University of Alberta - Autonomous Robotic Vehicle Project RoboSub 2022:

Jenny Lee, Stevie Desmarais, Drew Delcioppo, Justin Francis, Sergii Penner, Kirill Makhachev, Rachel Ellis

***Abstract*-. This paper details the design strategy and implementation of Auri, the Autonomous Robotic Vehicle Project's submarine for the RoboSub 2022 competition. This year the team focused on completing the pre-qualification task, completing the buoy task and the torpedo task via vision recognition. This was an interdisciplinary effort - building on years of iteration of our mechanical frame design, custom PCBs, and software architecture. A stable mechanical platform and gradual upgrades to our computer and sensor boards have provided the software team with months of additional testing time to develop and refine its perception, planning, and control systems. With these improvements, we are confident Auri has the ability to flexibly and reliably execute all targeted missions in an uncertain environment.**

I- COMPETITION STRATEGY

This year, one of the main decisions made by ARVP was to use the existing robot from 2019 instead of rushing the manufacturing of our new robot. This allowed the team to focus on the end-to-end integration of all its mechanical, electrical, and software components. We'll begin the competition either facing perpendicular or away from the gate, decided by a coin flip. Auri should easily identify the gate after diving and some searching and recognize the two photos on the gate. Passing through the gate, specifically the G-man side with 6-8 90-degree rotations for maximum style points. Auri will then move to touch the buoy that corresponds to the G-man side. Then, using our vision system. Then, we'll move to the torpedo shootout. Using our sonar system Auri will move towards the final octagon surfacing task. The goal is to surface within the octagon signifying the end of our run.

II- MECHANICAL DESIGN

ARVP has been working on development of a new robot, Arctos, since 2019. However, gauging performance potential has led us to believe that Arctos requires further development before it can formally succeed AURI and compete on a world-class level.

A. Overall Design

AURI consists of a highly modular frame of lightweight aluminum with ample mounting space for auxiliary assemblies and easy access for modification and repair. AURI's hull encases electronic components in a primary and two secondary sealed acrylic tubes. Branching from this structure is a series of auxiliary assemblies that accomplish two key functions, sensing and manipulation. The sensor system consists of a series of cameras as well as nonvisual sensors like a data-velocity logger (DVL) and hydrophones. The manipulation assemblies include torpedo launchers and droppers.

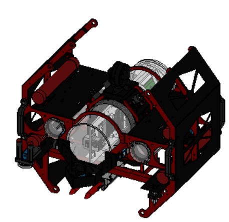

Fig. 1 Auri's Main Assembly

B. Waterproofing

A central challenge of any UAV design is utilizing electrically powered components in an aquatic environment. The main body of electrical components are sealed within the primary acrylic hull, a cylindrical tube sealed at the center by two sets of O-rings. A similar design is used to encase the batteries in two auxiliary cylinders connected to the main body with jacketed wiring. The cylindrical nature of these chambers both reduce wear and maintenance on the O-rings and allows for an even pressure distribution, contributing to minimal leakage. Before each pool test, these chambers are pressure tested using modified bicycle pumps and a vent plug built into each tube. Other electronic components such as servo motors are waterproofed using marine epoxy in accordance with an ARVP developed and vigorously tested protocol, allowing for the procurement of cheap and extremely reliable motors.

C. Torpedos

The torpedo subsystem is one of the most significant deviations from previous years. The previous compressed gas based system was deemed to be unreliable. The new mechanism uses spring powered torpedoes with a lever based release mechanism using servo motors. Springs at the back of the levers hold them in a horizontal position. As the rear facing servo rotates the lever spring is compressed, lifting the hooks from the torpedo and effectively launching it. These changes should improve on both reliability and safety metrics.

