University of Alberta - Autonomous Robotic Vehicle Project
RoboSub 2020: Arctos Awakens

Connor Chin, Willard Farmer, Jenny Lee, David Lenfesty, Mohammad Kebbi,
Gabriel Risbud-Vincent, Adesh Sangione, Jason Shukla, Curtis Stewart, Salina Trac, Nicholas Wengel

Abstract — **This paper details the design philosophy behind ARVP's newest robot, Arctos, and the team's competition strategy while combatting the uncertainties associated with COVID-19. In designing Arctos, subassemblies from previous years were improved and most notably a mechanical gripper was added to enable the robot to attempt every task for 2020. All custom-made PCBs were redesigned and updated to permit higher thruster power requirements along with increasing channels for actuator control. The addition of a front stereo camera and a downwards facing fisheye lens, along with updated software vision architecture, enables augmented underwater vision.**

I. COMPETITION STRATEGY

This year, one of the main decisions made by ARVP was to design and manufacture a new generation of robot, named Arctos, improving on previous years. With 8 thrusters, torpedo launchers, marker droppers, mechanical gripper, and a full sensor suite including a DVL, stereo camera, and hydrophone array, Arctos is fully equipped to attempt every task at competition.

The team's goal for RoboSub 2020 was to maximize the points for missions located near the dock, followed by the torpedo, dropper, and surfacing missions. Starting with the coin flip task, the robot will proceed to perform a barrel roll through the bootlegger side of the gate, thus choosing to complete the remaining tasks from a bootlegger perspective. Arctos will then advance towards the buoys, using the path as a navigational tool. Afterwards, it will employ sonar navigation with the random pinger to attempt the torpedo task and drop a marker in the correct bin. Lastly, Arctos will surface within the octagon.

Arctos' reliability is unknown since it is a brand new and untested robot. However, the hull design is quite complex, and we are unsure if the sealing reliability will be affected. Reliability was primarily assessed with prior knowledge of previous internal designs as well as those from other teams. Furthermore, because pool resources were inaccessible, the team was able to capitalize on updating robot infrastructure rather than focusing on pool tests. The design phase was the main focus for this year as the team sought to design a robot that could be used successfully for the next few competitions.

II. MECHANICAL DESIGN

A. Overall Design

With Arctos, ARVP makes a bold leap into minimalism. While previous robots had drag-inducing panels, Arctos features a skeletal frame. The hull was also overhauled, shifting from a cylindrical design to a rectangular one. Arctos also features an 8 thruster configuration and brand new subsystems for each mission. See Figure 1 for a rendered image of Arctos.

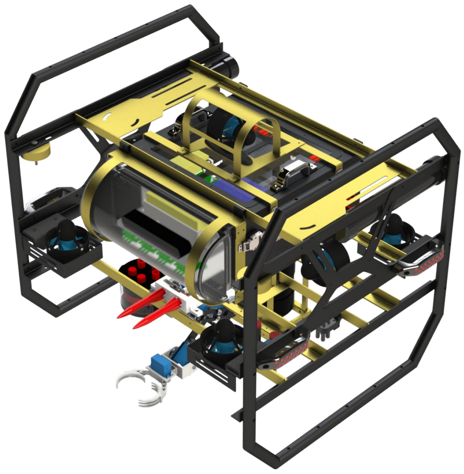

Fig. 1: Render of Arctos in SOLIDWORKS

B. Frame and Hull Assembly

A rectangular hull design promotes spatial efficiency along with the ability to stack electronic components for easy assembly. The hull was fabricated from 6061 aluminium metal and has 2 acrylic access points that seal using Parker standard O-rings (double seal) and compression latches. Additionally, all external electrical connections are routed through the backside of the hull to ensure centralized accessibility. Moreover, most of the hull is bonded rather than welded to reduce metallic discoloration.

Arctos features a skeletal frame that decreases surface area for drag while maximizing sturdiness. The majority of the frame was built from aluminium angles and sheet metal. However, the robot's side wings were fabricated from lightweight but high strength aluminium structural tubing. Also, the frame boasts a universal fastening system that eliminates confusion during assembly.

C. Electronic Trays

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

D. Mechanical Gripper

An exciting addition to the robot was the mechanical claw subsystem (see Figure 2). This assembly consists of 4 aluminium linkages, 4 servos, and a 3D printed manipulator. With these parts, the claw maintains 3 degrees of freedom along with an excellent reach.

