Design and Implementation of an Integrated, Performant Autonomous Underwater Vehicle

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Abstract **– The Caltech Robotics Team's newest robot, Crush, is an autonomous underwater vehicle designed for the 2015 intercollegiate RoboSub competition that is capable of precise movement and high-level autonomy. Designed and manufactured by over fifteen undergraduates at the California Institute of Technology, Crush is the second iteration after the team's last vehicle, Bruce. Crush's main features include a single, integrated pressure hull, active control over all six degrees of freedom, and a passive sonar system. These features allow the vehicle to maintain an arbitrary orientation, sustain a maximum surge speed of 1.5 knots, and locate an underwater sonar pinger. The vehicle includes a custom inter-process communication library that enables its advanced autonomous capabilities. Crush represents the latest advancement in low-cost actively—controlled autonomous underwater vehicle technology.**

Introduction

The Caltech Robotics Team (CRT) seeks to design and implement autonomous vehicles for the purposes of research, education, and outreach. The latest vehicle, Crush, allows the team's student members to develop engineering, communication, and collaboration skills in an exciting and hands-on manner. Crush's primary design goal is to successfully complete the challenging course in the Association for Unmanned Vehicle Systems International (AUVSI) Foundation and Office of Naval Research (ONR) RoboSub Competition. The competition takes place annually in July at the Transducer Evaluation Center (TRANSDEC) pool, at Space and Naval Warfare Systems Center Pacific (SSC Pacific) in San Diego, California. The competition realistically simulates real-world underwater vehicle tasks such as underwater manipulation, navigation, and visual inspection. The RoboSub competition elements include firing a torpedo at a small target, locating a sonar pinger, manipulating small objects, and dropping a pre-loaded marker into a bin. All of these tasks must be completed autonomously with no human in the loop. To complete these tasks, Crush must have sensitive visual and acoustic sensors, precise guidance, control and navigation, accurate object recognition, and effective object manipulation capabilities.

Design Overview

Crush is small autonomous underwater vehicle designed for precise and accurate movement in all six degrees of freedom. The team has learned many lessons from last year's vehicle, Bruce, and integrated that knowledge into Crush. The design has moved away from a totally modular, open frame design, towards an integrated single hull in order to save mass and volume and eliminate expensive and bulky underwater cables and connectors. Crush has six thrusters to control all six degrees of freedom that have a novel thruster configuration to achieve actively stabilized pitch and roll axes.

The electrical systems have also been improved by integrating all of the custom electronics onto four circuit boards, saving space while still remaining modular. The vehicle is powered by two lithium-polymer batteries giving Crush a runtime of over one hour. The electronics have separate power and battery systems for the actuators and for the rest of the electronics to provide complete isolation between the two circuits. The vehicle's software runs on a smaller Intel NUC™ computer system saving mass and volume. Crush uses a custom inter-process communication library to implement its vision, actuation, and autonomy systems.

