Cornell University Autonomous Underwater Vehicle: Design, Strategy, and Implementation of the Kraken and Leviathan AUVs

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***Abstract*—Kraken and Leviathan are the two vehicles designed by CUAUV for the 2021 virtual AUVSI Robosub competition. Leviathan, the secondary vehicle, has been completely re-designed and manufactured since the last competition and has yet to compete in the TRANSDEC competition pool. The team has worked to improve the design features to better optimize for our competition strategy in both the redesign of our Leviathan and through continued testing and modification of Kraken. Both vehicles are complete and fully tested, and set the groundwork for the net in-person competition.**

I. Competition Strategy

The Cornell University Underwater Vehicle (CUAUV) team has and continues to aim for the ultimate goal of advancing our technologies to complete all competition tasks. As a team, we have continued to make the major design decision for several years of creating and utilizing two vehicles simultaneously during the competition to better optimize for points given the time constraint of the competition run. For the 2021 year, utilizing two vehicles for simultaneous task completion continues to be the team's overarching strategy. However, we have made several important strategy changes since our last opportunity to compete.

The team has recognized the idea of utilizing two vehicles in tandem as a game-changing competition strategy. One of the largest drawbacks of completely re-designing and manufacturing two vehicles annually is that the sheer amount of work hours required to do so is not only a huge strain on team members but also necessitates that full vehicle pool testing must start later in the year when both of the redesigned vehicles are ready. As such, the team has decided to switch to an alternating rebuild cycle whereby the main vehicle and the secondary vehicle are completely rebuilt during alternating years and only modifications to the one vehicle are made. This allows for software updates to be tested in the pool using one vehicle continuously throughout the year while the second vehicle is rebuilt. This change in the team's design cycle strategy has been a large improvement as it has allowed for more immediate testing feedback for software changes.

A major factor that led the team to maintain the strategy of completely rebuilding our vehicles every year in the past was the need to pass down technical information to each generation of members in the team by carrying out a full design cycle each year. This biennial design cycle that we have now adopted also allows for the team to preserve technical knowledge. Carrying out a full design cycle–from design to manufacturing to testing–of one AUV each year allows for each incoming class of student members to experience each stage necessary the design of one operational vehicle.

Over the past year, the constraints due to the COVID-19 pandemic have affected how we as a team have been able to carry out the strategic design of our two vehicles and have resulted in a slightly different design cycle than expected. Due to campus closure in the previous academic year and limited in-person lab access during this past academic year, the completion of the design cycle of Leviathan has been carried over from the 2020 through this year. Despite these circumstances, the Leviathan vehicle (shown in Figure 1) was able to be fully completed and tested this year, and is one of the vehicles we are presenting for this 2021 virtual competition.

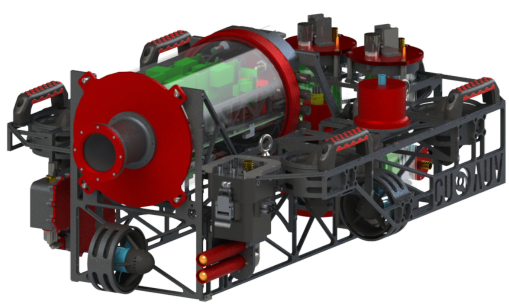

Fig. 1. Render of Leviathan AUV

The Leviathan vehicle that we worked to rebuild this year has a drastically different mechanical structure from our previous secondary vehicle and reflects a change in the strategic role of our second vehicle. In past years, the second vehicle served in an auxiliary capacity to the main vehicle. While we planned on dividing tasks among the vehicles, the secondary vehicle was allocated only simpler tasks and and the main vehicle was used for more complex tasks requiring object manipulation using actuators. With our vehicle Leviathan, we are moving towards a goal of developing further our secondary vehicle to work more equally in conjunction with our main vehicle instead of in a more auxiliary role. As a larger vehicle is able to be equipped in a more comparable manner to the main vehicle, Leviathan aims to carry out the strategy of a more equal divide of competition tasks between the vehicles.

