California Institute of Technology RoboSub 2021 Technical Design Report

Allie Cheng, Zane Taylor, Elise Liu, Sandra Chea, Irene Crowell, Josh Hejna,
and the rest of the Caltech Robotics Team

***Abstract*—Like many others, the Caltech Robotics Team was only able to work remotely this year due to the COVID-19 pandemic. With this opportunity to focus on new developments, we prepared for RoboSub 2021 by following two guiding principles: (1.) Improve the vision and navigation of our existing subs, Flo and Deb, in order to improve our ability to score points during in-person competitions, and (2.) Develop Gerald, a new fully functional and capable sub, that will be used to replace Flo, thereby maximizing our point-scoring potential. By competing with Deb and Gerald together, two subs specifically designed for cooperative operation, we hope to divide and conquer the competition tasks. Specifically, the software team focused on improving navigation and vision: further developing our use of an extended Kalman Filter (EKF) and improving the robustness of detections by applying machine learning techniques to more cases. The electronics team continued to assemble Deb's boards and conducted hydrophone transmitter testing, using an emulator to simulate communication between two subs. The mechanical team used SolidWorks and FEA analysis to design and test our newest sub, Gerald.**

I. Competition Strategy

Given that we were working remotely due to the COVID-19 pandemic, the team approached the season with two leading principles to our competition strategy: (1.) Continue to develop the software and electronics on our existing submarines to be able to accurately and consistently complete recurring competition elements, such as following a path or hitting buoys, and (2.) further our goal of having two submarines in the water by designing a new sub, Gerald, that can be used in the water with Deb and allow us to retire our oldest sub, Flo. Our team split to divide their time across these two principles, with the software and electrical team working mainly to improve our current subs, Deb and Flo, while the mechanical team developed a new sub, Gerald.

While the specifics of the competition tasks and elements change from year to year, the general concept of the challenges stay the same. Our goal for each in-person competition is to be able to complete the following tasks:

(1) Passing through the gate, with style points
(2) Following the path
(3) Hitting buoys
(4) Dropping markers
(5) Following the random pinger
(6) Surfacing in the octagon
(7) Shooting torpedoes
(8) Picking up and manipulating game elements

Because of this, at the beginning of our season this year, the electrical and software teams decided to focus on improving the ability of our current subs, Flo and Deb, to complete these tasks. The electrical team focused on finishing boards for Deb, as well as developing the hydrophone system, which will be used for communication between the two subs and for the random pinger task. This development involved the creation of an emulator, which was used to simulate the transmission of signals between two subs in motion. The software team focused on increasing the accuracy and precision of our vision and navigation system through the addition of learning algorithms for keypoint estimation and color segmentation, and updating of our state estimation procedures.

In addition to improving our current subs, having two submarines is another vital part of our competition strategy, allowing us to complete more tasks in the given time limit and score more points. In past years, we planned to compete with Deb and Flo in the water, where Deb is able to communicate with Flo and give her direction as needed. Flo, who was designed as a solo sub, would only be able to receive Deb's commands and would not be able to send any of her own. However, Flo is a few years old, and we have run into increasing difficulty with her as her technology ages and begins to fail. As she gets older, more and more time is spent on troubleshooting her already existing capabilities, taking away from time that could be spent on developing novel systems to improve the capabilities of both subs. In order to have two truly functional submarines in the water as soon as possible, the team decided to start working on a new submarine, which could compete with Deb as Flo is slowly retired. For this reason, a large portion of the work the mechanical team did this year was designing a new submarine, Gerald, and running various simulations to test the submarine under expected loading conditions. The design and simulation work done this year has prepared us to begin manufacturing in the coming season.

II. Vehicle Design (Novel Aspects)

A. Mechanical

In 2020, as things shut down due to the COVID-19 pandemic and students were told to leave campus, our mechanical team switched gears from finishing the assembly of Deb, the sub that we had planned on putting in the water with Flo to compete at Robosub 2020, to designing our newest sub: Gerald, shown in Figure 1.

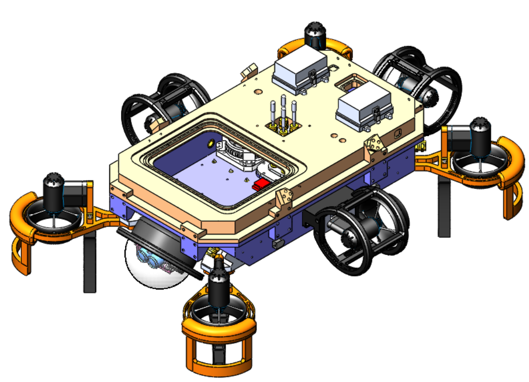

Fig. 1. CAD of Gerald.

When designing Gerald's hulls, we drew upon our knowledge from working with Deb and Flo and what aspects of their designs are unfunctional or inconvenient. These design aspects can be categorized as a few key hull components that we used as guiding principles for designing Gerald: more usable internal mounting space, improved vision for more accurate localization and navigation, a flexible hull that could allow for design changes even after manufacturing, and battery pods.

