The Building of Leviathan

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Abstract— **With an emphasis on education and outreach the University of Colorado Boulder RoboSub team began design on Leviathan. Through a mix of coursework, and workshops the team taught students critical robotics knowledge and applied that knowledge to the vehicle creating robust mechanical, electrical, and software systems. The vehicle combines the best of our previous entries with systems that eliminate flaws faced in the past.**

A. Design Strategy

The team's strategy for the 2017 robosub started with an emphasis and investment in education. This was done with a multi faceted approach to see what method provided the most effective.

The first plan of action was delegating more complex systems to capstone teams. This allowed for them to be developed with the rigour and effort required. This year the electrical system was done in this manner due to the massive scope of building a backplane system that incorporated power management, voltage regulation, and custom control system. The results were very favorable, not only were the specifications met on schedule but excellent documentation is part of the capstone design process and will prove to be invaluable to future team members to understanding the design choices made.

Workshops and tutorials were provided as well in order to share knowledge and experience with as many members of the team as possible. These included PCB design, component design, software development, ROS basics, and using professional CAD programs such as Altium and Solidworks. Although the benefits of this program are not apparent from the onset we feel very confident that by participating and organizing these events team members are honing and building necessary skills. The benefits will become much more apparent in years to come as new members gain experience at a faster rate and veteran students can practice the fundamentals in a fun and social environment.

The more novel technique we executed this year was working with professors on campus to help cater course material to AUV related studies. This was done specifically with the advanced robotics class and incorporating advanced sensor fusion techniques into lectures and homework assignments. The results of this have impacted the team in a massive way. The software team improved in skill, passion, execution, dedication and forged closer relationships with college faculty. This classroom approach will be aggressively pursued due to the effectiveness and viability.

B. Vehicle Design

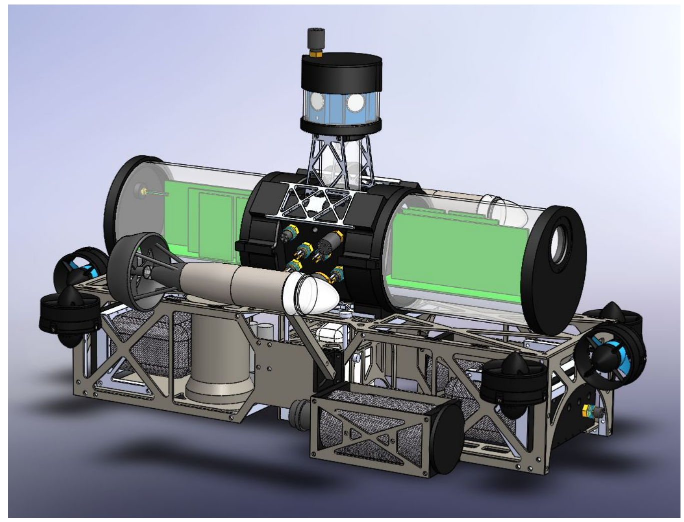


Fig 1. Complete Solidworks rendering of Leviathan 2017 competition vehicle

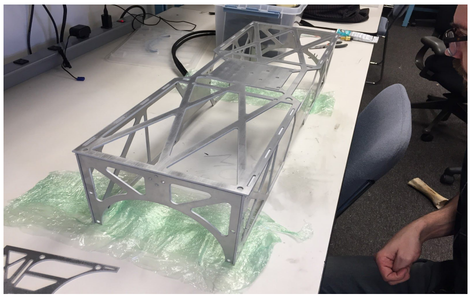
1. Mechanical

The mechanical systems of leviathan have been built from the ground up to complement the team's advanced sensor suit. Focusing on innovation and education, without compromising performance, the mechanical team incorporated new composite materials, in addition to new fabrication and sealing techniques.