While the vehicle Kraken (see Figure 2) remains the only vehicle equipped with a doppler velocity logger for more precise position estimation, both vehicles are equipped with pneumatic valves for use with external manipulators and full

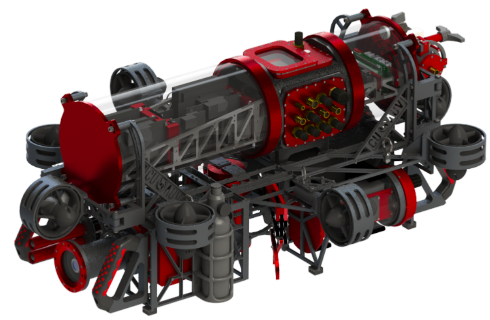

Fig. 2. Render of Kraken AUV

hardware necessary for acoustic pinger tracking. Adding increasingly more functionality to our secondary vehicle allows for two important strategic contributions. First, in future competitions we will be able to complete more tasks in parallel, which optimizes the number of tasks that can be completed within the given time and allows for more processing time for each task. Second, it allows for potential failure of one vehicle to be less detrimental as each vehicle should be able to complete most of the other vehicle's tasks should the other vehicle fail.

Completion of tasks in parallel depends greatly on the ability for coordination to exist in real time between the two vehicles. Because of this, inter-sub communication has been a feature on which we have prioritized improvement. Communicating location and task progress between the vehicles is essential for successful parallelization of tasks, which has been our overarching goal when planning competition strategy. This past year, we have made great strides in our goal of fully fledged real-time communication between the vehicles via acoustic sensing.

Although there is no physical competition this year, our current vehicles are built to implement a task-splitting strategy, which we hope to also execute in the next opportunity for an in-person RoboSub competition. Both Kraken and Leviathan are able to use image recognition and precise movement to complete first the Choose Your Side (Gate) and Make the Grade (Buoys) tasks. The two most computation intensive and time consuming tasks, Collecting (Bins) and Survive the Shootout (Torpedoes) can be divided between the two vehicles, with Kraken attempting Collecting and Leviathan attempting Survive the Shootout simultaneously. Because both vehicles are equipped for pinger tracking, whichever vehicle finishes first can attempt Cash or Smash (Octagon). If both vehicles are able to finish tasks at similar times, one vehicle will remain stationary while the other attempts to surface in the octagon in order to avoid collision due to simultaneous movement of the vehicles.

II. Design Creativity

A. *Mechanical*

Given our team's goal of inter-vehicle communication, this past year the mechanical team designed and manufactured an enclosure that holds a PCB which controls a piezoelectric crystal. The piezoelectric crystal essentially acts as an acoustic pinger and thus can send signals that our hydrophones system can detect and process. This will allow for inter-vehicle communication during the competition as one vehicle can send acoustic signals which the other's hydrophones can receive and process. While the team has talked about this goal for as long as we have had two vehicles, this is the first year that we have a completed and validated enclosure for this purpose. Figure 3 shows the PCB designed by the electrical team on the left and a cross-section view of the cylindrical enclosure that the PCB is mounted in. The port coming out the top of the enclosure is a SEACON electrical connector and the port on the bottom is a BlueRobotics penetrator which allows wires connected to the piezoelectric crystal in the water to reach the PCB inside the enclosure.

