Ryerson Rams Robotics: Technical Design Report

Feroz Balsara, Nabila Abraham, Yasamin Ahmadzadeh, Maria Botos, Gabriel Casciano, Karan Guglani, Sy Khaledi, Hamza Mahdi, Omar Shariff, Luka Subotincic, Joseph Wan, Matthew Mirvish

Ryerson University, 350 Victoria St, Toronto, ON M5B 2K3

July 8, 2019

***Abstract*—Felix is Ryerson University's 2019 Autonomous Underwater Vehicle for the RoboSub Competition. In just 11 months, Ryerson Rams Robotics (R3) has designed, manufactured, and tested its very first AUV. Felix's design is remarkably simple allowing us to field a consistent and reliable submarine.**

I. COMPETITION STRATEGY

R3 is a university robotics student group based out of Ryerson University in Toronto, Canada. We are a robotics collective, meaning that we are comprised of several small sub-teams. Each sub-team competes in different competitions, but works with the group as a whole to share knowledge, advance STEM education, and bring new innovations to the robotics community. Throughout the years R3 has built basketball playing robots for a local NBA team, manufacturing robots for Airbus, Mars rovers for the University Rover Challenge, and much more. We strive to push the boundaries of our knowledge, and refuse to settle for "good enough".

Though we have a history of success, we come into RoboSub knowing the difficulty of the competition. As a rookie team we know that overambition in attempting to do all the tasks could very easily lead to not being able to do any of the tasks well. As such, our strategy for 2019 is very simple; we would like to field a submarine that operates consistently and is able to perform the simplest tasks. To determine which tasks to complete the team created a matrix comparing the number of points gained to the perceived difficulty of accomplishing the task. After careful analysis the following routine was determined to be our optimal strategy:

The submarine will start in a known orientation and will then drive towards the gate, aligning itself with the 40% section. It will then drive smoothly through the 40% section of the gate maintaining a fixed heading. Upon clearing the gate the sub will use its hydrophone array to navigate to our requested pinger at the "Stake through the Heart" task and fire two torpedos through the open oval. Finally, we will request the pinger be changed to the one below the octagon to where the robot will navigate and surface.

We also have designed the sub such that it is a platform for future years to build upon without the need to spend time fabricating a new chassis. Careful consideration was given to the configuration of pneumatics, sensor penetrators, and overall chassis design such that future years would be able to easily reconfigure the robot.

II. VEHICLE DESIGN

A. *Mechanical*

Our mechanical design is a product of many months of CAD and simulation prior to any actual build. After determining our basic requirements for maneuverability and manipulation, we brainstormed a few concepts and divided mechanical members into smaller groups to create designs using Solidworks. From there we thoroughly assessed each finished concept through rigorous FEA, various simulations, buoyancy and flow calculations, and thermal performance. Our final design was a single circular flat-topped hull with protruding wings intended to improve planar travel underwater by housing 8 thrusters for 6 degrees of movement. Heat dissipation however proved to be the most influential aspect of the design. We made use of two large acrylic tubes to house all of the internals, coupled together via a large aluminum central body. Milled on a 5-axis CNC, this piece provided the strength to mount all structural components as well as serving as a heat sink for all of the electronics inside. The fact that this component is 5-axis also proved incredibly useful for making custom machined sealing surfaces, improving waterproof wiring pass-throughs, and allowing the control systems to be optimized in favor of our camera geometries. This resulted in a more streamlined and compact vehicle making it incredibly stable while improving on-the-spot maneuverability. The rigidity of the central body supports the wings for reliable navigation, and safe impact absorption from the surroundings.

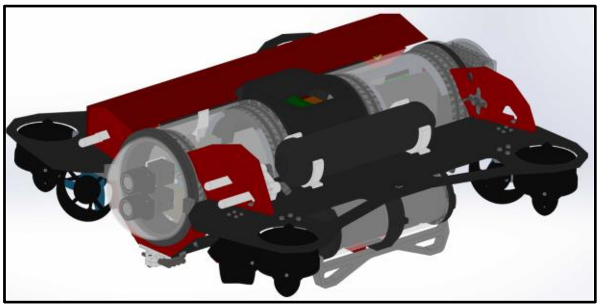


Figure 1: Top view of Felix showing the wings, dual front cameras, and electronics hull.