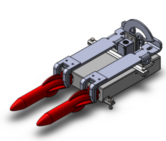

Fig. 2 Torpedoes Assembly

D. Droppers

Like the torpedo system, the droppers system is a completely redesigned subassembly for AURI. An ABS base gives the droppers stability and a single servo motor allows the release of the markers, by rotating 90 degrees to drop a single marker and 180 degrees to drop both. The markers can be easily reloaded by removing the caps at the top of each plastic cylinder, which lock into place. The dropper is operating in accordance with a corresponding fisheye camera, the interplay involved is discussed further in our software section. Markers were tested using CFD software in order to optimize hydrodynamic effects.

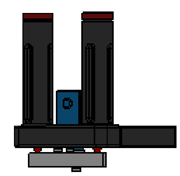

Fig. 3 Marker Dropper Assembly

E. Electronic Trays

The Electronic components are held by a series of ASA trays, which easily slide out giving easy access to the electronics boards as well as large electronic components such as the Jetson Xavier processor for modification or repairs. These boards are arranged in a triangular configuration, maximizing the flat board space which can be attained inside a cylindrical hull. Additionally, cable management is simple as necessary wires can be routed through the center of the triangular board assembly. This also allows good board visibility for troubleshooting.

F. Hydrophones

Three hydrophone sensors are mounted to AURI's underside. These pingers each record the frequency of incoming sound waves allowing for effective 3D acoustic mapping. This system is discussed more in later sections.

III- ELECTRICAL DESIGN

Prior to and throughout the COVID-19 pandemic, the electrical team has mostly been focussed on designing, assembling, and testing an improved electrical system for the Arctos robot. Electrical work on AURI was mostly in the form of maintenance and slight improvements such as replacing the solenoid-based torpedo launchers with servos as had been designed by the mechanical team. The following are some of the significant electrical improvements to AURI for the 2019 RoboSub competition.

A. Power Distribution

The power distribution system was redesigned for increased modularity. The system is implemented as a carrier board with insertable converter boards. Output voltage of the converter boards is dictated by the selection of two resistor values. A buck-boost DC/DC switching regulator is located on each board. The converter boards and slots (implemented as edge connectors) are standardized so that any converter can fit into any slot. The carrier board contains supporting circuitry to create critical and non-critical versions of the voltage rails. Thus, when the kill switch is removed, electrical systems that are deemed critical can remain on while other systems are turned off. A render of the power distribution system is shown in Figure 4.

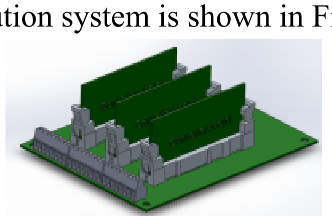

Fig 4. Power distribution system

B. Battery Hot-Swap System

On the battery monitoring board, hot-swapping capability was incorporated on the electronics battery rail. Hot-swapping was achieved with the LTC4418 IC. This IC connects one of two valid channels, based on voltage and priority. The valid voltage range for each channel is determined using a resistor divider chain based on the hysteresis current of the IC. This prevents the batteries from discharging too far and is within the tolerance of the MOSFET switches.

C. Cable System & Battery Upgrades

New cabling was installed for the T200 Blue Robotics thrusters with heat shrink wrap placed near the penetrators for added strain relief. Additionally, expandable cable sleeving was used to route the 3-phase thruster wires to maintain effective cable organization and management. AURI's electrical source are ZIPPY Compact 6200 mAh 4s 40C lithium-ion polymer batteries which have been shown to have a lower internal resistance, thus reducing voltage sag under heavy current draw.

IV- SOFTWARE DESIGN

In 2021, we began utilizing Docker which allows you to package and run applications in isolated environments. With this change we can now run on our software stack on any operating system (Windows, Linux, OSX). This solves the classic "works on my machine" software design issue and allows to easily isolate different modules.

