Cornell University Autonomous Underwater Vehicle: Design, Strategy, and Implementation of the Castor and Pollux AUVs

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***Abstract*—Castor and Pollux are Cornell University's 2018 autonomous underwater vehicles (AUVs) for the AUVSI RoboSub competition. For the team's 19th season competing in the competition, we have once again revolutionized the way we build AUVs. Both vehicles were designed, manufactured, and tested from the ground up in ten months. Castor and Pollux have been designed with innovation and reliability as the priorities. CUAUV once again strives to reimagine what AUVs can do.**

I. Competition Strategy

CORNELL University's Autonomous Underwater Vehicle (AUV) team has a tradition of pushing the boundaries of AUV technology and breaking the rules to do remarkable things. Three years ago our vehicles Thor and Loki became the first vehicles to be entered into TRANSDEC in tandem, forever changing the way our team approached the RoboSub course. Prior to developing two vehicles every year, CUAUV strove to complete every task on the RoboSub course, but found that time was the biggest limiting factor in achieving this goal. With two vehicles, our team is able to split up the tasks to successfully tackle every mission. Last year at competition we successfully launched another two vehicles, Artemis and Apollo, in TRANSDEC at the same time, moving closer towards our goal of completing all mission tasks. This year, we have built two completely new vehicles from the ground up, Castor and Pollux, to complete all the challenges RoboSub has to offer.

The largest decision CUAUV makes every year is whether or not to continue developing completely new vehicles. Each year the team builds two highly complex systems and we spend a majority of the year designing, manufacturing, and testing each vehicle before even hitting the water in April. Our team could easily reuse the same vehicles for more than one year, thus being able to increase our testing time by eight months. Without needing to spend the Fall designing, Winter manufacturing, and Spring debugging, we would be able to get right back into the water with no downtime from the pool. However, the utmost priority of the team is learning, and rebuilding the vehicles every year maximizes this opportunity. By developing new vehicles each year, every team member is able to work on a mission critical project and learn about the vehicle development cycle. An additional reason we redesign the vehicles every year is so returning members can learn from their mistakes and improve the new subs. Having gone through the vehicle design cycle up to three times previously, seniors on the team are given the opportunity to try "experimental" projects on the subs that have never been attempted before, such as vectored thrusters, active ballast, and inter-vehicle communication. Building upon their extensive experience, many of these projects enable the team to push the limits of underwater technology.

Unlike previous years where our two vehicles were designed with the goal of each being able to accomplish all mission tasks, this year we designed the two vehicles with specific tasks in mind. Castor was designed with the intent of completing the more challenging manipulation tasks such as Cash In, Play Roulette, and Play Slots. Pollux is aimed to complete the less manipulation reliant tasks including Shoot Craps, and Path. The decision to design vehicles specialized for tasks stems from the rigors of making two vehicles and limited testing time with each vehicle. In order to balance the available time with each vehicle, we approached the design and development of Castor and Pollux as a cohesive system that works together to accomplish the same goal. Together Castor and Pollux are expected to successfully achieve all the tasks in RoboSub.

After careful point analysis of the tasks, the proposed competition strategy for Castor is to firstly complete Find Casino and Enter the Casino on the red side. Castor will then follow the first path and go straight to following the second path to find Play Slots. Castor will not immediately Play Slots but will remember the location of the task for later. Castor will then start tracking the random pinger to either Cash In or Roulette. At Roulette, the vehicle will buy a gold chip from the dispenser and drop the gold chip into the green section of the table. Castor will then track the pinger to Cash In. At Cash In, Castor will attempt to pick up the red balls in the red bin and then proceed to pick up the balls in the green bin with its second manipulator. Castor will then go to Buy Chip to collect a yellow ball. Having picked up a gold chip and at least two red and green balls each, the sub will surface in the square while holding the recovered objects. After surfacing, Castor will find and drop the red balls in the red bin below the water. Castor will repeat this process with the green balls and attempt to place them into the yellow funnel below the water. Lastly, there will be two pre-loaded blue chips that Castor will place into the above water yellow funnel. The decision to use the blue golf balls for Cash In instead of Roulette comes from a balance between attempting every task and utilizing simple and robust manipulators. The order of playing Roulette or Cash In first will differ based on the random pinger, but Castor's strategy at each does not change. After completing Roulette and Cash In, if there is sufficient time left, Castor will return to its previous location in order to find Play Slots. Castor will first pull the arm to play the game and then attempt to fire two torpedoes through the yellow slot.