The central aluminum body also houses the end effector on our submarine. This is highly favorable because it allows the grasping zone of the effector to be aligned directly beneath the center of the submarine, which is symmetrical both front to back and side to side. From a controls perspective this results in much simpler movement since the same action going in one direction can be symmetrically applied to the opposite thrusters.

Our end effector itself is unique in that it is built around the function and form factor of our downward facing camera. Below the exact center of the submarine is a camera, and around its field of view the end effector rests in a non-obstructing retracted and open position. Once the submarine locates an object below itself, the sub can reposition itself accurately before actuating the gripper. This was done to make programming and reliability as robust as possible, eliminating as many unnecessary correctional movements as possible for aligning and interacting with objects. The end effector itself is made from flat CNC machined plate parts and is also symmetrical to keep the software simple.

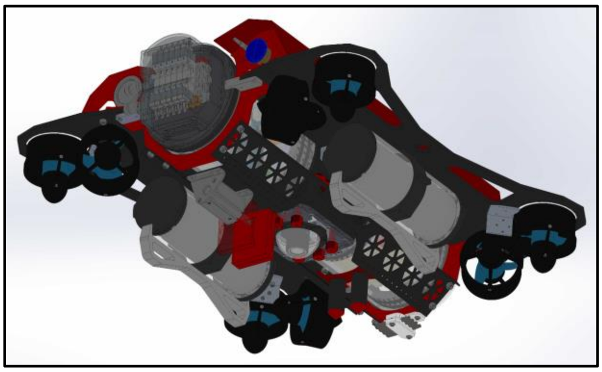


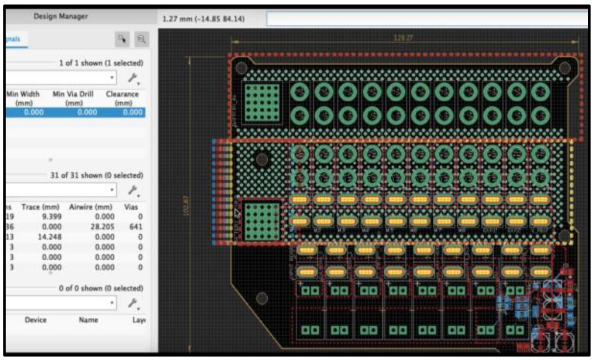
Figure 2: Bottom view of Felix showing gripper, downward facing camera, and solenoid housing.

B. *Electrical*

We have chosen the Nvidia TX2 as the primary processor for its computational power and low power consumption, paired with a ConnectTech Orbitty carrier board which also offers a small form factor ideal for our tightly packed hull. The TX2 utilizes Ethernet to communicate with the rest of the system through an off the shelf ethernet switch. For data collection from various sensors and output to solenoids and thrusters, we decided to use two STM32 Nucleo boards to simplify the design process and to allow us to focus more on building a robust control system. Each subsystem features a custom shield for its specific application, thus allowing us to test each independent of the other.

The input subsystem takes data from the 2 main sensors on the submarine, communicating with the pressure sensor over I2C and the IMU over serial. The power monitoring system utilizes the 12-bit ADCs onboard the microcontroller to monitor how much power is being sent to each thruster, and the voltage levels of the two batteries. The output subsystem communicates to the ESCs via PWM and triggers the pneumatic solenoids via a simple MOSFET circuit. Both the input and output systems were designed with expandability in mind, thus, each system has extra ports available for the future should we choose to add more sensors, thrusters, pneumatics, etc.

Our system features a unique all in one power distribution system, that consists of a single 6-layer custom PCB to distribute power to all 8 thrusters as well as regulate the battery voltage to a 12-volt rail to supply power to the various subsystems. From there each subsystem regulates the voltage down to the level required for each systems application. Although we don’t utilize a DVL, the power distribution board was designed for it with a 12 to 24 volt boost converter available should we choose to add the DVL in years to come.



