California Institute of Technology RoboSub Technical Design Report

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***Abstract*—The Caltech Robotics Team's autonomous underwater vehicles (AUV) Flo and Deb were designed for precise maneuvering at the 2020 RoboSub competition. Prior to the COVID-19 outbreak, our new submarine Deb was on track to be performing at the competition. Flo has competed in 3 RoboSub competitions, with improvements made each year. Mechanical work was done this year to improve her gripper system for ease of use, and create a stronger, more accurate torpedo system, while electrical work centered around maintaining Flo's performance, and improved robustness. Software work focused on new vision algorithms and improved sensor fusion to allow both subs to more accurately sense the position of themselves relative to objects in the world. Together these systems allow for careful navigation by both subs of the TRANSDEC course and precise interaction with game elements.**

I. Competition Strategy

Although details of the competition have not been fully released, the team planned to build upon our success and strengths in previous years, while challenging ourselves to do new tasks. Specifically our target tasks were:

(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 (Bottles)**

Items in bold were those which were key technical focuses for us this year, and the main area for improvements to Flo. In addition, having two submarines was an important part of our strategy, allowing us to do more tasks during the time limit, and accumulate more points. Because the gate, path, and marker bins are recurring competition elements, we felt confident in our ability to repeat our performance on these tasks from previous years and quickly get those points. In addition, we had experience following the pinger accurately, and based on the large point value of the random pinger task, we felt it was important to include this as part of our efforts. In order to receive random pinger points, it is usually necessary to score points at the torpedo task and the surfacing area. Together, these tasks were those we felt could contribute a good source of points, while requiring a reasonable amount of time from the software team to robustify code from previous years' attempts.

The tasks that we felt would require a much larger amount of effort, but that we still wanted to attempt, included shooting torpedos and manipulating the bottle game element. Last year's changes to Flo introduced a new gripper, which we wanted to make stronger, and adapt to the specific target item. In addition, we came up with a novel torpedo approach the previous year that was non-actuated for close range torpedo placement. This year, we hoped to return to a more traditional torpedo design in order to shoot from a better vantage point.

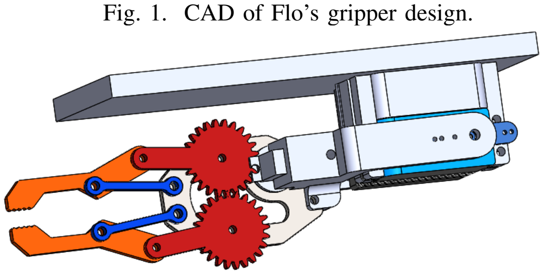
The team divided their resources for the first half of the year by having the software team focus on improvements to Flo, the mechanical team on completing construction of Deb, and the electrical team splitting time between maintenance to Flo's systems, and designing new boards for both subs to bring the systems in line with each other using a cleaner interface. Having an existing, working, vehicle proved immensely helpful for the software team at the beginning of the year, allowing them to test new algorithms in the pool without waiting for any manufacturing, while the mechanical and electrical teams could dedicate their time to the new vehicle. We were lucky enough to have pool access weekly throughout the year, during which we focused on gathering data to improve Flo's EKF sensor fusion and LQR controls. We also used the same time to do pressure tests on Deb to ensure she was watertight before adding electronics.

II. Vehicle Design (Novel Aspects)

A. Mechanical

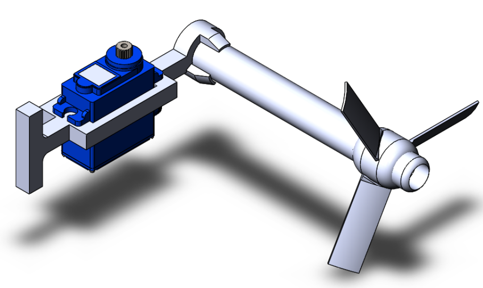
While designing the gripper for our vehicle, we emphasized simplicity above all else. In order to effectively pick up a variety of objects, a two-pronged claw was developed that could be opened and closed by a single waterproof servo. The use of a waterproof servo removes the need for a heavy pressure vessel to protect it from the outside environment, reducing the amount of torque which is needed to actuate the gripper. In an ideal world, a simple gripper might only need to consist of the end effector itself, but Flo's crowded underside and the requirement not to obstruct our cameras mandated that we introduce an additional degree of freedom into our design. This allows for the gripper to be moved in and out of the cameras' frame, thereby removing the obstruction to Flos vision during regular operation, while also allowing vision to be used to verify an effective grab during gripper tasks. Finally, the introduction of this degree of freedom has the added benefit of allowing the gripper to extend below the vehicle's "feet" during operation, while stowing itself safely in front of the vehicle at other times. We did initial testing of this gripper system last year, using rapid 3d printing prototyping, while the focus this year was on making the system stronger and less failure prone.

