Cornell University Autonomous Underwater Vehicle: Design, Strategy, and Implementation of the Odysseus and Ajax AUVs

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***Abstract*—Odysseus and Ajax are Cornell University's vehicles for the AUVSI RoboSub 2019 competition. For the teams 19th year competing we have once again attempted to push the boundaries of AUV technology. Both Odysseus and Ajax have been designed, manufactured, and tested from the ground up, in just under ten months. For the first time in CUAUV's history both subs have been designed to be capable of completing nearly every task.**

I. Competition Strategy

Cornell University Autonomous Underwater Vehicle team (CUAUV) has a tradition of pushing the boundaries of AUV technology and breaking the rules to do remarkable things. Four 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. Last year we found that developing two vehicles designed around two tasks was effective, but ultimately not very robust and reliable. As such, this years vehicles Odysseus and Ajax have been redesigned from the ground up to be able to complete nearly every task. This presents us with a variety of options in choosing how to tackle the RoboSub course and allows us to adjust our strategy on the fly. With these two vehicles, CUAUV has the potential to complete all the challenges RoboSub has to offer.

Each year the team faces the decision of choosing whether or not to continue designing, fabricating, and testing two completely new vehicles. Choosing to re-use either one or both vehicles would save the team huge amounts of development time and money, and also give our software team the ability to develop missions on a stable system throughout the year. However, the top priority of CUAUV has always been learning. By rebuilding our vehicles each year, we are able to maximize how much our members are able to learn, and ensure that the knowledge we have acquired throughout the years continues to be passed on to our younger members. Additionally, rebuilding our vehicles each year gives our older members the opportunity to build upon their previous work and learn from any mistakes they made along the way. This often leads to major improvements in our core infrastructure which greatly helps to improve the reliability of our vehicles. Furthermore, senior members are able to take on more "experimental" projects which are what help CUAUV to push the boundaries of underwater technology.

As mentioned, last year the team developed Castor and Pollux around individual tasks. It was decided that Castor would handle all tasks requiring any sort of manipulation, while Pollux would handle the mechanically simpler tasks such as buoys and pipe. From a complexity standpoint this approach made a lot of sense. By only having one vehicle with a pneumatic system, we could focus on our designs for this vehicle and ensure a relatively robust actuating system. However, in terms of robustness, this was not the best approach. This was due to the fact that if Castor suffered from a serious failure, we lost the ability to gain a majority of the points the competition has to offer. As such, this year we chose to design both subs to have a pneumatic system. However, while Odysseus will have the full pneumatic system, Ajax will have a simpler version that only supports torpedoes and droppers. By approaching our designs in this way we can still maintain a lower level of complexity for Ajax while greatly increasing the reliability of our vehicles by giving Ajax the ability to perform every task outside of Expose to Sunlight. In this case if either vehicle fails, the other should be able to perform most/all of the tasks on its own. Additionally, we have increased the reliability of the pneumatic systems themselves by adding a series of different valves. These valves prevent flooding of our air tanks and valve enclosures which has caused failures in the past.

While Odysseus and Ajax are both designed to be able to complete a majority of the course on their own, we intend to have them both complete their own designated tasks so that they work as one cohesive unit. To ensure optimal timing in completing the tasks, our strategy for this competition is as follows. As Ajax does not feature a downward manipulator capable of picking up objects, Odysseus will start its run first, followed by Ajax.

Odysseus will first pass through the 40% side of the Enter the Undead Realm task. Once completed it will then proceed to pick up both the crucifix and the garlic outside of the gate. Once picked up it will then track paths and make its way to Drop Garlic. For the duration of Drop Garlic we intend to have Odysseus hold onto the crucifix and only use its other manipulator for handling the garlic. Having arrived at Drop Garlic it will then proceed to identify the image currently displayed. Once this has been completed it will then attempt to move the lever in order to uncover the other bin. Once Odysseus believes it has moved the lever it will attempt to find the other image. If it successfully can identify the image then it will proceed to drop the first garlic into the bin. Upon success it will then find and pick up the other garlic and then proceed to drop that garlic into the bin as well. Once drop garlic has been completed, Odysseus with then track a pinger to the Expose Sunlight task. At Expose Sunlight it will attempt to pick up the other crucifix and then proceed to drop both onto the coffins. Once this has been completed Odysseus will then open the closed coffin and proceed to pick up the dracula pvc structure. It will then proceed to pick up the other dracula and then surface in the octagon.