1 of 1 shown (1 selected)

Min Width (mm)	Min Via Drill (mm)	Clearance (mm)
0.000	0.000	0.000

31 of 31 shown (0 selected)

ns	Trace (mm)	Airwire (mm)	Vias
19	9.399	0.000	0
36	0.000	28.205	641
13	14.248	0.000	0
3	0.000	0.000	0
3	0.000	0.000	0
3	0.000	0.000	0

0 of 0 shown (0 selected)

Device	Name	Lay

Figure 3: Power distribution board design

The hydrophone subsystem utilizes a Raspberry Pi Compute Module 3 (CM3) as its primary processor, the CM3 then communicates to a MAX10043 16-bit simultaneously sampling ADC through a high speed SPI protocol. Each hydrophone signal is first passed through a simple RC filter to remove low frequency noise, afterwards the signal is then amplified through a 65dB gain preamp. After the signal has been processed it is then fed into the ADC where the signal can be digitized at a rate of 800k samples per second, where special software determines the heading.

C. *Software*

The software system is composed of 3 major blocks: control, sensing, and execution. These three blocks all connect to each other using ROS [3], and combined form our autonomous system. The sensing system is composed of two sub-components: the odometry system and the vision system. The odometry system is based around an unscented kalman filter, fusing data from the IMU, pressure, and cameras to produce a pose in 3D space. Specifically, the down-facing camera is put through a novel monocular odometry algorithm based on [1].

The vision system uses data from both the front-facing stereo and down-facing monocular camera to identify task elements including the gate, path segments and buoys. For most of these elements we still use traditional computer vision methods instead of machine learning simply because it was too unreliable in our testing and required large datasets. The positions of task elements are recovered from images and then converted to 3D with the help of the odometry system and placed as coordinate frames in TF [4].

The control system is responsible for converting the high-level navigation commands - like setpoint regulation and trajectory following - into raw commands being sent to thrusters. At the core of this system is a Cascaded Proportional Integral Derivative controller (CPID), which keeps the simplicity of normal PIDs while proving to be much better than normal PIDs in tests, especially for setpoint regulation. The output of the PID is then run through the submarine’s dynamical model, heavily based on [2]. This approach has proven both in simulation and in reality, to be both simple and effective.

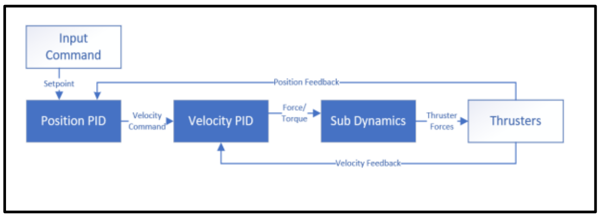


Figure 4: Control system block diagram

The two systems are combined at a high level by the execution system. This system takes in the observations made by the sensing system and tells the control system how to move the submarine. This is where all of the task-specific autonomy is implemented using a state machine, powered by the smach library [5].

In order to facilitate software development, we keep our code in version control on GitHub, as well as doing per-commit build testing to ensure all code will at least run. This cuts down on code failing to compile during the often time-limited testing windows.

III. EXPERIMENTAL RESULTS

Three primary methods of experimentation were used during the development of the sub: Finite element analysis using Solidworks, digital simulations of competition tasks using Gazebo, and practical testing in water. The combination of these methods have ensured the reliability of the system while highlighting potential issues.

Stress analysis simulations were used to determine the optimal size and shape of the wings. The analysis was particularly useful in determining the placement of the anchor points or handles. Results of the simulation showed that raising the sub via anchor points located at the front and back of the wings would require additional reinforcement of the wings, increasing weight and making accumulator mounting more difficult. After further studying the issue, the optimal location of the anchor points was found to be on the sides of the sub eliminating the need for additional reinforcements. Without these studies the design may have resulted in bending of the aluminum wings, leading to a potential leak or failure during lifting.

Due to limited access to pools, the team utilized a modified version of Gazebo to simulate the sub in water. The simulation included a simplified model of the sub and elements of the competition. Although the model is simplified, the location of all critical sensors, such as the IMU, hydrophones and thrusters are accurate. This allows for accurate simulation of full competition tasks without entering water. This dramatically reduces test times for new versions of code by identifying issues with the algorithm, and aids in our rapid development of new code.

