CTHULHU: The Design and Implementation of the Duke Robotics Club's 2022 RoboSub Competition Entry

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Abstract — **Introducing Cthulhu, the 2022 RoboSub entry of Duke Robotics Club. While we transition back in person, we continue to build upon our core tenets of flexibility and reliability. Our team of 25+ student engineers has built an AUV which not only can reliably perform fundamental movements, but can also effectively execute high-level complex tasks by concurrently running these fundamental building blocks. Our priority was to design simple, modular systems with minimal interdependence that can be tested and iterated upon virtually. Notable strategic additions include: revamped mechanical actuators, upgraded computer vision, precise acoustic sensing, and a flexible task planning framework.**

I. Competition and Design Strategy

Based on our experience from prior years, we had a good idea of what tasks would appear in competition. We would have to pass through the gate, followed by some combination of bumping buoys, dropping markers, shooting torpedoes, and picking up objects. We would also need to be able to follow the task markers – meaning our AUV would need to see the marking lines and register the acoustic pingers. We chose to keep general robot design flexible so we could easily debug components on the fly and quickly adapt to the specifics of this year's competition.

Our overall strategic vision is to focus on places where we can use our most reliable systems to complete *core tasks*. These tasks make up our core competition strategy, and are expected to be completed on every competition run. We also identified some additional tasks that we have high confidence in but did not include as part of our core competition strategy due to on-site complications. We will dive deep into this task prioritization in the subsections below.

A. General Strategy: Flexibility and Modularity

A major part of our general strategy this year was a focus on navigational reliability and maneuverability, removing limitations on what Cthulhu can sense and accomplish. We iterated on our acoustics and CV systems, adding another hydrophone array and stereo vision cameras to increase confidence in their predictions. These detection algorithms are a key part of our competition strategy, making sure that Cthulhu is always able to navigate to points of interest and plan tasks out accordingly. Because movement is a part of every task, maintaining a high level of maneuverability is key for our competition strategy. We designed our cascading controls system to be worry-free, allowing reliable control in all 6 degrees of freedom.

We have continued to build upon our lean, organized codebase based on Robot Operating System (ROS) where the code for each software system (e.g. computer vision, controls) lives in its own package. A new task planning system was built using state machines, affording us flexibility and ease when developing new tasks. All code is highly documented, with README's for each package and docstrings for all functions. This emphasis on organization has proved crucial for quickly onboarding new members, as well as facilitating a streamlined development process. Removing the friction of developing new features has increased our productivity and allowed us to cover a wider range of tasks in our competition strategy.

B. Choose Your Side - Gate

We made it a top priority to consistently identify and move through the gate, since this is the standard qualification task. Our mechanical design and controls system are already well-suited to handle the movement required for going through the gate. CV can accurately identify the boundary of the gate and the tick in the middle. It also creates a depth map telling us approximately how far the robot is from the gate using stereo vision.

With all of the above inputs and our bottom-up task planning framework, we are confident that Cthulhu's CV system is reliable enough to recognize the gate. We will elect to do a coin flip to decide our robot's initial heading. Our cascading controls system will maintain a fixed heading as Cthulhu move's through the gate.

Because Ctuhlhu's frame and thrusters afford 6 degrees of freedom, we are confident that we can accomplish any style tasks. While moving through the gate, we will perform two 360 degree rotations.

C. Make the Grade - Buoys

The buoy task is another core component of our competition strategy. Thanks to our deep-learning-based computer vision algorithms, this task became fairly simple. Our CV is robust enough to correctly identify path markers and buoy locations, even from a distance and in a variety of lighting conditions. Cthulhu will follow the path markers until it can see the buoys, after which it will move to bump the buoy corresponding to the bootlegger. We were able to integrate this task into our autonomous runs with minimal added complexity thanks to our modular task planning framework.

D. Collection - Bins

The bin task is not core to our competition strategy, but we are confident that we can navigate to the bins and drop markers in them. Our redesigned actuators and downward facing camera greatly simplify the bins task. Once Cthulhu navigates to the bins, CV can tell us the position and distance estimates with stereo vision.