One of Deb's most unique features is her "+"-shaped design. While this was an interesting design problem on paper, it is not very practical in actual use: the "+"-shape resulted in a small internal footprint, reducing the available space for mounting our electronics package or other internal sub components. To resolve this, for Gerald, we decided on returning to a "box"-style design, i.e a rectangular main hull, which yields a larger internal cavity (Figure 2). Along with having a larger internal cavity, box designs are also more simplistic and durable and have fewer points for potential watertight failure. The main concern for a sub with a large internal cavity is being overly buoyant. However, we are able to counteract this by machining the hulls out of aluminum alloy, rather than other materials that may have a higher strength-to-weight ratio. Aluminum is cost-effective and has an optimal density that is able to provide adequate weight to counteract the buoyant force.

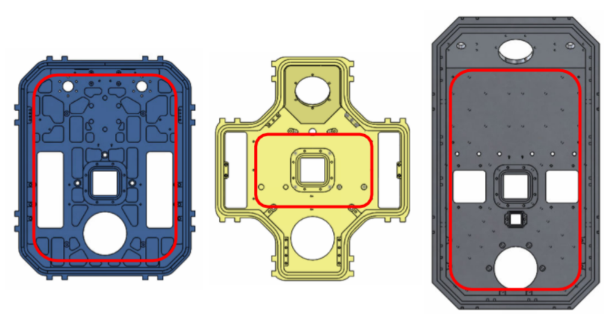

Fig. 2. Hull internal mounting space capability of Flo, Deb, and Gerald. We see that subs with "box"-style designs, like Flo and Gerald, have a larger usable internal cavity than subs with "+"-shaped designs, like Deb.

To improve Gerald's vision, we are incorporating a multi-camera system (Figure 3). The lower hull contains a fixed large camera dome, which holds a servo-driven gimbal camera enclosure (Figure 4) for a permanent pair of stereoscopic cameras. From using similar gimbal camera systems in the past, we know that the system's main downfall is limited visibility directly underneath the sub, making it difficult to complete tasks such as tracking an object as the sub tries to grab it with a manipulator. To eliminate this blind spot, we have designed Gerald to have an additional removable secondary "belly" camera (callout in Figure 3) which sits on the bottom face of the lower hull. This rotating "belly" camera will provide direct observation for activity beneath the hull that the primary camera cannot see. This will provide an additional point of reference for aligning Gerald over marker targets or other visual targets.

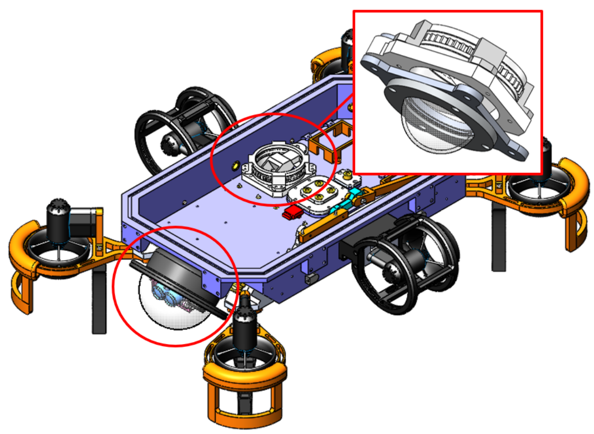

Fig. 3. Multi-camera system. This includes a dual stereoscopic camera gimbal in Gerald's large front dome, as well as an additional "belly" camera, mounted directly on his bottom hull.

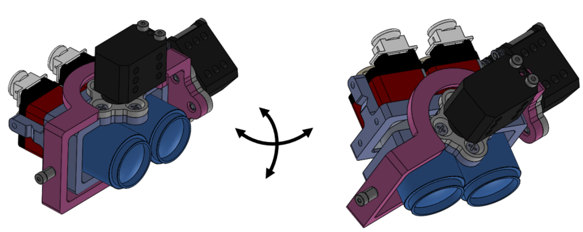

Fig. 4. Servo-driven camera gimbal inside front camera dome. The gimbal allows for independent rotation about two axes.

Gerald's removable "belly" camera is part of the sub's new "multiport" system. A novel design being introduced with this sub, the multiport system provides flexibility to the hulls, even after the manufacturing process has been completed. Typically, once a hull is manufactured, there is no room to introduce new additions or functionality without disassembling the sub and milling directly into the hulls, which is very risky and, in the worst case scenario, could compromise the sub's ability to hold pressure. With Gerald, we introduced the concept of multiports: larger rectangular ports on the lower hull that can be sealed with a rectangular plate, as shown in Figure 5, or with another interchangeable plate, such as one that contains extra servo ports or small footprint sensors (e.g. sonar) or one that contains a secondary camera. Multiports enable modification of hull accommodations post-manufacturing, giving Gerald the ability to accommodate features that could not be anticipated during the initial design phase and that cannot otherwise be easily added after construction.

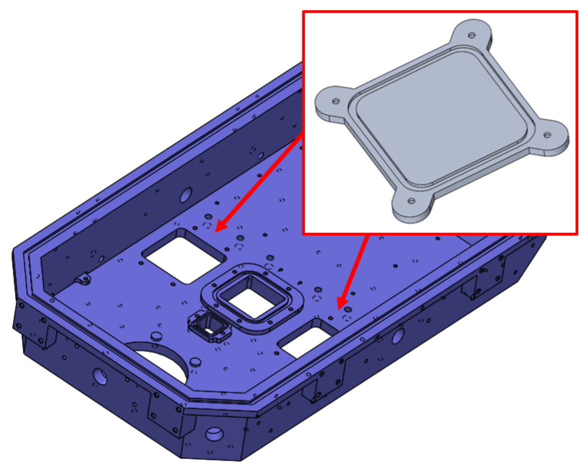

Fig. 5. Multiport system in bottom hull.