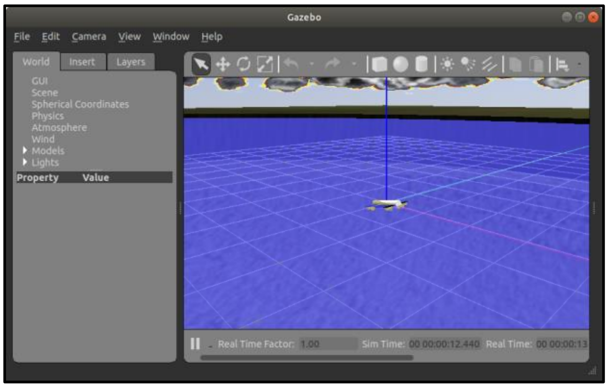


Figure 5: Sub simulation in Gazebo

Despite the convenience of the previous methods, the most effective testing method has proven to be physical testing in water. Early component testing of the sub began in August 2018 with initial versions of the torpedoes and markers. This testing helped determine the optimal geometry of the torpedo's for accuracy and optimal pneumatic pressure for distance. By February 2019, the team utilized an early prototype for in water testing named Franklin. The wings for Franklin were made from laser cut acrylic, and the electronics were stored in a watertight Pelican utility case. The tests with Franklin showed many potential issues with the final design of the sub including the location of the tether, the need for more vertically oriented directional thrusters, and the effect of battery placement. Franklin also revealed that the simulations in Gazebo were extremely accurate.

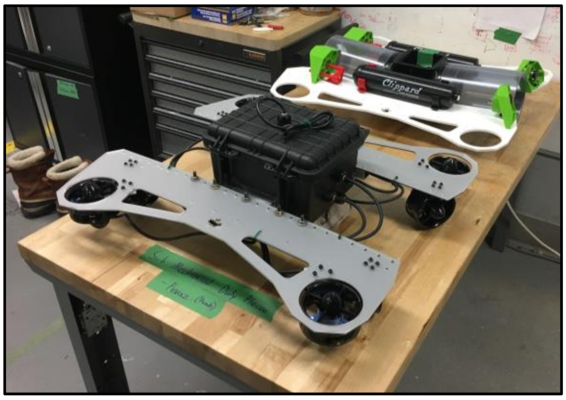


Figure 6: Sub prototypes - Franklin (front) and Francine (back, last prototype made before Felix)

The final phase of practical testing has begun with the completed sub, Felix. Extensive testing was done with Felix revealing initial areas of water ingress. Felix is now water-tight and has begun water-based tuning and calibration to ensure accurate movement in competition. Going forward, R3 will continue to test Felix in water, adding more game elements until the competition.

Figure 7: Testing Felix underwater

IV. ACKNOWLEDGEMENTS

R3 would like to thank Ryerson University and the Faculty of Engineering and Architectural Science for its support during the past academic year. Specifically the team would like to thank Joseph Amankrah and Peter Bradley for their tireless support and wisdom. Additional thanks to NeuronicWorks Inc. for their support and mentorship of this team throughout the design process. Finally, we send our gratitude to all our generous sponsors.

V. REFERENCES

[1] V. Creuze, “Monocular Odometry for Underwater Vehicles with Online Estimation of the Scale Factor,” in *IFAC 2017 World Congress*, Toulouse, France, Jul. 2017. [Online]. Available: https://hal-lirmm.ccsd.cnrs.fr/lirmm-01567463.

