University of Southern California AUV: USCTurtle Design, Build, and Operation

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Abstract

This journal characterizes the design and build of the Manta Ray, an autonomous underwater vehicle (AUV) constructed by USC AUV for the purpose of competing in the 2023 Robosub Competition. The Manta Ray was built over a period of three years and utilizes only limited legacy hardware from previous USC team designs. The design of the Manta Ray focuses on creating a reliable and robust platform that uses modularity to remain viable for many years.

1.0 Introduction

The University of Southern California Autonomous Underwater Vehicle Team's foremost objective for the 2022-2023 academic year was to create a submarine that could reliably navigate complex environments with autonomous capabilities. To this end, 21 undergraduate and graduate students—distributed amongst mechanical, electrical, and software subteams—met at least two nights per week over the course of three years, designing, prototyping, testing, and revising both core and ancillary systems. The creation of the Manta both provided students an opportunity to develop technical engineering skills and created a robust and expandable design intended to last for many years.

2.0 Competition Strategy

In 2019, the previous USCTurtle design performed well, but sustained damage during the competition. Rather than attempting to rebuild the USCTurtle, learnings from that design were used to design the Manta Ray. Similar to the USCTurtle, the design of the Manta Ray focuses on reliability and modularity, but does so with a larger hull that can house more internal components and isolate sensor circuitry. The redesign required completely new mechanical, electrical, and software components to be built.

The competition goals for this year are focused on core functionality and creating a base hull, electrical infrastructure, and software that can be expanded upon in the future. One major constraint this year was access to machining equipment and time. These limitations drove the decision to focus on core functionality, which includes object recognition, autonomous navigation, and reliable movement, over attempting to have the AUV complete multiple extra tasks.

The limited machining availability allowed additional mechanisms such as grippers, droppers, and torpedo launchers to be designed, but these mechanisms were not integrated into the AUV this year. These initial designs can be tested and expanded upon over the following years now that core functionality has been achieved. These designs informed decisions on mounting points for modularity as well as the main hull design so that the additional mechanisms can be easily installed.

3.0 Design Creativity

3.1 Large Hull

The Manta Ray incorporates learnings from the previous USCTurtle design. One particular issue with the USCTurtle was that some components such as the batteries were mounted in pods outside the hull. This created an issue during competition where the electrical connection between the batteries and the hull was not reliable, which caused issues in powering the AUV. The Manta Ray has a larger hull in order to fix this issue and issues like it. Enough space is given to house all of the main electrical components, reducing the required quantity of costly waterproof electrical connections. The larger hull space also benefits sensor signal clarity. Previous designs put the sensor electronics close to the power circuitry, which created noise. The new, larger hull provides enough space to separate these circuits and create a clearer signal.

3.2 Robust Construction

The hull of the Manta Ray forms the core of the submersible and is the base for future expansion of the AUV. Efforts were made to ensure that the hull was reliable and could be easily repaired. The main hull has three segments that connect to form a line. The center segment is the main attachment point for the internal components and external wings. This segment has many holes cut in the exterior to which sealed panels are connected. These panels are easy to swap out and contain features such as connectors to external systems or windows for camera vision. These panels can be quickly removed for access into the central segment for repairs. The other two hull segments are identical transparent cylinders that fit over the components that are mounted to the center segment. These cylinders provide good visibility to the interior of the submersible for quick diagnosis of malfunctions. Additionally, these segments can be quickly detached by removing a minimal amount of fasteners for quick repairs.

3.3 Modularity

Although the desire for modularity on the USCTurtle did create a few issues, modularity was still a desired design goal for the Manta Ray. Modularity allows for auxiliary mechanisms to be easily swapped out as RoboSub competition tasks change, which means that the base hull can be easily reused for future competitions. The hull and wings of the Manta Ray design include many mounting points where components can be added, modified, or removed. Motor mounts can be easily adjusted to alter the orientation of the thrusters. Some mounting points were designed with special consideration to common RoboSub tasks like torpedo, dropper, and object manipulation. Although these mechanisms were not part of the competition strategy for this year, preliminary design work was conducted on these mechanisms and incorporated into the hull for easy addition in the future. Such mounting locations include two beams that run the length of the hull. These beams can easily be machined to mount future mechanisms, and have already been pre-machined to accommodate future task mechanisms. Larger components such as external enclosures and tanks can be mounted to rails on the lower hull. Panels at the middle of the hull that serve as the interface between the interior and exterior of the submersible can be easily swapped and machined as needs change. The interior of the hull can also be easily modified. Truss-like frames hold plates that can be modified or swapped to accommodate printed circuit boards and other electrical components.

3.4 Electrical

The electrical team focused on delivering electronic hardware which enables key AUV functionality. This year, the electrical team completed the vehicle's four main printed circuit boards (PCBs), the design of electronics that support GPS-coordinate data logging, the design of analog signal conditioning circuits for a passive sonar system, and digital signal processing (DSP) algorithms to enable the passive sonar system to perform direction-of-arrival calculations.

