LEVIATHAN: The Design and Implementation of Duke Robotics Club's 2016 AUVSI Competition Entry

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Duke Robotics Club is proud to announce its return after an 8 year hiatus with its entry into the 2016 Robosub Competition: Leviathan. Leviathan is designed to be a modular platform that will serve Duke Robotics Club for years to come. Leviathan's outstanding waterproof mechanical design is the result of extensive research, simulation, modeling, and in-house CNC machining. In dozens of hours of testing no capsule has ever leaked, and the vehicle has proven highly maneuverable in every direction. The electronics team has combined four brushed motor drivers, three hydrophones, two cameras, two inertial measurement units, a doppler velocity log, an altimeter, an on-board computer, and two isolated power systems to create a fully featured platform for informing and running the computer science team's code. The Python software stack retrieves the sensor data and fuses it to obtain an estimation of state. It uses this state estimation to judge its position in a probabilistic decision tree for task selection and motion planning. The software stack also handles the controls, setting the speed of each thruster to maintain a stable orientation and move towards intermediate goals. Leviathan was the result of incredibly hard work by students at Duke University. We're especially grateful to our mentors and our sponsors, The Lord Foundation and the Duke Student Government Student Organization Funding Committee.

I. INTRODUCTION

LEVIATHAN is the 2015-2016 Duke Robotics Club autonomous underwater vehicle. It represents the club's return to the AUVSI Robosub competition after last competing in 2008. Work on the project, split between three different subsystem teams (subteams), began in Spring 2014. The mechanical subteam was responsible for the electronics enclosures, actuators, frame design. The electronics subteam was responsible for the power architecture, the sensing systems, the onboard computation hardware, and the firmware for the microprocessors. The software subteam wrote software to control the robot, handling everything from sensor fusion to motion planning to computer vision. Lastly, the testing team was responsible for ensuring the quality of the other subteams' contributions. As all former team members have long since graduated, and no key mentors of that period remain affiliated with the university, this year's entry was the result of rigorous engineering design processes rather than institutional memory. Despite these obstacles, Duke Robotics Club has produced a sophisticated AUV that will lead the club into its renaissance.

II. DESIGN OVERVIEW AND STRATEGIES

A. High-Level Approach

Because it has been almost ten years since Duke last competed, the design process began with a detailed study of the competition rules, previous score results, and previous design entries, instead of with designing improvements for a previous entry. Research revealed that many teams struggle to implement even basic functionality, and many others are unable to use sophisticated features because of reliability problems. This research led the team to prioritize navigation-based tasks and to build a highly maneuverable AUV. The goal was to create a design that is sufficiently modular that new instrumentation and robotic manipulators could be added later without difficulty, and a design that would be robust and reliable enough to function as designed at the competition, something that many teams struggle with.

Due to the limited knowledge and personnel of any young team, additional constraints were developed to help focus the team's efforts, to try and make the most of engineering efforts. Competition rules and requirements were weighted against soft factors to develop the following additional design constraints:

- Make maintenance and troubleshooting as easy as possible
- Focus on navigation-based tasks, but allow for modular upgrades
- Give up size/weight optimizations for potential functionality
- Give up size/weight optimizations for greater independence of the subteams
- Favor reliability and robustness over complexity and additional functionality

Focusing on these constraints sped up development, allowed subteams to make significant changes with minimal impact on others, and greatly simplified testing and integration.

B. Vehicle Design

1) Hull

One of the mechanical subteam's top priorities was designing a capsule system that can be opened quickly, requires little maintenance, and never fails. The vehicle hull system consists of a single main capsule, two battery capsules with removable end-caps, and two permanently-sealed camera capsules.

Acrylic was selected for the main capsule material because simplicity in diagnostics was such a high design priority, after being vetted for mechanical appropriateness with simulation. The ability to visually inspect the contents of the capsules was important because of the immaturity of the leak detection, power management, and logging systems. Throughout the integration process, the ability to quickly see if a given light on

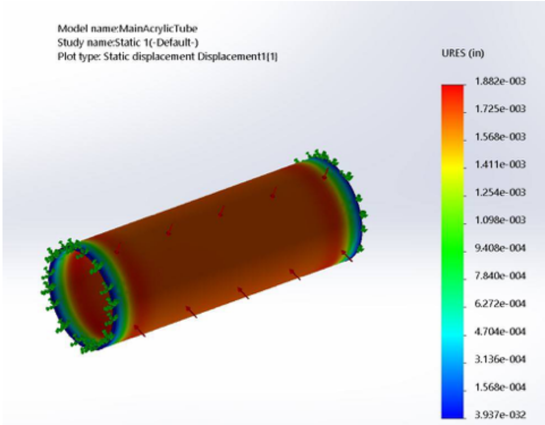


Fig. 1: Simulation of the Capsule

a board is illuminated, or verify that a given wire is connected without having to open the main capsule, was invaluable.