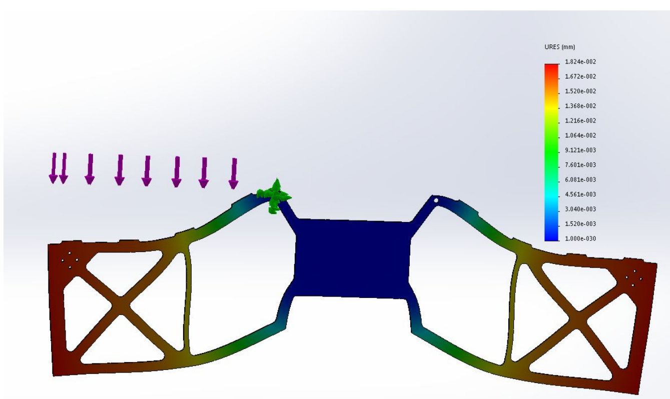
1.1 Midcap

The 2017 vehicle's main hull is a 3 chamber "mid-cap" design. There are 3 spaces coming off of the central mid-cap where connections enter and exit the vehicle. The mid-cap design reduces cable lengths, and provides a stable and accessible electrical base for the vehicle. The front main hull chamber allows space for the main computer, ethernet switch, USB hub, and other off the shelf electronics. The rear half of the main hull houses the custom backplane, which includes vehicle control and power systems. The final top chamber, called the periscope, contains the 360 camera, and Inertial measurement sensors. The inclusion of the Occam Omni 60 360 degree camera was a major driving factor in the vehicle design the past two years. In caligula the whole main hull was oriented vertically which led to major stability issues. By reducing the vertical section to only the periscope the vehicle's stability is greatly improved. The Main Hull is comprised of around 90 separate components. Our choice to develop a multi piece midcap was motivated by machinability and desire to improve the mechanical team's skillset. As all machining is done in house we decided that machining a single piece midcap would be outside the team's abilities, and that the cost of a mistake was too high. This large number of components creates more potential failure points and as a result is harder to seal; this tradeoff is acceptable to us, but we must constantly monitor the integrity of the hull.

1.2 Frame



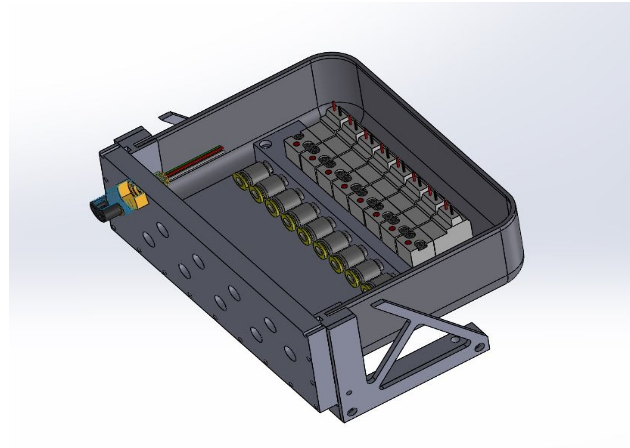
The mechanical design of the 2016 sub Caligula had several critical faults. First the novel design of a vertical tube for the electronics housing was a critical mistake. At the time a novel choice and while the calculations suggested relatively limited effects to stability, the vehicle was quite unstable compared to more conventional horizontal tube platforms. These stability issues made active vehicle control necessary eliminating the possibility of a closed loop system. Ultimately the integration timeline only allowed for us to attempt to hardcode motor values, which was unsuccessful. The vertical hull also made accessing the electronics difficult due to a lack of clearances between the electronics shelving and hull itself. In the 2017 hull design we avoided these mistakes by creating a predominantly horizontal hull and by incorporating a custom waterjet frame that also included a sub-frame for the team's new Nortek DVL. The vehicle's frame was water jet cut from an 1/8th inch aluminum sheet.



The frames exact design was determined by extensive finite element strength analysis. This will keep weight down and provide students with learning opportunities and experience which are representative of professional situations

1.3 Enclosures

Leviathan Contains a large number of ancillary enclosures including pre-fabricated ones such as the Nortek DVL in addition to custom, designed and fabricated, enclosures. The ancillary enclosures consist of the hydrophone array the battery enclosures, the pneumatic/actuation systems, and a downward camera enclosure.



The downward facing camera housing is a traditional aluminum housing. The enclosure is comprised of a face sealed endcap with ethernet port, custom machined aluminum tube, and a permanently sealed glass lense.