Fig. 1. CAD of Flo's gripper design.



We previously determined that the use of solenoids and permanent magnets to actuate our markers and torpedoes led to localization and navigation issues for the vehicle. We hypothesize that the varying magnetic fields from the movement of the magnetic components affected the calibration of our magnetometer. In order to mitigate this problem, the torpedo and marker launchers were redesigned to be triggered by waterproof servos. Unfortunately, the limited number of through-holes built into Flos pressure hull restricted us to 3 servos, with 2 being set aside for the gripper. As such, we leveraged our earlier work with golf balls as markers to design a servo-actuated marker dropper that can fire both markers at once with a single servo. This allows us to use our servos in the most efficient way possible while also reducing the magnetic interference affecting our vehicles navigation capabilities. This lack of servos also lead to a redesign of our torpedoes. Last year, we implemented a passive system which fired off both torpedoes at once. The system worked by having a catch inside a tube that held back both torpedos, which were small ball shapes, and opening upon putting the tube through the torpedo target and sliding out. While this design worked, we wanted to focus this year on how to make new designs for our torpedos for Deb which were actuated. As Deb had more servo connectors in the design, the primary idea for Deb's torpedos was a rotating torpedo powered by a twisted rubber band. The torpedo would be preset before the competition, and held in place with a servo. When fired, the servo would release and the torpedo would spin to allow for a straight path in the water, as seen in the CAD below.

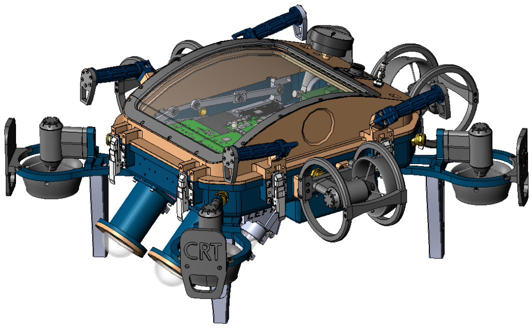
Fig. 2. New Torpedo Design for Deb.



B. Electrical

The design of the electrical system aims to allow the computer to communicate with the various

Fig. 3. CAD of Flo in 2019.



sensors and motors on the sub while also isolating potential problems in the sub. The electronics are soldered on PCBs, which have various functions ranging from supplying power to the other boards to interfacing with the sensors and servos.

The sub is powered by two 26 volt LIPO batteries, one which powers the computers and sensors and the other which powers the thrusters and motors. We separated these so that problems with the motors do not affect the performance of the computers. We generate any other voltages needed for our sensors and motors on those boards. The computer uses serial ports to communicate with various peripherals, and custom boards with STM32 microcontrollers do sensor signal processing before relaying the information back to the computer.

One novel feature we are developing is to monitor the battery voltage levels during operation. We noticed that the force exerted by our thrusters changes as the battery's voltage changes. To prevent this from affecting our control system, we will use the battery voltage measurements to compute the thruster's force as it changes.

We have also made some developments for an inter-sub communications system. While we have only started recently, we developed an emulator that would simulate the signals as it travelled between subs, allowing us to see how the movement of the subs shape the waveform from transmitter to receiver. We can also process these simulated signals to test various communication schemes and design our hardware to utilize the most effective of them.

C. Software

1) State Estimation: Using our DVL velocity measurements and AHRS orientation data as inputs, we craft an 12-dimensional extended Kalmann Filter (EKF) to estimate our sub's pose in the water. This EKF leverages the sub's dynamics to predict the sub's motion through the water, even between important sensor updates such as the DVL, which only fires once per second. An EKF is well suited to this task, as 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.