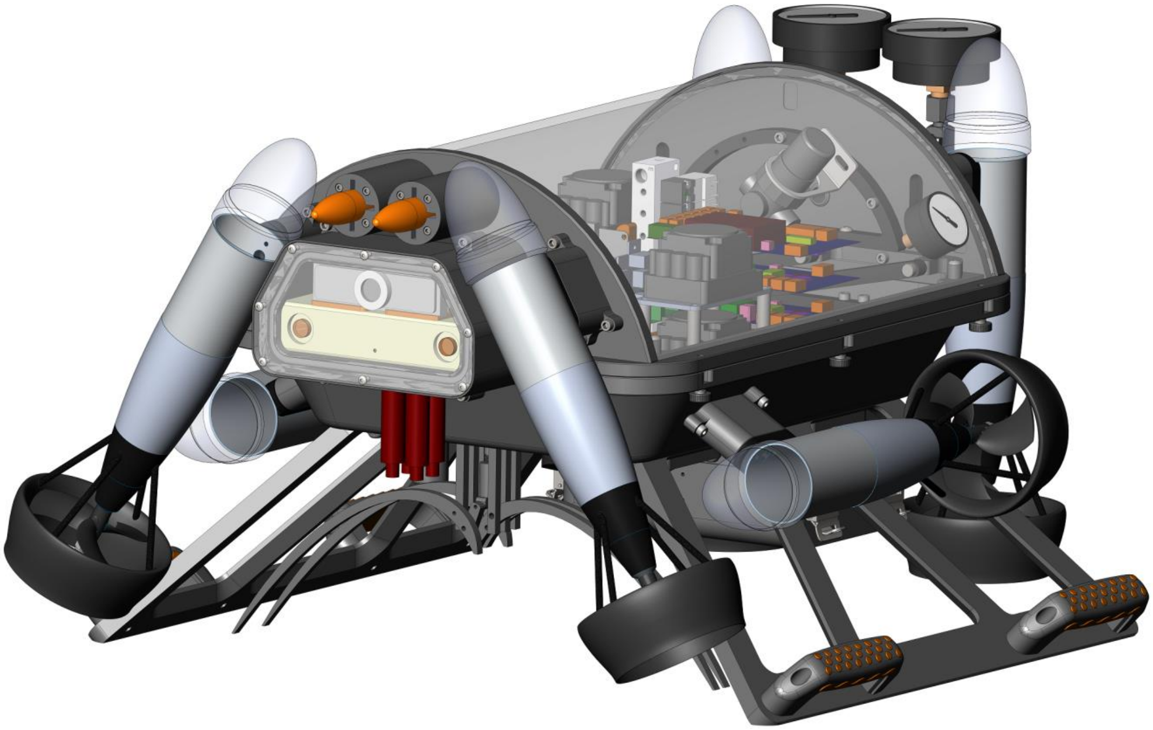

Fig 1. Computer Aided Design model of Crush.

Mechanical System

Crush’s mechanical systems include the main pressure hull, external electronics modules, thrusters, and the pneumatic system. Each component is connected directly to the main pressure hull and is sealed to prevent water ingress. All parts were designed using SolidWorks computer-aided design software. Pressure-critical parts were simulated using ANSYS™ finite element analysis software. The main aluminum structural components were machined using a 2-axis waterjet cutter and 3-axis computer-numerical controlled mill. Machining toolpaths were generated with HSMWorks™ computer-aided manufacturing software. A CAD model of the overall vehicle is shown in Figure 1.

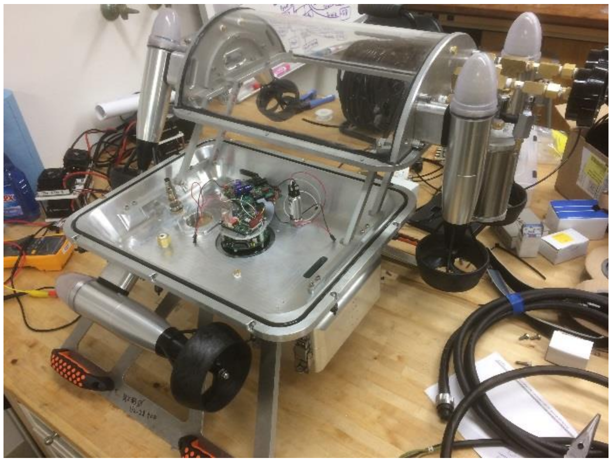

Fig 2. The main pressure hull pivots open on a four-bar linkage for easy electronics access.

Main Pressure Hull

Crush’s main pressure hull connects to all other enclosures. The hull consists of a bottom machined from a single piece aluminum, and a dome made of an acrylic half-cylinder with aluminum end caps. The aluminum bottom provides the strength and rigidity for the entire vehicle, which was validated before manufacture with Finite Element Analysis. A single O-ring provides the seal around the aluminum bottom. All of the external enclosures seal against the main pressure hull, which greatly simplifies wiring. Unused modules can easily be sealed using a simple aluminum plate, since the O-ring groove is located on the main pressure hull. The clear acrylic top allows the state of the electronics to be easily viewed. The dome mounts to the aluminum bottom using a four bar linkage to allow easy access to the electronics inside (see Figure 2). Cutouts in the bottom of the hull provide mounting points for the Doppler Velocity Log and a downward facing camera.

The inside of the pressure hull contains all of electronics, which are mounted to acrylic plates. The custom circuit boards are stacked on top of each other to save space. One underwater connector is used to provide an Ethernet interface to the surface.

External Modules

The external modules contain electronics that have special requirements that prevented them from being placed in the main hull. Modules can be swapped out easily without changing the design for the main pressure hull.

Camera Module: The forward facing cameras require a clear line of sight, so they are mounted to the front of the vehicle behind a clear polycarbonate window. Besides the two cameras, there is an attitude and heading reference sensor which must be protected from magnetic interference. Finally, the hydrophone elements are mounted beneath the camera enclosure to minimize interference.

Battery Module: Both batteries are mounted underneath the main pressure hull to lower the center of gravity. The enclosure seals using latches, allowing batteries to be easily replaced in the field.

