RoboSub 2023 Technical Design Report

University of Alberta (Autonomous Robotic Vehicle Project)

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***Abstract*—For the 2022-20223 development cycle, ARVP moved to a new AUV development platform, intended for a three-year lifecycle. Emphasis was placed on an iterative design process with small workpieces. ARVP's desired course strategy necessitated a reevaluation of dynamics control, the creation of a minimally viable pinger system, a dedicated thermal solution, new subsystems, and an overhauled software stack. These competition goals culminated in the development of ARVP's new AUV, Arctos. The sonar system design strategy highlights long-term system architecture planning as the colorlight FPGA provides headspace to move the computation requirements of the onboard computer in future development cycles. Additionally, FFT of convolution methods will be applied for the pinger based on a < 10-degree accuracy during performance testing. Mechanical design strategy for the claw subsystem displays the creative aspects of iterative design and manufacturing, while thermal solution discussions demonstrate the fundamental calculations applied when developing benchmark tests and making engineering decisions. Software design strategy covers conversations reached to commit to a PID cascading controller for reliability, rather than optimized performance when compared to LQR and MPC.**

Fig. 1: Solidworks Render of Arctos

I. COMPETITION GOALS

A. Defining Success Metrics

At the beginning of the 2022-2023 development cycle, ARVP recognized that Auri – the robot fielded in 2022 – had reached maturity as a development platform. Auri physically and computationally lacked space to justify redevelopment. Additional requirement definition meetings found that ARVP harbored significant technical debt that could not be eliminated over one year due to documentation and turnover inconsistencies during COVID. However, ARVP quadrupled membership and quintupled financial assets in 2022-2023. As a result, purchasing equipment specialized for AUV development was feasible, but time had to be devoted to teaching new members and managing individual work packages.

Thus, ARVP set the goal of moving to an entirely new AUV optimized for a three-year development cycle. The robot had to allow modifications over its lifecycle and break down work into small pieces for many members. The team also accepted a move towards an iterative design process to boost educational opportunities and generate documentation.

Success metrics were tied to the performance of the new robot, called Arctos, at RoboSub 2023 exceeding Auri. ARVP decided that increasing the functional scope of Arctos compared to Auri through new subsystems and a software stack overhaul was preferable to improving the reliability of previously completed tasks. This strategy allows room for improvement in future development cycles on the same platform, despite increasing complexity. Impact on competition performance has been mitigated by increasing administrative focus on design documentation deliverables to garner points.

B. Course Strategy

As outlined in Table 1, Arctos will complete the coin flip task and do a barrel roll. To maintain positional information during these disorienting maneuvers, sensor fusion between both a DVL and IMU is required. [1] This information should update Arctos' position in a mapping module. Motion Control will have to have essentially no steady state error or oscillation – prompting consideration of PID, LQR, and MPC complexity vs deliverable reliability. Discussions can be found in Section II.

Nevertheless, both DVL and IMU sensor drift makes accurate interactions with both buoy images impossible. Consequently, Arctos requires front-facing and bottom-facing cameras to provide additional mapping updates of competition obstacles throughout a course run. In preliminary sprints, ARVP's vision systems revealed minimal technical debt. As a result, pinger use during the torpedoes and octagon surfacing task will be limited to basic applications. Once Arctos is near competition obstacles, it will apply visual servoing to hone in on exact locations; a behavior tree should control this decision-making rather than a state machine to reduce mission planning rigidity. [2]

However, continual use of cameras dramatically drains battery and generates heat. Thus, Arctos requires an increased battery carrying capacity compared to Auri and a dedicated thermal solution. The addition of new claw and dropper subsystems also necessitates ample mounting space and penetrators.

