University of Alberta - Autonomous Robotic Vehicle Project
RoboSub 2021: Arctos Strikes Back

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***Abstract*- this paper details the improvements that were made on ARVP's latest robot Arctos along with the team's competition strategy and procedures in creating a safe work environment for the team during the COVID-19 pandemic. This year, all the required components for Arctos and it's subassemblies were manufactured and are waiting to be assembled as COVID restrictions allow. Although Arctos was fully designed prior to last year's competition, there were still many improvements made such as the implementing new sensor systems, fine tuning assemblies such as the torpedoes and droppers and re-designing the claw. In addition, the electrical team redesigned several boards to improve space efficiency and system compartmentalization, and the software team further expanded on the Gazebo simulator utilizing additional libraries for simulating and safely controlling the claw assembly.**

I- COMPETITION STRATEGY

This year the main goal of ARVP was to manufacture, build and refine Arctos and all of its subassemblies, including 8 thrusters, marker droppers, torpedo launchers, and sensory system. The key to Arctos' design was increasing the range of tasks the robot is capable of performing, which required the creation of a new mechanical claw and corresponding sensor system.

The primary competition strategy this year is largely an expansion on our strategies in previous years, remaining constant on our positions of historical strength and developing new strategies for our areas of weakness. First we will find and pass through the gate, and thanks to our software systems' upgrades, we are now capable of performing the necessary barrel rolls to maximize potential points. Arctos will then advance towards the buoys, using the path as a navigational tool. Next Arctos will attempt the bin task using the new mechanical claw to lift the bin cover and the dropper to drop the marker into the bin. Afterwards, Arctos will employ sonar navigation with the random pinger to attempt the torpedo task. Finally, Arctos will pick up the bottle, drop it into the correct target, and emerge within the octagon. According to our estimates, this route should net us more than 6000 points, which is a notable improvement over previous years.

II- MECHANICAL DESIGN

Fig. 1: Render of Arctos

A. Overall Design

Keeping with our previous themes, Arctos took inspiration from the Star Wars universe. The wings, centrally located control unit and structural supports were adapted into reality and molded into a functional robot. The base structure of the robot was polished, with the hull and wings becoming rectangular and octagonal respectively in order to improve accessibility and structural integrity.

B. Hull and Frame Assemblies

The rectangular prism shape of Arctos' hull was chosen to maximize space efficiency while maintaining structural stability as shown in Figure 2. The structural components and walls were machined from plates of 6061 aluminum while the two access points at the front and top were cut from acrylic sheets and tubing. Both access points are sealed using double Parker standard O-ring steals along with compression latches. All components of the hull structure were bonded together as opposed to welding to reduce metallic discoloration.

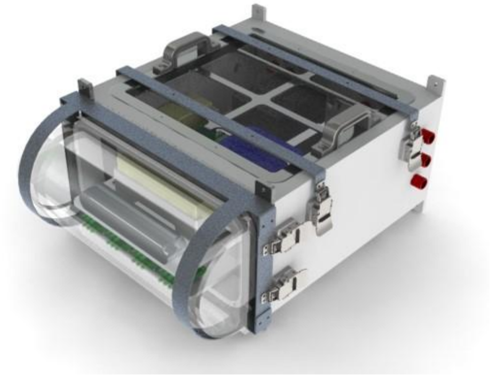

Fig. 2: Render of Arctos' hull

The primary design feature for the frame was the skeletal design which allows for minimum weight while allowing flexibility for mounting components and other subassemblies such as the camera enclosures and torpedo launchers. The frame was made using aluminum tubing for the two "wing" structures and aluminum angles to connect them.

Fig. 3: Render of Arctos' frame

C. Electronic Trays

The trays consist of two 3D printed panels that slide using low friction tape. As a result of the design of the hull, spatial efficiency of the electronics layout increased considerably compared to previous years, where a cylindrical hull was used. Lastly, the top and bottom trays are organized by functionality to optimize cable management.

