Cornell University Autonomous Underwater Vehicle 2008: Design and Implementation of the Triton Autonomous Underwater Vehicle

Abstract

The CUAUV Triton is a new inspection class Autonomous Underwater Vehicle developed by a team of undergraduate students at Cornell University for the 11th annual AUVSI/ONR Autonomous Underwater Vehicle competition. Successful elements from the CUAUV 2006-2007 competition vehicle, Proteus, such as a cantilevered rack and twin hot swappable battery pods were further refined while new elements were introduced to further the team goals of vehicle reliability, versatility and testability. New features include more reliable sealing, better thermal management, modular trimming, a more sophisticated downward camera, better dockside support and more advanced vehicle diagnostics. Pool testing with the previous vehicle enabled the team to develop software even as the mechanical and electrical elements of Triton were being completed. Sensors include forward and downward facing cameras for the visual aspects of the mission, forward and downward facing Tritech PA500 altimeters for obstacle avoidance, a 3DM-GX1 orientation sensor, a depth sensor, and a custom-made passive acoustic sensor. Triton is 8kg lighter than Proteus allowing for easier deployment, has a frame wide enough for a Doppler Velocity Log, and uses double bore seals that are rugged enough to seal the vehicle at depths exceeding 100 feet. These features enable future research oriented lake missions for Triton. Overall, the vehicle is fully capable of autonomously completing all of the mission tasks set forth for this competition.

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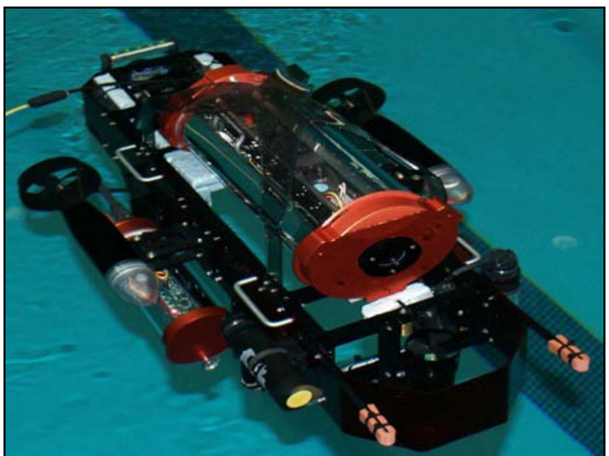
Introduction

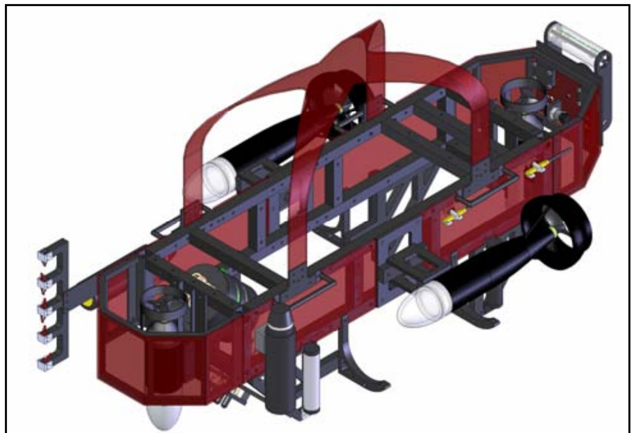
CUAUV's primary objective each year is to win the Association for Unmanned Vehicle Systems International (AUVSI) underwater competition. Teams from across the world come to compete at this annual event, which takes place each summer at the TRANSDEC Facility in San Diego, California. For the competition, each vehicle must demonstrate its autonomy by completing various tasks while remaining completely submerged. This year, the theme is Underseas 11. Vehicles will be expected to pass through a validation gate, follow colored paths, locate buoys, and drop markers into appropriate bins, travel through a duct, and track an acoustic pinger before surfacing. For more details, visit http://www.auvsi.org/competitions/water.cfm



CUAUV Triton in the water at a pool test.

