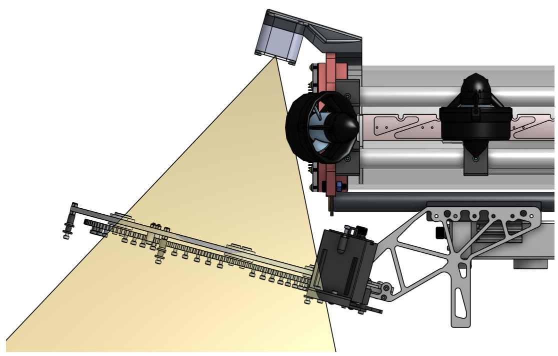

Fig. 6: Side view of the camera and mount.

E. Design of Camera Mount

We have decided to shift our downwards-facing camera to the highest point on Kingfisher by designing a new camera mount. A more durable design offers a complete downward view of all of our manipulation tasks. The increased height allows us to maintain vision tracking on objects where other positions would interfere with the camera’s focal range, providing us with clear pictures throughout all operations while minimizing the footprint of the sub itself.

Fig. 7: Our perception model first detects keypoints, and then uses these to deduce the orientation of objects.

Fig. 8: A sample image from our synthetic training dataset, showing the buoy and gate marker for this year's competition.

F. Improvements to Perception Systems

This year saw our team's first experiments with custom perception models. In the past, we relied on off-the-shelf object detectors like YOLO [3]. While easy to integrate, these pre-built solutions could not provide all of the information necessary to complete complex tasks like sample retrieval. An object detector like YOLO draws two-dimensional boxes around objects detected in an image but does not provide any information about how the object is oriented in three-dimensional space. Especially with complicated objects like this year's samples, knowing which way an object is oriented – in addition to where it is located – allows for grasps to be performed more consistently.

We replaced our previous object detectors with a hybrid system that blends machine learning and classical computer vision techniques. Inspired by the work of Zhou et al. [4] and Yu et al. [5] A deep neural network is trained to identify known keypoints on objects of interest, like the tip of the coral sample or a corner of the bin. Then, these detected keypoints are fed into a classical pose estimation algorithm that determines the pose of the object in 3D space. This new model enables us to approach objects from specific directions. For example, when completing the torpedo task, our vehicle always shoots perpendicular to the target, even if it initially approaches from some other angle.

Training perception models require large amounts of annotated data (i.e. example images with labels on the objects to be detected). In years past, we traditionally produced our training datasets by recording images during water tests and manually labeling the objects in each frame. This approach was simple but severely limiting for two reasons. First, the visual environment during our water tests differed significantly from the competition pool, so our training data transferred poorly to the competition environment. Second, the need for human annotators limited the size of our training datasets. This year, we alleviated both of these issues by making use of synthetic data. We used the Nvidia Omniverse toolkit [6] to render thousands of synthetic images of the competition objects in randomized underwater environments, with annotations computed automatically. Because we were able to generate so many example images in such varied environments, we are confident that our new models will still perform well at competition.

G. Design of Acoustics System

We have completely redesigned our acoustics system with the goal of creating a modular, vehicle-agnostic solution. We have created an integrated acoustics module that houses a phased array of five ultrasonic transducers, as well as supporting electronics. The module is attached to the vehicle externally and communicates with the onboard computer via a high-speed Ethernet link. The electronic system comprises a five-channel analog front-end and a Xilinx Zynq 7000 FPGA. The front end is capable of driving the transducer array in both receive and transmit modes at frequencies ranging between 25 KHz and 1 MHz, and the FPGA is responsible for digital signal processing. With this platform, we can perform pinger localization, and we will be able to implement inter-vehicular communication and relative positioning in the future without any hardware changes. Additionally, the system can be used as a low-resolution sonar with digital beamforming. With its modular design and capable hardware, our new acoustics system will provide a foundation for operating multiple AUVs as we introduce new vehicle designs in the future.

H. Improvements to Electronics Systems

At previous competitions, electrical components were the root of many issues we faced, and thus the Electrical team's primary focus was on reliability and usability. We were able to use many tools such as an oscilloscope that was sponsored by Teledyne LeCroy to get to the root cause of any faults and perform endurance tests with repeatable results. These findings have helped influence design decisions that have improved thermal conditions inside the sub and reduced the chances of component failure under normal and extreme conditions.