Thrusters

Crush uses a unique thruster configuration (Figure 3, right) of six brushless VideoRay™ PRO 4 thrusters. Because of the linearity of Newtonian forces and torques, this configuration can apply any force and torque in any direction. This allows Crush to actively control all six of its degrees of freedom. Even though some of the thrusters flow against each other, neither the resulting turbulence nor battery drain has been an issue. Normally, the six thrusters would be configured with a pair of thrusters on the heave-surge, surge-sway, sway-heave planes placed symmetrically around the origin (Figure 3, left). This traditional thruster was avoided because it configuration severely restricts the mechanical design of the vehicle.

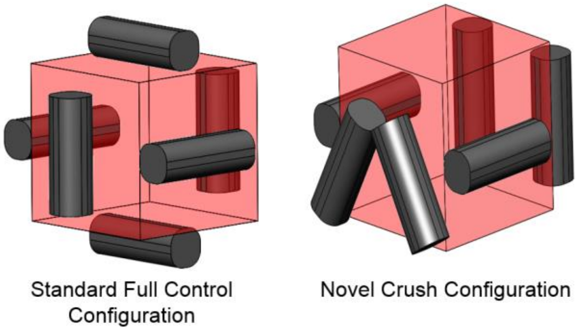

Fig 3. The black thrusters are mounted to a red simulated cubical frame. Both configurations provide control over all six degrees of freedom, but the Crush configuration allows the thrusters to be more easily positioned.

Pneumatic System

A high-pressure pneumatic system provides power for two torpedo launchers, two marker droppers, and a single degree-of-freedom gripper. The pressure is stored in a pressurized tank in the back of the vehicle at 100 psi, and is regulated down to 60 psi for each subsystem. The gripper (shown in Fig. 4) is closed with a pneumatic cylinder, and passively opens with the help of a spring-loaded mechanism.

Fig. 4. The gripper is actuated by a pneumatic cylinder located above the gripper mechanism.

Electrical System

Crush's electrical system provides power and communications for all sensors, computation, and actuation onboard in a robust and power efficient manner. The electrical system uses a combination of custom and off-the-shelf components to achieve the cost and performance requirements of the system. See Figure 5 for a view of the electronics mounted within the pressure hull.

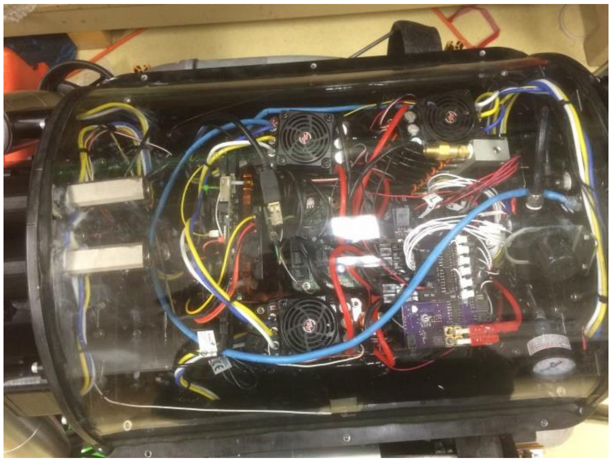

Fig. 5. The electronics inside the hull. The thrusters are mounted directly to the main pressure hull so that no underwater connectors are needed.

Mechatronics system

The thrusters use a separate power system to avoid noise and interference with the rest of the electronics. One 10 amp-hour, 22.2V lithium-polymer battery provides power to the motor power board. This board provides over voltage, under voltage, reverse voltage, and overcurrent protection using an electronic fuse to limit downtime and reduce wasted power. The electronic fuse is also connected to the kill switch to provide quick, reliable power shutdown to all of the actuators. In addition, it isolates control signals coming from the rest of the electronics to maintain the isolation barrier. The motor power board is then connected to six electronic speed controllers (ESC). The speed controllers electronically commutate the brushless DC thrusters.

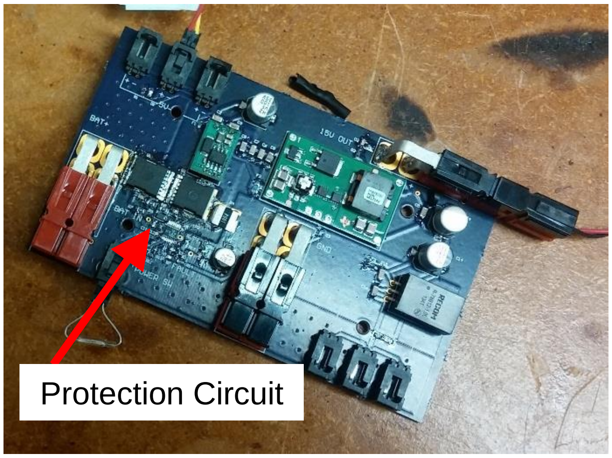

Fig. 6. The computer power board. The lower left contains the protection circuitry while the rest of the board contains voltage regulators.