The vehicles other enclosures use an innovative carbon composite, aluminum hybrid enclosures. Carbon fiber tubs with aluminum sealing components, uses each material in its optimum manner. The carbon tubs greatly reduce both cost and weight; the rigid carbon composite easily resists crushing at competition depths. The permanently attached aluminum sealing collar, interfaces with the removable aluminum cap. The removable caps mounts electronics and connectors. By utilizing the machinability and hardness of aluminum for the sealing components reduces the chances of sealing issues. Composite materials are becoming ever more utilized in industry. Developing composite engineering skills for current and future members, better prepares students to excel after college.

1.4 Actuation

The Leviathan's Actuation system consists of a simple eight station manifold that uses three way valves to service two torpedo launchers, two marker dropping mechanisms, and four linear actuators that provide for up to four manipulators with custom end effectors. The Manifold is supplied by a paintball tank rated to 3000 psi which is regulated down to a safe working pressure. This actuation system is able to independently fire multiple torpedoes, multiple markers, and perform the fine object manipulation tasks to achieve maximum points. This system is housed inside a custom carbon fiber enclosure with the end effectors manufactured out of aluminum and carbon fiber.

2. *Electrical*

In order to overcome wiring and stability problems experienced in previous years this years electrical system was built to integrate into a custom backplane solution. The majority of the electronics were designed as part of a senior design class which provided rigorous testing throughout two semesters to guarantee the quality of our electrical systems.

The custom electrical systems are our battery merge board, backplane, power conversion board, and controls board. In addition to our custom electronics we also have an advanced sensor suite to help with navigation, and the many task RoboSub has to offer.

2.1 Merge Board

The electrical system starts with our two 10Ah 14.8V, 10C LiPo batteries. These batteries can each provide 100A of continuous current, allowing us to run all six of our Blue Robotics and both Video Rays at maximum current draw with little trouble. To safely draw from these batteries in parallel we built a battery merge board. The merge board is controlled by a high voltage ideal diode or-gate. This or gate drives two 300A MOSFETs allowing current from the battery whose voltage is higher. This maintains even voltage across both batteries. When the voltages are the same it draws from both circuits equally.

In order to reduce the temperature inside of the vehicle the merge board was designed with large power and ground planes. These planes allow the whole board to dissipate heat during heavy operation, and provide strong heat sinks for the high power MOSFETS. The planes and motor traces were designed to keep the operational temperature of the board to around 30 degrees Celsius.

The merge board also contains our kill switch which controls our actuation system and allows for safely stopping the 140A nominal current going to the motors. This kill switch uses a logical and gate to accept a kill line from both a microcontroller as well as a physical circuit. The if our microcontroller detects excessive current draw it will trigger the kill switch. Or if at any point the diver desires to kill the vehicle a single-pole, single-throw (SPST) switch rests on the outside of the vehicle. These switches then drive the gates of eight parallel NMOS MOSFETs tied to our motors.

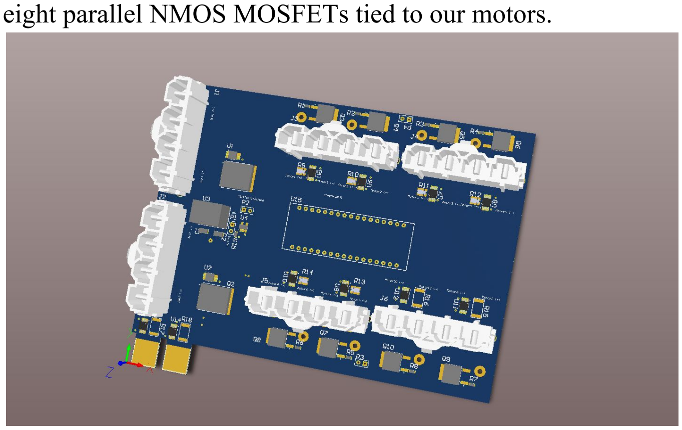


Fig x: 3D Representation of the merge board

2.2 Backplane

The second subsystem in Ocean's 7's project is the backplane. This is a board used to route all power traces and PWM signal traces throughout the hull of the AUV. The backplane was designed to allow slotted connections for all of the other submodules in the system. This slotted design allows us to quickly substitute identical copies of boards in case of part failure.