Triton is CUAUV's newest littoral hovering AUV. The new vehicle borrows from the successful elements of the Proteus AUV while including significant changes that improve vehicle reliability and usability. The vehicle's mechanical structure supports all pressure vessels and sensors as well as actuators and thrusters. The main electronics are contained in a single clear acrylic hull on a hull rack. To improve maintainability the hull may be removed from the electronics rack without disconnecting any of the electronics. Two hot swappable battery pods provide power for the vehicle.

Structure



CAD model of the vehicle structure

The vehicle structure includes the frame and infrastructure that supports the components of the submarine. This includes mounting for all pressure vessels, sensors and thrusters in addition to trimming and crane attachment systems.

Box Frame

The vehicle is built around a welded aluminum box frame. All of the vehicle systems are anchored to this frame, which measures 26.25''x 9'' x 5''. The new box frame is wide enough to accommodate an RDI Workhorse DVL for lake tests.

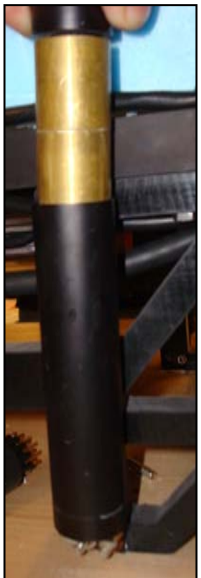
Skids

The skids attach to the bottom of the box frame to act as a built in stand for the vehicle. They are waterjet cut from ½" Delrin.

Exterior Side Panels

The side panels are laser cut out of transparent 1/8" red acrylic sheet. They provide improved hydrodynamics as well as mounting space for the altimeters, marker droppers, and sponsor logos.

Trimming



Trimming system.

The trimming system allows precision trimming while maintaining a low profile physical appearance. The system uses brass weights in anodized aluminum tubes. One tube is fastened to each skid, allowing for the possibility of fine trimming in any necessary direction. To change the number of weights, the inner rod simply slides out of the tube, providing access to the weights, which can then be removed or added appropriately.

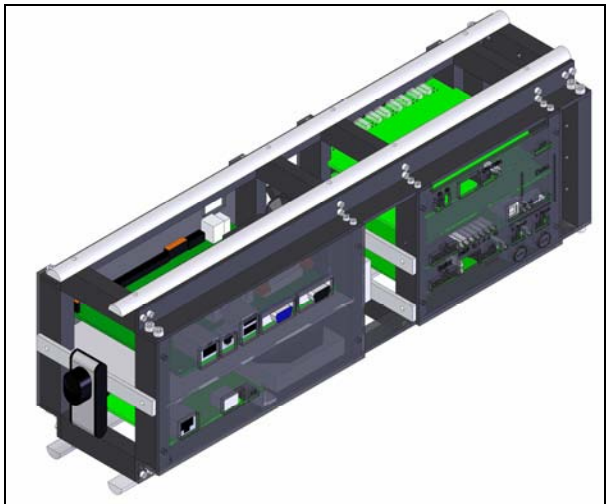
Crane Hookpoint

At the competition in San Diego, the vehicle is hoisted into the water by a crane attaching at a single hookpoint. In previous years, a rope harness was used, which was unsightly and led to many other problems including an incident in which a rope was sucked into a thruster. To improve on this, a steel wire harness that is rigid enough to hold its shape is used. To prevent the wire from scratching the hull, an acrylic superstructure was added.

Shrouds

The shrouds at the fore and aft of the vehicle reduce drag and protect the main body of the vehicle from collisions. The shrouds are built out of an acrylic shell on a Delrin frame. The acrylic provides a smooth surface and the Delrin provides both rigidity and durability. The front shroud also supports the grabber, and the back shroud supports the switchbox.

Upper Hull Rack



CAD model of the upper hull rack

The upper hull rack provides space to mount the vehicle's electronics and cameras. The rack is cantilevered off of the rear endcap so that the hull can be removed without cutting off power to any of the onboard electronics.

Rack Structure

The main structure of the rack consists of four aluminum L-beams mounted together on two vertical and two horizontal beams to form bulkheads of open rectangles. This allows for both heat and air flow through the rack. All of the parts for the rack were machined in-house, saving time and money. The entire rack is cantilevered from the rear endcap. Acrylic guides mount to both the top and bottom horizontal bulkheads to allow the hull to slide on easily, and to support the front of the hull.