Studying Duke's previous entries provided the team with several key design insights. Duke's 2003 vehicle, Charybdis, had bore-sealed capsules that were reliable but difficult to open. Scylla, the 2007 vehicle, had a face-sealed main capsule that did not require prying like Charybdis, but still had eight screws that needed to be precisely torqued to ensure an even seal across the ring. Worse, in 2008, the plastic sealing face cracked from over-torquing the sealing screws, destroying the vehicle. This year the mechanical team successfully combined the strengths and weaknesses of these two designs to develop a capsule topology that is easily removed, highly robust, and has never leaked.

The sealing flange bore-seal design combines the robustness and simplicity of bore seals with features that make removing the end cap much easier. The acrylic-mating face of the sealing flange is machined to match the exact piece of acrylic tubing with which it seals. Mating the removable endcap directly with the acrylic was intentionally avoided; the tolerances of acrylic tube are imprecise enough that even one of the correct nominal size can be outside the recommended parameters of the chosen o-ring. This metal flange creates a surface that can be used with a jack screw to remove the endcap with no risk of cracking. Although the metal flange adds size, weight, and construction complexity, it provides a durable interface to the endcap and ensures the o-rings have a perfect sealing surface.

Fig. 2: Capsule exploded view

The removable endcap was originally designed with two o-ring glands so that either a single o-ring could be used for removability, or an additional one could be added for higher reliability. After test, there was no noticeable difference in difficulty of removing the endcap, so both o-rings were ultimately used. The removable endcap also serves as the interface for the vehicle's SubConn and SEACON waterproof connectors. On fixed side of the capsules, valves ensure that the removable endcaps are immobilized by vacuum during removal.

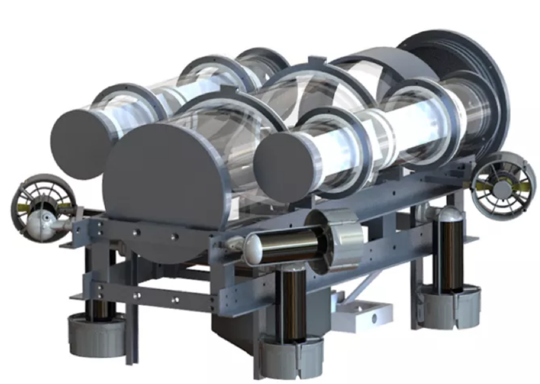
As part of a larger design consideration of minimizing capsule openings, the camera capsules were redesigned to be permanently sealed. The risk of sealing the capsule with an inaccessible imperfection in the optical path of the camera was outweighed by the simplicity of fewer removable seals that have to be maintained and tested.

2) Frame

The frame consists of two aluminum "cross sections" that hold the main and battery capsules in place with polypropylene bushings to prevent the acrylic tubes from scratching. These cross sections attach to an aluminum box frame designed with extra mounting area for components to be added or moved during integration and testing. The frame was designed so that the center of mass is directly beneath the center of buoyancy, making Leviathan self-righting. In this way, good mechanical design simplified the work of the computer science and electronics subteams, an overall design success.

3) Battery Pods

The primary considerations in designing the battery system were ease-of-testing and reliability. Software is one of the most complicated aspects of this competition, and the ability to test without interruption for as long as possible provides a competitive advantage. Two discrete, hot-swappable battery pods enable longer tests without the need to open the main capsule, saving time and reducing the possibility of leaks. The vehicle uses two power circuits, each fed by an isolated supply, and two separate battery pods, allowing quick replacement of one without affecting the other (e.g. allowing the replacement of the motor circuit battery after a long pool test without having to reset the computer by replacing its battery). The pods have the same robust bore seal and collar design of the main pod, making them resistant to leaks. They also each contain a 3D-printed sliding battery tray holding a 22.2V 8Ah Lithium-polymer battery. Glued onto each tray is an LED voltage indicator, allowing charge to be quickly checked.