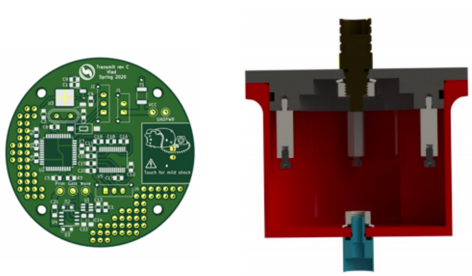

Fig. 3. Transmit PCB & Cross Section View of Transmit Enclosure

One of our other competition strategies described in the above section was to add functionality to our secondary vehicle to make it more capable to complete more difficult tasks. To aid in achieving this goal, the frame of our 2021 competition vehicle Leviathan (shown in Figure 4) encloses the thrusters. and has many extra mounting holes. Because the thrusters are within the frame, the overall structure is larger than any secondary vehicle's frame in the past as well as the current main vehicle's frame. This has allowed us to take a more modular approach to vehicle design, as enclosures can be added or removed much more easily than in our previous very compact designs. Therefore, our team can add more enclosures as we manufacture them without planning out the exact space that the enclosure will occupy on the vehicle.

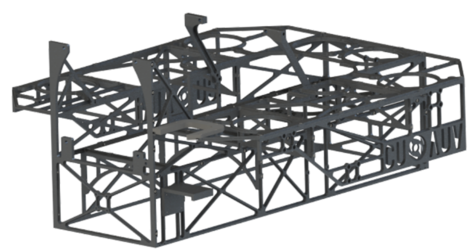

Fig. 4. Render of the Kraken Frame

There are two other advantages that we have seen to this new frame design approach. First, moving enclosures around easily allows for easier correction of the vehicle's static pitch and roll using enclosures vice our typical method of foam and weights. Second, because we have changed our competition strategy to the biennial design cycle, it will be much easier to design mounting solutions for updated enclosures or sensors that we would like to include on Leviathan for the 2022 competition than it has been on Kraken (which was previously known as Odysseus and was used in the 2019 competition). One draw-back of the large frame design, however, is that the vehicle is much more unwieldy and awkward to carry. This may seem like an insignificant issue, however we typically are very thoughtful about ergonomics when designing the vehicles' frames because of the many times members of the team have to carry the vehicles as well as deploy and recover them from the pool. Future iterations of the frame will attempt to combine what we learned regarding the convenience of modularity and the importance of ergonomics.

Additionally, the mechanical sub-team has taken a different approach to the manipulator design this year than in previous years. In the past, our team designed a manipulator during the same design cycle as the rest of the vehicle assuming that the object would be PVC tubing. After the 2018 competition with golf balls, we were unsure what the manipulation object would be so we re-designed a golf ball manipulator for the 2019 competition which ended up using PVC pipe. Therefore, for the 2021 competition vehicles, a manipulator deployment system (shown in Figure 5) was designed during the same design cycle as the rest of the vehicle instead of the entire arm or grabbing mechanism. The goal of the manipulator deployment system is to extend linkages as far as possible using only two pistons. These linkages have mounting holes at the end for easy integration of a grabbing mechanism that could be designed after the rules are released and the manipulation object is known.

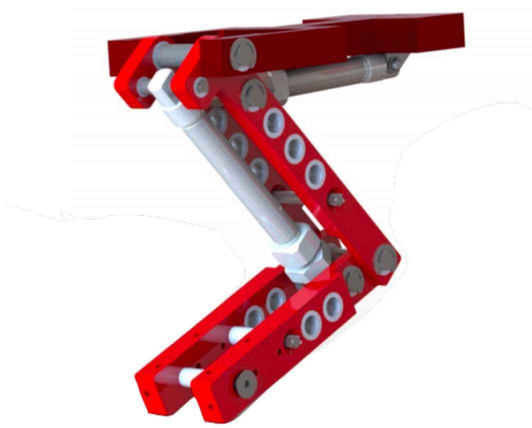

Fig. 5. Manipulator Deployment System for 2021

B. Electrical

With each re-design of a vehicle, our team also designs, manufactures, and tests the custom PCBs that comprise the vehicle's electrical system, improving upon the previous year's designs and working to fit the mechanical constraints of the new vehicle. One of the more novel aspects of our overall electrical system design is the modular multi-board design that we implement. Because we greatly value an electrical system designed for unit testing at any stage of the design cycle and swappable components, an overall modular architecture is something we retained from previous years when designing the new electrical system used in Leviathan.