Fig. 2: Render of Mechanical Gripper

E. Torpedo Launchers

The reliability of the torpedoes assembly (see Figure 3) was increased by switching from a pneumatic to a spring-actuated system. Arctos features a two torpedo system that is controlled using a servo motor. Each missile is propelled using stainless steel compression springs that are housed in a 3D printed body. Lastly, the assembly was designed for independent control to ensure higher targeting accuracy.

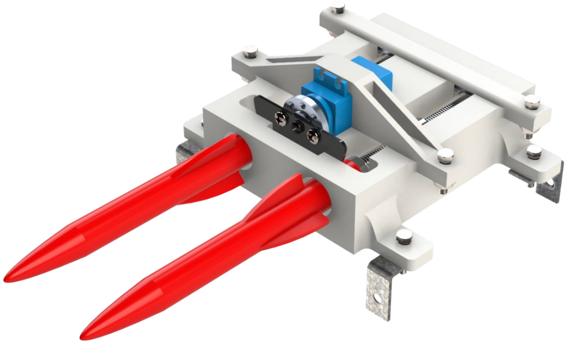

Fig. 3: Render of Torpedoes

F. Marker Droppers

The new marker droppers assembly (see Figure 4) has a 3D printed body and is actuated using a waterproofed servo motor. The design is simple yet functional since each marker can be controlled individually.

Fig. 4: Marker Dropper Assembly

For a full list of components used in Arctos, see Appendix A.

III. ELECTRICAL DESIGN

The major technical focus for 2019-2020 was re-working and upgrading existing electrical components to ensure compatibility with Arctos. Many system features ensure a smooth and low-impact transition into the new platform. However, as part of this transition, several functional upgrades have been made.

A. Power Distribution

To support additional motors, an extra battery was required, which increases the existing 4 on Auri to 5 on Arctos. Consequently, the power systems were revamped.

The existing infrastructure permitted changes for this year to be minimal and non-invasive. An extra power rail at 7V was required for driving servos, which was easily added as another module to the power converter carrier board. Likewise, the battery monitoring board only had to be extended, rather than redesigned, to support an additional two motors.

To improve system functionality, an experimental battery levelling system was also developed. This will allow Arctos to optionally pull power from the most charged battery in the system, improving system operational time and reducing battery wear.

B. Sonar

While it was operational last year, Auri's passive sonar system had a few operational issues. To resolve these, the preprocessor board had an extra channel added, which increased the accuracy of location estimation, as well as allowing the possibility of adding three-dimensional location in the future. Additionally, an integrated embedded data acquisition system was developed, shown in Figure 5, which interfaced directly with the sonar preprocessor. This eliminated the old requirement for a seperate BeagleBone Black and PruDAQ board, reducing power usage, system complexity, and space requirements, even while adding an extra channel of capacity.

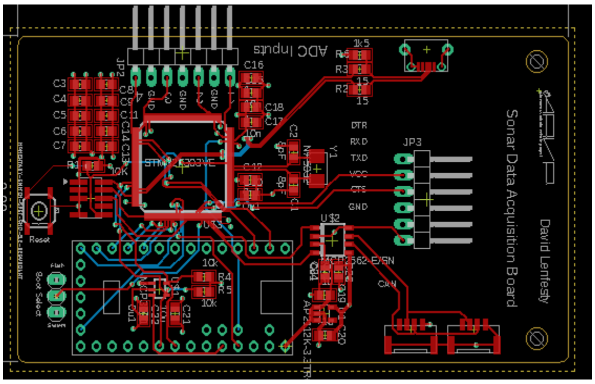

Fig. 5: Sonar Data Acquisition Board

C. Indication and Diagnostics

With the success of using RGB led strips to indicate Auri's state, the team decided to implement the feature into Arctos. Moreover, a new LCD interface will be added, which will allow operators to monitor critical system information in the pool or on the dock.

This is all possible by using CAN bus, with the UAVCAN protocol in all critical systems. This allows us to monitor critical functionality and stats, as well as providing a reliable backbone for command and control.

IV. SOFTWARE DESIGN

With an already strong and mature codebase, the focus for 2020 was to maintain existing systems, update outdated software, and support the new AUV design.

Utilizing the ROS framework, we may decentralize services (nodes) and distribute information with a publisher-subscriber model. This makes our codebase, modular, expandable, and easy to use.

The robot follows a simple decision-making pipeline, within the categories of perception, planning, and controls.

A. Perception

Computer Vision

This year, the software team invested in a ZED stereo camera. Using stereo imaging, we can measure the distance between the robot and nearby objects. As noticed last year, even with consistent lighting, colors between targets may become indistinguishable underwater. This was demonstrated by the hard to see vampire buoy light green target barrier. By using a stereo camera, we reduce our reliance on color-vision at close ranges.