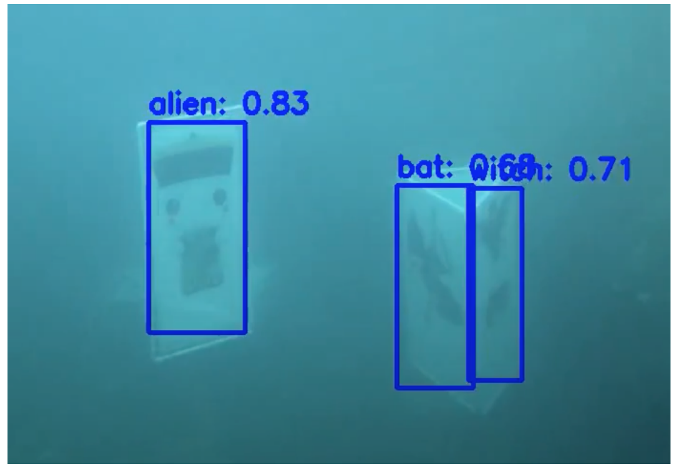

Fig. 1. Buoy Object Detection via Detecto CV

Although this is a more difficult task overall, Cthulhu is prepared with all the necessary components to execute it. As such, it is not a core task but one that we feel can be reliably completed as part of our strategy.

E. Survive the Shootout - Torpedoes

While Cthulhu has a torpedo actuator, we were unable to fully test it in a realistic scenario at depth. We decided to focus on perfecting the marker-dropper and claw actuators instead. As a result, the Torpedo task is not a part of our competition strategy.

F. Cash or Smash - Octagon

The Octagon task is the most challenging, but still part of our competition strategy. Our improved acoustics system allows us to accurately identify the location of acoustic pingers, which will be switched on for the Octagon Task. Developing a more reliable acoustics system was a major priority this year, as we knew the Octagon and Torpedo tasks did not have path markers pointing to them.

Given the current capabilities of Cthulhu, we have confidence in locating and surfacing inside the octagon. Our competition strategy is not dependent on picking up the bottles and moving them to the tables, as we have not tested our claw enough. Given the complexity of the undertaking, we decided it was more prudent to focus on other core tasks.

II. Design Creativity

A. Mechanical Subsystem Novel Aspects

Cthulhu features a new suite of servo-based actuators. In previous years, we had issues with the reliability of existing mechanisms. Because our competition strategy is reliant on some core tasks that should be completed with 100% confidence, we decided to revamp each of our actuators to make sure they would be reliable in all cases.

Cthulhu's new claw is significantly more versatile than its predecessor. Our original claw only had two jaws, while our new design has four. The quad-jaw design allows our claw to obtain a secure grip on a wide variety of objects.

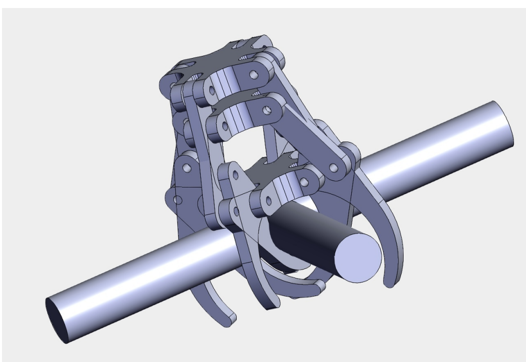

Fig. 2. Quad-jaw Claw

B. Electrical Subsystem Novel Aspects

The electrical team allows other subsystems to abstract away the low-level implementation details and simply trust that the electrical components on board will work when needed. Much of the year was spent on reinforcing existing features of Cthulhu, with a reorganization of the electrical stack and improvements to the acoustics system.

1) Electrical Stack Overhaul: After a few years of iteration on Cthulhu, we found that the electrical stack had incurred some technical debt that affected the reliability of our components. To remedy this, we tore down and rebuilt Cthulhu's power distribution and computer systems. We replaced aging components and redesigned the internals of the capsule to support upgrades to our CV, sensor fusion, and acoustics systems.