D. Mechanical Gripper

Arctos is the first robot in ARVP history that utilizes an in-house designed mechanical claw system. This system will enable us to attempt new competition tasks, such as removing the bin cover and picking up the bottle before surfacing. The claw moves using four servo-motors which have been waterproofed using marine grease and epoxy. A series of sensors allows the robot to determine claw position and status including three rotary encoders to determine the position of each link as well as a proximity sensor to determine if the claw has successfully picked up an object. These sensors constitute the mechanical basis of a feedback control system which enables the claw to report back its location and whether it has successfully picked up an object. Finally, a new testing and verification procedure was implemented this year to prevent reliability issues in claw functionality.

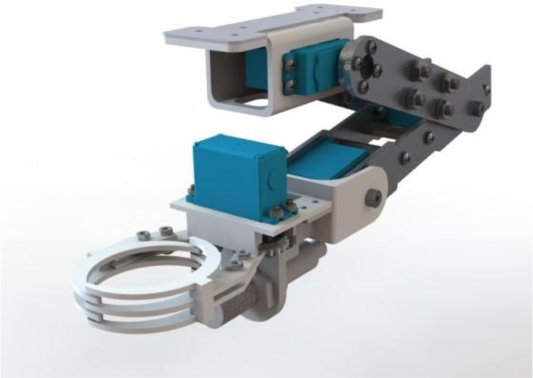

Fig. 4: Render of claw

E. Camera Enclosures

Arctos features two camera enclosures to house the fisheye and stereo cameras as shown in Figure 5.

Fig. 5: Render fisheye camera enclosure

The enclosures are made from standard acrylic tubing enclosures from Blue Robotics as well as ABS 3D-printed parts to mount the camera inside the enclosure, and to mount the enclosure to the robot frame. The cameras are also connected to the computer in the hull via penetrators. This enclosure design reduces the number of parts needed drastically when compared to enclosure designs on previous robots.

F. Torpedo Launchers

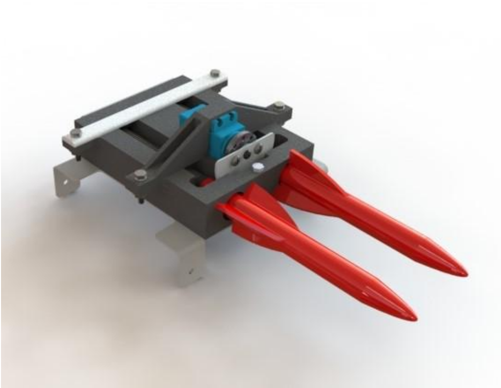

Fig. 6: Render torpedo launcher

Torpedoes have been an integral part of essentially all previous ARVP robots. Since retiring AURI, ARVP has moved away from the CO_2-based torpedo launchers, favoring a spring based approach in order to improve firing reliability. The torpedoes are first primed by compressing a spring, and are then held in place using a semicircular stop which can be disengaged using a servo motor. A small turn releases the first torpedo, and a subsequent turn is required to release the second torpedo, giving Arctos the ability to hit two separate targets. The torpedo assembly is firmly mounted to Arctos' frame, allowing the robot itself to aim the torpedo at a target.

G. Marker Droppers

The marker dropper assembly design contains two droppers that are released using the same motor that the claw uses. The caps on the top of the assembly can be removed for easy reloading of the droppers without having to rotate the servo. All the parts are 3D-printed using ABS as shown in figure 6.

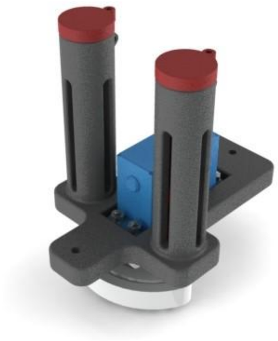

Fig. 6: Render marker droppers

III- ELECTRICAL DESIGN

COVID-19 working restrictions have caused limitations in the team's abilities for printed circuit board (PCB) assembly and functionality verification. Despite this, we have created new designs for improved performance, modulation, and compactness. Should these new systems turn out to be faulty, we can build their simpler versions for troubleshooting with the unused parts ordered prior to the pandemic.