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. These estimates are fundamentally noisy, especially at a distance, so a simple covariance model in function of distance was used in conjunction with an iterative product of multivariate Gaussians [3] to converge upon the elements' true position. A minimum covariance on all estimates was enforced (process noise) since multivariate Gaussians are prone to converge on false positives. The ZED stereo camera also provides an alternative metric for depth estimation, which does not rely on projection estimates.

The mapping system requires initial estimates as priors, but these estimates are rapidly updated and corrected by the vision system. Figure 6 shows the map as viewed by the robot, with the translucent blue spheres representing the 95% confidence intervals of each element.

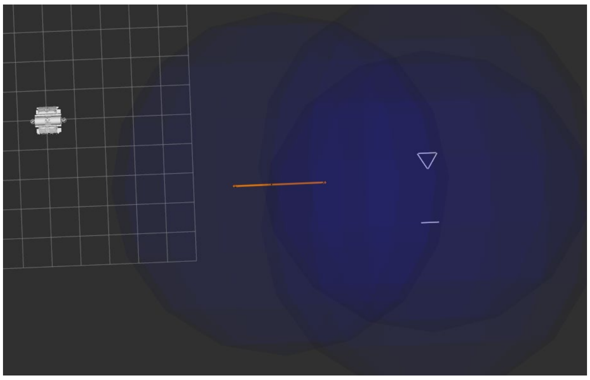

Fig. 6: Map Priors - Testing Course (RViz)

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 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.

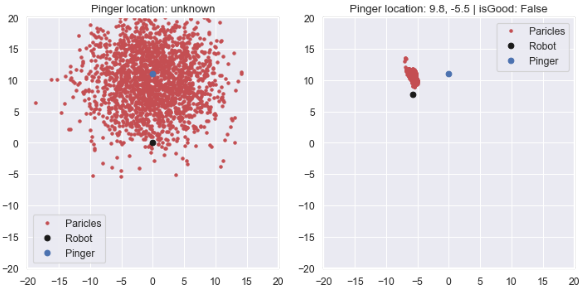

Fig. 7: Particle Filter in Action

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.

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. To combat this issue, one of the software team's biggest focuses was on improving the robotic simulator. Previously, we had used a ROS package called uwsim. Unfortunately, uwsim is no longer actively supported and is limited in the possibilities for development. The team has now shifted to Gazebo, an industry standard. 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: The Continuous Improvement team. The team built an apparatus to test thrusters in an aquarium to gain accurate thruster load data. 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. Because large gatherings are restricted, experimenting with these subsystems were difficult to delegate. As a result, the team relied on mathematical analysis, as opposed to prototyping.

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. In particular, Raymond Matthias, Erin Lee, Rebecca Blanchette and Don Villacencio have been key allies throughout the year. We would also like to thank our advisors, Dr. Bob Koch and Dr. Michael Lipsett, for their 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. We would also like to thank all our contributors for their support during our 2020 Crowdfunding Campaign to support the fabrication of Arctos, where over $6,400 was raised.

REFERENCES

[1] J. Redmon, S. Divvala, R. Girshick, and A. Farhadi, “You Only Look Once: Unified, Real-Time Object Detection,” 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016.

[2] D. Bolya, C. Zhou, F. Xiao and Y. J. Lee, "YOLACT++: Better Real-time Instance Segmentation," 2019, 1912.06218.

[3] C. E. Rasmussen and C. K. I. Williams, “Gaussian Processes for Machine Learning”. The MIT Press, 2006.

[4] C. Knapp and G. Carter, “The generalized correlation method for estimation of time delay”, IEEE Transactions on Acoustics 1976, Speech and Signal Processing ASSP-24(4), 320-327.

[5] N. Gordon, D. Salmond, A. Smith, "Novel approach to nonlinear/non-Gaussian Bayesian state estimation”. IEEE Proceedings F on Radar and Signal Processing 1993 140(2), 107–113.

[6] D. Fox, W. Burgard, and S. Thrun. "The dynamic window approach to collision avoidance". Technical Report IAI-TR-95-13, University of Bonn 1995.

Appendix A

COMPONENT TABLE

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
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, Fisheye	$600
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	Various	Multiple Packages	n/a
Team Size (number of people)	45			
HW/SW expertise ratio	2:1			
Testing time: simulation	500 hours			
Testing time: in-water	8 hours			

Appendix B

OUTREACH ACTIVITIES

Our Mission - *"To promote, develop and apply the use of robotic systems to current and future generations"*

Historically, community outreach has always been the foundation of ARVP's mission. The team takes pride in fostering interest and promoting awareness of science, technology, engineering, and mathematics (STEM) related fields. These activities have been recognized by the Association of Professional Engineers and Geoscientists of Alberta (APEGA), awarding the team with the prestigious APEGA Foundation Outreach grant since 2018, as well as from Shell, awarding the team with the Shell Enhanced Learning Fund (SELF) in recent years.