Wire Routing

The L-beams of the rack provide convenient channels to guide wires. To facilitate routing, holes are drilled for cable ties in all four L-beams. This provides an accessible, neat and functional wire routing scheme.

Board, Fan and Camera mounting

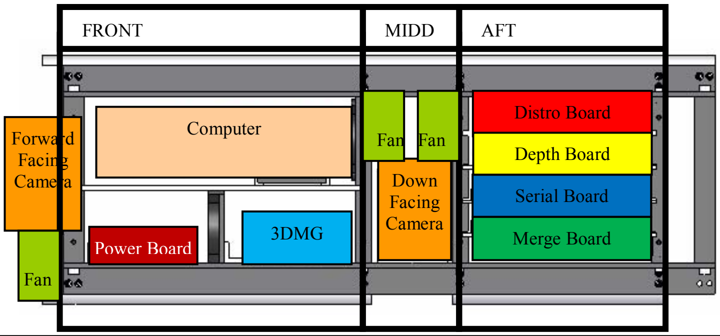


Diagram showing positioning of boards, fans and cameras in the upper hull rack.

Aft Section:
The CUAUV-built Merge, Distribution, Serial and Depth boards slide into 1/8" slots in the vertical bulkheads of the aft section. Lasercut acrylic panels hold the boards in place, channel the air flow and provide labeling for connectors.

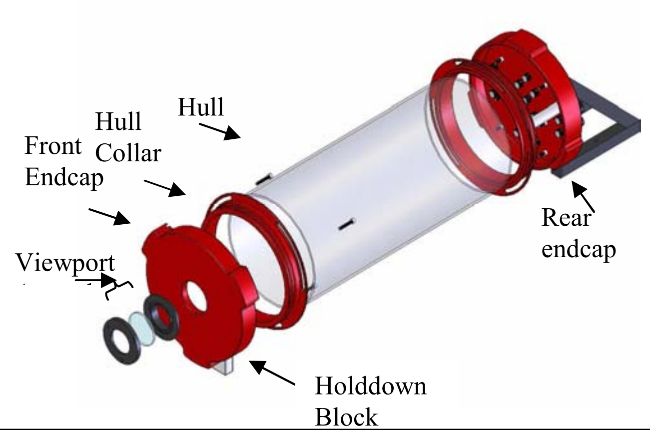
Middle Section:
This section is devoted to the downward facing camera and two fans, one pointed backwards to blow over the distribution board, the other pointed forwards to cool the computer. The camera is located in this section so that it is as close as possible to the vehicle's center of rotation.

Front section:
The computer is mounted on a static dissipative ABS/PVC tray, which slides into 1/8" slots in the front pair of bulkheads. The 3DM-GX1 mounts to a plate which is bolted directly to the bottom L-beams. In the front of this section, beneath the forward facing camera, is a third fan that pulls air over the computer power board. Lasercut acrylic side panels provide a channel for air flow and connector labeling.

Pressure Vessels

The vehicle's pressure vessels are constructed with clear acrylic hulls and aluminum bore seal systems consisting of an endcap and sealing collar. Bore o-rings are used to provide reliable sealing without the finickiness of face seals. Aluminum was chosen to improve thermal conductivity and for its excellent structural characteristics. To prevent o-ring extrusion during sealing, the bore of each seal is beveled 15 degrees.

Upper Hull Pressure Vessel



Exploded view of the upper hull assembly.

The upper hull pressure vessel provides sealing for the electronics. It consists of a front endcap assembly, hull assembly and rear endcap assembly.

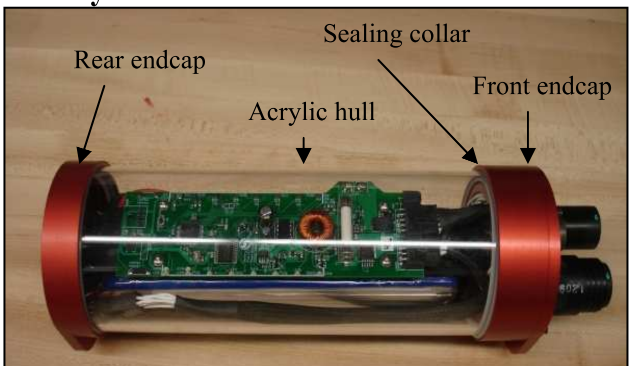
Front Endcap Assembly
The front endcap assembly seals to the front of the upper hull and provides a removable viewport for the forward facing camera. The viewport system consists of a viewport collar, sapphire viewport, and viewport flange. When the hull slides over the rack, a slot in the front endcap fits over a holddown block which prevents the cantilevered rack from lifting up.