In particular, we have carried over the use of two interconnecting backplane PCBs, while re-designing the boards themselves. One large PCB contains connectors to individual boards that handle power distribution, thruster control, sensing, actuation, and communication with the main vehicle processor. This board handles the routing of all power traces as well as receive and transmit traces necessary for the RS-232 communication that each board implements. This design is immensely important for both incremental testing during build-up of the vehicle and continued software testing throughout the year. Because individual boards are able to be connected and disconnected to the rest of the electrical system, hardware issues occurring on one board are able to be quickly resolved by swapping the board for a replacement while the original board is debugged, and the regular flow of software testing is able to be resumed quickly with a functional vehicle.

This year, because each of the two vehicles are designed in an offset timeline, the individual PCBs in each vehicle's electrical system are not identical to one another. While this introduces more complexity, as the team this year has needed to engage in simultaneous debugging of one existing electrical system and a re-design of the other vehicle's electrical system, it has not eliminated the benefit of having removable boards. Although each vehicle has different PCBs, the team has developed and tested multiple copies of each circuit board for both vehicles. This allows for quick recovery from hardware issues during testing, and even handling of the extreme case of every board in the electrical system failing.

One addition to the vehicle's existing power management system that the team has worked on developing this year is a battery management board that could be implemented within each of the modular battery pods themselves. While this has board has not been included in Leviathan's design, it has been designed and is planned on being integrated into the net vehicle design iteration. The board is designed to not only provide information about current drawn from the vehicle's batteries directly to the vehicle's processor when the pod is in use, but also to facilitate charging and discharging of the batteries themselves.

This year, extensive testing has been done to determine whether the addition of a fourth hydrophones element to the vehicle's existing acoustic tracking system would increase the accuracy of the vehicle's pinger tracking. Currently the vehicle is equipped with an external isolating enclosure that houses the three acoustic sensing elements and the custom PCB and development board used for signal processing and data communication. This year the necessary firmware has been developed to accommodate the addition of a fourth hydrophones element perpendicular to the existing three elements, for determination of the azimuthal angle with respect to the acoustic signal. Through many iterations of acoustic tracking testing with the vehicle, it was determined that such an addition to the system could allow for more accurate determination of signal location when the vehicle is located above the signal source. In addition to the necessary firmware development, updates to the mechanical enclosure were also made to support this change.

In addition, this year major work has been done to further develop the system implemented for acoustic communication between vehicles. Since the previous year, a mechanical enclosure has been developed and a transducer modified and integrated with it designed specifically for acoustic communication between vehicles and under signal transmission and waterproofing constraints. Extensive work has also been done to develop and test the signal processing algorithm implemented for this system. The algorithm that has been tested with our current vehicles allows for acoustic communication in the frequency range of around 50kHz, to be distinguishable from pinger tracking necessary for the competition tasks.

C. Software

The team has made several new improvements and additions to software projects implemented for Kraken and Leviathan.

One exciting project that has been developed this year is infrastructure to better facilitate manual image tagging by team members. This new infrastructure would allow us to better take advantage of the past vision data collected. One of the major obstacles to creating an effective vision system, is that the characteristics of images captured underwater at the TRANSDEC facility are very different from those captured at our university pool at which we test, due to everything from lighting to water opacity. This newly developed infrastructure makes it possible for efficient tagging of a large quantity of pre-existing data for use in training our machine learning models to create models equipped to handle images with characteristics similar to those encountered during the competition.