A. Power Distribution

To consolidate boards that control similar processes and reduce electrical system complexity, last year's experimental battery levelling design was added to the battery monitoring board without having had to change the board dimensions. In fact, the number of components on the monitoring board was reduced because the levelling system only has a single output as compared to the multiple outputs of the monitoring system (one for each battery).

B. Actuation

Since the torpedo launch system has been altered to use servo motors instead of CO_2-based launchers, we have removed the solenoid drivers from the actuation board. Along with the removal of the I2C connections, a significant amount of the board is now open for future scalability.

C. Sonar

Our sonar system consists of two PCBs: a preprocessor which filters and amplifies the incoming signal and an integrated embedded data acquisition system. We have implemented an ethernet connection on the latter for improved communication with the Jetson computer. Future plans include creating infrastructure to be able to program the board with the ethernet connection, thus supplanting the USB connection and its components as well as combining the two PCBs for improved space efficiency and compartmentalization.

IV- SOFTWARE DESIGN

In 2020, we introduced Gazebo into our software stack as the new simulation platform. This helped us to continue developing new systems, despite the challenges imposed by the pandemic. The focus for 2021 was to fix bugs introduced by our migration to Gazebo, implement physical interactions in the simulator and add support for Arctos' mechanical claw.

Utilizing the ROS framework, we developed decentralized services (nodes) which communicated with each other using a publisher - subscriber model. This makes our codebase modular, expandable, and easy to use.

The software systems governing Arctos can be broken up into three categories: perception, planning, and controls. Each category follows a simple decision making process and organizational structure.

A. Perception

Computer Vision

The computer vision system for Arctos is designed to detect the objects Arctos will encounter in the competition using various computing algorithms like machine learning. ARVP constantly looks for ways to improve the accuracy of its models as it enhances our robot's ability to safely complete the assigned tasks.

While the pandemic forced us to limit the testing of the ZED stereo camera, added last year, our computer vision system was used extensively within the simulator while requiring minimal changes. To detect the distance between the robot and objects in the simulator, we heavily relied on our depth estimation algorithms which proved to be sufficient. This will change as we transition back into conducting regular pool tests, which would allow us to resume testing our stereo camera and work on improving the accuracy of our depth estimations.

At long ranges, we use traditional deep learning-based color-vision methods. This includes YOLO v3 [1] and YOLACT [2] which achieve rapid object detection and image segmentation, respectively.

Mapping

The mapping node is the main tracking interface between perception and planning. It is used to store and update positional estimates of all competition objects.

The position of competition elements is estimated using 2D-to-3D projections of their bounding boxes passed from the vision node. However, these estimates are noisy with farther objects introducing further uncertainty. To filter these estimations, we use a simple covariance model in function of distance in conjunction with an iterative product of multivariate Gaussians [3]. A minimum covariance on all estimates was enforced (process noise) since multivariate Gaussians are prone to converge on false positives. This enables us to converge towards the elements' true position with more confidence. Adding sensors like the ZED stereo camera will also provide more features to use for depth estimation and improve our accuracy.

Our mapping system requires prior information about the position of the competition objects. These initial estimates are rapidly updated and corrected with data obtained from the vision system. Figure 6 shows a map of the gate and the two buoys as viewed by the robot. The translucent blue spheres represent Gaussian intervals representing the 95% confidence intervals for each element.

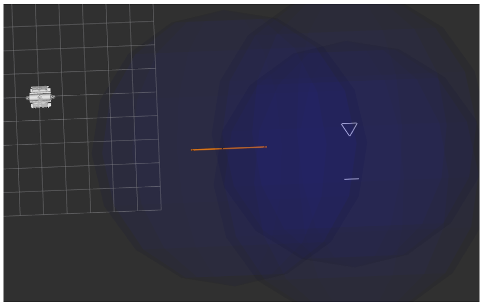

Fig. 6: Map Priors - Testing Course (RViz)

Passive Sonar

In order to compute the time difference of arrival (TDOA) for a hydrophone pair, we use generalized cross-correlation with phase transform (GCC-PHAT) [4].