Hull Assembly
The hull assembly consists of two hull collars glued onto a 15.75" long, 7" diameter acrylic hull. The hull collars contain double bore seals. Slots in the hull collars allow the hull assembly to attach to the front and back

endcaps with 60 degrees of rotational independence.

Rear Endcap Assembly
The rear endcap seals to the back hull collar of the hull assembly. The rack is bolted to the rear endcap. Seacon connectors (MCBH-6, MCBH-8 and MCBH-10) provide an interface to external devices and power. The depth sensor threads into the endcap. To support the entire cantilevered rack and hull, triangle braces attach the endcap to the frame.

Battery Pod Pressure Vessel



Assembled Triton battery pod.

The battery pods provide Triton's electrical power. Each pod contains a lithium polymer battery pack and a custom printed circuit board to handle monitoring and battery safety. The pod has two underwater connectors, one for charging and the other for discharging. While in use on the vehicle, only the discharge connector is plugged in. The charge connector allows for the batteries to be charged without opening the pod. A Deep Sea Power and Light pressure relief valve prevents any excess buildup of pressure during charging. This allows the battery pods to always remain sealed, decreasing the risks of improper assembly and leakage.

Battery pod rear endcap
The rear endcap includes two bore o-ring glands for sealing, a flange for mounting the pod to the support, and a three point shelf for supporting the battery pod rack. Much of the endcap is machined out to allow for installation of the Seacon connectors and Deep Sea pressure relief valve

Battery Pod Hull Assembly
The battery pod hull consists of a hull collar and front endcap epoxied to a 9” long 3.5” diameter hull. This hull can be taken off of the battery pods without disconnecting the electronics.

Mounting
Triton’s battery pods are cradled by two supports in the frame. Two quick release pins provide easily removable attachment to the supports. This improves serviceability and decreases the time necessary to change batteries

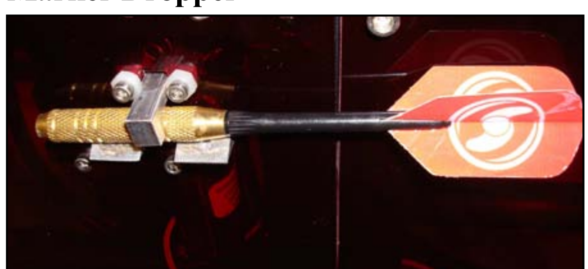
Potting

To splice underwater cabling 3M Electrical insulating resin is used. Molds are made for potting in HDPE blocks.

External Devices & Actuators

Triton features several external devices and actuators including marker droppers, a grabber, thrusters and a switchbox.

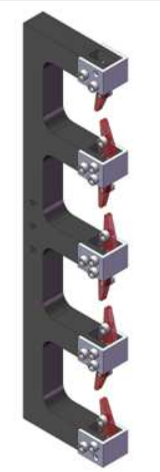
Marker Dropper



One of Triton’s marker droppers holding a CUAUV customized dart.

The marker dropper allows Triton to drop markers consisting of modified darts into bins as a part of the competition. Each of the two marker droppers on the vehicle uses a pull solenoid and holds one dart. Each dart is held horizontally and relies on gravity and water resistance to rotate and fall vertically after being released. This orientation minimizes space requirements.

Grabber



Triton's Grabber

The front grabber on Triton is designed to consistently capture and fully constrain the "safe" without becoming entangled in any other mission apparatus. The openings of the comb-shaped body of the grabber are dimensioned to allow clearance for the PVC frame of the safe. The small flippers that block the openings pivot in order to accept the "safe" into the opening, and are spring loaded to ensure that the "safe" remains fully secured

Thrusters

VideoRay GTO Thruster mounted to Triton.