TABLE I. TASK SCOPE OVERVIEW

Task Title	***Strategic Verdict***
Destination Choice	Abydos
Coin Flip	In Scope
Style Points	Barrel Roll
Two Image Buoy Bump	In Scope
Correct Order Firing of Both Torpedoes	In Scope
Remove Lid Cover and Place Droppers	Potentially In Scope
Surface In Octagon	In Scope
Chevron Manipulation	Out of Scope

C. Arctos' Annual Development Strategic Vision

Mechanically, Arctos will require increased interior space, access points, and a dedicated thermal solution. The frame should allow for mounting modularity. New claw and dropper subsystems will be developed, and the mechanical variance will be low over the next three years – so maintainability/simplicity is key.

Arctos requires additional batteries and a minimally viable pinger system. Electrical tech debt is high, so members will be taught how to re-design PCBs with minor quality-of-life improvements. No additional complexity will be added this year.

On Software, a stack overhaul will occur to improve modularity and structure. Critical work packages include motion control, mission planning, vision pipeline, and embedded systems. Packages will be evaluated periodically and complexity will be cut if necessary to mitigate scope creep.

Administratively, the capital exists to procure new sensors, actuators, and manufacturing equipment. Considering the influx of members, iterative design with small work packages are a priority. Documentation should also be emphasized to increase learning opportunities.

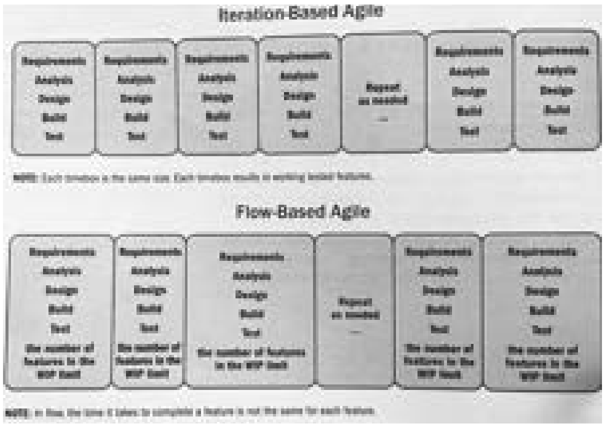

Fig. 2: Iterative vs. Flow Based Agile [3, p.24]

In terms of management, ARVP lacks the historical data required to use Analogous or Parametric Estimating to develop a predictive life cycle with a WBS. [4, p. 183] Additionally, student managed teams lack the stability to accurately manage scope or undertake large-scale bureaucratic processes. Thus, ARVP will apply a flow-based agile methodology. Development should be feature-driven, and members will be managed through meta scrums to avoid formal processes or internal non-technical documentation. [3, p.111]

II. DESIGN STRATEGY

A. *Arctos Overview*

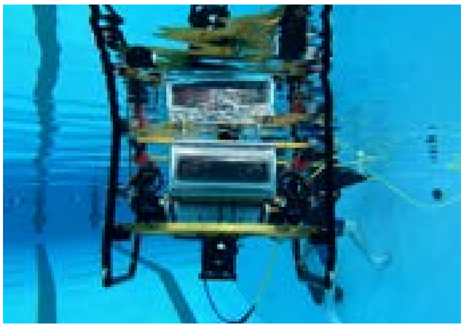

Fig. 3: Arctos as of May 23, 2023 without Subsystems

Artocs employs a rectangular hull machined from bonded aluminum plates with an acrylic front cap, allowing camera vision, and a top lid to access batteries. Both access points are held in place by aluminum straps to maintain o-ring seals. External wiring is routed via penetrators on the hull's rear wall. Arctos' frame is made from stock L-brackets and welded aluminum tubing, creating excess mounting space to test new subsystem designs and configurations.

In addition to a Jetson Orin and other stock components mentioned in Appendix A, Arctos' electrical trays harbor the battery monitoring and carrier board, which draw power from one Lipo battery, convert it into 5V and 12V and power the platform. The remaining four batteries power the 8 thrusters. The communications hub, internal environment, and actuator boards transfer, display, and action data across the platform. While the sonar boards handle pinger detection.