Once Odysseus has reached the second pipe location, then Ajax will begin to make its way through the 40% gate. After successfully making it through the gate, Ajax will then follow the first pipe to slay vampires. Ajax will first attempt to touch the Jiangshi bouy followed by the image of the Draugr on the three sided buoy. Once completed, Ajax will attempt to make its way to the Stake through Heart task. Once at this task Ajax will first fire a torpedo through the heart of the vampire. Following this it will then attempt to move the lever and then proceed to fire the second torpedo through the now open Oval.

II. Vehicle Design

Cornell University Autonomous Underwater Vehicle has been designing, manufacturing, and testing AUVs for close to 20 years. Odysseus and Ajax are the culmination of our extensive experience and are the most capable vehicles we have designed to date. This year we approached our design cycle for both vehicles with the intent to focus on reliability and capability, while taking a more conservative approach towards innovation. One of the common concepts for CUAUV since we started designing two vehicles back with Thor and Loki is the idea of a “primary” and “secondary” vehicle. Each year our “primary” vehicle was developed to have “full functionality,” allowing it to complete any of the tasks for that years competition, while our “secondary” vehicle was only designed to complete basic tasks. This year however, we have decided to move away from this concept. Instead, we have designed both vehicles to be able to complete a majority of the tasks. This approach has allowed us to greatly extend our potential competition strategies as well as created an additional layer of reliability in the event that one vehicle suddenly becomes unable to perform a task, or function at all. Both vehicles build upon what the team has learned from designing its predecessors while still making strides in electrical and mechanical design. Overall, Odysseus and Ajax are Cornell University’s most reliable and capable vehicles to date.

A. Mechanical

Each year CUAUV completely redesigns and fabricates all of the mechanical components for each AUV. This is an extremely time consuming task that the team spends hundreds of hours on. However, the team has not grown any larger since before we began developing two new vehicles each year. As such, the mechanical team has taken to reusing some of the more time consuming components from year to year. Such components include the midcap for Ajax, the thruster shrouds for each vehicle, and the hydrophones enclosure. The need to reuse these time intensive parts was foreseen after the development of last years vehicles and the decision to continue developing two vehicles was made for this year.

One of the novel aspects of our mechanical designs are the interchangeable SEACON panels attached to the midcap of both Odysseus and Ajax. As our electrical design changes from year to year the electrical connections required also vary. As such, the seacon connections required also change from year to year. As the SEACON panels are easy and quick to design and fabricate, the interchangeability of their design allows us to continue to make electrical and mechanical innovations without needing to replace the midcap. This allows us to push some of the more time- intensive components such as the midcap on a two year design cycle rather than a one year cycle. In spite of this, over 90% of Odysseus and 88% of Ajax are completely new for the 2019 RoboSub competition.

One of the most notable changes in the mechanical system for this year is the redesign of the frame for Ajax. Last year CUAUV created a new vehicle unlike anything we had built before, in the form of Pollux. Pollux’s square frame and hull designs were intended to allow us to maximize space efficiency while keeping the overall volume of the vehicle similar to that of its predecessors, Apollo and Loki. However, as this was the first time we had created a square design, we were unable to take full advantage of the design’s potential. Learning from last year's mistakes, the frame for Ajax was completely redesigned. The new frame features a smaller width profile compared to Pollux, while supporting more external enclosures than ever before. This has allowed us to move the Ajax hydrophones enclosure to a spot which will have much less vibration in the frame. Additionally, the new frame also is able to support an external valve enclosure for the pneumatic actuating system, something never before seen on CUAUV’s smaller vehicles. Having the pneumatic system will allow Ajax to perform tasks such as bins or torpedoes which has never been possible for its predecessors.

Fig. 1: Ajax's biggest design innovation is its innovative small yet functional frame. It features support for more external enclosures than ever before as well as dedicated room for trimming foam while having one of the smallest profiles to date. The electrical system is also almost identical to Odysseus.

Similarly to the frame, the internal design of Ajax has also been improved greatly compared to Pollux. One of the biggest changes for this year has been the redesign of the Ajax electrical racks. With last year being the first year of designing racks for a square hull, we were not able to take full advantage of the square design, which resulted in a cramped internal system. Additionally, last year we attempted to create a "lifting" racks system which would allow the electrical racks to be elevated out of Pollux for easier debugging. We chose to abandon this concept for this year as the wire length connecting the SEACON panels to our custom backplane boards, ultimately prevented the racks from lifting farther than 20% of their designed length. Instead we chose to opt for a more spacious design. Removing the lifting system allowed us to spread out the custom PCBs connected to the racks. This has ultimately allowed us to introduce a higher quality cooling solution in the form of additional fans and a proper channel for air flow as well as the additional room has allowed for easier access to the boards for debugging.