While Castor is completing its run of the course, Pollux will be attempting a different set of tasks. Pollux will be deployed after Castor has successfully completed Enter the Casino. Pollux will follow Castor's lead and Find the Casino and then Enter the Casino in the red side of the gate. From there, Pollux will start to follow the first path and begin its way to Shoot Craps. At Shoot Craps, Pollux will locate and touch the Six dice and then the Five dice, adding to eleven. Pollux will then follow the second path to Play Slots.

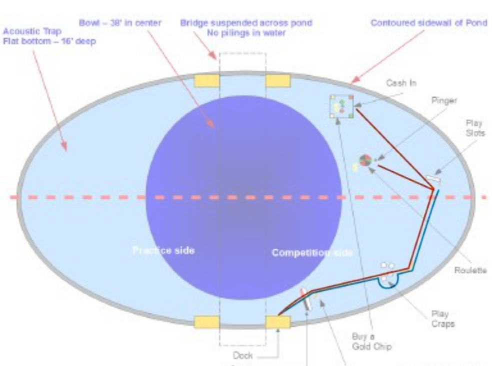

Fig. 1: The course plan for both Castor (in red) and Pollux (in blue). Castor's main goals are completing the random pinger, Cash In, and Roulette. Pollux will aim to accomplish Path and Shoot Craps.

The strategy for Pollux to attempt fewer tasks than Castor is mainly based on CUAUV's past experience deploying two vehicles at competition. The primary sub is always sent out to the course first in order to maximize the available time to complete the more challenging tasks. As a precaution, the secondary sub is held back from starting its course run until the main vehicle has successfully started tracking the pinger. This is done for two main reasons: minimizing reset time and eliminating any vehicle collision. In the event that Castor does not successfully track the random pinger, Castor needs to be killed and brought back to the dock for a second mission run attempt. By waiting for tracking confirmation before launching Pollux, we eliminate the additional time that would be required to pull back two vehicles as opposed to one. Secondly, by waiting for Castor to head towards either Roulette or Cash In first, we can guarantee that there will be no collisions in the gate or path area between the vehicles. Our team is actively working towards achieving inter-vehicle communication, and until this is possible, we exercise precautions for the vehicles to not interfere with each other.

II. Design Creativity

Castor and Pollux are the result of 19 years of developing AUVs at Cornell University. These two vehicles have more capabilities than any other vehicle in very compact form factors. There have been numerous design changes and innovations this year on both vehicles. This was CUAUV's first year with a new design approach to both the vehicles that stemmed from a desire to balance potential for competition performance as well as maximize the learning opportunities for every member on the team. The primary vehicle, Castor, was designed with conservative innovation in mind. As a result Castor builds upon what the team has learned from building its predecessors while still making strides in both mechanical and electrical design. The secondary vehicle, Pollux, was designed with the goal of revolutionizing our AUVs for the future. Approaching Pollux in such a unique and different perspective resulted in a vehicle that is significantly different than any other AUV that Cornell University, or any RoboSub team, has ever made.

A. *Mechanical*

Prior to CUAUV entering two vehicles in RoboSub, every mechanical part was redesigned and remade every year. This year with two vehicles in development, more parts have been reused for a second year than we have ever recycled before. The overall team size has not changed since doubling the number of subs and there is a limited number of work hours available to the team to design and fabricate new parts every year. Due to this limitation, the decision to reuse major parts, such as the main hull midcap and the hydrophones enclosure, has greatly driven the overall design of the vehicle. The reuse of time intensive parts was a decision that was foreseen last year during the design cycle when the team decided to continue developing two vehicles. This can be seen in both Castor and Pollux's hulls with the interchangeable SEACON underwater connection panels. It is significantly easier to machine new SEACON panels every year than to design and manufacture a new hull. The ability to develop completely new mechanical systems for the vehicles every year allow the team to continuously learn and push the design and innovation of our AUVs. Despite some of the major projects being on a two year cycle, over 88% of Castor and 98% of Pollux are completely new for the 2018 competition season.

The most notable change in the mechanical system this year is the compact size of Castor. This was made possible by implementing a new *Teledyne* Pathfinder Doppler Velocity Log (DVL). With the new Pathfinder DVL, Castor has a significantly smaller footprint - over $\frac{1}{3}$ smaller than that of last year. The new DVL has allowed us to almost entirely eliminate the need for a secondary electronics rack, enabling us to eliminate numerous external enclosures by integrating them into the new space in the main hull. With the significantly reduced size of the fore hull, the team made the change from using epoxied acrylic tubes, that we have been using for over ten years, to a machined aluminum hull. This new forehull design allows for a much larger heat sink and direct thermal path from the hot components of the computer to the surrounding water.