The primary motivation behind the backplane was to eliminate the tangle of wires often seen inside of past CU vehicles. All power cables are now routed through the backplane and individual rails can be wired directly from the backplane to their component with fewer crossing wires. The backplane, like the merge board, also was designed with large traces in order to mitigate heating.

This PCB also integrated into the mechanical system, supported by a special frame which allows us to more easily remove the hull in the event of a part failure. The frame supports the backplane and the additional boards lifting them off the acrylic.

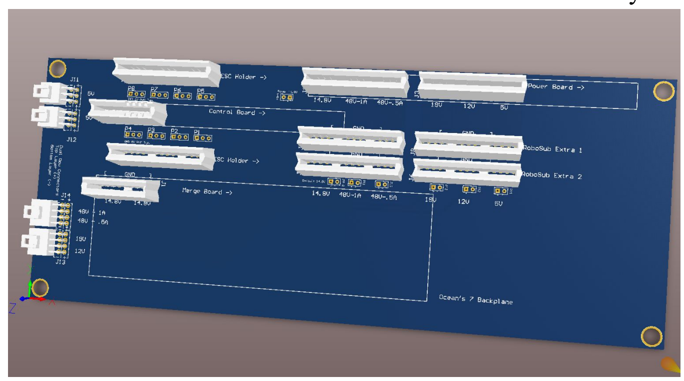


Fig x: 3D Representation of the backplane

2.3 Power Conversion

The power conversion board takes in 14.8V from the merge board through the backplane and converts it into various voltages in order to power each of the other electrical systems on the AUV. The power conversion board also contain a microcontroller for current sensing.

Through a variety of buck and boosting switching converters, largely from Linear Technology, the power conversion board provides stable current at many voltages. We are able to power all of our digital electronics from a 5V, 1A converter. This is the voltage running the microcontrollers as well as the vehicles kill-switch. The mechanical actuators and network switch are powered by a 12V, 3A converter. The main computer, a Gigabyte Brix with an i5 processor runs of a diode protected 19V, 4A rail. And our power conversion board contains two 48V, 0.5A lines to power our Nortek DVL as well as our Point Grey power-over-ethernet (POE) camera.

In order to better track our system's power usage each voltage rail has a current monitoring AD8217 fed into an on board microcontroller. While the microcontroller on the power conversion board is not fed directly into the kill switch like the one on the merge board, it can still alert the main computer to potential shorts or failures in the system.

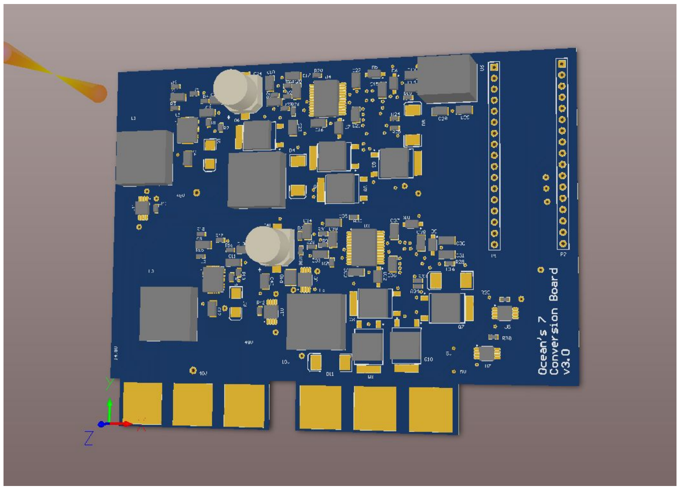


Fig x: 3D Representation of power conversion board

2.4 Control Board

Controls is a critical part of any system, and allowing a digital control system to operate at high speeds can help make tuning as well general operation smoother. As such the vehicle features a new control board based around an STM32 Arm Cortex M7 microcontroller. This powerful microcontroller allows us to use simple UART transmission interfaces, contained ample PWM driving registers, and allowed us to do quick interrupt based controls.