I. Design of Thermal Reduction Plate

Knowing that our current heat distribution stifles our runtime and general heat flux capacity, we needed a solution to tackle the coming changes. The development of the thermal plate takes advantage of the integrated fans and provides a streamlined mode of heat transfer, essentially transferring heat with the cooled water surroundings directly through the endcap. The way this works is by an array of fins extruding from an aluminum plate that effectively increases the surface area of the heat transfer medium by mimicking the concept of a heat sink.

J. Improvements to Controls Systems

Our controls team spent the year refining a new auto-trim system for Kingfisher. This system runs in the background and watches the accelerations created by the thrusters. By comparing these measured accelerations to the expected accelerations calculated from a dynamics model, the auto-trim system can continually adjust the model parameters to better match reality. These dynamics parameters include simple quantities like vehicle buoyancy, but also more complex terms like hydrodynamic drag. By running this system continually, instead of relying on a traditional offline model identification process, our team is able to make physical changes to our vehicle without needing to re-balance it. Kingfisher is also able to pick up heavy objects without issue since it adjusts its center of mass in real-time to remain balanced.

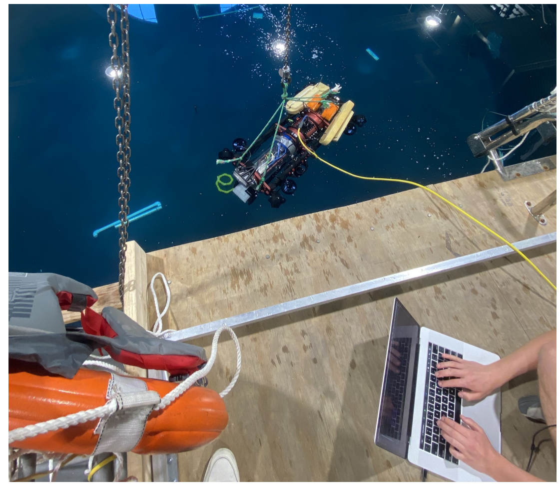

Fig. 9: In-water test in Field Robotics Center tank.

III. Testing Strategy

TartanAUV has been incredibly fortunate to have continued access to a workspace in Carnegie Mellon University's Field Robotics Center for building and testing our robotic components, even amidst recent construction projects in the building. We are privileged to have access to a 12-foot water tank specifically designed for AUV testing, which allows us to conduct flexible and robust vehicle tests frequently throughout the academic year. Additionally, the Carnegie Mellon Athletics Department graciously offers the Cohon University Center pool as an underwater testing space which, being a larger pool, allows us to run more extensive tests of our navigation system with game elements arranged more similarly to competition scale. While we strongly value opportunities, like those described above, to do full-scale tests of our vehicle in competition-like settings, they can require significant time and resources. To mitigate such overhead, we have adopted a hybrid testing strategy including standard in-water tests, small-scale bench tests, and simulation.

When pursuing new tasks, we employ a rapid prototyping approach. First, we construct 3D models of designs that advance already proven concepts. We then design a minimal-cost prototype, carefully balancing time and monetary expenses, and with that prototype perform a small-scale out-of-water

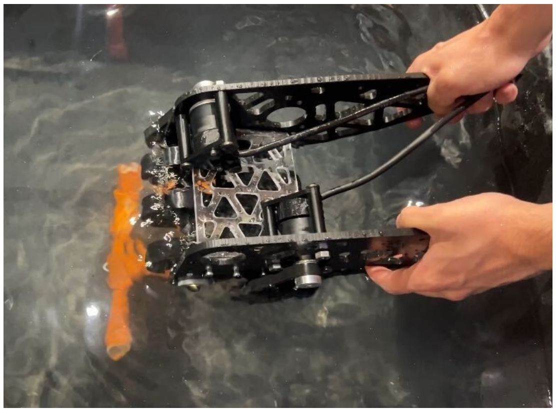

Fig. 10: Small-scale in-water test of prototype intake.

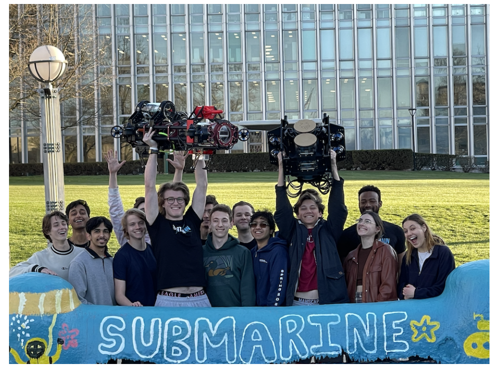

Fig. 11: Painting the Fence is a Carnegie Mellon tradition that our team participates in annually.