2) Acoustics: This year, the team decided to take on the challenge of designing our own amplifiers for the hydrophone array. All amplifier and filtering modules were housed on a single PCB, which was more space-efficient and allowed for similar trace lengths—a critical characteristic of our system that relies on the precise timing of signals from the different hydrophones.

Since the characteristics of the pings were known, everything was built around the specific frequency range and current magnitude. Low-pass filters with a cutoff frequency of 50kHz were used to eliminate noise and upper harmonics. Additionally, given the very low signal currents from the hydrophones, a total gain of 10kV/V was applied conforming to the desired output signal characteristics.

Processing occurs in two steps. First, we use one array to obtain an initial guess for the octant in which the pinger is located relative to Cthulhu. The four hydrophones are generously spaced 0.3 meters apart in a right triangular pyramid configuration. Using a Butterworth bandpass filter [5] on the desired frequency, we obtain the time differences between the pings in the x, y, and z axes as they reach each hydrophone. After performing a cross-correlation to obtain the time differences, we can derive our "guess octant".

Next, we use our guess and the other hydrophone array to precisely locate the pinger. The second array consists of four hydrophones spaced just millimeters apart in a square. Using synchronized readings from the hydrophones, a Short Time Fourier Transform is used to obtain a magnitude and phase list. After several window selections, a final small window is determined based on the stability of the phase difference between each hydrophone pair. The phase differences and the guess from the first step are inputted into our Time Difference of Arrival algorithm to locate the exact horizontal and vertical bearings for the pinger.

C. Software Subsystem Novel Aspects

1) Computer Vision: The CV team's primary focus this year was improving our stereo vision algorithm, which allows us to identify the 3D locations of target objects. Detecto [1] generates bounding box predictions for target objects, and with stereo vision, we now can estimate their depths as well. This information is crucial for the task planning team, which not only depends on position but also depth data to ascertain whether Cthulhu is within an acceptable range of a target object (e.g. a pipe that needs to be gripped by a claw).

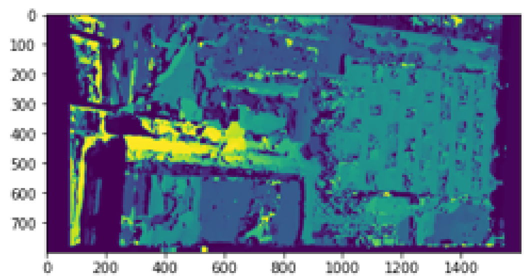

Fig. 3. Calculated Disparity Map used for Stereo Vision

Stereo vision is possible due to Cthulhu's two frontward facing cameras. We first collected calibration images, which involved simultaneously capturing an image from each camera of a checkerboard held at varying angles and depths. We then performed stereo camera calibration, which provided the relevant matrices to rectify image pairs. We then used stereo semi-global block matching (SGBM) with OpenCV to create a disparity map and convert it to a depth map for each image pair. Finally, to obtain depth measurements for target objects, we created a binary mask for each bounding box prediction, applied this to the depth map, filtered outliers, and calculated the median depth value for the object.

2) Controls: Last year, we revamped our controls algorithm to utilize "cascade control" [3] via nested PID loops (one for position, and one for velocity) rather than a single position PID loop. The outer position loop guides in the correct general direction, and the additional velocity loop corrects any local disturbances. We spent this year adding new functionality, such as implicit depth hold and power control, which allocates a relative power for each of the 6 degrees of freedom. We also spent time tuning PID constants to nail down Cthulhu's maneuverability and stability.

3) Task planning: The abstract, bottom-up task planning architecture we built last year breaks up high level tasks into fundamental tasks that can be combined, reused, and executed concurrently. Consider the high level task of moving through a gate, shown in Figure 4. Tasks are modeled as state machines, where the output of one fundamental task influences the next course of action. We continued to build our toolbox of modular fundamental tasks, which allowed us to write competition tasks for this year's competition strategy.