The completion of the vehicle's main PCBs involved the schematic design, layout, and assembly of a single PCB which can be used as two of the four main boards, meaning that only three designs are required for AUV operation. The circuits on this board include a MOSFET switch and associated gate driver controller be either a physical switch or microcontroller IO, voltage and current sensing circuits and a two channel ADC for telemetry, a COTS I2C to PWM daughterboard for electronic speed controller (ESC control), and I2C optoisolators to allow these systems to communicate with other circuits in the sub using separate power supplies. Board stackup design and layout was performed with Autodesk Eagle, and team board designers used a four layer stackup with 4oz/sqft outer layer copper with two internal 1oz/sqft ground planes to allow for high current carry capacity while maintaining signal integrity. These boards were assembled in-house with a mix of reflow soldering and hand soldering.

The electronics design of the GPS sensor required team members to learn to interface with a COTS GPS module, and then communicate with that device over long runs of cable which could have presented signal integrity challenges. To overcome these potential signaling issues, I2C cable driver circuits which had been implemented elsewhere in the vehicle's electronics were repurposed to ensure communication between the electronics on the AUV's main boards and the GPS hardware.

The analog signal conditioning circuit design builds on previous team experience to finalize a sonar analog signal processing board which can be integrated with separate power supplies and DSP hardware solutions. The analog signal conditioning circuits themselves consist of a low-noise preamplifier and variable gain amplifier (VGA). Gain control is provided by digital to analog converters (DACS) which are commanded via I2C.

The team's digital signal processing effort yielded an algorithm which can determine the direction of arrival of an incoming pulsed sinusoid in a three-hydrophone triangular array. More work will be done in the areas of signal detection to ensure robust performance at the competition.

3.5 Software

The software team for AUV at USC spent the last year focusing on writing all of the necessary code to get the vehicle safely moving in the water. Due to a lack of documentation from previous years and reusable code from USCTurtle, the software team had no code that they could use from previous years and had to spend most of their time researching and developing the basic code architecture of the vehicle. The develop architecture uses the Robot Operating System (ROS) as the middleware, a combination of the You Only Look Once (YOLO) model and the Oriented FAST and rotated BRIEF (ORB) feature detection algorithm for computer vision, and a simple proportional-integral-derivative (PID) control system to stabilize the sub using an inertial measurement unit (IMU) and the computer vision for the sub.

A major limitation for the software team this year was that the team did not have access to a functioning sub since the USCTurtle was not functional and the Manta Ray was still under construction. This required the software team to develop most of the software for the sub using simulation through UUV Simulator, which provided a platform based on Gazebo and ROS to create and test various software for the sub such as control systems using simulated actuators and sensors[1]. Tuning the UUV Simulator software to simulate the Manta Ray was challenging, but a simulation of our sub in UUV Simulator with limited accuracy was generated and an ROS communication architecture that could be used for the Manta Ray was developed.

A Simultaneous Localization and Mapping (SLAM) model to both map and localize the vehicle to make maneuvering around the environment easier was considered, but due to the limitations of the sensors on the vehicle, the vehicle would likely be unable to consistently localize itself with the features from the IMU and camera alone. To overcome this limitation, we created a simpler computer vision system that relies on the Zed API to get depth information from the Zed-M camera, a YOLOv4 Tiny model trained on various underwater objects, and an ORB feature detector to localize the features of objects detected from the YOLOv4 Tiny model. Information from these algorithms and the IMU with some hard-coded logic was used to localize the vehicle relative to objects that are in front of the vehicle.

The guidance, navigation, and control of the Manta vehicle are very simple and based on 6 PID controllers for each degree of freedom for control, a Kalman filter for navigation, and a simple trajectory generator that makes the vehicle come to a gradual stop for guidance. Most of this code is based on a GitHub repository from Ted Sender, an alumnus of Ohio State University's AUV team[2]. The software team successfully met its goal of creating all of the necessary software to get Manta safely moving in the water.

4.0 Experimental Results

During Manta's development, numerous tests were conducted to evaluate the structure of the Manta Ray and its hydrodynamic interactions. Simulation was used extensively to better understand the performance of the Manta Ray before it had been built.

4.1 Fluid Flow Analysis

To better understand the hydrodynamic properties of the Manta Ray and better inform our software controller, several cycles of analysis and tests were performed. Computational Fluid Dynamics (CFD) analysis on a representative model of the sub was performed in SolidWorks Flow Simulation utilizing expected nominal sub velocities in order to obtain drag coefficients for all three translational degrees of freedom of the submarine. Once drag properties were obtained analytically, a series of wind tunnel tests were performed in efforts to validate the analysis results. The wind tunnel testing consisted of a scaled down 3D printed model of the Manta vehicle, with wind tunnel properties scaled in order to achieve similarity to the flows used during the CFD analysis. The resulting drag coefficients obtained from the analysis and test will be further validated by in water testing of the integrated vehicle. Having well established values for the hydrodynamic coefficients of the sub help to build a more robust control system, and the ultimate goal for future iterations of the Manta Ray is to implement these calculations into a more sophisticated control algorithm such as a linear quadratic regulator.

4.2 Finite Element Analysis

Since the two hull wings are an important part of the hull design and the core of the submersible, they were optimized to minimize their weight. A lighter submersible leads to better competition performance, so an effort was made to design recurring components for minimum weight. Finite element analysis was used to determine the thickness and internal geometry of the wings. An appropriate thickness was chosen based on the anticipated deflection of the wings when subjected to the greatest load, which was when the submersible was being carried out of water. The analysis was also used to remove as much material from the inside of the wings as possible while maintaining favorable deflection and mounting points.

5.0 Acknowledgements

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6.0 References

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