The new software stack is entirely executed in Docker containers, creating consistent and reproducible environments across different machines. Additionally, core dependencies have been updated such as Ubuntu 18.04 to Ubuntu 20.04 and ROS 1 melodic to ROS 2 Humble.

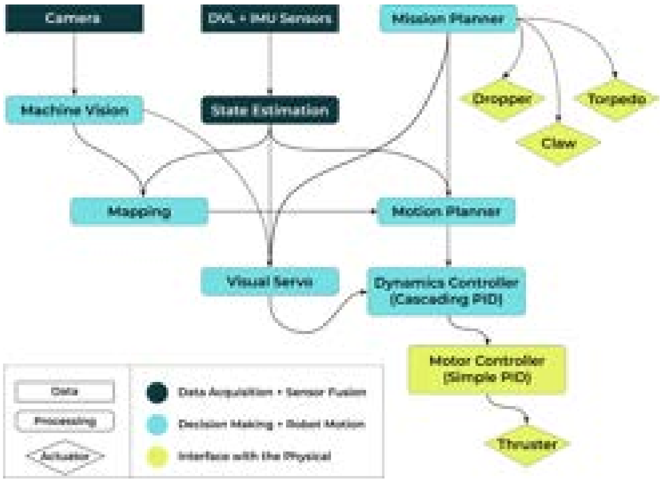

Fig. 4: Software System Chart

B. *Electrical Design Strategy Highlight*

The key electrical deliverable this cycle was the pinger system, which had to be simple while leaving room for expandability to implement signal processing. As the intention was to design iteratively, FPGA was chosen for its capacity to develop software & hardware simultaneously and its allowance of various system trials before finalizing system architecture. [5, p. 16] A colorlight FPGA module was chosen for its form factor and solderability. Additionally, colorlight modules operate using an open-source toolchain, allowing for future redevelopment.

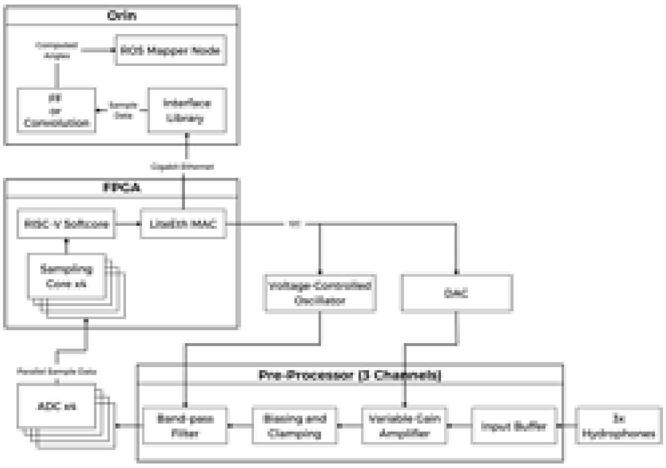

Fig. 5: Sonar System Diagram

The pinger system detects soundwaves through three hydrophones spaced 1.5cm apart. Given the pinger frequency and the speed of sound in water, sound waves reach Arctos with a 3.75cm wavelength. The spacing of hydrophones is less than half a wavelength as relative phase offsets are used to find the angle of detection. [6]

Either FFT or convolution can calculate the phase offset. FFT may be faster, but convolution is more robust against multi-path reflections. Testing strategy details can be found in Section III weighing the options. Nevertheless, a high-sample rate but tightly packed approach was selected to reduce the angular error caused by approximating the pinger signal as a plane wave, as opposed to coarser convolution techniques.

In future development, the pinger system will move FFT/convolution onto the FPGA rather than relying on the Orin Jetson. This may require the use of a sliding DFT to further reduce computational requirements. [7] Furthermore, additional hydrophones may be purchased to eliminate the plane wave approximation.