The control board slots directly into the backplane with PWM lines emitted on either side to provide signals to the ESCs. It takes in packaged sensor data from the vehicle PNI Trax IMU as well as the Nortek DVL as well as desired pose from the CPU and then implements our control algorithms. These algorithms then adjust the PWM outputs to each of the eight motors to move the vehicle locally to the next setpoint.

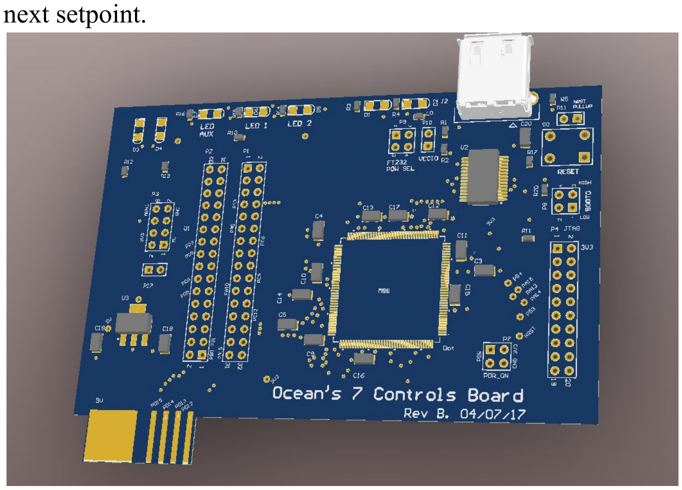


Fig x: 3D Representation of controls board

2.5 Cameras

In addition to our new custom electronics, Leviathan features an advanced sensor suite. This includes several powerful cameras. The most prominent is sourced from a local Boulder robotics vision company.

The Occam Omni 60 contains five 1.8 Megapixel cameras which are stitched together to provide steady 60FPS video in a complete 360 degree panorama of the vehicle. It operates over USB3.0 which plugs directly into our main computer. The lense on each of these cameras gives a 58 degree field of view. This camera should help with obstacle detection, and allow the vehicle to take non-standard approaches to tasks such as torpedoes, as well as the new octagon.

In addition to this camera we have a global shutter Point Grey (now FLIR) BlackFly 1.3 Megapixel camera as our downward facing camera. This camera is paired with a Theia Lense to give us wide FOV. This camera was selected to give us stable images while moving, and to assist on early path detection and control critical vision tasks present throughout the competition.

Our final camera is an oCam 5MP USB 3.0 Camera. This camera faces forward and integrates easily into our ROS based software system. Direct memory access allows the camera to place images directly into main memory bypassing the CPU and reducing overhead. The oCam will be especially helpful for buoys allowing us to track objects until the are totally obscuring the 65 degree field of view. Its small form factor also allowed us to place it inside the main hull without disturbing our other hardware.

2.6 hydrophones

Leviathan's hydrophone system consists of nine Aquarian AS-1 hydrophones designed to determine the heading, distance, and elevation of an incoming acoustic wave. The nine hydrophones are arranged in a 3 by 3 array of nine hydrophones. The location of the hydrophones relative to one another allows for the detection of acoustic waves between 20 kHz and 40 kHz while also preventing spatial aliasing. The hydrophones interface directly to an embedded system that is independent from the submarine's primary computer. This system's sole responsibility is to determine the heading, distance, and elevation of an incoming acoustic wave relative to the vehicle's location. The embedded system consists of three, high-performance, ADC chips, nine low noise amplifiers, an STM32F M4 microcontroller, and a Xilinx FPGA. The FPGA is running a custom algorithm implemented in Verilog and VHDL. As a result, the hydrophone array – coupled with the custom algorithm – behaves as a passive sonar system rather than an acoustic point-source locator. In effect, the algorithm implements adaptive-beam forming, simultaneous multiple-source identification, and signal extraction.

Theoretically, the algorithm is capable of determining the heading, distance, and elevation of multiple sound sources to within a tenth of a degree. The development of this system is ongoing and currently untested.