2) Control: Rather than use standard PID control to guide our robot through the water, we implemented a Linear Quadratic Regulator (LQR) with the use of Drake's LQR solver [1]. An LQR is a provably-optimal control scheme for multidimensional linear systems. It achieves this optimality by leveraging 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 vehicles dynamics are non-linear, we must locally linearize them around the target state, discretizing our system, before solving for the optimal LQR gain K. Then, we analyze our computed controls with an eye towards gracefully addressing thruster saturation. To do so, we impose the following the 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. Given 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 borderline trivial; it took only twenty minutes to tune our LQR controller compared to PID controllers, which took many months on previous vehicles.

3) Visual Object Detection: Our object classification algorithms rely on leveraging a mixture of classical higher order features such as colours, contours, and edges, along with point features such as SIFT descriptors, machine learning approaches such as the Convolutional Neural Net (CNN) You

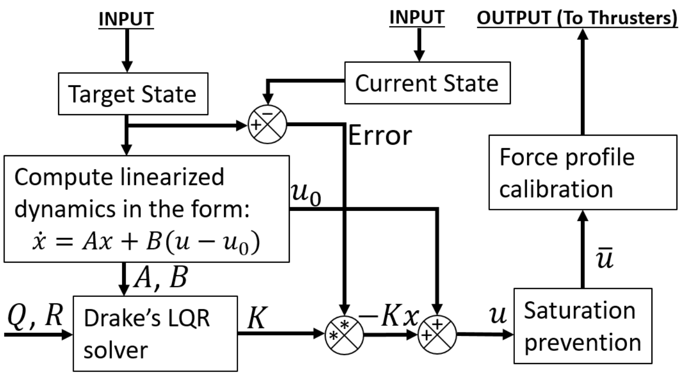


Fig. 4. 6-DoF controller diagram. The dynamics are linearized about the target state to compute the LQR gain, which is applied to the error term to compute the control output.

Only Look Once (YOLO) [2], and a novel Gauss-Newton minimization algorithm used to localize and verify the structure of rectangular detections.

While we are approaching tasks from a great distance, or tasks that have very complex features, such as buoys with pictures, we have found the YOLO CNN to be the most effective. However, it is unable to extract orientation information from the target, and it is also very slow (1 FPS on the Intel Nuc), meaning that other approaches are necessary 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 identy 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. This is done using multipoint Gauss-Newton minmization to find how skewed and rotated the object is, thus allowing us to figure out where a normal vector facing out of the object would lie. With this information, we are able to align to the target more cleanly, and complete up-close tasks. We can also use this reprojection to identify and reject outliers; for example, if we find a detection that claims that the bins are facing sideways, we know (or at least certainly hope!) that this is a misdetection and should be ignored.

One new vision algorithm we began working on this year was an implementation of the "Sea-Thru" algorithm to color correct underwater images