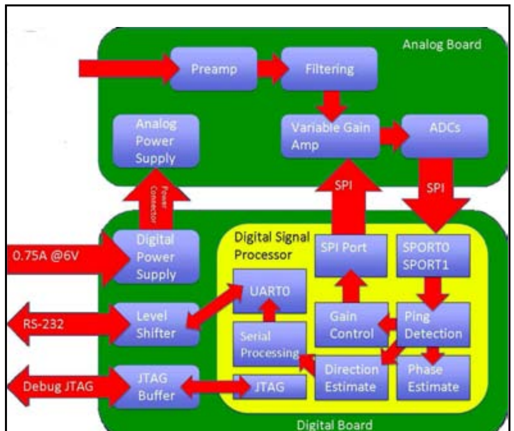
Four VideoRay thrusters are used for propulsion of the vehicle. Two horizontal thrusters (GTO) provide forward, backward, and yaw motion; and two vertical thrusters (60mm) provide depth and pitch changes. A custom built motor controller stack mounts inside the thrusters and communicates with the computer.

Each thruster mounts to the vehicle using a custom attachment block containing a Seacon HUMK-5 connector.

Switchbox

Triton's switchbox consists of the kill, mission start and main power switches. Pulling down a breaker shaped handle disables the thrusters. The handle bar glows red when the vehicle is killed and green when unkilled. The kill switch utilizes epoxy-cast electronics, magnets and reed switches for contactless actuation. The mission start switch uses similar components and functions as a momentary pushbutton. The switch glows blue when a mission is running. The main power switch is an off-the-shelf polyurethane toggle switch.

Passive Acoustic Array



Flow chart describing hydrophone system function.

Triton's hydrophone system uses four Reson TC4013 piezoelectric elements to detect incoming sound waves. The elements output electrical signals to an analog front-end circuit board. This board provides pre-amplification, filtering, variable gain amplification and analog-to-digital conversion. Eight Microchip MCP6S21 variable gain amplifiers (VGAs) provide up to 40 dB of software adjustable gain on each channel. The signals from the VGAs are sampled at 2 MHz with 12 bits of resolution using two AD7266 ADCs. These ADCs use a proprietary SPI protocol to communicate with a Blackfin BF-537 digital signal processor (DSP), which lies on a separate circuit board within the hydrophone enclosure. The DSP estimates the heading and elevation of the sound source and sends this information to Triton's computer.

Triton’s hydrophone enclosure

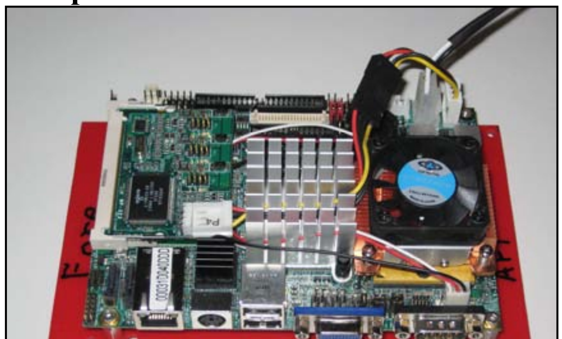
The back endcap of the hydrophone enclosure has a Seacon MCBH-6F connector to communicate with the submarine and a MCBH-8F connector for debugging with JTag. On front endcap four custom glands allow the wires from the Reson elements to pass through the endcap without the elements being potted directly into the endcap. This allows more flexibility in element mounting and future use of the elements with other systems. Both endcaps have a double bore seal design similar to the battery pod pressure vessels.

Sensors

In order to complete its mission, Triton has several sensors, including altimeters, a depth sensor, a 3DM-GX1 and two cameras. Two Tritech PA500 altimeters provide distance to bottom and nearest forward wall. Depth measurement is obtained using a MSI UltraStable-300 pressure transducer read by a microcontroller using an external ADC. A Microstrain 3DM-GX1 orientation sensor provides the vehicle's orientation in 3D space. Two cameras are used to complete the visual parts of the mission: the downward camera is an AVT Guppy F-046 Color CCD Camera and the forward camera is a Logitech QuickCam Pro for Notebooks Webcam.