Concurrently a phase delay technique is being used that uses data from the three leading edge hydrophones. the phase delay between these three points is in turn used to find an approximate heading of the pinger.

Once the telemetry is identified the data is packaged and sent to the submarine's primary computer in real-time allow the software to make accurate planning predictions.

2.7 Pose Estimation Hardware

Pose estimation is a complex robotics problem and usually involves the integration of many sensors. One of the most common sensors used is the GPS but this is not available for underwater applications. As such many top teams rely on Doppler Velocity Loggers (DVLs) to accurately find their position underwater. Our team is no different, using our newly purchased 1MHz Nortek DVL to sense our velocity, and integrate in order to map our position through transdec. The Nortek DVL is aided by a PNI Trax AHRS IMU. This inertial measurement device provides linear accelerations and angular velocities for the vehicle allowing us to gain a greater sense of how the vehicle is moving in the water.

Both of these devices are integrated into our system through custom ROS packages which allow us to pull out relevant data and apply it to our control systems.

3. *Software*

Improving on last years architecture, Leviathan was programmed with an improved software architecture. Building on top of ROS we decided to break the system into 4 subsystems; Controls, Perception. Our goal with this design was to make the system easier to customize. ROS is used as the communication network between all of the software application. We planned a well organized set of topics, so any part of the application could subscribe to information it needed.

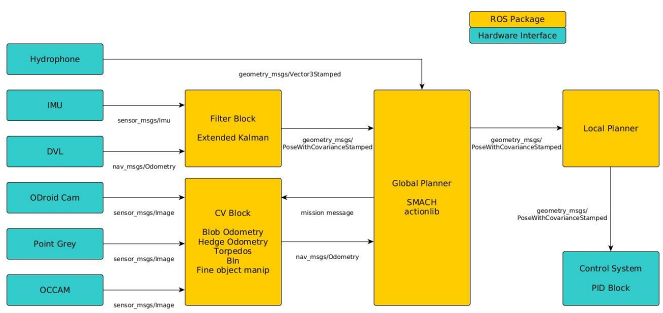


fig x. Software graph

3.1 Control System

The control system was designed in three stages. Each stage builds from the previous allowing us to focus our efforts tuning them one at a time. They will be referred to as follows: Motor Control, Local Planner, and Mission Planner.

The motor control algorithms were designed as part of the electrical system initially and were later integrated into software. Using early models of the vehicle the team attempted to determine the plant of our AUV and implement it in Simulink. These models allowed us to tune controllers for heading, and velocity. The motor controls are based on the 6DOF the vehicle can operate in. Each degree of freedom had its own separate controller.

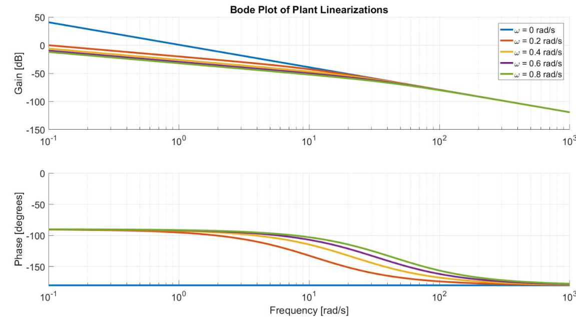


Fig x: Simulated Bode response of vehicle plant linearized at varying velocities

Initially, PID the team implemented PID loops, and attempted to tune the approximated linear system of our vehicle. But due to the nature of fluid drag increasing with the square of velocity, as well as the buoyancy requirements of our vehicle these proved to be unstable in most cases. The integral control was especially susceptible to integrator wind up, causing our system to “dolphin dive” or turn motors to full reverse/forward despite having reached a desirable steady state position.