C. Mechanical Design Strategy Highlight

To generate heat dissipation design requirements, full-throttle tests of Arctos' onboard computer – the Jetson Orin – were conducted and found that operating temperatures reached 90℃ after 40 minutes, exceeding the safe operating temperature of 80℃ on its Thermal Transfer Plate (TTP). [8] Thus, the Orin's TTP was thermally pasted directly to the hull as a heat sink.

$$R_{conv} = R_{total} - R_{cond} = 0.58\,°C/W - \frac{L}{kA}$$

$$\frac{1}{hA} = 0.58\,°C/W - \frac{6.6mm}{(205\,W/m°C)(75mm)(73mm)}$$

$$A = \frac{1}{hR_{conv}} = 0.0295m^2$$

R_{conv} = convective thermal resistance
R_{total} = total thermal resistance
R_{cond} = conductive thermal resistance

h = convective heat transfer coefficient
A = surface area for heat transfer
L = length for conduction
k = conductive heat transfer coefficient

Hull conduction and external convention were considered and benchmarked against the Orin's maximum allowable thermal resistance of 0.58 °C/W. [8] Based on thermal pasted area approximations, theoretical conductive thermal resistance totalled 0.0059 °C/W. Convective resistance calculations assumed forced convection of air at 3m/s. Thus, a minimum conductive area of 0.0295 m2 was determined, which is easily met by Arctos' internal hull surface area. The strategy for heat dissipation confirmation can be found in Section III.

Fig. 6: Basic (a), Parallelogram (b), and Track (c) Claw Prototypes

Claw subsystem design was handled iteratively this year. Initial design requirements were drafted based on mock ups of obstacles and profile restrictions of the frame. Each prototype was physically developed after calculation and design work was complete, in order to build manufacturing prowess on ARVP. Prototype (a) optimized for simplicity with spur gears. Prototype (b) optimized for smooth motion via parallelogram linkages. Prototype (c), chosen based on go/no-go decisions in Section III, optimized for interchangeability and range of motion with parallel grippers along a track.

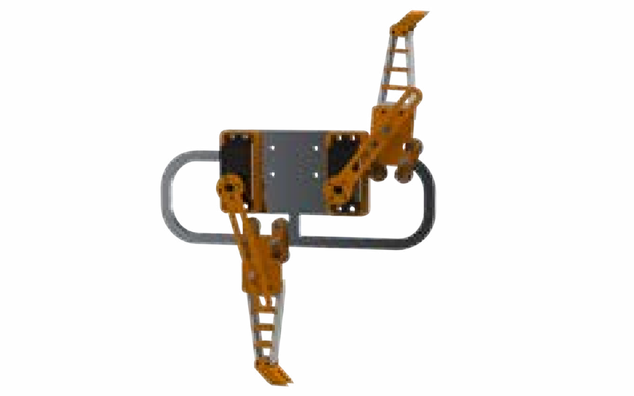

Fig. 7: Soft Gripper Design

For Prototype (c), a soft gripper was manufactured using a frame made of thermoplastic polyurethane (TPU) and cross beams of polyethylene terephthalate glycol (PETG). The design utilizes the Fin Ray Effect, allowing compliant envelopment of objects without embedded actuation. [9]

D. Software Design Strategy Highlight

Previous development platforms utilized an LQR controller. However, lack of documentation restricted improvements to lengthy tuning pool tests. Similarly, discussions with control experts confirmed that adding time horizons to the LQR controller to create an MPC is currently beyond ARVP's technical capacity.

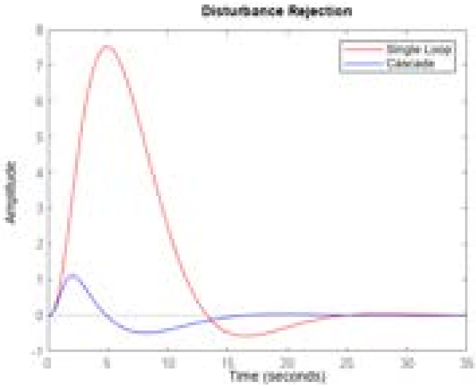

Fig. 8: Representative Improvements to Disturbance Rejection

Thus, Arctos' 2022-2023 dynamics control was overhauled for simplicity. A cascading PID controller is used, with one controller for each of the 6 axes of motion of the vehicle. The controller converts world coordinate targets to targets in the body frame which is used by the independent PID controllers to generate RPM targets for our ESCs.