Computer and Peripherals

Computer



Triton’s computer.

Triton uses a Commel LS-371 3.5" motherboard with an Intel 2.0 GHz Core 2 Duo processor and 2 GB of RAM for vision, mission and control processing. The computer communicates with its sensors and devices using a custom serial interface board consisting of a 14-port USB to RS232 adapter. A compact flash card is used to provide storage in a shock resistant, fast, and low power medium. To communicate with the shore, Triton has both a wireless and wired tether.

Software

Triton’s software is an evolutionary step forward on CUAUV’s software architecture. The software runs on top of the Debian Linux distribution. Triton software features vision algorithms, expanded mission parameters and a Vehicle Abstraction Layer.

Shared Memory System

In order to allow for efficient interprocess communication, the software uses a custom shared variable system built on top of POSIX shared memory. Variables are defined in an XML file with a name, type and default value.

The shared memory system is accessible from Python, C and C++ using wrapper functions. Any process on the vehicle can access these variables indexed by name. A watcher infrastructure allows threads to block, waiting for a particular shared variable to change. Custom daemons communicate with sensors and vehicle systems to map data between shared memory and the associated physical devices.

Vision

The vision system is written in C++ and uses the OpenCV vision processing library. The system is designed so that separate daemons are used for each of the mission tasks. The mission activates daemons when it needs data from them. The vision daemons first preprocess the images by color to highlight potential object and then use contour finding. The contour finding assigns a probability that an object is recognized to be used by the mission.

Buoy Finding
The buoy finding code locates the center of mass of the orange pixels in frame. It uses a pixel count to determine when the vehicle has reached the buoy.

Bin Finding
The bin finding algorithm preprocesses the image by looking for and isolating black areas. It then creates a contour of that area and examines the size, shape and aspect ratio to determine if the contour is indeed a bin.

Suit Finding
Suits are recognized by first identifying red in the image. Contours are then created and run through a series of comparisons to see how well they match the suits. Contours that are too small or oddly shaped or intersect the edge of the bin are ignored.

Pipeline Finding
In order to identify pipelines along the bottom of the pool, an image is first segmented by orange and then eroded and dilated to remove small features. The processed images are then run through contour processing to determine if any of the collections of pixels resemble pipe by checking each contour for size, aspect ratio and rectangularity. If it finds something that might be a pipe, it records the heading and aspect ratio.

Image processing of a piece of pipeline.

Safe Finding
The safe is found by looking for large areas of orange and then homing in on their center of mass.

Duct Finding
The duct is found by locating the yellow bands around the front or back edge. Once the vehicle is inside the duct, it follows the yellow line down the center.

Mission

The mission planner is built upon two subsystems: a ‘planner’ and a ‘task’ subsystem. The planner schedules everything from ‘task’ blocks. Each task can encapsulate subtasks which must be completed for the objective to be complete. This structure allows for incredibly rich, dynamic missions to be written quickly, with the planner system taking care of many of the details that would have had to be encoded in a more procedural system.

The mission planner is a tree-walking, multithreaded program, which is written in Python due to the complexity of the planner and ease of coding in Python. The planner instantiates each element of the user-given task list, allows the tasks to add sub-tasks, and executes these subtasks when their turn is up. The planner is always running in the background, ready to cull completed tasks and notify tasks further down the line that it's their turn to run. The planner also ensures that 'exclusive' tasks, such as movement primitives, only run one-at-a-time.

Each task is allowed to give the planner a list of "dependencies", which are simply aliases to shared variables. The planner monitors the requested lists of shared variables in separate threads and notifies the tasks to run when their "dependencies" change.

Vehicle Abstraction Layer

The Vehicle Abstraction Layer (VAL) creates a vehicle object that can be accessed by the mission. The vehicle object gives the mission access to both real and virtual sensors as well as basic movement commands. A debug environment allows the shared variables to be imported into a Python terminal allowing easy read write access to the vehicle's shared memory system.