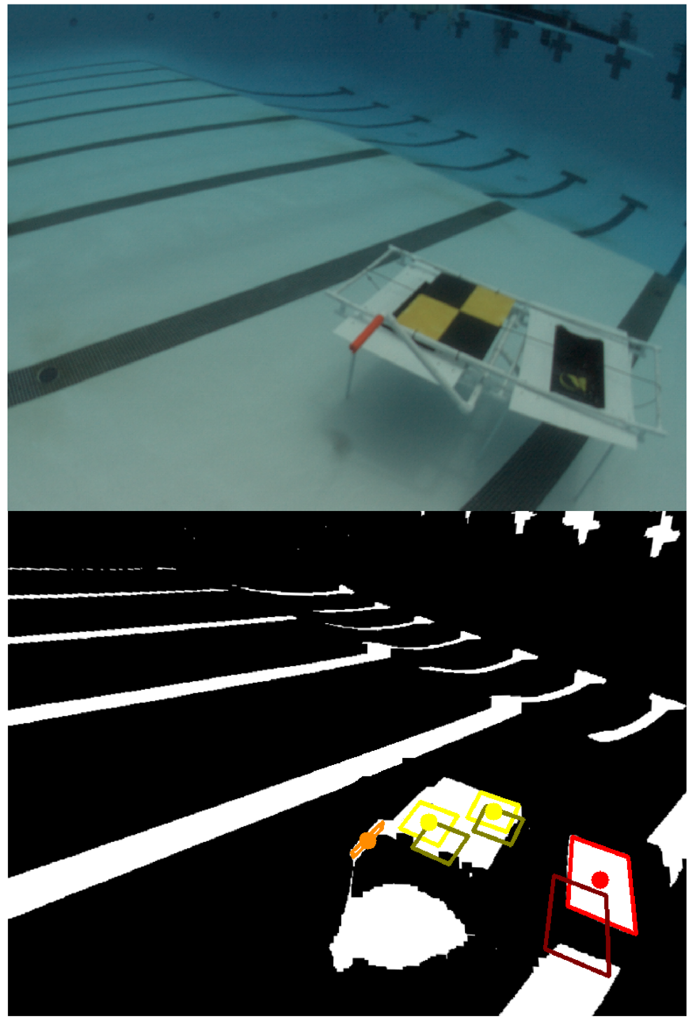


Fig. 5. Example of detector using Gauss-Newton minimization to extract the orientation of the marker bin and the marker bin cover. The dots represent the center of each validated contour, and the brighter rectangles represent the detected rectangular region. The darker rectangles are the projection of 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.

to restore the physically realistic colors of objects, as if they were seen in air [3]. This would be enormously helpful at the TRANSDEC, in order to correct for the green tint of the water and the depth dependent changes to object colors, because the Sea-Thru algorithm works by estimating a physical model of the environment to calculate the "original" image.

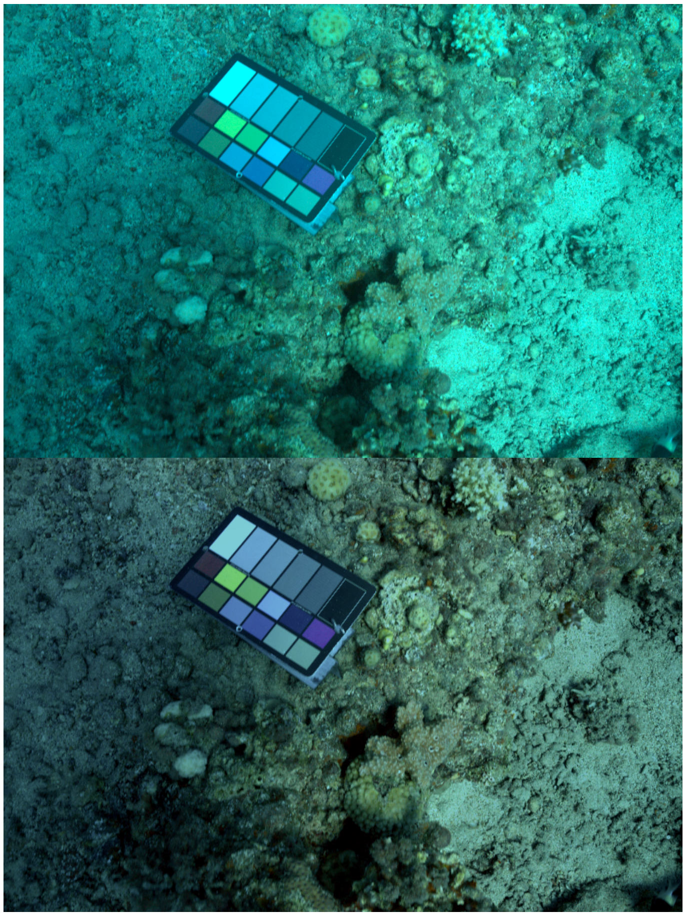


Fig. 6. The results achieved by our implementation of Sea-Thru to color correct a color chart in deep water.