To further improve our localization performance, we added a sound source tracking with a Sequential Importance Resampling (SIR) particle filter [5]. This made our system much more resilient to missing ping data as well as outliers. Figure 7 shows how initial estimates of the pinger location are narrowed down using the passive sonar system.

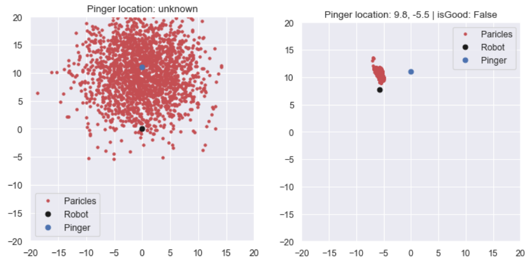

Fig. 7: Particle Filter in Action

B. *Planning*

Arctos' mission planner is a state machine implemented in C++. Using a library of commands, missions are easy to create and modify. Commands are of varying complexity and are built upon each other from simpler commands. This model allowed us to scale our planning system while still handling asynchronous events including timeouts in a robust way.

The key benefit of a code-based approach is that we may handle static checking. By using the *boost::outcome* library, we may handle errors at compile time rather than midway through a mission where errors could cause a catastrophic failure. This provides some guarantees about a mission before it is tested and helps prevent simple errors such as a missing timeout.

C. *Control*

LQR Control

For low level control, the robot uses a Linear Quadratic Regulator (LQR) control system. From a mathematical model of the robot and a linearized dynamic model of the underwater system, we are able to control all degrees of freedom simultaneously. Once the LQR controller receives a goal, it handles all thruster actuation.

The main focus for this year was to advise and support the new robot design. Mechanical design is the most important factor for the best possible control. Asymmetrical weight distributions could heavily complicate the robot's model. In addition, consultation was necessary for thruster configuration as certain configurations may work well mechanically but may also negatively affect the controllability of the robot.

Motion Planning

A setback with using LQR control for positional control is that there was no way to control the path the robot would take to move to its goal. This often resulted in very unpredictable and inefficient movement from the robot. In order to remedy this problem, we integrated the ROS based motion planning library move-base into our stack. We used the dynamic window approach (DWA) algorithm [6] for local robot navigation. This generates velocity commands to send to the LQR controller. The addition of the motion planner made it possible to have much more control over the robot's overall movement and has allowed the team to obtain more consistent results when performing missions.

Arctos Claw

With the addition of a mechanical claw to Arctos, the software stack would now need to integrate a manipulator. The controller for the arm would need to solve the inverse kinematics equations derived from its mechanical constraints and the corresponding joint configurations.

We implemented this controller using a ROS package named MoveIt. From the mechanical design of the arm, we generated a Unified Robot Description Format (URDF) file containing the descriptions of the links and joints. Using this file, we were able to implement a controller that plans the motion of the manipulator given a claw position.

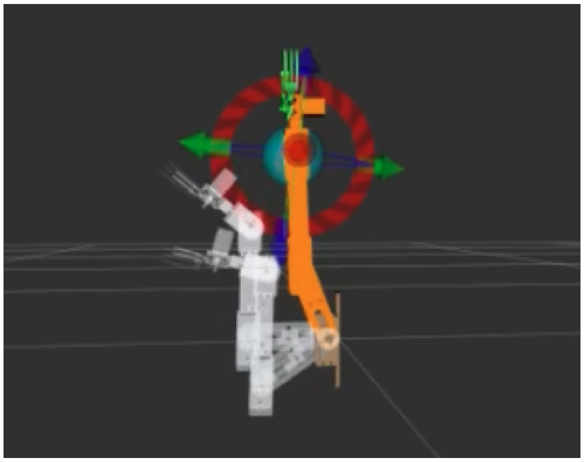

Figure 8: Manipulator control to a provided goal

With this prototype of a claw controller, we will start integrating the manipulator with our mission planner to simulate complicated pick and place tasks. The claw also introduces new challenges to our vision pipeline, as object detection capabilities would need to be expanded to allow for better manipulation.