Another of Gerald's novel concepts is the further development of battery pods (Figure 6). These battery pods allow access to the batteries through two small hatches on the upper hull, so the batteries can be removed without having to open the main hulls. This reduces the chance of water getting inside the sub while swapping batteries and limits the jostling of electronics. We had explored the idea of battery pods with Deb, however those pods wound up being unfunctional due to inconvenient latch placement and incorrect pod size. With Gerald, we have resolved these problems by correctly sizing the pods to provide adequate room for the batteries, as well as mounting the latches in an easily accessible location on the sub's upper hull, rather than on the sub's crowded underbelly.

While designing Gerald, we considered the manipulators that would be mounted externally. In

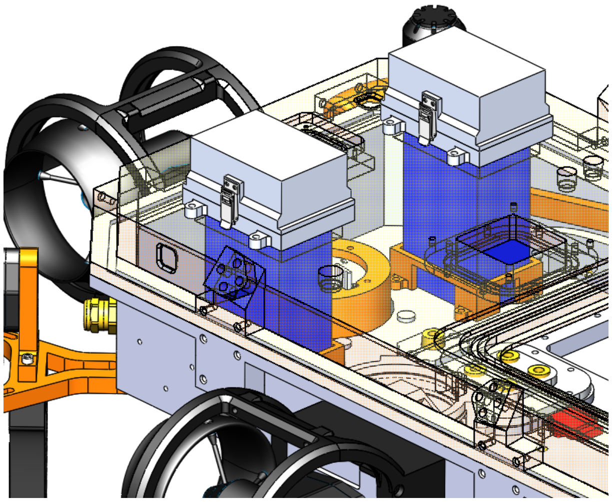

Fig. 6. Battery pods on Gerald.

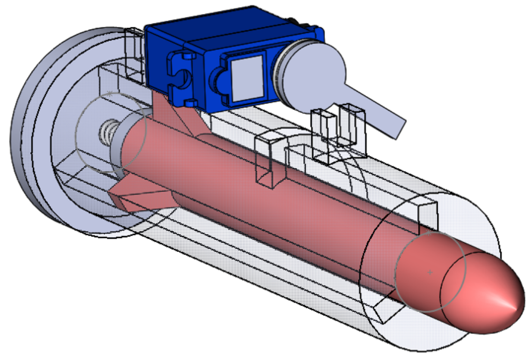

Fig. 7. Torpedo launcher concept.

particular, we wanted to develop a servo-actuated torpedo launcher. Flo had an unactuated torpedo launcher because she had too few servo ports to actuate both our gripper and a torpedo launcher. The mechanism would drop torpedoes after being driven into and making contact with a specific pool element. While non-traditional, this torpedo launcher was very accurate and worked consistently during our tests. However, with Gerald, we wanted to return to a more traditional actuated torpedo launcher system to see if we could design a mechanism that would work just as accurately and consistently as the unactuated mechanism on Flo. An actuated torpedo mechanism would also allow us to launch torpedoes from farther away, a better vantage point for the sub's visualization systems. The currently proposed design uses a servo arm to hold a specialized torpedo within its chamber until it is ready to be launched (Figure 7). When the target is in sight, the servo arm is moved out of the way, and a spring releases, pushing the torpedo out of the chamber and through the target. Once we are able to test in water, we will continue to develop the specific geometry of the torpedo to ensure that it is able to move in a controlled line through the water.

B. Electrical

The electrical systems of the sub are designed to allow the computer to communicate with various sensors and motors while also isolating potential problems in the sub. The electronics are soldered on PCBs, which have functions ranging from supplying power to other boards to interfacing with different sensors and servos. The sub is powered by two 26 volt LIPO batteries: one of these powers the computers and sensors, while the other powers the thrusters and motors. The power supply is split in this way so that problems with the motors do not affect the performance of the computers. Any other voltages needed for our sensors and motors are generated on those boards. The computer uses serial ports to communicate with peripherals. Custom boards with STM32 microcontrollers do sensor signal processing before relaying the information back to the computer.

In past years, we have noticed that the force exerted by the thrusters is dependent on the voltage of the batteries. Because of this, one novel feature we have been working to develop is to monitor the battery voltage levels during operation and use this battery voltage measurement to compute the thrusters' force. By doing this, we can keep changing battery voltage from affecting our controls systems.

Since working remotely due to COVID-19, we have used the NumPy Python package to develop an emulator that simulates the transmission of signals between two subs in motion. The emulator simulated the full channel: modulation and transmission of the signal from one sub, as well as detection and demodulation of the signal on the other sub. This allowed us to analyze how the movement of the subs shaped the waveform from transmitter to receiver. We have used this emulator to test various communication schemes and have designed our hardware around the schemes that have shown to work best during testing, i.e. the simulator indicated which schemes had more bit loss and desynchronization at higher bitrates. So far, we have tested Differential Quadrature Phase-Shift Keying (DQPSK), Frequency Shift Keying (FSK), QPSK with two simultaneous frequencies, and Orthogonal Frequency Division Multiplexing (OFDM). OFDM showed to be best with regards to having minimal desynchronization issues, and thus reducing bit loss. We plan on continuing to develop the emulator, allowing it to account for deformation of the signal, which is commonly caused by reflection off surrounding surfaces.