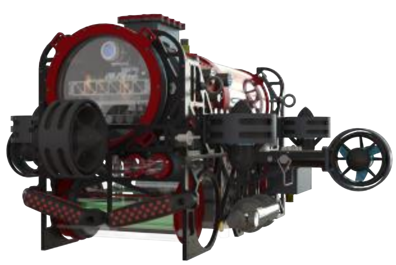

Fig. 2: Castor featuring a transparent fore hull and the collision mitigation shrouds surrounding the thrusters. This vehicle is significantly smaller than any full featured vehicle CUAUV has made.

The manipulators on the vehicles are specially designed to maximize reliability in picking up golf balls. An initial design of the manipulators was highly complex but had the capability of both picking up the golf balls from the bins in Cash In as well as moving them within the vehicle to place them into the above surface funnels. However, with the large number of moving parts in these initial designs, it was decided that having multiple simple manipulators was more reliable and time efficient than having one complicated manipulator. The main goal of the final manipulator design was being able to use the same mechanism to both pick up and release the balls, thus simplifying the design significantly. The manipulators were inspired by tennis ball pickup machines, utilizing a mesh bungee system to pick up and hold the golf balls. This mesh allows Castor to pick up multiple balls at the same time and decreases the precision needed to accurately pick up at least two balls from each Cash In bin. A linear piston is used to push the balls back through the mesh for release. The vehicle is designed to have four of these manipulators, two larger downward facing ones designated for picking up from the Cash In bins, one smaller downward facing manipulator for picking up the yellow golf ball at the Buy Chip dispenser, and one smaller forward facing manipulator for depositing golf balls inside the surface funnels.

Fig. 3: Pollux's biggest design innovation is the unibody aluminum hull. The secondary vehicle features an identical electrical system to the main sub in a much smaller form factor.

The Pollux main hull is vastly different than any of CUAUV's past 18 vehicles. Its revolutionary design was made possible by a new Computer Numeric Control (CNC) machine in Cornell University's Emerson Learning Machine Shop. The new CNC provided CUAUV with a higher degree of control and accuracy in manufacturing parts than was possible in previous years. Pollux's hull was machined from a single piece of aluminum, making it more durable and reliable underwater with less sealing surfaces. Compared to Castor's circular cross-section that is not space efficient for rectangular Printed Circuit Boards (PCBs), Pollux features a rectangular hull that utilizes the available space for electronics much more effectively, thus being able to house an identical electrical system in a hull that is almost 40% smaller. This space efficiency is greatly noticed in the control of the vehicle, eliminating the positive buoyancy problems encountered with the last two mini-subs. This hull also provides the same thermal advantages of the Castor forehull.

Both Castor and Pollux feature eight *Blue Robotics* T200 thrusters for maneuverability underwater. However, these thrusters are often the unfortunate first point of collision. Last year during CUAUV's RoboSub semi-finals run Artemis had an unfortunate encounter with the side of TRANSDEC which broke one of our thrusters. This incident was just one of numerous thruster casualties and this year both vehicles feature a new collision mitigation system for all our thrusters. Each thruster now features a simple yet highly effective shroud that absorbs all the impact in the event of a collision. The shroud design underwent significant Finite Element Analysis (FEA) in order to generate the most lightweight part while not interfering with water flow and providing no force transmission to the delicate thrusters during impact. Over fifteen simulations were run on these parts including cyclic loading tests, fatigue analysis, and frequency resonance simulations. These simple shrouds are the result of four months of rigorous FEA and over two months of CNC machining.

B. *Electrical*

Castor and Pollux feature identical electrical systems with interchangeable custom PCBs. Every board on both subs were designed, populated, and tested by electrical members on the team. The decision to use custom boards for the entire electronics system allows the electrical team to learn about designing a full system architecture, which is the priority of CUAUV. The identical electrical systems make designing and testing easier due to only needing to debug a single system for both vehicles. This structure also has the added benefit of facilitating debugging by providing a means of isolating a known problem in one vehicle by systematically interchanging components from the other vehicle. Additionally, every PCB now has a smaller footprint than any previous version, with sensor board being just over 2" in height and width.

One of the biggest things that sets CUAUV's electrical system apart from other AUV electrical systems is the multiple backplanes that allow for increased system integration and plug-and-play capabilities of all the PCBs. This allows for easy maintenance and quick access to the individual boards. To further ease in debugging the boards, each board now features more test points and indicator LEDs than before. These allow the boards to be quickly debugged without even having to remove the board from the vehicle.