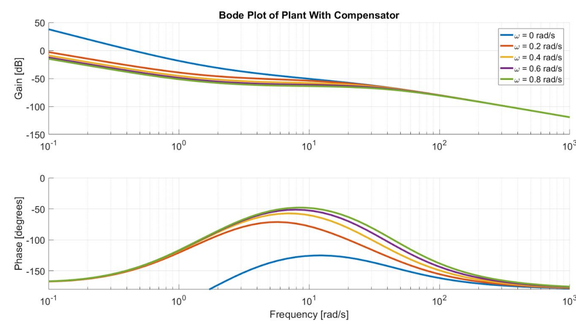


Fig x: Simulated Bode response after lead-lag compensation applied ad different velocities

The team used two approaches to combat these phenomena. In order to prevent integrator windup the team switched to lead-lag networks, which allowed us to achieve similar characteristics to PID controllers without implementing the full PID controller. Using digital control strategies we were still able to implement the lead-lag networks without significant long term data storage. In order to fight the effects of drag we gain scheduled the outputs of our motor controllers. This allowed us to increase our output force as the velocity of the vehicle increased.

Finally, each of the 6DOF controllers were combined using simple linear algebra in order to account for the interactions between the controllers, i.e. pitch and roll maneuvers potentially affecting depth due to the nature of the motor arrangement. These final signals were then converted to PWM signals and sent to the ESCs to control the output of the motors.

The early mathematical analysis was used as a basis for our early controls. This was then further tuned to account for changes in the vehicle's dynamics.

The Local Planner was designed as a flexible system that can handle the path planning for all situations. The control system uses Bezier curves to handle the path between locations. Bezier curves allow for smooth transitions, and the ability to set the final desired heading. As the vehicle moves along the curves new setpoints are provided to the local controller which causes the robot to match our desired poses. The curves are planned based on data from the mission planner providing the vehicle with Point A to Point B control through advanced paths.

The Mission Planner is a State Machine implemented in the SMACH framework. SMACH was chosen because it allowed for fast prototyping of the state machine. The planner also uses actionlib to designate actions, this package works by spawning a subprocess for the action. This allows the Mission planner to send and monitor a desired task while continuing to monitor other aspects of Leviathan. The mission planner is the integration step between perception and the rest of the control system.

3.2 Perception

The localization is based on a data input from serial communication from the DVL and the IMU's. The DVL takes care of both velocity and position outputs which can be compared to one another to verify accuracy. The IMU and DVL are combined with visual odometry in an extended kalman (EKF) filter. The EKF takes these three components and generates a pose estimate.

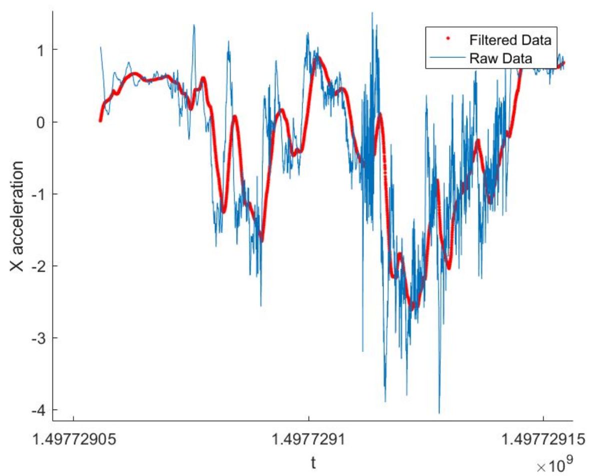


Fig 2. Above is shown the filter results on one axis of the IMU acceleration.

3.3 Computer Vision

Computer vision (CV) is used to aid in the completion of many of the tasks. At this time the main tasks being completed with the assistance of computer vision are the buoy task, the hedge, as well as general guidance from objective to objective. This is done by the use of openCV libraries that allow for quick application of many image transformations. In the future the plan is to further develop the CV software on Leviathan in order to provide feature detection for spatial mapping.

CV helps with the buoy, and the hedge, by detecting the obstacles in Leviathan's field of view then determining if they are a part of a task at hand, a path indicator, or debris. The main algorithm in use as follows:

- Read image
- Blur with a gaussian filter
- Edge detection using a Canny edge filter
- Find contours
- Calculate moments of each contour
- From moments determine shape of object
- If it is a shape pass it into CNN for verification
- Calculate orientation of shape with respect to Leviathan's reference frame
- Print orientation message to the control system

This algorithm relies heavily on the convolution neural network to be trained correctly as it is what has a final say in if a shape is, or is not, important which required many images of the obstacles in different settings such as lighting, or dirty water. After having been passed through the neural network there are smaller steps that will be followed, however these mainly pertain to how the controls will deal with the orientation data of the object.