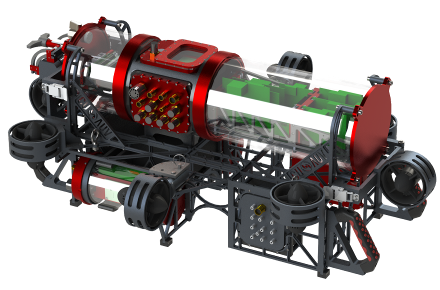

Fig. 2: Odysseus featuring newly redesigned midcap and frame. The acrylic window of the midcap allows for an LCD display used for debugging, while the newly redesigned frame has moved the external enclosures inwards, making it one of the smallest primary vehicles to date and removing a large portion of external cluster.

The manipulators for Odysseus this year are specifically designed to maximize reliability in picking up pvc structures. As last years design was meant specifically for picking up golf balls, we were forced to completely redesign our manipulators for this year. Ultimately, we wanted a design that would be able to both pick up and drop off structures. From last year we learned that a simple design tends to be the most reliable. As such, for this years design we chose to implement a simple scissor arm. The arm itself is driven and retracted by a single pneumatic piston. Extending the arm closes the claw and picks up the desired object, while retracting the arm opens the claw, allowing us to drop the object onto a target. For efficiency in completing tasks, two scissor arms will be mounted onto Odysseus, allowing us to pick up multiple objects at a time.

B. Electrical

Odysseus and Ajax feature almost completely identical electrical systems with interchangeable custom PCBs. Every custom PCB was designed, populated, and tested by members of CUAUV's electrical subteam. The team chooses to use custom circuitry rather than mostly off the shelf components in order to allow members to gain knowledge and experience in developing a full electrical system. This is important to CUAUV as learning is the team's primary goal. The two electrical systems are developed to be almost identical in order to make designing, testing, and maintaining the vehicles simpler. Having identical systems allows us to systematically swap boards between vehicles in the event of an issue, eventually allowing us to isolate the problem. Additionally, almost every custom PCB has seen a decrease in size, allowing for the introduction of new boards such as LED board. The LED board is a completely new custom PCB designed for this year's competition. The board controls a series of individually addressable LED strips. By communicating to the main sub computer through RS-232 communication, the board can display the current status of a vehicle during a mission run. This allows for real-time debugging of mission issues as the software team can be aware of exactly what the vehicle is doing at any given time.

One of the more novel aspects of CUAUV's electrical system design is the use of multiple backplane PCBs. Each vehicle has two backplanes, one which connects the custom PCBs, and a SEACON backplane, which connects the PCBs to the rest of the electrical system such as thrusters, the Jetson TX2 computer, and external sensors and devices. These backplanes increase system integration and allow for the plug-and-play capabilities of the other PCBs. This allows for changes to the system to be made quickly, as "extra" connectors allow for components to be integrated into the system that weren't originally intended. Furthermore, the backplanes help in debugging signal issues as they allow for simple and easy connectivity tests between PCBs and between PCBs and external devices. In the theme of designing for reliability, this year all of the custom PCBs feature duplicated signals on each side of their respective connectors.This ensures that signals will still be properly transmitted even in the event of connector damage. Furthermore, additional fuses have been added to the power paths of several boards in order to prevent damage to other components on those lines in the event of a major failure such as a short. This ensures that entire boards will not need to be replaced in the case of such an event.

One of the biggest challenges CUAUV has faced in terms of electrical design is our hydrophones system. As we chose not to use an off-the-shelf solution, our team has continued to build upon our tracking system to be more reliable and robust. A part of this is ensuring we do not have bad placement of the external enclosure, which can often result in unwanted noise from vibrations in the frame. In addition to focusing on better placement in our mechanical design, large strides have been made in our analog-design and digital signal processing for this year. A series of new filters and auto-gain features have been added which have proved to greatly increase reliability and remove false readings. Additionally, a large effort has gone into developing a transmit functionality for our hydrophones system. Fully fleshed out, the combination of being able to transmit and receive acoustic signals will allow our two vehicles to communicate under water.