The hydrophones system has been completely redesigned to feature both analog circuitry and a new Field-Programmable Gate Array (FPGA) for on-board signal processing. The acoustic system on our vehicles has always been one of the biggest challenges our electrical team faces. By not using an off-the-shelf developer kit, our team has been continuously building upon our tracking system to be more reliable and robust to noise. The biggest advancement this year is the board's capability to not only receive signals but also have transmit functionality. This takes the team closer to the goal of establishing underwater inter-vehicle acoustic communication.

Fig. 4: Rendering of the new hydrophones board. The FPGA for on-board signal processing can be seen in the middle of the board. The circuitry for transmitting in order to establish future inter-vehicle communication can be seen in the bottom left.

In an effort to facilitate debugging of the custom boards and learn more about how our boards work, a completely new test board was designed this year. This board is an off-vehicle stand alone board that allows other boards to be plugged in and individual functionalities to be tested. Some of the features of test board include examining the output voltage and current through boards, active monitoring in power channels, and sending and receiving packets through serial and CAN bus. These off-board quick debugging features eliminate numerous hours isolating issues on the vehicle.

C. *Software*

Numerous software developments were made on CUAUV for Castor and Pollux. One of these changes was the decision to change the main vehicle computers from an *Intel* Core i7 based high performance CPU to an *NVIDIA* Jetson which features a power and heat efficient GPU. In past years the CPUs were often maxed out due to the demands of the vehicle's software and the Jetson's GPU provides an elegant solution to our heavily linear algebra based computational needs. The Jetson allows for much faster and more efficient vision processing. The team has spent over eight months integrating the new computer to work with our custom software stack and migrating the control and vision subsystems to run on the Jetson GPU.

Another large architectural change our software system adopted this year was the integration of the Docker containerization. Docker containers allow for uniformity in computer systems as well as easy deployment of our software to both Castor and Pollux and development computers. With a team of software developers using personal devices, build servers, and multiple vehicles, dependency management and environment consistency is a problem that we have faced the past years. Integrating Docker into our software system, makes it easier for both new and returning members to contribute to the ongoing software development, and ensures all code will run the same everywhere regardless of physical machine.

CUAUV's vision system is more advanced than ever before. This year we have employed Machine Learning (ML) for object detection and classification. For many years, we have recorded logs of camera video and all inter-process communication during testing and competition runs. This set of logs form an extensive data set of images for training, testing, and verifying our ML algorithms for automatically labeling and classifying objects. This advancement in our software system makes our vision much more reliable in correctly detecting and classifying mission elements while requiring significantly less developer hours.

As autonomy of CUAUV's vehicles advances through the years, we continually strive to further the autonomous capabilities of the vehicles. This year we have implemented a functional version of Simultaneous Localization And Mapping (SLAM) in order to dynamically map the vehicles environment. This is especially useful for Pollux which does not have a DVL to provide positional information. SLAM is expected to be used on both vehicles on the RoboSub course in order to better navigate TRANSDEC and complete mission tasks efficiently.

III. Experimental Results

Castor and Pollux began their design phase in late Summer of 2017 and underwent over four months of mechanical and electrical design. The mechanical team largely employed *ANSYS* and *Solidworks Sim* to conduct rigorous FEA. The electrical team spent the Fall going over every new board design in design reviews and developing the new hydrophones system. In the Winter, both our mechanical and electrical teams spent five months manufacturing and populating the new parts for Castor and Pollux. Integration in the Spring was when all the work from the mechanical, electrical, and software teams came together to create two completely new autonomous vehicles. This was the first time in four years that the team was able to get the main vehicle in water on our targeted date. Since mid-Spring Castor has logged over 120 hours at the pool.

Since the end of the school year, CUAUV has spent every day at the pool writing and testing missions in preparation for RoboSub. All missions successfully run in the CUAUV simulator and pool time is now spent translating the missions to work on both Castor and Pollux with the real mission elements. Until RoboSub, CUAUV plans to continue testing our vehicles in the pool every day. This time in the pool will be spent perfecting the missions each vehicle is tasked to do and making each task robust to environmental changes. The manipulator design is also undergoing continuous fine tuning and revisions in order to produce the most reliable golf ball manipulation mechanism. Out of pool time will also be spent continuing to merge our software system to run seamlessly on the Jetson GPU.

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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; and SEACON.

Gold Sponsors: LORD Microstrain; Connect Tech Inc; Adlink Technology Inc.; and Shaw-Almex.

Silver Sponsors: IDS; Surface Finish Technologies; Phillips 99; and Empire Automation Systems.

Fig. 5: The 2017-2018 CUAUV team with this year's vehicles Castor and Pollux.