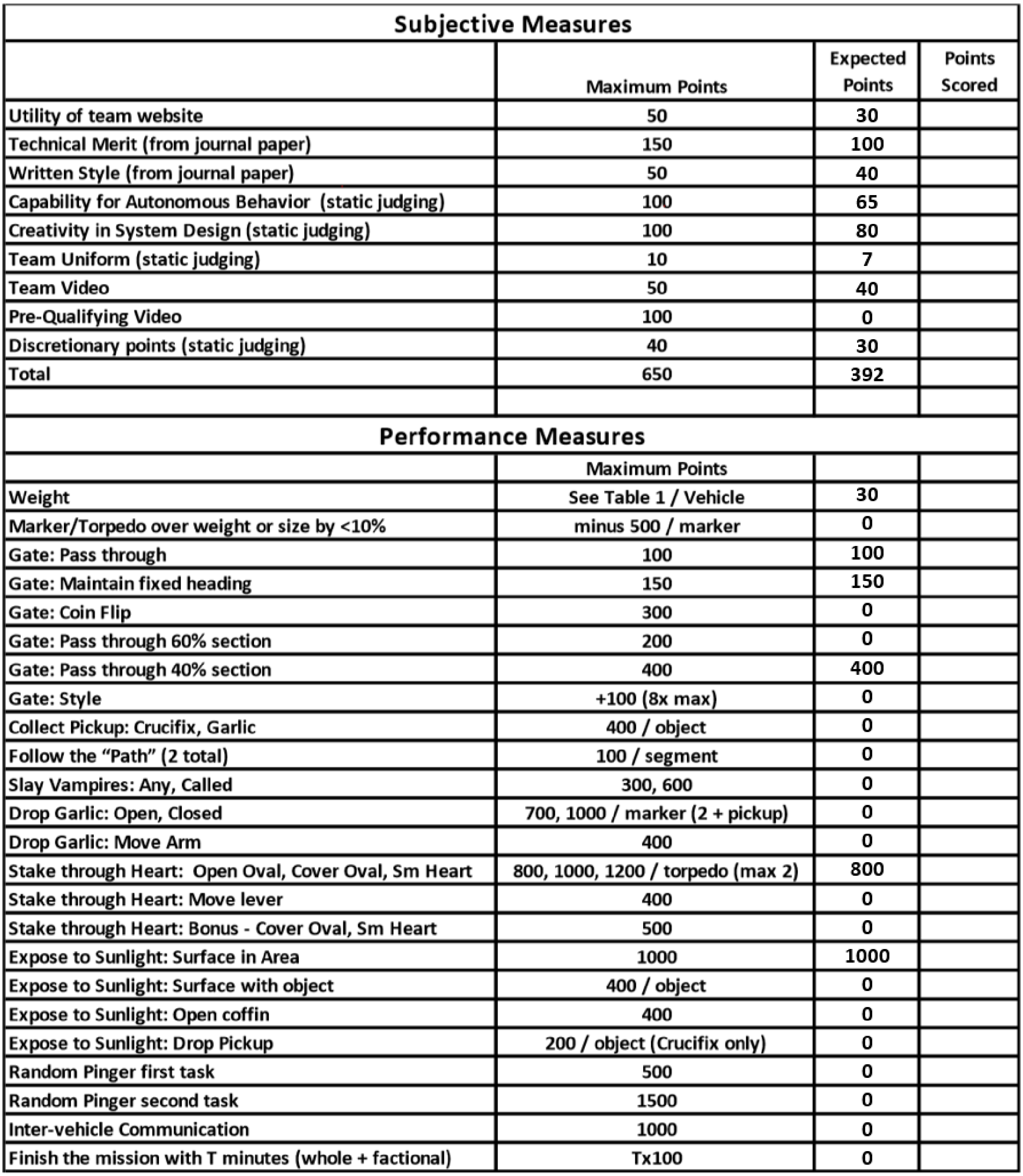
[2] T. I. Fossen, *Guidance and control of ocean vehicles*. John Wiley, 1999.

[3] M. Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, “ROS: An open-source robot operating system,” in *ICRA Workshop on Open Source Software*, 2009. [Online]. Available: http://www.willowgarage.com/sites/default/files/icraos09-ROS.pdf.

[4] T. Foote, “Tf: The transform library,” in *Technologies for Practical Robot Applications (TePRA), 2013 IEEE International Conference,* ser. Open-Source Software workshop, Apr. 2013, pp. 1–6. DOI: 10.1109/TePRA.2013.6556373.

[5] J. Bohren and S. Cousins, “The smach high-level executive,” *Robotics and Automation Magazine*, IEEE, vol. 17, pp. 18–20, Jan. 2011. doi: 10.1109/MRA.2010.938836.