III. Experimental Results

In-water testing of our vehicle takes place in Caltech's Braun Pool. Reserving two lanes of the 25 yard long outdoor facility, we are able to test Flo's systems and perform code changes on the fly through an ethernet tether connected to pool-side equipment. Sharing the pool with other users does limit our ability to string multiple tasks together in a single test, but the opportunity to debug the vehicle in the water has proven invaluable during our design process. In particular, experience during testing helped us make design decisions that allow for for safer vehicle operation, and faster identification of failures before they can become catastrophic. A primary example of this is our use of positive pressure inside the AUV. Even though the changes in relative pressure between the inside of the hull and the surrounding environments put more wear on the O-ring seals versus if we were to negatively pressurise the vehicle, the positive pressure allows us to monitor Flo for any bubbles that would warn us of an ongoing leak.

Even more valuable than the hardware lessons learned during in water testing are the software lessons. Due to limited access to pool time, our software team saves logs from each run in the pool, including all visual footage. Because objects look so different underwater, it is important to write vision algorithms designed around accurate photos, and train our machine learning models on the same. Capturing footage in advance and debugging later saves invaluable amounts of in water time. The four hours we spend on average each week at the pool can then be used to debug the strategy and motion of the submarine.

Acknowledgment

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Ocean Level Sponsors:
Caltech
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Video Ray
Rhonda MacDonald

Sea Level Sponsors:
Dropbox
Danco
Team Grandma

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Appendix A: Component Specifications

Component	**Vendor**	**Model/Type**	**Specs**	**Cost (if new)**
Bouyancy Control	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		Donated
Motor Control	Built into the thrusters			
High Level Control	LQR controller, uses (in part) Drake's LQR solver [1]			
Actuator 1	HiTec	HS-5086WP	IP67 50oz-in	52.89
Actuator 2	Savox	SW0250MG	69.4oz-in	30.99
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	NUC	8 core processor	Reused
Internal Comm Network	-	UART	-	
External Comm Network	-	Ethernet	-	roughly $150
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	$15,000.00
Camera(s)	Allied Vision	Guppy Pro F-046	62fps	Re-used
Hydrophones	Teledyne	RESON TC-4013	1Hz-170kHz	Re-used
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 [4], OpenCV [5], YOLO [2], Drake [1], Eigen [6]			
Team Size (number of people)	25			
HW/SW expertise ratio	12 programmers, 10 mechanical engineers, 2 electrical engineers, 2 Business team members			
Testing time: simulation	200 hours (vision algorithm simulations)			
Testing time: in water	140 hours			

Appendix B: Outreach Activities

We strive to spread the love for Robotics and STEM within our local area. This year, our two biggest outreach events were collaborations with some local Girl Scout troops, and with students from Escondido Charter High School's FRC team, team 2839 the Daedalus Project. More photos of both events available upon request.

At a local STEM and Robotics expo organized by the Girl Scouts, which was targeted at young girls and Girl Scouts in the area, we hosted a booth that was designed to give very young girls (4-8 years old) an introduction to what robotics can be like. We helped them craft cup-bots, which use a miniature motor and a slightly-off-center popsicle stick to "dance" across the table, as the off-center popsicle stick jerks it around. They decorated the cups to their hearts' contents, adding pipe-cleaner arms and googly-eyes (and in one case a very demonic expression). The older girls then were able to help wire up their robot (read: feed a wire up to a metal connector and wrap it around), while we helped the younger girls get theirs set up. Finally, they were able to flip the switch and watch their robots dance! It was truly wonderful seeing how excited many of them were, and I sincerely hope that this shows all of them that they have the option to pursue robotics in the future.

Fig. 7. Helping young girl scouts get their first experience with robotics. As can be seen in the second image, the popsicle stick on top of the cup spins rapidly, allowing the cup robot to "dance" when placed on a table.

We also invited down FRC team 2839 from Escondido Charter High School to tour our lab and learn about our approach to robotics. We gave them a presentation on what RoboSub is, and thus what one example of robotics they could look forward to in college would be, as well as to how our sub worked. They were able to ask us questions about how various sensors worked, and our rationale behind various component designs and task strategies, so that they could then take those lessons back to their own team and use them to grow and develop. Overall, they learned a lot, and we sincerely hope that we were able to encourage them to continue to pursue robotics in the future!

Fig. 8. Giving a lab tour and presentation about robotics and RoboSub to Escondido Charter HS students.