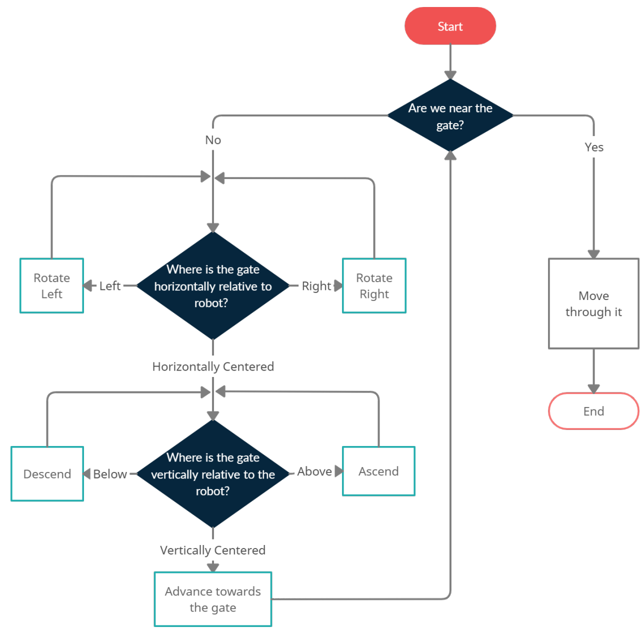

Fig. 4. Flowchart of Gate Task

III. Experimental Results

A. Mechanical

Despite COVID-19 restrictions, all mechanical designs underwent thorough testing. During the semester, the mechanical team was able to rapidly prototype and test actuators in a large sink in our lab. Once our actuators passed preliminary testing, we tested them in a more realistic setting at a dive pool to evaluate performance at depth. This two-stage cycle of prototyping and testing was key for our design process, allowing for quick design iteration while also keeping reliability as a main goal.

We also continued efforts to waterproof new components that were added to Cthulhu over the year. New stereo vision camera enclosures, hydrophones, and pressure sensors were all held at depth for extended periods of time to make sure Cthulhu would be safe underwater. This extensive testing ensured that Cthulhu would be competition ready for the summer, even with new features being added in final sprints.

B. *Electrical*

The electrical team integrated a new Arduino micro-controller into the electrical stack. A complete remodeling of Cthulhu's electrical stack resolved past issues with flaky connections and inaccurate sensor data. This undertaking also served as an important knowledge transfer tool, with new team members getting a full understanding of Cthulhu's electrical system.

The acoustics system saw large improvements in prediction accuracy and precision. The additions of a second hydrophone array and custom filtering PCBs proved fruitful. The amplifier gain was extensively tested in a large sink as well as a dive pool, verifying that the board outputted a clean signal across all 4 channels. While the new acoustics system is more complex, it affords a level of reliability that was necessary for our competition strategy.

C. *Software*

The controls team heavily relied upon a virtual simulation environment to refine and tune our new nested PID loop algorithm. We developed an automated testing package to tune our PID constants via the Ziegler Nichols method [3], which performed well. We tested these PID constants in the simulation, and we validated that the robot was able to quickly maneuver to any desired local position or velocity while minimizing the amplitude of oscillations around the setpoint. Once we nailed down our testing workflow in the simulation, we were able to transfer it to in-person pool tests using the physical robot.

The task planning team likewise performed the bulk of testing in simulation. We designed a number of virtual models, such as a gate, buoys, and pipes, and we laid out these objects in the simulated environment to mirror a competition setting. Using our "mock computer vision" shown in Figure 5, task planning was able to treat the virtual environment as if it were its fully-fledged