4. Business

This year the business strategy focused on creating as big a presence as possible on campus and in the community. The central idea being that as our profile increases our ability to raise funds and recruit new members will scale accordingly.

These efforts include participating in a variety of events. With on campus efforts such as the annual welcome festival and having regular tabling events for promotion within the engineering center. As well as going to local maker faire's, the annual sparkfun AVC competition, and presenting in front of the grassroots Boulder is For Robotics meetup community.

Membership has increased dramatically from theses efforts with last years eight person team growing to nearly 40 active members. With various levels of commitment, experience, and age these moves will ensure a successful team for many years to come.

Taking every opportunity to create a presence in the local community has paid dividends as well. It has created a closer bond with local robotics companies such as Sphero, MDA systems, Occipital, as well as the various robotics labs on campus. 6 members of the team have been able to get internships or jobs in the area of robotics, partially due to the teams networking and outreach efforts.

C. Experimental Results

Rigorous testing has occurred on Leviathan's many subsystems throughout the design process. This has culminated in 100 hours of pool testing being scheduled for the vehicle throughout the summer.

Part of the nature of the electronics being designed through a senior capstone was that each system was tested as part of the engineering process. Unit tests of the each subsystem provided valuable information that lead to some minor and some major changes in the design of our electrical systems.

The backplane for instance initially was going to contain communication lines, but due to improper shielding we discovered through EMF testing that data quickly became corrupted. Due to the eight EMF producing motors surrounding the vehicle we decided to eliminate communication lines in this revision of our backplane in favor of shielded cables to provide more protection to the high speed data.

In addition we drastically changes elements of the powerboard in order to increase the current outputs of the respective voltage rails. During integration testing the team discovered in order to provide maximum current to a simulated digital many of our devices the boards voltages would drop significantly. Our 48V line initially dropped as low as 26V. This was rectified for final hardware changing out MOSFETS with higher power ratings, as well as adding larger inductors.

Finally, testing on the control board showed that UART communication at standard 9600 baud was too low to sustain the vehicle due to the massive amount of sensor data. As such we were able to increase the baud rate to account for the full pose and setpoint vectors of the vehicle being sent at 100+ Hz.

In addition to electrical testing the mechanical system was tested as critical components were developed. Several weeks of testing went towards the seals of our 6 part main hull. Initially, the hull leaked due to some improper sealing techniques. But switching to a more heavy duty marine epoxy, as well as adding final hardware including our connectors reduced the leaking significantly.

There were still minor leaks though, letting in approximately an eighth of an inch of water in about half an hour of pool testing. This was eventually isolated to a few trouble spots with waterproof cameras being placed in the vehicle and were quickly patched.

After completely sealing the vehicle, the team began full hardware tests integrating our electronics and mechanical system. Initial testing focussed on tuning stability for simple controlled maneuvers, and the kill-switch. Additionally, through runs the team collected data on our various sensor to allow the vision team to simultaneously tune CV algorithms.

Continued testing through the summer will integrate in the Local and finally Mission planner as we proceed towards the competition. Building these systems up from low levels will hopefully provide a stable platform moving forward.

D. Acknowledgements

We would like to thank our faculty sponsor Nikolaus Correll for enabling us to work on this project. Also our many sponsors including Nortek, Aquarian Audio, Molex Connectors, PNI, Sparton, Occam, MacArtney, Video Ray, and XIO technologies.

E. References

[1] B. Siciliano, and O. Khatib, *Springer Handbook of Robotics*, Berlin, Germany, Springer International Publishing, 2008

[2] A.Sedra and K.Smith., *Microelectronics 7th ed.*, New York, NY, Oxford University Press, 2014

[3] G. Franklin, J. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems 7th ed..,* Upper Saddle River, NJ, Pearson Inc, 2015