test, verifying the basic motion of a system. Subsequently, we perform a small-scale in-water test, wiring up the motion systems of each module and manually manipulating the setup to crudely simulate the submarine's movements while submerged in a small bucket of water. By placing the submarine in the water for an extended time, we can identify fatigue issues with the systems, as well as the source for high current draws for each module. With feedback from software team members who intend to write the controls of the system, we can spot mechanical flaws in our systems and make effective design iterations. Once a final design proves successful in small-scale in-water tests and the software team is confident in their ability to write effective control software, we choose sturdier materials for the final product, and develop the hardware and software of the system in parallel. At this point, tasks can be attempted in full-scale in-water tests.

Apart from task attempts, full-scale pool tests are reserved primarily for either data collection or navigation and control screening. Full-scale data collection is made simple with the data logging capabilities of our submarine's software development framework, Robot Operating System (ROS). With ROS, we are able to record camera and positioning data during our in-water tests for later analysis, integration into simulation, and creation of machine learning datasets. Full-scale tests for navigation and controls screening are run to make optimizations to the software tested in underwater simulations that leverage the UUV Simulator package [7] in Gazebo. Gazebo, built on ROS alongside our software stack, enables us to test the software we design on our personal machines, as the software is run with the same protocols in simulation and in the real world. Together, full-scale, small-scale, and simulation-based testing strategies form an invaluable framework for ensuring the reliability of our submarine's integrated software and hardware platform and the reproducibility of its underwater performance.

IV. Acknowledgments

Our work as a team would not be possible without the support of incredible mentors at Carnegie Mellon University like Michael Kaess, George Kantor, Tim Angert, and Melisa Orta Martinez. We would like to thank the Field Robotics Center for access to the Robotics Institute machine shop along with water testing facilities and storage space. We would also like to thank Catherine Copetas from the School of Computer Science for her tremendous help in our sponsorship efforts and work with university members. Additionally, we would like that thank Alicia Gorman and the Carnegie Mellon Athletics Department for their generosity in granting use of the Cohon University Center pool for more extensive water testing. Lastly, we would also like to thank our generous corporate sponsors: Gold (Movella, Altium, Teledyne, Carnegie Mellon), Silver (Hakko, Leidos), Bronze (Lockheed Martin, IMC), and Friends (PCBWay). We are excited to continue working with these phenomenal partners in keeping RoboSub thriving at CMU while paying it forward by spreading STEM in our community.

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TABLE I: Kingfisher Components

Component	Vendor	Model/Type	Specs	Custom/Purchased	Cost	Year of Purchase
ASV Hull Form / Platform	Custom	Main Enclosure	NA	Custom	NA	2019
Waterproof Connectors	Blue Trail	20x Cobalt	Specs	Purchased	$42-$65 ea.	2019
	Subconn	Ethernet Circular	Specs	Purchased	$250	2019
Actuation	Blue Trail	Underwater Servo SER-110X	Specs	Purchased	$500	2023
	Blue Robotics	M200 Motor	Specs	Purchased	$160	2024
Propulsion	Blue Robotics	8x T200 Thruster	Specs	Purchased	$200 ea.	2019
Power System	Custom	Power Distribution Board	NA	Custom	NA	2023
Motor Controls	Blue Robotics	9x Basic ESC	Specs	Purchased	$36 ea.	2019
	Polulu	Mini Maestro 18 Channel	Specs	Purchased	$42	2023
CPU	Nvidia	AGX Orin	Specs	Purchased	$2000	2023
Teleoperation	NA	Personal Computers	NA	NA	NA	NA
Compass	NA	See IMU	NA	NA	NA	NA
Inertial Measurement Unit	Movella / Xsens	MTi-300 AHRS	Specs	Purchased	$500 (Discounted)	2019
Doppler Velocity Logger	Teledyne Marine	Pathfinder	Specs	Purchased	$20000 (Discounted)	2019
Cameras	Luxonis	2x OAK-D W PoE	Specs	Purchased	$500 ea.	2024
Hydrophones	NA	5-element Phased Array	NA	Custom	NA	2023
Vision	YOLO V3, Darknet ROS			Custom	NA	NA
Localization and Mapping	Global Map, SBL Acoustics			Custom	NA	NA
Autonomy	Inverse Dynamics, PID Controller			Custom	NA	NA
Open Source Software	ROS, OpenCV, Gazebo, UUV Simulator, Darknet ROS			Custom	NA	NA