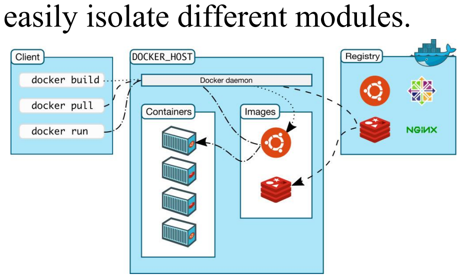

Fig 5: Docker Architecture

The main computer on the robot that runs all the high level software is a Jetson Xavier. The 8 core processor allows for quick code base compile time and tensor cores allow deep learning models to run at fast frame rates. Utilizing the ROS framework, we developed decentralized services (nodes) which communicate with each other using a publisher - subscriber model. This makes our codebase modular, expandable, and easy to use. The software systems governing Auri can be broken up into three categories: perception, planning, and controls. Utilizing these systems Auri can continually decide where it needs to go, how to get there, and the actions required once it gets there.

A. Perception

Computer Vision

The computer vision (CV) system for Auri primarily uses the object detection model YOLO v3 [1]. This model operates usings the open source neural network framework Darknet. Darknet is written in C (and CUDA), allowing the model and framework to easily integrate with our ROS codebase [2]. Deep learning models are superior in comparison to traditional CV methods and have proven to be effective in varying: orientations, distance and lighting conditions.

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. To filter these estimations, we use a simple covariance model in function of distance in conjunction with an iterative product of multivariate Gaussians [3]. Our mapping system requires prior information, 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.

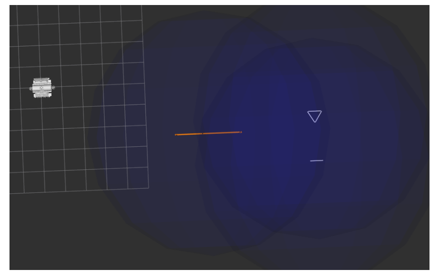

Fig. 6: Map Priors - Testing Course (RViz)

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.

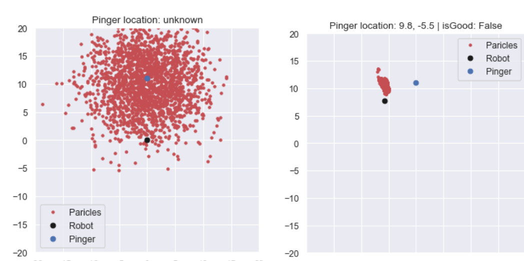

Fig. 7: Particle Filter in Action

B. Planning

Auri's 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. 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 velocity goal, it handles all thruster actuation. In order for the LQR to accurately control the robot, the relation between input power and thrust must be known. A rig was made to measure the thrust of the motors with a load cell at various inputs. With this setup we were able to find the peak thrust of the motors at various RPMs, and the time delay to reach this thrust. This data was used to properly set the B-matrix for the LQR, and to accurately convert motor input to thrust for data analysis.

Motion Planning

A setback with using LQR control for positional control is that there was no way to control the path the robot takes. 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 takes in positional targets and generates velocity commands to send to the LQR controller until the target is reached.

PID & Visual Servo for Torpedo

Using our computer vision bounding boxes, and depth camera we can estimate the location in 3D space of the torpedo target. Then utilizing a PID controller [7] we control the robot to center on the torpedo target and then fire the torpedoes when the error to our target is low.

V- ACKNOWLEDGEMENTS

It has taken many years for ARVP to flourish into the streamlined, self-sufficient organization that it is today. Beyond the dedication and contribution of our members, the group could not have done its work without the support of many partners, advisors and mentors.

In particular, ARVP would like to thank the Faculty of Engineering at the University of Alberta for providing generous funding, space, and tools so the team can do its best work. In particular, Vic Ly, Erin Lee, Rebecca Blanchette and Don Villacencio have been key allies throughout the year. We would also like to thank our advisor Dr. Micheal Lipsett for all his help with approvals and advice regarding the team’s control system and Robert Donovan for his ongoing support both as a mentor and as a diver during our pool tests.

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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	30 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 able to invite a high school robotics club in March to our pool test. Around 30 high school students and chaperones observed our robot Auri successfully complete the qualification tasks while tethered using direct control. This outreach event was a super fun experience, where we not only had the opportunity to promote what we do at ARVP but also learn about the incredible accomplishments these high school students achieved at their own robotics competition. We hope they continue to pursue their interest in robotics and would love to have them become part of ARVP in the future.

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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