The current design for transmitter implementation consists of a microcontroller, Direct Digital Synthesis (DDS), filter and amplifier, and lastly the hydrophone transducer. The phase/frequency modulation (whichever ends up being best from the ongoing emulator testing) is done with the microcontroller, and then the DDS will convert the digital output to a corresponding sine wave.

C. Software

In order to save time and increase productivity as we move forward with future in-person competitions, the software team focused on making changes to the three main aspects of the software used across all our subs: state estimation, control, and visual object detection. Since all our subs use the same software base, improvements made this year can be carried through to future years, regardless of what sub the team is using.

1) State Estimation: We use DVL velocity measurements and AHRS orientation data as inputs to create a 12-dimensional extended Kalman Filter (EKF), which we use to estimate our sub's pose in the water. The EKF uses the sub's dynamics to predict the sub's motion through water, even between sensor updates, such as the DVL that updates at a frequency of 1-hertz. The EKF's predictions are fairly accurate because the sub is moving slowly enough that many effects are approximately linear (thus fitting the EKF's conditions) for the timesteps we are working under.

This year, we have begun work to better handle orientation updates. Handling predictions of orientation properly while avoiding gimbal lock requires using quaternions in the sub dynamics. To properly handle linearization of quaternion operations, we have begun a significant reformulation of the EKF itself [1].

2) Control: Instead of using a PID control to guide our submarines through the water, we use Drake's Linear Quadratic Regulator (LQR) solver to implement an LQR, which is a provably-optimal control scheme for multidimensional linear systems [2], visually described in Figure 8. This is due to how LQRs leverage a model of the sub to take full advantage of the system dynamics.

Our 18-dimensional LQR controls the six translational and angular errors, the six integrals of those errors, and the six rates of change of those errors. Since the vehicle's dynamics are non-linear, we must discretize the system by locally linearizing the vehicle's dynamics about the target state before we can solve for optimal LQR gain, K. We then analyze our computed controls to address thruster saturation. To do this, we use the following prioritization scheme. The output of the LQR controller is decomposed into four components: (1) forces required to keep the sub static, (2) other vertical forces, (3) all other torques, and (4) all other forces. Using this breakdown, the software sums up, in this order, as much as possible of each component that can be added while staying below the thrusters' thrust caps.

Experimentally, this controller was far superior to even our best-tuned PID control systems. In addition, tuning the cost matrices for the state errors and the controls, Q and R, is nearly trivial; it took only twenty minutes to tune our LQR controller compared to PID controllers, which took many months on previous vehicles. The controller has performed well enough that we have not made significant changes this year.

3) Visual Object Detection: Our object classification algorithms use a combination of classical higher order features such as colours, contours, and edges, as well as point features such as SIFT descriptors, machine learning approaches such as the Convolutional Neural Net (CNN) You Only Look Once (YOLO) [3] and a novel Gauss-Newton

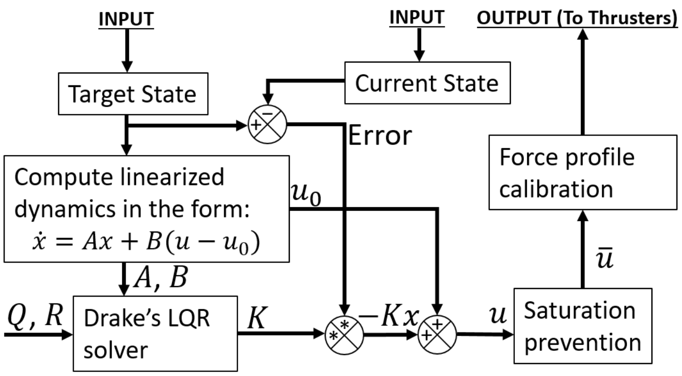

Fig. 8. 6-DoF controller diagram. The dynamics are linearized about the target state to compute the LQR gain, which is applied to the error term to compute the control output.

minimization algorithm used to localize and verify the structure of rectangular detections.

When approaching competition tasks from afar or when approaching tasks with complex features, such as buoys with pictures, we have found the YOLO CNN to be the most effective. However, it is very slow (1 FPS on the Intel Nuc) and is also unable to extract orientation information from the target. Because of this, we must use other methods for fine-grained approaches closer to the target. Once we are close to the target, colors and other high-level features such as circular and rectangular shapes become more clear, allowing us to use different static or adaptive thresholding techniques to identify them. Once identified, if we are able to see any rectangular shapes, such as the outline of bins, we can find the 3D orientation of the object using multipoint Gauss-Newton minimization to find how skewed and rotated the object is. This allows us to figure out where a normal vector facing out of the object would lie. With this, we are able to align to the target and complete close-range tasks, as shown in Figure 9. This reprojection is also useful for identifying and rejecting outliers; for instance, if we find a detection that claims that the bins are facing sideways, we know that this is most likely a misdetection and should be ignored.