Over the past year, many improvements have been made to the visualizer developed and utilized for intermediate testing of mission modules. Because of the setup overhead associated with in-water testing of software updates with our vehicles, in it inefficient to carry out in-water testing frequent enough to keep up with software updates. As such, an effective simulator is extremely necessary for testing updates to mission modules for rapid development of our software stack. The necessity of an effective simulator has also increased during the past year with the COVID-19 pandemic posing increased barriers to in-person testing. Because of this, this year the team has worked to further improve the existing simulator to incorporate more realistic graphics and physical environment characteristics, and improve networking with the existing software stack.

III. Experimental Results

There were four intermediary integration stages that our team planned to meet in order to validate vehicle functionality and performance. These four stages are a design validation review, out of water integration testing, in water testing, and finally, testing vehicle performance on competition tasks.

A. Design Validation

The design validation checks and reviews for Kraken and Leviathan were completed during the

2019-2020 school year prior to the pandemic, but it is worth mentioning our process because it was an integral part in ensuring that system integration went smoothly during this past academic year.

Members of the mechanical, electrical, and software teams went through a set of rigorous design reviews to check whether their constraints and objectives were met or not. Each member of the team has their own project, so it is important that the team as a whole is aware of each person's project as well as how it will interface with other projects. Mechanical members present their ideas, CAD models, and FEA simulation results at a series of four design reviews to the sub-team. Members of the electrical team presented and got feedback at two design reviews, the first to review the project's schematic and the second for their PCB layout. The software team had roughly two design reviews for each project to first ensure that the theory behind their projects were sound and second to test that their code worked in the CUAUV Visualizer.

Based on previous years, we knew that it would take an entire semester to design and model a vehicle that would meet our constraints and objectives. We designed this vehicle in the Fall 2019 semester.

B. *Out of Water Integration*

The second stage of testing was ensuring that the vehicle behaved as expected out of the water. We set a deadline for when all electrical, mechanical, and software mission-critical projects were to be manufactured, integrated and independently tested in our lab space. More specifically, at this point all of mechanical components had been fastened together leak tested in the pool for approximately 8 hours, the electrical system was connected, powered, and all communication channels were receiving data, and the software to perform basic functions like spinning thrusters, reading sensor data, and viewing camera images was working.

Because of the COVID-19 pandemic, meeting this goal was the most challenging. We spent a large majority of the school year adjusting to an almost entirely virtual team format with very limited access to our lab space. We took advantage of the time we did have in person to work and aimed to meet the out of water integration goal by late February/ early March to ensure that we would have ample time to test and debug the vehicles when they were put in the water. At this point, we also did not know whether the competition would be online or in person, so we wanted to plan to be ready to practice competition tasks before the end of the school year.

In a typical year, our team would be able to complete this task over roughly three weekends with essentially every member of the team in our lab space helping. We were only permitted to have 3 or 4 members in lab this year at a time, however, and only for a few hours at a time. This made it difficult to estimate the amount of time it would require to complete full vehicle integration. We originally estimated that it would take half of a semester, however there were more restrictions placed on lab access as the number of people at Cornell with COVID-19 increased. In the end, it took roughly one semester to finish integrating and testing the vehicle out of the water. We made a final push to get everything done by early March, which was our worst-case scenario goal.

C. *In Water Testing*

After the vehicle performed as expected out of the water, we were able to test its functionality in the water. Not only did this test whether the vehicle would leak or not, but it also allowed the software team to tune the vehicle controller, the mechanical team to add foam and weights to trim the vehicle, and the electrical team to validate pressure and depth sensor readings. We were also able to confirm that the thrusters could move the vehicle through the water and the cameras were able to collect sufficent images.

This stage took multiple trials in the pool to fully validate all sensors and software against requirements. We took the time to ensure that the vehicle was fully validated because at this point we knew that the competition would be fully online, so we did not need to rush to start practicing the competition tasks.

D. *Performance Testing*

There are currently a few members of our team at Cornell that are beginning to test more experimental software and electrical projects over the summer of 2021. Our team decided that because of the mostly remote nature of the past year, the focus of a lot of the members of our team could be shifted toward designing experimental projects or making existing infrastructure more robust. This included exploring machine learning strategies to complete previous years' competition tasks, improving the simultaneous localization and mapping (SLAM) that the secondary vehicle currently uses, and making our battery management system more robust.