APPENDIX A: EXPECTATIONS



Subjective Measures

	Maximum Points	Expected Points	Points Scored
Utility of team website	50	30	
Technical Merit (from journal paper)	150	100	
Written Style (from journal paper)	50	40	
Capability for Autonomous Behavior (static judging)	100	65	
Creativity in System Design (static judging)	100	80	
Team Uniform (static judging)	10	7	
Team Video	50	40	
Pre-Qualifying Video	100	0	
Discretionary points (static judging)	40	30	
Total	650	392	

Performance Measures

	Maximum Points		
Weight	See Table 1 / Vehicle	30	
Marker/Torpedo over weight or size by <10%	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)	0	
Collect Pickup: Crucifix, Garlic	400 / object	0	
Follow the “Path” (2 total)	100 / segment	0	
Slay Vampires: Any, Called	300, 600	0	
Drop Garlic: Open, Closed	700, 1000 / marker (2 + pickup)	0	
Drop Garlic: Move Arm	400	0	
Stake through Heart: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	800	
Stake through Heart: Move lever	400	0	
Stake through Heart: Bonus - Cover Oval, Sm Heart	500	0	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with object	400 / object	0	
Expose to Sunlight: Open coffin	400	0	
Expose to Sunlight: Drop Pickup	200 / object (Crucifix only)	0	
Random Pinger first task	500	0	
Random Pinger second task	1500	0	
Inter-vehicle Communication	1000	0	
Finish the mission with T minutes (whole + factional)	Tx100	0	

APPENDIX B: COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control				
Frame	Viking Machine	Waterjet Aluminum	Custom	Sponsored
Waterproof Housing	Protocase	CNC Machined	Custom	Sponsored
Waterproof Connectors	Blue Robotics	M10 Penetrators	Custom Bored	$4.00 each
Thrusters	BlueRobotics	T200	~11.2 lbf of thrust	$169.00
Motor Control	BlueRobotics	Basic ESC		$25.00
High Level Control	Custom			
Actuators	SMC	Various		~ $35.00
Propellers	Supplied with thrusters			
Battery	BlueRobotics	BATTERY-LI-4S-18AH-R2-RP	18 Ah @ ~14 V	$289.00
Converter & Regulator / Distribution	Custom			
CPU	Nvidia	TX2	256-core GPU, 4-core ARM64 CPU, 8GB ram	$479.00
Internal Comm Network	D-Link		8-ports	~$30.00
Comm Interface	Ethernet			
Programming Languages	C++, Python, C			
IMU & compass	LORD	3DM-GX5-25	500hz, .1 degree, 0.02 mg resolution	~$1500.00
Pressure	BlueRobotics	Bar02	accurate to 4 cm, resolution of 0.16mm	$88.00
Cameras	FLIR (was Pointgrey)	BFLY-PGE-14S2C-CS	ethernet interface, 1.5mp resolution	$309.00
Hydrophones	Aquarian Audio	AS-1	1hz-100khz +/- 2dB	$395.00
Manipulator	Custom			
Open source software	ROS, OpenCV, Eigen			

APPENDIX C: OUTREACH

R3 is not just an engineering design team, we have members from almost every faculty at the university including arts, science, business, and humanities. We draw on this diverse member-set to create connections with groups that otherwise may not interact with engineers or STEM fields. This mix of skills creates unique and impactful insights into many aspects of design approach that are often overlooked.

Most recently R3 helped found a FIRST robotics team for children from communities with low STEM enrollment. We invited middle school and high school students from all over the province- some who have never even held a screwdriver, to come to our workshop three times a week and work with us to build a robot for the FIRST Robotics Competition. The project was a huge success with the team winning awards at all the district events they attended, including leading their alliance to two upset victories at the Ryerson FRC District. Several students we mentored now want to pursue STEM fields, with one member choosing to pursue engineering at Ryerson this year.

In addition, the team is a huge presence in the community having been featured at countless conferences, industry sponsored events, maker fairs, and hosting high school robotics competitions. We are a continual presence at the Ontario Science Center, and our demos are often the most popular event with adults and children alike. Beyond in person events the team has been featured on national television at least once per year since its inception, and has been featured in numerous online and print publications.