However, a major flaw with thresholding methods is that they rely on color information that varies significantly from our test environment to the TRANSDEC, making it difficult to find parameters that perform well in both environments. In the past,

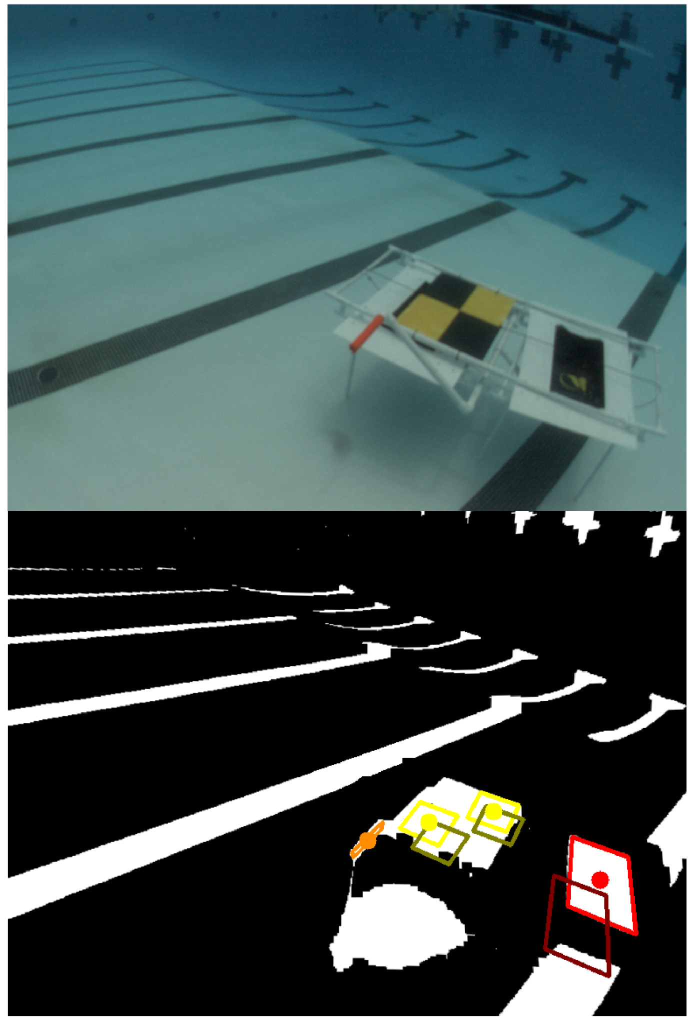

Fig. 9. Example of detector using Gauss-Newton minimization to extract the orientation of the marker bin and the marker bin cover. The dots represent the center of each validated contour, and the brighter rectangles represent the detected rectangular region. The darker rectangles are the projection of the estimated pose; they are what is "behind" the detected rectangle. Here, the red rectangle is the black inside of the bin, the yellow rectangle is the yellow rectangular portions of the cover, and the orange is the bin handle. The white regions are potential areas of interest.

we explored color reproduction approaches based on physical models [4].

This year, we developed two additional approaches.

The first is to apply a neural network to the color-segmentation problem. Our network, based on YOLACT (Figure 10), integrates global image information into the decision for each pixel [5]. With contextual color information accounted for, performance should be more robust to environment changes.

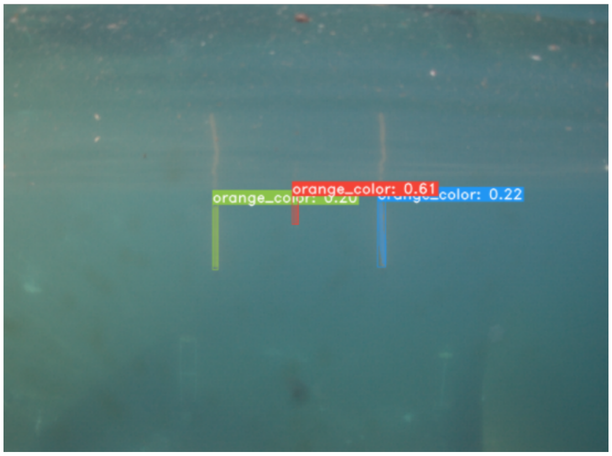

Fig. 10. Our YOLACT++ based semantic segmentation extracts all orange regions from the image at pixel granularity, and does so with the added robustness of a learned detector, outperforming a hand-tuned implementation.

The second approach is to create a second neural-network-based object detector that learns contours directly (Figure 11). Along with labels of detections, we also output "keypoints." This circumvents the need for color segmentation because we can extract orientation information directly from these keypoints. Our current iteration is built on Detectron2 [6].

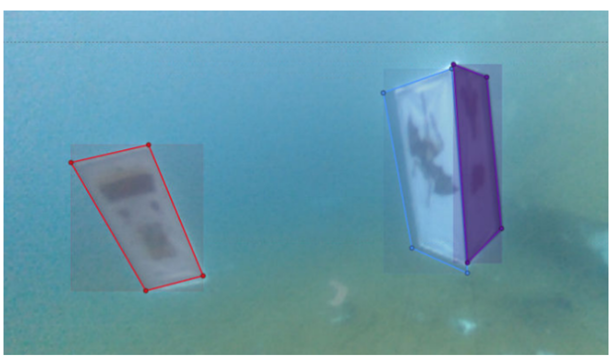

Fig. 11. An example label using the keypoints-based object detector built in Detectron2. The network will learn the precise quadrilateral contours, allowing use of geometric pose recovery techniques, such as our Gauss-Newton minimization.