III. TESTING STRATEGY

A. Electrical Testing Strategy Highlight

As the initial FPGA system objective was to enable maximum simulation testing, the sampler system was end-to-end testing before physical benchmarking or in-water tests. Preprocessor testing centered around isolation of components for root cause analysis of system performance. For board operation confirmation, the preprocessor board will be run until pings are identified on an oscilloscope, then connected to the acquisition system, where ADCs and the sampling system have already been validated.

Performance testing will be run during regular pool tests using FFT. Initial testing will be done by manually rotating the robot to different angles and determining rough accuracy. If the accuracy is reasonable within 20 degrees, precision testing will be conducted by placing the robot in a known location and moving the pinger between marked angles.

As previously stated, vision systems will take over once Arctos can identify competition obstacles. Thus, acceptable final system accuracy is < 10 degrees, and tests will be concluded if accuracy is < 5 degrees. The system should have a theoretical resolution of 1.44 degrees, but 2 degrees shall be used to account for system noise and quantization error. If acceptable accuracy does not materialize within two pool sessions, ARVP will move to convolution methods and consider post-processing spatial filtering to improve data.

B. Mechanical Testing Strategy Highlight

Unfortunately, with electrical trays placed in Arctos during pool tests, accessing the Jetson Orin is nigh impossible. Consequently, the Orin's thermal solution was tested in air with a sealed hull to increase dissipation requirements and match actual operation conditions. The Orin has an internal temperature recorder and failsafe, thus tests were planned to stress the Orin until failure or the one hour mark, which dramatically surpasses standard stressed operation time. Internal temperatures of the CPU were to be recorded every 5 minutes. Any measurement above a safety threshold of 70℃ would be deemed as a failure requiring additional heat dissipation methods.

Fig. 9: Arctos During Heat Dissipation Testing

The maximum temperature recorded during testing was 69.00℃. Considering the test was complete in air without forced convection, ARVP decided to conduct a processing heavy pool test by collecting ROS bags for model training as a cooling performance test. Over an hour of operation, CPU temperatures never exceeded 40℃.

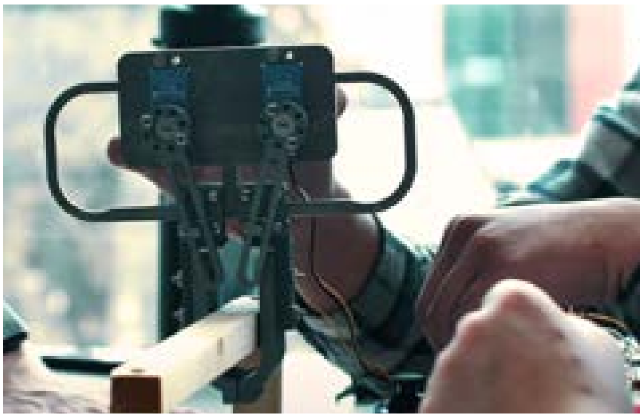

Fig. 10: Track Design Benchmark Test During Introduction Video Shooting

Claw benchmarks for a go/no-go decision was based on a physical pickup test of the dropper bin lids. Qualities used to identify success include servo angle when latched around handles, range of motion, success rates at various instigation angles, and force sensed gripping power. While all three prototypes were capable of lifting the bin cover at various angles, only the track design proved successful at various engagement depths with the obstacle. Additionally, the limited range of motion of both the simple and parallelogram designs reduced the acceptable instigation angles. Thus, the track design was chosen for further refinement and implementation.

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Frankie Mantella - Who serves as ARVP’s industrial PCB development counsel.