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D. Bridge

The bridge is the structure on which all main capsule electronics are mounted. The bridge is designed hold all of the electronics and wires neatly, with a dedicated center channel for wire routhing. This flexibility allowed the electronics stack to be modified as the design evolved with further research and testing. The bridge is composed of two pieces of quarter inch acrylic, two inch-wide aluminum rails, and hardware that joins them. The rails are joined directly to the removeable main-capsule endcap, as shown in the above figure. The hardware attached to the acrylic sheets can be loosened and the entire apparatus moved to a ”skeleton” structure allowing the hardware to be worked independently of the normal frame. This allows the mechanical team to modify the removable endcap at the same time that the electronics team works on the bridge.

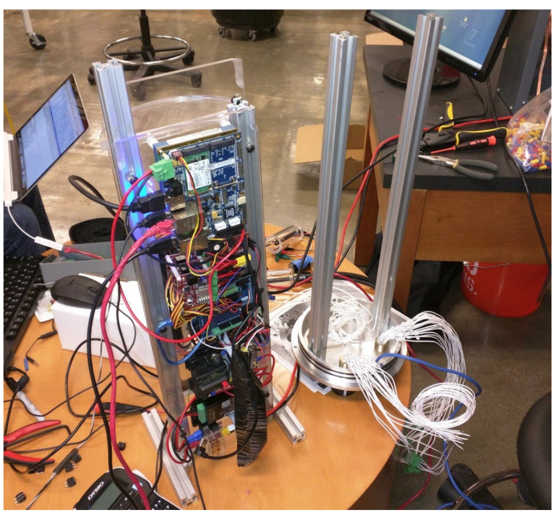

Fig. 3: The Bridge

Mounted on the bridge is an Acromag 6400 single board mil-spec computer, a ConnecTech carrier board, 3 Atmega microcontrollers, four dual-motor brushed motor drivers (not pictured), two IMUs, an acoustics filtering board (not pictured), a USB hub, a switchable thermal breaker, adjustable DC-DC power converters, and a fuse box. The fuse box and thermal breaker provide adequate overcurrent protection in the event of an electrical failure. The digital components interact over the USB hub network, and all external connections are made through detachable plastic connectors.

E. Actuators

In line with the goal of focusing on navigation based tasks, no actuation has been implemented beyond thrusters for vehicle motion. SeaBotix BTD150 thrusters were chosen because of their easily sealed electrical interface, their simple mechanical mounts, and their discount through Seabotix's generous sponsorship. Four vertical thrusters are mounted on each of the four corners, giving the vehicle freedom to move up and down the Z axis (heave) and around the pitch and roll axes. Four horizontal thrusters attached on the bow and stern at 30 degrees allow the craft to sway, surge, and yaw. Testing showed that this angled configuration offered greater sway control at the cost of less efficient surge, a reasonable tradeoff when considering the relatively short length and duration of the competition course.

F. Sensors

Leviathan uses a combination of motion, vision, and acoustic sensors to understand its own state and the world around it. Localization and mapping of the AUV's environment is one of the hardest challenges of underwater robotics and was the driving factor behind many of our design decisions. The sub uses two Microsoft LifeCam Cinema cameras, a Teledyne Doppler Velocity Logger, an Omega PX309 pressure transducer, an array of three Aquarian Audio Products H1c hydrophones, two SBG Inertial Measurement Units, and a thermocouple to monitor the internal capsule temperature of the robot. This raw sensor data is processed and sent to the computer where it is combined and used to determine the output of the sub's actuators.

1) Acoustics

A passive hydrophone array is used to triangulate the location of the Benthos ALP-365 acoustic pinger. The task's foremost obstacle is reaching a minimum analog-to-digital sampling rate on a microcontroller. In order to sample the 40 kHz signal, a Cortex M3 microcontroller. The signals from the three Aquarian H1C hydrophones individually pass through pre-amplifiers, a 8th order butterworth low pass filter board, and then to the microcontroller where they are band-pass filtered to isolate the pinger's signal. From the cross-correlation-peaking/Time-of-Arrival/difference-of-phase of the three signals, the location of the pinger can be calculated. Currently, the array fails to pick up every ping– preliminary investigations point to the microcontrollers poor sampling rate so an exploration of other microcontrollers with faster ADCs is necessary. An ultimate design would require an array that accurately triangulates the pinger within a reasonable passive listening time, aiding the guidance-decisions made by the main computer.