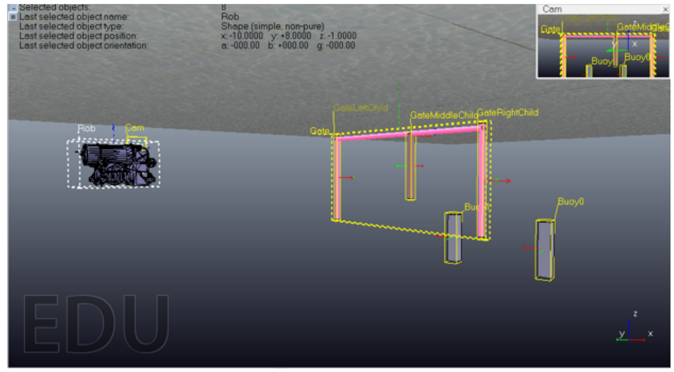

Fig. 5. Simulation Environment With Mock Computer Vision

real life counterpart. Within simulation, task planning demonstrated that Cthulhu could successfully complete the gate task, style tasks, and buoy task.

D. *Pool Testing*

The COVID-19 pandemic taught us that in-person pool testing is a luxury, and time spent at the pool should be optimized accordingly. As such, we made an effort to conduct heavy testing of all subsystems in the simulation during the week to prepare for pool tests each weekend. Our in-pool time was still limited due to the pandemic, but our weekly pool tests were used to validate that our core robot systems were healthy and reliable, giving each sub-team confidence to continue layering on complexities.

IV. Acknowledgments

Duke Robotics Club is housed within Duke University's Pratt School of Engineering. We gratefully acknowledge the Duke faculty and administrative staff who have helped and continue to help make the club a success. We are indebted to Pratt Director of Undergraduate Student Affairs Jennifer Ganley, our advisor Professor Michael Zavlanos, our lab manager Ali Stocks, and the Engineering Alumni Council. Furthermore, we owe our continued success to our long-time sponsors: The Lord Foundation, Duke Student Government, General Motors, and SolidWorks. Finally, we thank RoboNation, whose commitment to RoboSub empowers student engineers like ourselves to explore our passion for robotics to the fullest extent.

V. References

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[3] O. Arrieta, R. Vilanova, and P. Balaguer, “Procedure for Cascade Control Systems Design: Choice of Suitable PID Tunings,” International Journal of Computers Communications & Control, vol. 3, no. 3, p. 235, 2008.

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APPENDIX A: COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Custom/Purchased	Cost	Purchase Year
Buoyancy Control	Blue Robotics	Subsea Buoyancy Foam: R-3312	Purchased	135.00	2022
Frame		8021 Aluminum, custom	Custom	500.00	2019
Waterproof Housing		Polycarbonate, custom	Custom	1,100.00	2019
Waterproof Connectors	MacArtney	Subconn/Seaconn Connectors	Purchased	2,000.00	2019
Thrusters	Blue Robotics	T200 Thruster	Purchased	1,790.00	2021
Motor Control	Blue Robotics	Basic ESC	Purchased	300.00	2021
High Level Control	Arduino	Arduino Nano Every	Purchased	13.50	2022
Actuators	Hitec	32646W HS-646WP	Purchased	158.60	2022
Propellers					
Battery	Turnigy	16000mAh 4S 12C	Purchased	102.18	2022
Converter	QSKJ	QS-1212CBA-150W	Purchased	45.38	2021
Regulator					
CPU	Intel	NUC 6i7KYK	Purchased	825.00	2019
Internal Comm Network	TP-Link	TL-SG1005P V2	Purchased	40.00	2021
External Comm Interface	NetGear	Nighthawk R7000	Purchased	143.75	2019
Compass					
Inertial Measurement Unit (IMU)	Vector Nav	VN-100 Rugged IMU	Purchased	1,335.00	2022
Doppler Velocity Log (DVL)	Teledyne	Workhorse Navigator 1200	Purchased	10,000.00	2018
Manipulator		Marker Dropper and Claw	Custom		
Algorithms					
Vision	Luxonis	OpenCV AI Kit: OAK—D-PoE	Custom	600.00	2022
Acoustics	Aquarian	H1a Hydrophones	Custom	600.00	2022
Localization and Mapping		Extended Kalman Filter, SLAM	Custom		
Autonomy		Custom task planner			
Open Source Software		Docker and ROS			
Inter-Vehicle Communication					
Programming Language(s)		Python, C++, Lua			