Power system

One 10 amp-hour, 22.2V lithium polymer battery provides power to all of the other electronics. The computer power board, seen in Figure 6, operates similarly to the motor power board and provides the same protection to the input. In addition, the board provides 18V, 12V, and 5V rails.

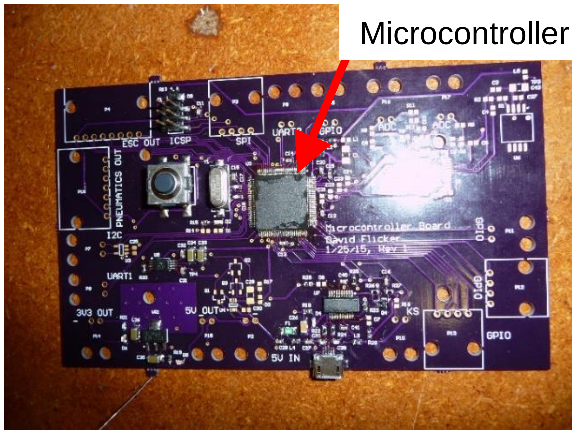

Fig. 7. The microcontroller board. The central chip is the microcontroller while the rest of the board provides supporting features like filters and connectors.

Microcontroller system

The microcontroller board, shown in Figure 7, provides low-level communication to sensors and actuators that cannot be controlled directly by the main computer. Crush uses an Atmega2560™ microcontroller as it provides many integrated peripherals and is simple to program. The microcontroller board provides pulse-width modulated signal for the motor controllers, an analog-to-digital converter for analog sensors, and general-purpose input/output pins for digital signals. An anti-aliasing low-pass filter is used to avoid aliasing noise. The board communicates with the main computer over USB.

Sensors

Crush uses a variety of sensors to gather the crucial information it needs to navigate and understand the underwater environment. The vehicle has two forward facing cameras and one downward facing camera to perform visual recognition of the competition elements. A passive acoustic system is used to identify and locate the sonar pinger. An Omega PX-319 pressure sensor is used to provide depth information to the vehicle.

Cameras: There are two forward facing cameras: a Point Grey Bumblebee stereoscopic camera and a Genius 120-degree field of view webcam. The webcam provides the wide field of view for target identification while the Bumblebee uses its two image sensors to provide depth information. One additional Genius webcam faces downward within the main pressure hull to identify the bins and other targets on the bottom of the pool.

Attitude and Heading Reference System (AHRS): A VectorNav VN-100 Rugged provides accurate orientation and attitude information in 3D space, Crush uses the AHRS to control the rotation axes and for dead reckoning its path through the water.

Doppler Velocity Log (DVL): A SonTek Argonaut DVL provides accurate velocity measurements in all three dimensions, which is used to estimate and control the vehicle's position in the water.

Hydrophones: Four L3 Ocean Systems piezoelectric elements mounted in a diamond pattern listen for sonar signals. Signals from the hydrophones pass through a pre-amplifier to boost their signal for transmission to the analysis board. This board uses a quad simultaneously sampling analog-to-digital converter to sample the signal. The digitized signal is processed on a Texas Instruments Stellaris Launchpad microcontroller, and information is sent to the main computer via UART. The signal undergoes a Fourier transform and is bandpass filtered around the frequency of the pinger. Finally, the signals are cross-correlated to determine the heading to the pinger.

Software System

Crush runs Ubuntu Linux on an Intel Core i5-4250U processor mounted on an Intel NUC™, which provides high performance computing in a small form-factor. A Samsung 840 Pro 256 GB solid-state drive provides power—efficient, mechanically-robust non-volatile storage. While not submerged, the team can connect to the vehicle over WiFi.