In an effort to improve the reliability and capabilities of our electrical system, one of the main focuses for this year has been improving the firmware of some of our core

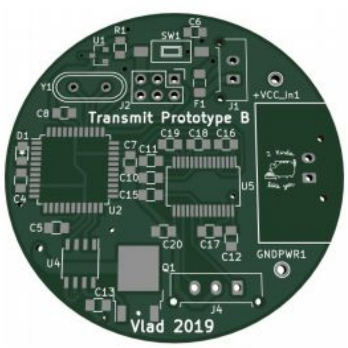

Fig. 3: Rendering of the new transmit board which will serve as part of the core for future inter-vehicle communications.

custom PCBs. Many of these improvements involve adding additional layers of over-current and under-voltage protection. In previous years, only simple fuses were really used as a means of preventing shorts. To improve upon this we added current-draw and voltage measurements to custom PCBs such as our power distribution board and our merge board. By then setting threshold levels in the firmware, each board is now capable of detecting shorts on the devices they supply power to, and subsequently disabling the device. This prevents damage to the shorted board and LED indicators allow us to see when such an issue arises. As merge board also supplies power to the DC-DC converters that feed into the power distribution board, this creates an additional layer of protection.

C. Software

Numerous software improvements were made this year for Odysseus and Ajax. Last year the team made the decision to switch from using an *Intel* Core i7-based CPU to an *NVIDIA* Jetson which featured a highly efficient GPU. This change allowed us to take advantage of GPU acceleration for our vision algorithms as well as our heavily linear algebra- based computational needs within the vehicle's controller. However, converting much of our code to make full use of the GPU was a much more daunting task than originally expected. As such, this past year we have been heavily focused on improving our usage of the Jetson's GPU, and have been able to see decent performance increases compared to the CPU used in the past. Auxiliary benefits we realized by switching our onboard computer to a Jetson are noticeably improved submarine battery life and in-hull thermals.

We have continued development on our STRIPS-like automated mission planner named Flamingo. Flamingo now features inequality-based pre-conditions for tasks and automatically detects mission failures and re-plans accordingly.

CUAUV's vision system is more advanced than ever before, with the newly developed vision framework and improved tooling within the vision subsystem. The vision framework provides convenient and well-documented routines for common tasks we perform in our vision modules. Additionally, the vision framework provides generic implementations of vision-related machine learning algorithms. For many years, we have recorded logs of camera footage 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 year, we have been developing a new network-accessed storage system for text and video logs and associated metadata which will be integrated into our CUAUV Automated Vision Evaluator (CAVE). This new storage system will allow us to easily discover and share datasets of mission element footage among developers. These advancements in our software system all work towards making our vision algorithms better able to correctly detect and classify mission elements.

A DVL or a doppler velocity log, is a sensor that CUAUV has historically used to determine our vehicles' positions and velocities underwater. However, our smaller vehicles ("mini-subs") Apollo, Pollux, and Ajax do not feature a DVL. As such, CUAUV has developed and continued to improve upon a version of Simultaneous Localization and Mapping (SLAM). SLAM was first fully implemented and used by CUAUV last year at the 2018 RoboSub competition. While extremely useful, it still had several faults, the most prominent of which was the lack of support for integrating into SLAM within our mission and vision systems. This year, we have developed a new SLAM visualizer to support debugging as well as improve interpretability of the SLAM results. Additionally, we have begun work on new primitives within our mission and vision subsystems to allow our developers to easily integrate SLAM into mission and vision code.

In addition to the new SLAM visualizer, we have developed two new visualizers within our control subsystem. The first of these new visualizers is a new Unity engine-based visualizer for CUAUV's Fishbowl simulator. This new visualizer enables higher realism within the simulated vision we use for testing our vision modules. Additionally, the introduction of Unity's fully-featured physics engine paves the way for further improvements to Fishbowl. The second new visualizer we have developed is a visual configuration tool for the physical parameters of the submarine, such as the thruster positions and drag planes. This visualizer is a step towards moving away from the previous system of manually editing text-based configuration files and helps prevent a large range of bugs arising from incorrect configuration.

III. EXPERIMENTAL RESULTS

Odysseus and Ajax began their design phase in late Summer of 2018 and have 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 reviewing new board designs, creating and testing prototype boards, and re-designing the hydrophones system. During the winter, both the mechanical and electrical teams spent over five months manufacturing and populating the new components used for the creation of Odysseus and Ajax. The two design teams came together fully in the Spring for the integration of both vehicles. Building upon last years success we were able to meet both in-water deadlines this year and have successfully logged over a hundred hours of pool time with Odysseus since its original in-water date. Additionally, a focus on validation during the integration phase has allowed Odysseus to run since in-water without a single issue, a first for CUAUV.