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The Water Resources Lab - For access to tanks crucial to continual testing processes.

The Engineering Safety & Shipping Departments - For assisting the creation of travel plans and documentation.

The Engineering Student Society - For financial support in ARVP’s endeavors to further local mechatronics education.

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Altium & Gitlab - For access to enterprise development platforms free of charge.

Finally, ARVP would like to thank all our sponsors for their contributions to our success:

Diamond: Altium, UofA Engineering Program

Platinum: Aramark, ISS Mining Safety

Gold: Copperstone Technologies, Marl Technologies, Nortek, ESS

Silver: Rail Shop Services, UofA Computing Science

Bronze: Gitlab, Calvary Fence, MacArtney, General-Dynamics

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APPENDIX A

BILL OF MATERIALS

***General Component Specifications with Vendors, Spec Sheets, Prices, and Purchase Years are Available on Design Documentation Submission

DESIGNATION	COMPONENT	CUSTOM/ PURCHASED	QTY.
F000-00- Frame Assembly	Frame Assembly	CUSTOM	1
	24"x24.625" frame made from 1" aluminium pipe		2
	1"x1"x0.125" 6061 angle 25" long		2
	1"x1"x0.125" 6061 angle 24" long		2
	1.5"x1.5".0.125" 6061 angle 24" long		2
	1"x1"x0.125" 6061 angle 25.6" long		4
	21.9"x5.9"x0.0625" lasercut 6061 aluminium		2
	0.75"x0.75"x0.125" 6061angle 25.7" long		4
	0.75in x 1.5in Stainless Steel Eyebolt		8
	Aluminum Nylon-Insert Locknut		8
	4.7"x4.2"x0.125" lasercut aluminium		1
	3.5" disk of rubber		1
H000-00- Hull_Assembly	Hull Assembly for Robot 2020	CUSTOM	1
	13.25"x14"x0.25" 6061 aluminium		1
	0.625"x1"x0.25" 6061 tab		4
	custom machined aluminium		1
	8.875"x17.75"x0.25" waterjet cut 6061 aluminium		1
	6.5"x13.25"x0.25" 6061 aluminium		2
	1.25"x1.25"x0.25" 6061 aluminium		8
	8.875"x17.75"x0.25" waterjet cut 6061 aluminium		1
	13.25"x14"x0.25" waterjet cut 6061 aluminium		1
	11.5"x12.375"x0.5" machined aluminium		1
	13.5"x1.5"x7" machined acrylic		1
	Acrylic Front Cap Side Panel		2
	half a 6" diameter extruded acrylic tube		1
	laser cut and bent 3/16" 5052 aluminium		2
	blue robotics vent penetrator bolt		1
	blue robotics vent penetrator plug		1
	blue robotics penetrator bolt		20
	blue robotics penetrator nut		23
	blue robotics penetrator switch bolt		2
	blue robotics penetrator switch dial		2
	SubConn_mcbh 2f		1
	Hex Head 7/16" Screw		1
	MacArtney SubConn 8 pin Series_mcbh8f	PURCHASED	1
	MacArtney SubConn 8 pin Ethernet	PURCHASED	1