Crush's autonomy relies on its robust and well-developed C++ software architecture, consisting of the four processes diagrammed in Figure 8. This architecture was designed from scratch this year but was inspired by last year's design. The main goals were to simplify the software stack by consolidating individual processes while at the same time maintaining the modularity which helps with development, bug isolation, testing, and data logging. Each of the four processes encapsulates one or more threads and these four processes communicate with each other using a custom, interprocess communication (IPC) library based on a publisher-subscriber model. Processes can publish data to topics (illustrated as rounded rectangles) and subscribe to receive all data published to relevant topics. The team chose to write its own IPC library instead of using an existing framework such as ROS because the team wanted to have control over all parts of the message passing code.

Hardware process

The hardware process is dedicated to interfacing with the low-level hardware using serial communications. It communicates with the AHRS, DVL, and microcontroller. The microcontroller uses a custom serial protocol that allows for low latency updates to/from the depth sensor, kill switch, thrusters, and solenoids. The hardware process then uses all these sensors to create a unified state estimate including 3D position, quaternion-based orientation, and translational and angular velocities. Orientation is provided by AHRS, which internally fuses accelerometer, gyro, and magnetometer measurements using a Kalman filter. However, in order for this system to work well and be drift-free, the magnetometer on the AHRS had to be calibrated to account for the distortion of the fields caused by the vehicle. This was done by spinning the vehicle around in all orientations and processing the resulting data through a custom Mathematica script. The resulting orientation is used to integrate the instantaneous velocity data provided by the DVL in order to update our position estimate.

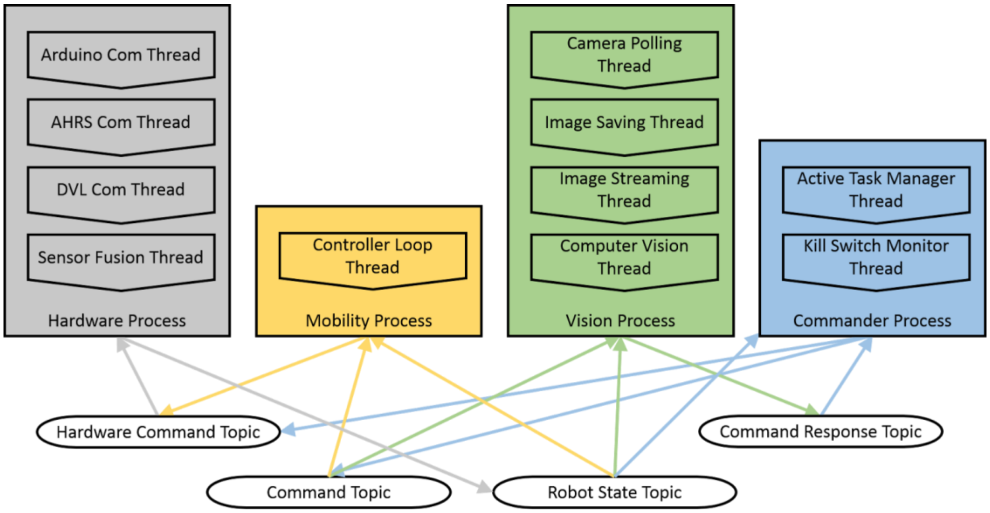

Figure 8. The software architecture of Crush showing the four main processes running on the vehicle and the interprocess communication channels. Each process can have multiple threads.

Finally, this position estimate is augmented using our depth sensor. This gives us a complete 12 dimensional state vector (position, orientation, velocity, and angular rates), which is periodically published to the robot state topic.

Controls

The mobility process uses the current state and a target state, received from the hardware and command processes respectively, in a custom 6 DOF dynamic-inversion-based control loop. The resulting thruster signals are sent back to the hardware process through the hardware command topic. This allows us to command the vehicle to any 3D orientation and any position in an earth-fixed frame.

Our control system uses three independent translational PD controllers to compute a desired translational acceleration. It also uses a quaternion-based PD controller instead of yaw, pitch, and roll PD controllers in order to isotropically compute a desired angular acceleration. However, due to the unique thruster configuration and misaligned principal axes, controlling the vehicle is not straightforward. Dynamic inversion is used to convert desired acceleration and torques in the North-East-Down frame into one force at each thruster using an accurate model of the vehicle generated from CAD. The Dynamic inversion formula accounts for the non-diagonal inertia tensor, buoyancy forces, and buoyancy torques. Finally, since the thrusters have been parameterized, their nonlinear thrust profiles can be taken into account to compute a desired thrust signal at each thruster. The entire process is diagrammed in figure 9.