Since the end of the school year, the team has spent almost every day at the pool writing and testing missions in preparation for RoboSub. To test missions we use a combination of simulation and real life testing on either Odysees or Ajax. CUAUV's software team has a custom built simulator which allows us to test mission code in a simulated environment. 3D modeling tools are used to replicate RoboSub's task structures which are then loaded into the simulator. By doing this, we are able to test a number of aspects of our mission code including our vision modules and autonomous decision making. However, the simulator in reality simulates a "perfect environment". As such, testing our mission code in the pool is critical and often reveals additional checks and functionality that needs to be implemented to make our code function in a real environment. Currently, almost every mission works either in simulation or on Odysseus/Ajax.

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 to ensure accurate drops of the PVC structures. The electrical team also continues to test and make changes to board firmware as well as populate backup boards for use in the event of a major board failure.

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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: IDS; Surface Finish Technologies;

APPENDIX

A. Expectations

Subjective Measures			
	Maximum Points	Expected Points	Points Scored
Utility of team website	50	50	
Technical Merit(from journal paper)	150	150	
Written Style(from journal paper)	50	50	
Capability for Autonomous Behavior	100	100	
Creativity in System Design	100	100	
Team Uniform	10	10	
Team Video	50	50	
Pre-Qualifying Video	100	100	
Discretionary Points	40	40	
Total	650	650	
Performance Measures			
	Maximum Points		
Weight	See Table 1 / Vehicle		
Marker/Torpedo over weight or size	minus 500 / marker	0	
Gate: Pass through	100	100	
Gate: Maintain Fixed heading	150	150	
Gate: Coin Flip	300	0	
Gate: Pass through 60% section	200	0	
Gate: Pass through 40% section	400	400	
Gate: style	+100 (8x max)	300	
Collect Pickup: Crucifix, Garlic	400 / object	800	
Follow the “Path” (2 total)	100 / segment	200	
Slay Vampires: any, called	300, 600	600	
Drop Garlic: Open, closed	700, 1000 / marker (2 + pickup)	2000	
Drop Garlic: Move Arm	400	400	
Stake through Heart: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	2200	
Stake through Heart: Move lever	400	400	
Stake through Heart: Bonus - Cover Oval, Sm Heart	500	500	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with object	400 / object	800	
Expose to Sunlight: Open coffin	400	400	
Expose to Sunlight: Drop Pickup	200 / object (Crucifix only)	400	
Random Pinger first task	500	500	
Random Pinger second task	1500	1500	
Inter-vehicle Communication	1000	0	
Finish the mission with T minutes (whole + factional)	Tx100	0	

B. 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			

C. Outreach Activities

CUAUV is extremely active in our local community and takes great pride in the various activities we do. Every member of our team is extremely enthusiastic about the vehicles we build and the skills they acquire while being part of the team, and are all eager to share what they have learned with the community.

Over the past year CUAUV has participated in or hosted roughly 15 outreach events. In the Fall, the team participated in Into the Streets, which is a campus wide outreach event in which students head into Ithaca commons to help out with whatever the local community needs. This has ranged from yard work, to construction, to helping out the local library. Additionally, CUAUV hosted an Undecided in Engineering Panel, to help freshmen and sophomore students in determining which majors they may want to go into and what those majors entail. CUAUV also had the honor this year of showing off our previous year's vehicles, Castor and Pollux, to young Science Olympiad participants in an attempt to further interest them in STEM fields.

In the Spring, CUAUV hosted a number of lab tours, workshops, and boy scouts and girl scouts events. This year CUAUV had the opportunity to host an event for young boy scouts to claim their Cyber Chip badge. This event consisted of a series of presentations given by our team members which attempted to educate the scouts on proper internet safety including how to detect scams, be safe when interacting with people online, and how to make a secure password. CUAUV also hosted several lab tours for women in engineering groups and high school First Robotics Teams. During these lab tours the team showed the students our lab space, our vehicles, and challenged their minds with a series of fun activities revolving around different engineering challenges. These challenges often included using arduinos to perform some simple task or solving some simplified engineering problem using different construction materials.

This year, the team also had the chance to show off our new vehicles, Odysseus and Ajax, at the Bits on Our Mind (BOOM) showcase. The event was attended by hundreds of people and is an opportunity for participants to show off the technical aspects of their projects.