III. Experimental Results

A. Mechanical

For the mechanical team, a large portion of our testing was centered around optimizing Gerald's designs. To reduce the weight of the hulls and obtain an optimal weight-to-buoyancy ratio, Gerald's upper and lower hulls will contain a number of cut-outs. These cut-outs do not go through the hulls but are used to remove any unnecessary material and weight from the hulls. When removing this material from the hulls, we are essentially making patches of thinner walls. To ensure that too much material is not removed, we are conducting a finite element analysis (FEA) by using a simulation to put the hulls under pressure conditions to mimic a pressurized sub that is underwater. This analysis is still ongoing.

Because Gerald has a long rectangular hull shape and because of the addition of multiports and other potentially obtrusive geometry that occupies a lot of vertical space inside the hull, we had to change the geometry of the sub's linkages. The linkages are used to prop the sub open to allow access to internal systems (Figure 12). In order to leave as much useable space as possible in the sub to mount electronics and to provide maximum stability to the sub while it is in the open position, the linkages must be mounted as close to the sidewalls of the hulls as possible. However, if we used a standard 4-bar linkage, this would cause interference with the "belly" camera multiport. Because of this, we created a modified 4-bar linkage system that includes a curved lower linkage that curves around the "belly" camera (Figure 13).

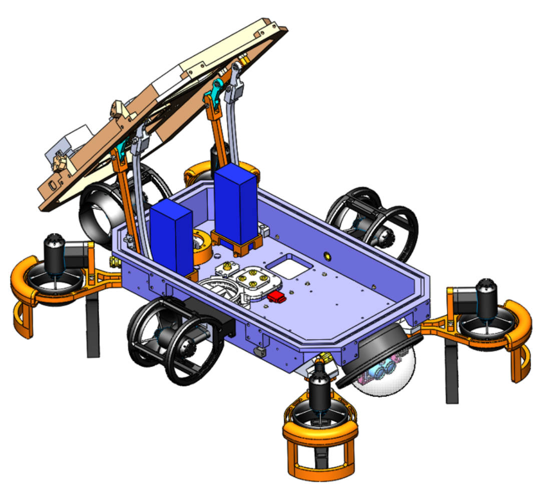

Fig. 12. Linkages in open configuration.

To verify the validity and stability of the linkages, we conducted a FEA where we simulated the

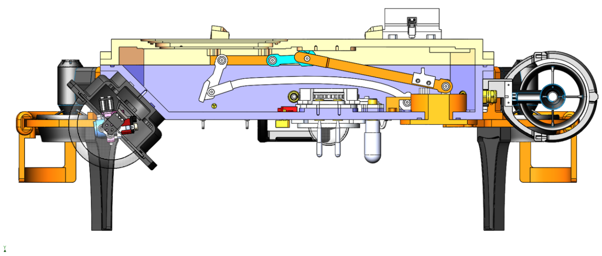

Fig. 13. Section view of linkages in closed configuration.

expected loading condition of the linkages when the hull is in its open configuration. From this we were able to estimate the stresses (top plot of Figure 14) and displacements (bottom plot of Figure 14) of the linkage system for different linkage geometries, allowing us to optimize the linkages for the open hull loading case.

B. Software

One of the main projects on the software team this year was to create an ArUco marker detector. ArUco markers are square binary fiducial markers that are often used to assist in pose estimation. They have a thick black border to enable fast detection and an inner black and white pattern that uniquely determines the ID. This design conveys enough information to recover a full 6-DOF pose from the detected marker.

In the past, we would only be able to start working on a commander after completing functional detectors for relevant game objects. Consequently, we have often run out of time to develop and test commanders. Issues further arose that were not readily attributable to either the detector or the commander but due to their tight coupling. Placing an ArUco marker on target objects in our test pool would allow us to reliably determine their locations, enabling parallel development of the detectors and commanders for a given task. Furthermore, reliable external localization is critical for tuning our internal localization methods: we can derive the sub's global pose from ArUco tags at known locations and make concrete statements about the performance of our EKF.