Vehicle Controller

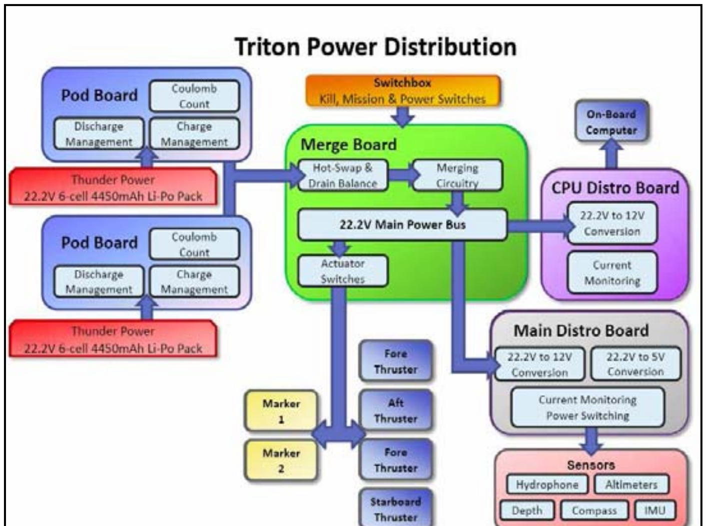
Triton uses a Proportional Integral Derivative (PID) controller operating at 10 hertz to control heading, pitch and depth. Velocity control is left open loop to reduce coupling.

Diagnostics Monitoring

Triton provides a wealth of data about the internal workings of its various systems. In order to display this data to the operator in a sane way, a custom curses based UI displays the data allowing any operator with an SSH client to view it. The UI is divided into several panes in order to fit all of the data from the various systems. The data display is color coded to alert the operator to any critical conditions.

Power

The power system provides the vehicle's computer and sensors with clean, isolated and regulated power. Triton's dual battery architecture allows the batteries to be hot swapped, enabling a battery change without loss of power.



Schematic of Triton's power distribution system.

Battery Pods

Each battery pod contains a single Thunderpower 22.2V, 4450 mAh Lithium Polymer Battery. A circuit board provides overcurrent and overdischarge protection, communication with the rest of the vehicle, and status monitoring. These functions are provided through a fuse for over-current protection, a comparator for under-voltage shutdown, and a dedicated fuel gauge IC that measures voltage and current flow to provide precise Coulomb counting and full charge detection. The LED fuel gauge bar graph can be activated manually by a reed switch, through serial communication and automatically when the remaining capacity changes.

Merge Board

The merge board contains the main circuitry that combines the power supplied by the vehicle's two battery pods, and distributes that power to each of the four thrusters and two marker droppers, as well as passes it off to the main power distribution boards. Inherent in this function is the ability to individually turn on and off power to each thruster and marker dropper, controlled by an external kill switch and commands sent from the vehicle's CPU. The merge board also enables hot swapping of battery pods and shore power.

Distribution Board

The power distribution subsystem provides power to the vehicle's electronics. These devices receive power through ports that can monitor current flow and shut off power to a device that appears to be faulting. LEDs indicate whether a port is powered on (green) or has been powered off in the event of a fault (red). In addition, electrical isolation is maintained between the vehicle's thrusters and actuators and the vehicle's electronics to reduce noise.

Vehicle Support

Triton's bench power and battery charging boxes simplify vehicle operation and maintenance. These boxes are built into rugged Pelican cases to withstand regular use and provide easy transportation.

Battery chargers

The new charging stations are built into rugged orange Pelican cases with panel mount frames in them. The main structure of the station is an aluminum panel, screwed into the panel frame, which supports all of the components either mounted directly to it or hanging below it. Each station contains a power supply, two battery chargers, two battery cell balancers, and cooling and power support components.

Bench power

The bench power box provides the vehicle with an unlimited runtime while on the bench. The box consists of a power supply mounted in a Pelican case. The power supplied by the box is monitored and reported by a modified battery pod board, which communicates status to the computer and an LCD mounted in the lid of the box. The bench power box can be hot swapped with batteries to power the vehicle.

Acknowledgements

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Gold: Cornell, Seacon, VideoRay

Silver: Deep Sea Power and Light, Digikey, Alpha metal, Molex, Advanced Circuits, Industrial Metal Finishing, Samtec, Analog Devices

Sponsor: Total Phase, Mouser, Polymer Plastics

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