APPENDIX

A. Component Specifications

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control	Home Depot	Owens Corning Foamular 250	Pink insulating foam	n/a
Frame	Shaw-Almex Industries	Custom aluminum waterjet	Custom	Sponsored
Waterproof Housing	In-house manufactured	Custom CNC enclosure	Custom	n/a
Waterproof Connectors	SEACON	HUMMER and WET-CON	Dry and wet connectors	$1675.00
Thrusters	Blue Robotics	T200	Brushless thruster	$2311.92
Motor Control	Blue Robotics	Basic ESC	Speed control	$400.00
High Level Control	CUAUV	6-DOF Dual Quaternion and YPR	Linear Least Square PID	n/a
Actuators	Clippard	UDR-08-2	Pneumatic piston	$79.19
Propellers	n/a	n/a	n/a	n/a
Battery	HobbyKing	Multistar High Capacity 4S	LiPo battery	$165.90
Converter	CUIinc	PDQ30-D	Iso 5V DCDC	$34.94
Regulator	Texas Instruments	LM3940	3.3V 1A SOT-223-4 LDO	$1.65
CPU	NVIDIA	Jetson TX2	Six 2Ghz ARM8 Cores	Sponsored
Internal Comm Network				
External Comm Interface	SEACON	HUMMER and WET-CON	Dry and wet connectors	n/a
Programming Language 1	Python Software Foundation	Python 3	Duck typed	Free
Programming Language 2	WG21/FSF	C++/GCC4	Compiled	Free
Compass	LORD Microstrain	3DM-GX4 and 3DM-GX5	AHRS	Sponsored
Inertial Measurement Unit (IMU)	LORD Microstrain	3DM-GX4 and 3DM-GX5	AHRS	Sponsored
Doppler Velocity Log (DVL)	Teledyne Marine	Pathfinder DVL	DVL	$11995.00
Camera(s)	IDS	UI-6230SE and UI-5140CP	cameras	Sponsored
Hydrophones	Teledyne Marine	RESON	Acoustic transducers	n/a
Manipulator	In-house manufactured	3D printed	Golf ball manipulators	n/a
Algorithms: vision	OpenCV Team	OpenCV 3	Transparent GPU Support	Free
Algorithms: acoustics	Joseph Gaeddert	Liquid DSP		Free
Algorithms: localization & mapping	Mur-Artal	ORB-SLAM2	Simultaneous	Free
Algorithms: autonomy	CUAUV	Mission planning system	Cooperative multithreading	Free
Algorithms: software	CUAUV/FSF	Software built for Linux+GNU	Numerous AUVSI RoboSub First-Place Finishes	Free
Team size	45			
HW/SW expertise ratio	12:7			
Testing time: simulation	100			
Testing time: in-water	120			

B. Outreach Activities

CUAUV prides itself in our extensive community outreach program. All members of the team are enthusiastic about the vehicle that we build and the plethora of skills that we gain and are eager to share these with our community. Every year we partake in numerous outreach activities with a variety of audiences.

In the Fall, CUAUV shared our vehicles with the Cornell University community by tabling at Homecoming 2017. This event reached numerous notable Cornell alumni, including Bill Nye “The Science Guy”. We also participated in the Upson Hall Dedication event, showing Cornell Engineering benefactors the vehicles that were soon to be housed in the new building. CUAUV also partook in the Inauguration of Cornell University’s newest President, Martha Pollack. This included a community wide quad fair and a private presentation of the team to President Pollack and the Dean of Engineering, Lance Collins. CUAUV also helped with a high school engineering program at Cornell University, exposing students to engineering that otherwise would not have the opportunity.

CUAUV also ran numerous workshops and outreach events in the Spring. Every year we hold Boy Scouts and Girl Scouts workshops with local troops. During these workshops the scouts are able to get hands on with Arduinos and learn how to code. CUAUV also played host to 30 children on Take Your Child To Work Day. Parents and children learned about our vehicles and were able to get hands on with making their own structures out of spaghetti. Our new vehicles, Castor and Pollux, were presented at the Bits On Our Mind (BOOM) showcase, sharing our accomplishments with over 300 people. The RAW Expo was an event where members were able to share the more technical aspects of the vehicle, particularly the mishaps and lessons that we learned while creating Castor and Pollux. Lastly, in the Spring

CUAUV spent time with the Engineering Diversity and the Women in Engineering programs to share our love of engineering with newly admitted students to Cornell University.

In addition to the organized events, CUAUV is often the first point of contact for university faculty to reach out when in need of private tours, benefactor visits, or even a casual chat with a prospective student and family. Our outreach is a continuous effort that CUAUV is proud of. Many of our team members even chose to attend Cornell because of the kind and enthusiastic CUAUV members they talked to at one of our numerous outreach events. The breadth of our outreach is inspiring and continues to push us to continue innovating.