Due to the pandemic, we have had limited access to pools, but preliminary results show robust detection of markers in underwater environments, as

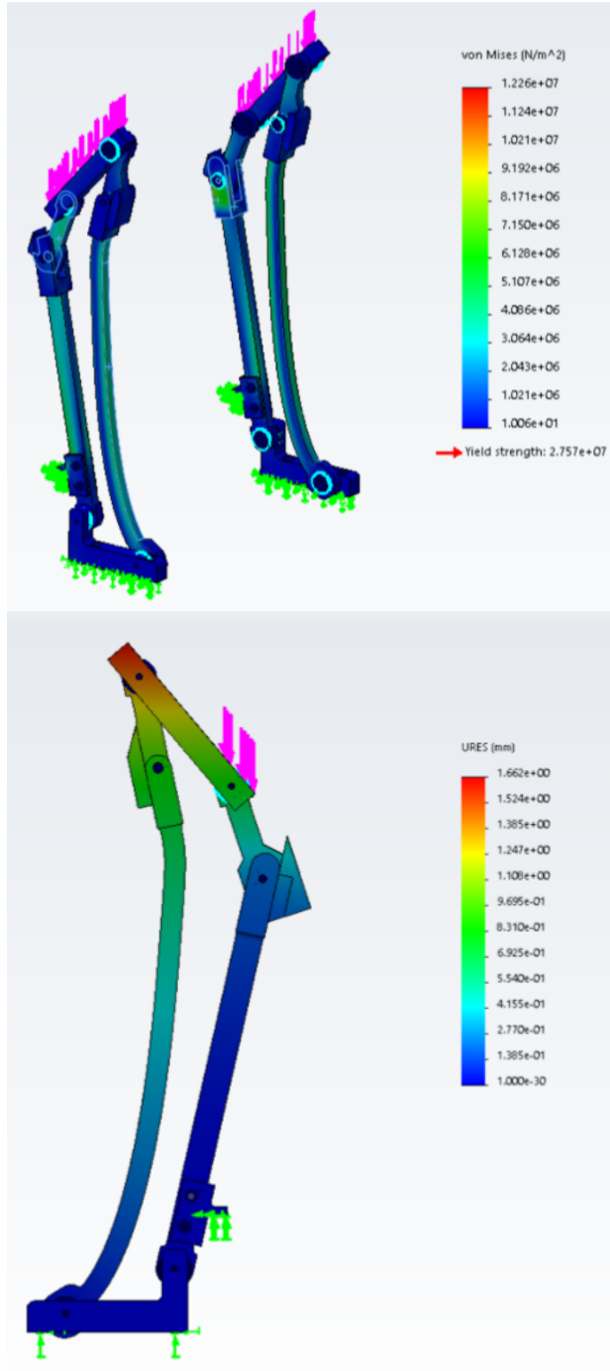

Fig. 14. FEA of von Mises stress (top) and displacement (bottom) of linkages in open hull configuration.

well as accurate pose recovery from those detections (Figure 15).

Because we collect camera captures from all competition and practice runs, we have accumulated an extensive backlog of data on which we can test new perception methods. This year, our focus was

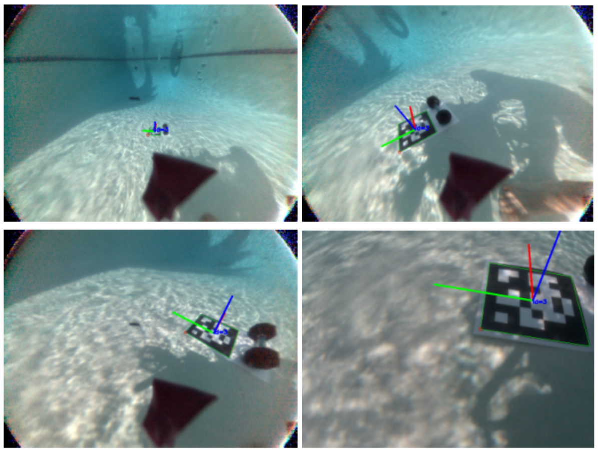

Fig. 15. Example ArUco marker detection at a variety of angles and distances, with 6-DOF relative pose information recovered under all conditions.

on testing new methods of gathering orientation data that are robust to the color differences throughout the day and between our practice field and the TRANSDEC. As described in the prior section, we experimented with both learned color segmentation and learned keypoint detection (Figure 16).

We have found success with both methods, training on our backlog of images. However, testing only on existing data has limitations we must address before use in competition. To name a few, we are unsure if detections are stable under a small image perturbation, and we are unsure whether our training data includes the full gamut of lighting conditions we will encounter. In addition, the current iteration of keypoint detection often returns multiple detections per object, which must be worked around at a higher level. Eliminating this issue at the source would produce a more performant system.

The final experimental project was simulating stereo vision. Our sub has two cameras, however, of two different types: one wide-angle fisheye and one with a narrower field of view. We wanted to see if it was possible to undistort the images from each camera and combine them to produce depth information derived from the stereo vision. Using two different cameras did not yield promising results. Because of the high competitive value of stereo vision, we are planning to include two identical cameras on future vehicles, rather than suspending development in this area.

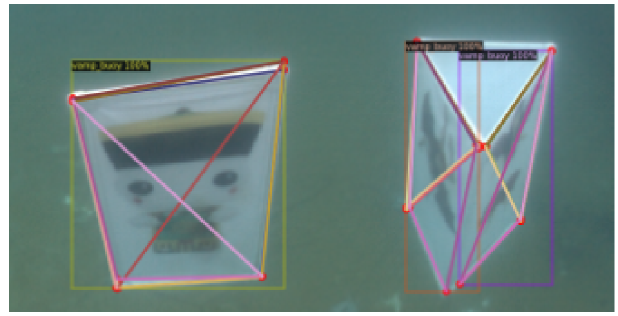

Fig. 16. The current version of the keypoint detector returns multiple detections per game object. In many cases there are both correct quadrilateral detections and incorrect triangular detections.