ARVP's outreach activities consist of internal and external opportunities related to the university, as well as our sponsors. In August, ARVP held its annual showcase event where sponsors and faculty supporters were invited to the pool to see the highlights of our achievements from RoboSub 2019.

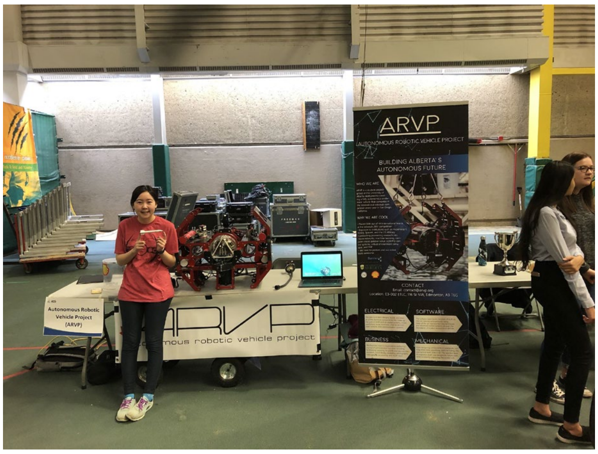

Fig. B1: APEGA Science Olympics

ARVP actively participated in this year's APEGA Science Olympics event, where students from grades 1-12 created their science projects and presented it to judges. Members presented last year's robot, Auri, while providing simplified descriptions to students of all ages. Members were able to showcase the importance of STEM-related fields of study and demonstrate their real-life applications to students. Not only was this an opportunity for students to further their knowledge of STEM fields, ARVP members were also able to learn from the cool projects that the students themselves had created!

Starting in January, ARVP began hosting official robotic seminar meetups. Team members provided a technical presentation along with a networking session for follow-up comments or questions. The seminar content was designed at the discretion of the presenter, ranging from technical milestones accomplished through ARVP to professional resume-building and career workshops.

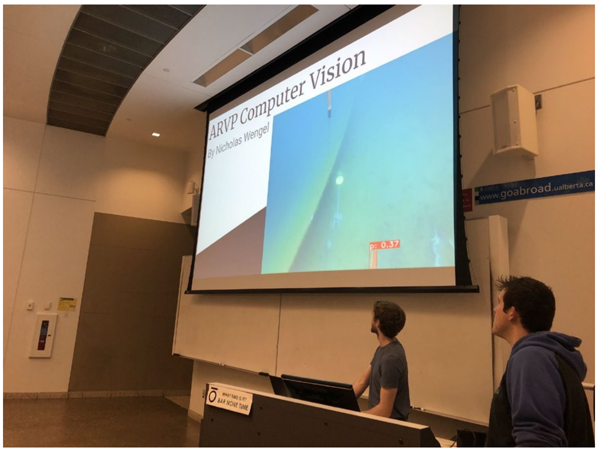

Fig. B2: Seminar Presentation for Computer Vision

Due to the COVID-19 restrictions, there has been a recent hiatus for in-person outreach events. Despite this, ARVP remains motivated in promoting and encouraging others to pursue a future in STEM fields. For example, one of our members, Jenny Lee, recently participated in an online mentorship interview with DiscoverE, an organization dedicated to improving science and technology accessibility for youth. In the interview, Jenny shared her experience on ARVP. She explored the skills, challenges, and achievements she encountered during her time in the club, bringing awareness to both ARVP and robotics alike.

Appendix C

SPONSOR LOGOS

UNIVERSITY OF ALBERTA

ENGINEERING U of A

APEGA FOUNDATION

GENERAL DYNAMICS
Mission Systems–Canada

methanex™
the power of agility

HONDA

RAIL SHOP
SERVICES INC.

NORTEK

Shell

AltaML

MARL TECHNOLOGIES

DC SOLUTIONS LTD.
"THE POWER EXPERTS"

SOLIDWORKS

Travis CI

Fort Vermilion
School Division 52

ISS Mine Safety .com

TELEDYNE DALSA
Everywhereyoulook™
Part of the Teledyne Imaging Group

Zubax

CAVALRY FENCE
VINYL FENCE EDMONTON

GitHub

MacArtney
UNDERWATER TECHNOLOGY

HOSKIN SCIENTIFIC

More information can be found at https://arvp.org/sponsors/