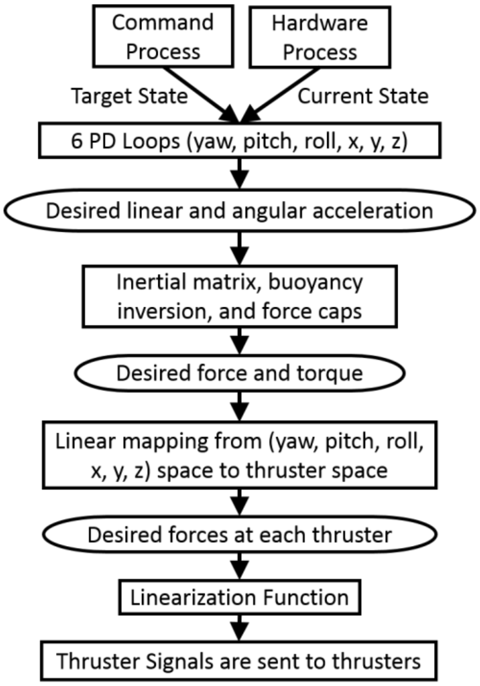

Figure 9. Overview of Crush's control scheme.

Vision process

The vision process turns raw images into actionable information about the world. The vision process asynchronously and continuously reads new frames from the attached cameras using OpenCV and a proprietary Point Grey library. The images are then corrected for distortions. Next, depending on the competition element, a variety of computer vision techniques are used to process the images, including edge detection, color thresholding, and contour analysis. The goal was to write vision algorithms that do not rely on precise color, but instead use more reliable contour and edge-based algorithms. Finally, the object location and orientation in an earth-fixed frame is shared with other processes over the command response topic.

Because of the many rectangles that must be detected by the sub (torpedoes, path, and marker bins), a novel algorithm based on Gauss-Newton minimization was developed to determine the orientation and position of any rectangle given the pixel positions of its corners. This allows the vehicle to accurately determine the orientation of these targets and their positions in 3D earth-fixed coordinates when looking at them from any direction.

Commander process

The Commander process is the highest level processing onboard Crush and is responsible for keeping track of the current task, how to accomplish it, and how to move to the next task after it is completed. To do so, it directs the other three processes using preprogrammed algorithms.

Vehicle Testing

Crush has undergone testing for the past 3 months in the Caltech pool. Both the mechanical and electrical systems underwent extensive testing prior to integration. Crush first entered the water on April 18th, 2015 for controls testing and tuning. Testing and tuning is still being completed in preparation for the RoboSub competition. A photo of Crush in the Caltech pool is shown in Figure 10.

Conclusion

Crush is an integrated, performant autonomous underwater vehicle designed to be an effective tool for research and education. The vehicle reliably and autonomously performs complex visual inspection and underwater manipulation tasks. Future work includes adding additional image processing capabilities and increased autonomy to further enhance the vehicle’s value and utility.

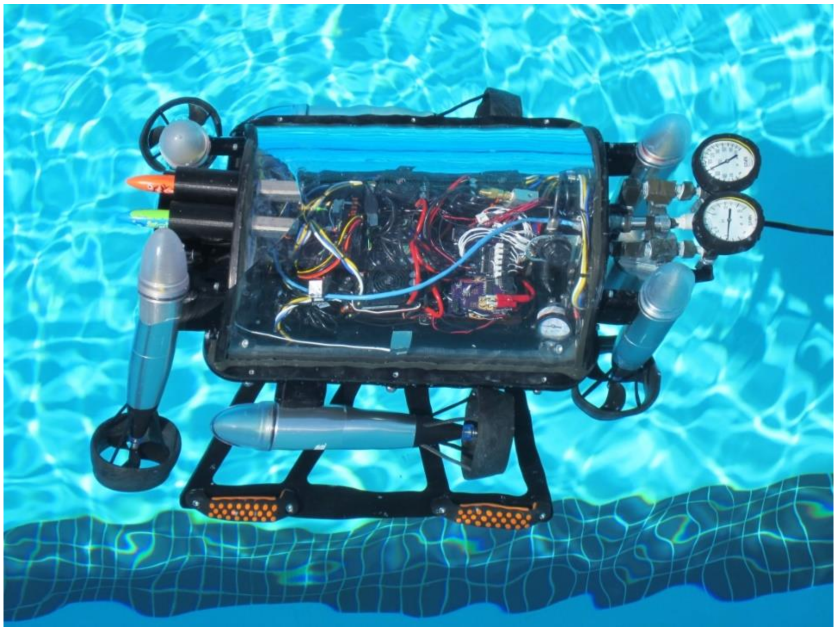

Figure 10. Underwater test. Pool time graciously provided by the Caltech Athletics Department.

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