D. Simulator

Last year, we migrated our simulation platform from UWSim to Gazebo. This was done not only to keep up with the industry standard for robotics development but also to take advantage of the myriad of features offered by Gazebo.

Gazebo utilizes an internal physics engine to simulate various interactions between rigid bodies. We used this feature to make the objects in the pool interactable and add realism to our tests. This gives us visual feedback on whether tasks like the buoy mission are completed with appropriate robot motion.

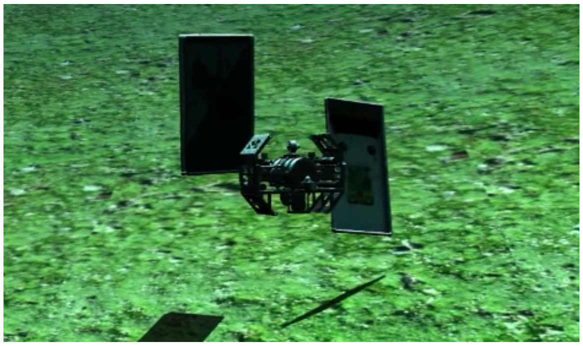

Figure 9: Robot interacting with buoy in the Gazebo simulator

We look to expand this functionality to more dynamic missions like the torpedo and dropper launches, where we can utilize the buoyancy plugin in Gazebo to simulate a realistic trajectory for the projectiles.

V-EXPERIMENTAL RESULTS

COVID-19 presented a large challenge for ARVP. Since March 2020, we have been unable to conduct pool-tests and this has negatively affected our ability to test the robot. The team has been working closely with the university to develop a safe working plan amidst the pandemic. The software team relied on the simulator in place of pool tests. By using Gazebo, simulations are more stable and are easier to analyze and view. In addition, Gazebo opens the door to using third-party tools if necessary. Now simulations are easier to conduct and, over time, may become more accurate.

In addition to software simulations, the mechanical team created a new sub-team this year: Furthermore, the team conducted finite element analysis to quantify the rigidity of the frame and evaluate its factor of safety. Lastly, in conjunction with other sub-teams, analyses such as kinematics, drag, Hooke’s law, and energy conservation were employed to further justify Arctos’ design choices.

VI- ACKNOWLEDGEMENTS

It has taken many years for ARVP to flourish into the streamlined, self-sufficient organization that it is today.

Therefore, ARVP would like to thank the Faculty of Engineering at the University of Alberta and its staff for providing generous funding, space, and tools so the team can do its best work. The faculty have worked tiredestly to support the team amidst the pandament by providing the team with tools to work safely and support in a remote setting. In particular, Raymond Matthias, Erin Lee, Rebecca Blanchette, Lisa White and Don Villacencio have been key allies throughout the year. We would also like to thank our advisor, Dr. Michael Lipsett, for his help with approvals and advice regarding the robot's design. With the help from our supporters we were able to give back to our community as outlined in Appendix B.

We would also like to recognize all our sponsors, without whom our robot would be non-existent. See Appendix C for a list of our sponsors and more information.

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Appendix A

COMPONENT TAB

Note: All prices are estimated in CAD for the total cost of each component type, not per unit.