	Series_dbh8f		
	1.125"x1.125"x0.5" 6061 aluminium		2
	Pull Handle 1950A200		4
	Steel disk weights		4
	Nortek Nucleus 1000 DVL	PURCHASED	1
E000-00-Electronics Tray Assembly		CUSTOM	1
	Updated Tray Base		1
	Bottom Electrical Tray 11.4"x14.6"x0.2" lasercut acrylic		1
	Top Electrical Tray 11.4"x15"x0.2" lasercut acrylic		1
Battery monitoring board	Battery monitoring board	CUSTOM	1
Carrier Board	Input: 4.5V - 36V , Output: 5V,12V	CUSTOM	1
	5V Converter board		1
	12V Converter board		1
	Communication Hub		1
	Mini FSESC4.20 50A x8	PURCHASED	8
	Internal environment board		1
	Actuator board		1
	Sonar Preprocessor board		1
	Sonar acquisition board		1
	Distribution block		2
	Gigabit Switch		1
	USB HUB		1
	ZED camera	PURCHASED	1
	0.96 OLED display		1
	Ethernet extenders		2
	screw tabs		4
	Camera tab		2
	3DM-GX5-IMU	PURCHASED	1
	Front Cap V2 laser cut and bent 1/8" 5052 aluminium		2
	Front Cap Connector V2 laser cut 3/16" 5052 aluminium		2
Aa00-00-T200 Thruster Assembly	blue robotics T200 thruster	PURCHASED	8
	Shell & motor		1
	Propellers		1
	3D printed vertical thruster mounts		4
	3D printed horizontal thruster mount		4
	Strafe Thruster Mount Top laser cut 3/16" 5052 aluminium		1
	Strafe Thruster Mount Bottom laser cut 3/16" 5052 aluminium		1
Sa00-00-Hydrophone Assembly		CUSTOM	1
	3D printed PETG Mount Bracket		1
	3D printed PETG Mount		1
	Hydrophones	PURCHASED	3
Om00-00-Orin Mount		CUSTOM	1

	Jetson Orin	PURCHASED	1
	laser cut and bent 1/16" aluminium Mount		1
	rubber layer inseam		1
	laser cut 1/16" aluminium plate hex		4
H000-BatteryBasketAssembly		CUSTOM	1
	laser cut and bent 1/16" aluminium basket		1
	laser cut and bent 1/16" aluminium gate		1
Ai00-00-Buoyancy Pod Assembly_2 in x 12 in Lg		CUSTOM	3
	2" Buoyancy Pods ABS Sch. 40		1
	2" Sch. 40 pvc caps		2
M000-00-Marker Dropper Assembly		CUSTOM	1
	3D printed PETG Dropper base		1
	3D printed PETG Dropper Cap		2
	machined aluminum Dropper tip		2
	3D printed PETG Tail Spiral		2
	HS-646WP HiTech Servo	PURCHASED	1
	3D printed part attaches to servo horn		1
Bc00-00-Fisheye Camera Enclosure		CUSTOM	1
	Machined aluminium tube		1
	blue robotics 2" enclosure series flange seal		1
	blue robotics 2" enclosure series flange		1
	blue robotics penetrator bolt		2
	blue robotics 2" enclosure series dome		1
	blue robotics 2" enclosure series retaining ring		1
	laser cut 1/8" aluminium lock		1
	laser cut 1/8" aluminium end lock		1
	Fisheye camera	PURCHASED	1
	3D printed camera mount		1
Torpedoes assembly		CUSTOM	1
	3D printed PETG Main body		1
	3D printed PETG Back		1
	Laser Cut Aluminum Release Plate		1
	3D printed PETG Endcap frot		1
	Laser Cut Aluminum Spring Cap		2
	3D printed PETG Torpedo		2
	High Torque Servo 35kg	PURCHASED	1
	machined Aluminum servo attachment		1
	3/16in Aluminum guide rods		4
	0.5in OD springs		4
Claw Assembly		CUSTOM	1
	Claw Plate Laser Cut From 3/16" Alumimium		1
	Plastic Ball Bearing 6455K97		8
	Cart Plate 3D Printed PETG		2
	3/16" dia. Aluminium Rod		2

	High Torque Servo 35kg	PURCHASED	2
	Servo Horn		2
	Claw Slider 3D Printed PETG		2
	Claw Servo Bumper 3D Printed PETG		2
	Claw Mount Laser Cut From 1/8" Aluminium		1
	Gripper Outer Frame 3D Printed TPU		2
	Gripper Cross Beam 3D Printed PETG		2
	Gripper Cross Beam 3D Printed PETG		2
	Gripper Cross Beam 3D Printed PETG		2
	Gripper Base 3D Printed PETG		1
	Gripper Base Beam 3D Printed PETG		1