In a typical year, our team would devote the entire summer to preparing for the competition and practicing the specific tasks. Without the in person portion of the competition this year, we are able to improve our vehicles in ways that will hopefully benefit the team in the long run.

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We would also like to thank all of our corporate sponsors, without whom we would not be able to compete:
Platinum Sponsors: Cornell University; Monster Tool Company; Teledyne RD Instruments; SolidWorks; Mathworks; Datron Dynamics, and SEACON.
Gold Sponsors: Tektronix; LORD Microstrain; Connect Tech Inc; Adlink Technology Inc.; and Phillips 99
Silver Sponsors: Polymer Plastics; IDS; Surface Finish Technologies;

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[1] B. Benson, "Design of a Low-cost Underwater Acoustic Modem for Short-Range Sensor Networks," Ph.D. thesis, Jacobs School of Eng., Univ. of California, San Diego, 2010.

APPENDIX A
COMPONENT SPECIFICATIONS

Component	**Vendor**	**Model/Type**	**Specs**	**Cost (if new)**	**Status**
Buoyancy Control	Home Depot	Owens Corning Foamular 250	Pink insulating foam	N/A	Installed
Frame	Shaw-Almex Industries	Custom aluminum waterjet	Custom	Sponsored	Installed
Waterproof Housing	In-house manufactured	Custom CNC enclosured	Custom	N/A	Installed
Waterproof Connectors	SEACON	Hummer and WET-CON	Dry and wet connectors	N/A	Installed
Thrusters	Blue robotics	T200	Brushless thruster	N/A	Installed
Motor Control	Blue Robotics	Basic ESC	Speed control	$400	Installed
High Level Control	CUAUV	N/A	N/A	N/A	Installed
Actuators	Clippard	UDR-09-02	Pneumatic piston	$80	Installed
Propellers	N/A	N/A	N/A	N/A	N/A
Battery	HobbyKing	Turnigy 10000mAh 4S 15C LiPo	LiPo battery	$300	Installed
Converter	CUlinc	PDQ30-D	Iso 5V DCDC	N/A	Installed
Regulator	Texas Instruments	LM3940	3.3V SOT-223-4 LDO	$21.65	Installed
CPU	NVIDIA	Jetson TX2	Six 2Ghz ARM8 Cores	Sponsored	Installed
Internal Comm Network	N/A	N/A	N/A	N/A	N/A
External Comm Interface	SEACON	Hummer and WET-CON	Dry and wet connectors	N/A	Installed
Compass	N/A	N/A	N/A	N/A	N/A
Inertial Measurement Unit	Microstrain	3DM-GX4 and 3DM-G5	AHRS	Sponsored	N/A
Doppler Velocity Log	Teledyne Marine	Pathfinder DVL	DVL	N/A	Installed
Vision	IDS	UI-6230 and UI-5140	Cameras	Sponsored	Installed
Acoustics	Teledyne Marine	RESON	Acoustic transducers	N/A	N/A
Manipulator	N/A	N/A	N/A	N/A	N/A
Algorithms: vision	OpenCV	OpenCV	computer vision library	N/A	N/A
Algorithms: acoustics	CUAUV	N/A	DSP	N/A	N/A
Algorithms: autonomy	CUAUV		Mission planning system	N/A	N/A
Open source software	CUAUV	N/A	N/A	N/A	N/A
Team Size	46				
Expertise ratio	$\sim$2.5:1		HW:SW expertise ratio		
Testing time: simulation	15 hrs				
Testing time: in-water	100 hrs				
Inter-vehicle comms	Teledyne + CUAUV	N/A	Hydrophones + Transducer	N/A	N/A
Programming Languages	Python, C, C++				