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control	Home Depot	PVC	2” PVC pipes + end caps	$40
Frame	ARVP	Custom	Custom aluminum waterjet	$1300
Waterproof Housing	ARVP	Custom	Custom CNC enclosure	$2000
Waterproof Connectors	MacArtney	SubConn Circular	8 contact	$1500
Frame anodizing	Anderson Anodizing	Type III Hardcoat	Black and Gold	$520
Thrusters	Blue Robotics	T200	Brushless thruster	$2170
Motor Control	Zubax Robotics	MYXA-B ESC	Closed-loop controllers	$1935
High Level Control	ARVP	18-state LQR	LQR controller	n/a
Actuators	Sparkfun	HS-646WP	Waterproof servo	$300
Propellers	n/a	n/a	n/a	n/a
Battery	HobbyKing	ZIPPY Compact	6200mAh 4s 40c LiPo	$500
Converter	ARVP	Custom	100Wx3, (12V, 7V, & 5V)	$450
Regulator	-	-	-	-
CPU	Nvidia	Jetson Xavier	8-core ARM processor, 512-Core Volta GPU	$1000
Internal Comm Network	CAN, I2C	n/a	n/a	n/a
External Comm Interface	Ethernet	n/a	n/a	n/a
Programming Language 1	C++	n/a	n/a	n/a
Programming Language 2	Python	n/a	n/a	n/a
Compass	LORD Microstrain	3DM-GX5-25	AHRS	$2800
Inertial Measurement Unit (IMU)	LORD Microstrain	3DM-GX5-25	AHRS	See above
Doppler Velocity Log (DVL)	Nortek	DVL 1000	DVL	$18000
Camera(s)	Stereolabs, ELP	ZED, USB Camera	RGB Stereoscopic,	$600

			Fisheye	
Hydrophones	Teledyne Marine	TC4013-1	1Hz-170kHz, Omni	$4500
Manipulator	ARVP	Custom	Custom Aluminum, PLA	$260
Algorithms: vision	pjreddie	Darknet / YOLO	Fast generic SSD	n/a
Algorithms: acoustics	ARVP	au_sonar	GCC-PHAT + Particle Filter	n/a
Algorithms: localization and mapping	ARVP	au_localization / au_mapping	UKF + Gaussian updates	n/a
Algorithms: autonomy	ARVP	au_planner	No FSMs, preemptable functions	n/a
Open Source Software	ROS, Gazebo, MoveIt	Various	Multiple Packages	n/a
Team Size (number of people)	60			
HW/SW expertise ratio	2:1			
Testing time: simulation	500 hours			
Testing time: in-water	0 hours			

Appendix B

OUTREACH ACTIVITIES

Community outreach has always been the foundation of ARVP's mission to foster interest and promote awareness of science, technology, engineering, and mathematics (STEM)-related fields. Members of ARVP are committed to providing comprehensive outreach opportunities that allow individuals to broaden their knowledge in STEM fields. This year, the team has dedicated time and resources to events that cater to individuals of all backgrounds. These outreach events prioritize an environment that is well-balanced between inclusivity and informativity.

We were fortunate enough in May to have the opportunity to communicate with and learn from the Surveillance Robotics Theme Lead, Adam Serblowski at Shell. Adam elaborated upon the incredibly intricate design and testing process all Shell vehicles undergo to operate on an active worksite. The robots created by both ARVP and Shell share many similarities; both operate in extreme environments. It is exciting and inspiring to see the current trajectory robotic technology is taking in the industry world, and thus and rekindled the attendee's enthusiasm in this area of innovation.

It is valuable to receive, but it is even more rewarding to give. ARVP members are passionate about robotics and engineering and have put efforts into educating students and encouraging them to pursue careers in STEM. In June 2020, ARVP participated as a panellist for a segment at the International SeaPerch Challenge, aimed at primary school students. The panel's purpose was to provide an intimate, first-hand account of their experiences engaging in engineering and robotics teams at a university level. The transition to the next academic level is a time of great uncertainty; it was an engaging discussion, and we hope to quell apprehensions the viewers may have had. It was wonderful to collaborate with individuals from RoboNation, Georgia Tech, and San Diego State University.

ARVP strives to instill a passion for STEM and to encourage others to pursue a future in STEM fields. The team strongly welcomes a diversified environment with individuals of all backgrounds. Members are all at different points in their degrees, including both undergraduate and graduate students. Although external outreach is the center of ARVP's objective in promoting the field of robotics, the team takes great pride in our members, and have always aimed to provide opportunities for career-related growth. Many of the members who have graduated from university remain as alumni advisors, and continue to help out with team activities. In January, ARVP's former mechanical lead Adesh Sangione hosted a workshop session for the team, with the objective of providing advice on career growth and how to create an effective resume. This opportunity has helped many members with preparing themselves for careers in the industry.

Appendix C

SPONSOR LOGOS

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