2) Computer Vision

The computer vision module is designed to provide estimates of objective positions relative to the robot. The module first cleans all images using contrast stretching and then thresholds in the RGB and HSV color planes to identify objectives. Two main approaches mark the positions of objectives on screen: the Hough Transform detects lines and circles via a voting algorithm, and separately contour analysis finds all contours in the image and evaluates them as possible matches with the objective. Once the objectives are marked on the image, determining position reduces to a geometry problem with a few unknown constants that are solved for with calibration images.

Fig. 4: Original image

Fig. 5: Image after Preprocessing

Fig. 6: mage after gate detection

G. Software Architecture

The majority of the vehicle's software is written in Python 3 and runs on Ubuntu Linux. The few separate Python processes communicate using a continuously running Redis publish/subscribe server, but most code is started via a single Python process that spawns children with Python's built-in multithreading and multiprocessing libraries. The controls were kept simple but effective. The robot balances each degree-of-freedom with a PID loop and maps the desired forces to thruster output by reverse-solving a simplified model of the system using the Moore-Penrose pseudoinverse function.

Readings from the pressure sensor and IMU are processed by Arduinos before being passed to the main computer over serial. The Arduino built into the IMU fuses its component sensors using the Direction Cosine Matrix Algorithm before giving back Euler angles. The DVL does its own, independent sensor fusion of its built-in IMU and doppler velocity readings to also return Euler angles, which are then fused with our IMU Euler angles on the computer.

The computer controls the thrusters by writing over serial to a separate Arduino. Motion planning of the robot is still under active development at the time of the paper's writing, but the most promising solution yet found utilizes Dijkstra's algorithm on a 2D internal grid representation of each obstacle to navigate between defined points relative to the obstacles.

III. Testing Process

Vigorous testing of the mechanical systems has been considered core to the entry's success and was utilized throughout the construction process. The initial designs were guided by bounded Solidworks simulations, placing theoretical bounds on the hull thicknesses needed to maintain integrity. Mechanical components were then stress tested early and often, with both the hulls and battery pods having completed multiple ten-hour trials at over 15 feet in depth. The electrical components were also tested often, but full-system tests were intentionally kept to a minimum because of the disastrous damage a single leak could cause the electronics.

The testing subteam developed specific tests for each subsystem that could be run in-lab. The team also recognized the rarity of full-system tests; together with the software team a program to record and play back all system parameters and values was created so that each test could be re-simulated and each run scrutinized. Data from these runs could be viewed in real-time or could be downloaded to a computer for later analysis.

IV. Experimental Results

At the time of this writing, Leviathan is a bare-bones vehicle capable of full freedom of motion at low speeds (roughly 2 knots translational speed). The vehicle has two functional cameras for identifying obstacles below and in front of it, three positioning sensors including a DVL for navigation, and a three independent pressure hulls. The robot is capable of basic motion planning and obstacle interpretation through vision. It has enough battery capacity to run for around 20 minutes with medium duty-cycle thruster usage (30-50%). Lastly, by the time of the competition, it is hoped that the vehicle will have also gained acoustic localization functionality for the final task.

Acknowledgment

Duke Robotics is a club within the Pratt School of Engineering. We are supported by the faculty here at Duke, and gratefully acknowledge the faculty and administrative staff here who have helped and continue to help make our club a success. Special thanks to Professors Michael M. Zavlanos, Kris Hauser, and George Konidaris, and our Undergraduate Program Coordinator, Lauren Stulgis.

Appendix

A. Outreach

Duke Robotics Club recognizes the importance of working with their local community and inspiring future generations of STEM students. They have worked with both local middle schoolers and high schoolers, helping Durham Academy Middle School coach a pilot FLL team and robotics afterschool program and mentoring Team 900 Zebracorns navigate the FIRST competition. They have also advised countless teachers' curriculums through a partnership with Project Lead the Way. Even though each member's time could have been spent bettering Leviathan the team still acknowledges how much more science and robotics can advance with each class of students. Duke Robotics Club wants to encourage as much innovation as possible, and they are proud to be able to spark ideas in generations of students to come.

B. Team Photos

Fig. 7: Team photos from the year.