Acknowledgment

The Caltech Robotics team would like to thank all of our sponsors for their support

Ocean Level Sponsors:
Caltech
Glendale Community College
Northrup Grumman
Video Ray
Rhonda MacDonald

Sea Level Sponsors:
Dropbox
Danco
Team Grandma

REFERENCES

[1] Sola, Joan."Quaternion Kinematics for the Error-State Kalman Filter." 2017. [Online]. Available: iri.upc.edu

[2] R. Tedrake and the Drake Development Team, "Drake: Model-based design and verification for robotics," 2019. [Online]. Available: https://drake.mit.edu

[3] J. Redmon, S. K. Divvala, R. B. Girshick, and A. Farhadi,"You only look once: Unified, real-time object detection,"CoRR,vol.abs/1506.02640,2015.[Online]. Available: http://arxiv.org/abs/1506.02640

[4] D. Akkaynak and T. Treibitz, "Sea-thru: A method for removing water from underwater images," 2019.

[5] Daniel Bolya and Chong Zhou and Fanyi Xiao and Yong Jae Lee, "YOLACT: Real-time Instance Segmentation," 2019.

[6] Yuxin Wu and Alexander Kirillov and Francisco Massa and Wan-Yen Lo and Ross Girshick, "Detectron2," 2019.

[7] M. Quigley, B. Gerkey, K. Conley, J. Faust, T. Foote, J. Leibs,E. Berger, R. Wheeler, and A. Ng, "Ros: an open-source robot operating system," in Proc. of the IEEE Intl. Conf. on Robotics and Automation (ICRA) Workshop on Open Source Robotics,Kobe, Japan, May 2009.

[8] G. Bradski, "The OpenCV Library,"Dr. Dobb's Journal of Software Tools, 2000.

[9] G.Guennebaud,B.Jacob et al.,"Eigenv3,"http://eigen.tuxfamily.org, 2010.

Appendix A: Component Specifications

Component	Vendor	Model/Type	Specs	Cost (if new)
Bouyancy Control	n/a	n/a	n/a	n/a
Frame	n/a	n/a	n/a	n/a
Waterproof Housing	Glendale Community College, DANCO	Custom Hull	6061-T6	Re-used
Waterproof Connectors	MacArtney	SubConn MCLPBH3F	3 pin	Re-used
Thrusters	VideoRay	M5	Max. Thrust (nominal): 10kg	Donated
Motor Control	Built into the thrusters			
High Level Control	LQR controller, uses (in part) Drake's LQR solver [2]			
Actuator 1	HiTec	HS-5086WP	IP67 50oz-in	Re-used
Actuator 2	Savox	SW0250MG	69.4oz-in	Re-used
Propellors	Videoray	M5	Max. Thrust (nominal): 10kg	Donated
Battery	Turnigy	LI-PO	129.5 Wh, 5000 mAh, 25.9 V	Re-used
Convertor	Custom, built into the boards			
Regulator	Custom, built into the boards			
CPU	Intel	Tx2	6 core CPU & 256 core GPU	Donated
Internal Comm Network	-	UART	-	-
External Comm Network	-	Ethernet & Fathom	-	Re-used
Programming Language 1	-	C++	-	-
Programming Language 2	-	Python	-	-
Compass	VectorNAV	VN-100 Rugged	800Hz data rate	Re-used
Inertial Measure Unit (IMU)	VectorNAV	VN-100 Rugged	800Hz data rate	Re-used
Doppler Velocity Log (DVL)	Teledyne	Pathfinder	12Hz data rate	Re-used
Camera(s)	Allied Vision	Guppy Pro F-046	62fps	Re-used
Hydrophones	Teledyne	RESON TC-4013	1Hz-170kHz	Re-used
Transmitter	Benthowave	BII-7511	30kHz-70kHz	$676
Manipulator	n/a	n/a	Custom design, 3D printed	Free (Free printing)
Algorithms: vision	See Software section on vision. Wide variety of tools.			
Algorithms: acoustics	Using phase-angle to find the direction of the accoustic pinger			
Algorithms: localization and mapping	Waypoint map of course. Localize using pinhole approximation.			
Algorithms: autonomy	Overall system is a series of unidirectionally linked finite state machines.			
Open Source Software	ROS [7], OpenCV [8], YOLO [3], Drake [2], Eigen [9]			
Team Size (number of people)	38			
HW/SW expertise ratio	10 programmers, 14 mechanical engineers, 12 electrical engineers, 2 Business team members			
Testing time: simulation	200 hours (vision algorithm simulations, FEA analysis, and hydrophone signaling emulators)			
Testing time: in water	20 hours			

Appendix B: Outreach Activities

As a team, we hope to spread excitement and passion for robotics and STEM to our local community. In past years, we have often collaborated with local Girl Scout troops to host events for the students to earn their robotics badges. We have also mentored students from Escondido Charter High School's FIRST Robotics Competition team, Team 2839 the Daedalus Project. In spite of not being able to attend or host in-person events this year, we still wanted to share robotics with other young students. A relative of one of our team member's is in kindergarten, and their class was doing a robotics unit in April to celebrate National Robotics Week. We provided the class with a video, featuring our sub Flo, explaining more about robots and how they are designed.