CORNELL UNIVERSITY AUTONOMOUS UNDERWATER VEHICLE TEAM

Design and Implementation of the Proteus Autonomous Underwater Vehicle

Abstract

The Proteus is a new inspection class autonomous underwater vehicle developed by students at Cornell University. Based on the idea that reliability results from extensive testing, the Proteus design is driven by three major requirements: the vehicle should be able to go quickly from live testing to deployment, run indefinitely, and sustain individual upgrades without system-wide effects. Thus, the Proteus philosophy aims to create a stable platform that is both easy to develop and easy to deploy. This journal paper details the Proteus technical design with special emphasis on the features that achieve these objectives.

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1 System Overview

After a brief explanation of our design methodology, we outline the overall architecture of the Proteus as well as key specifications. Next, the three major features of the Proteus are discussed in turn. Technologies related to those features are introduced in the relevant sections. Finally, we cover some other interesting projects that do not fit neatly within the three main categories.

Design Philosophy

Deeply affected by our vehicle's critical failure at last year's final competition run, reliability was made the top priority on Proteus. A number of behavioral requirements were created, some based on the competition, others to create testing conditions necessary to ensure reliability. Generating these requirements resulted in a philosophical consensus that drove later design work:

Allow easy testing under a wide range of situations.

Allow the vehicle to run continuously indefinitely.

Allow individual subsystems to be easily replaceable.

Key Components

Functional requirements like structural geometries and sealing techniques were then derived. Design at this stage became closely tied to the budget. As we received key sponsorships, major components like the computer, batteries, thrusters, and underwater cables were finalized. Other more subtle specification like communication protocols and connector pinouts were also finalized.

Construction

Detailed design and construction was broken down into seven discrete projects with rigorously defined interfaces and performance requirements. Each project team was expected to come up with an original design and take it through completion. As each project finished, separate design and use documentation were created to assist in the final vehicle integration.

Proteus at a glance

Physical	
Weight	50 lb
Dimensions (L x W x H)	40" x 20" x 18"
System Configuration	
Electronics	Single hull
Power	Twin enclosed pods
Propulsion geometry	Two horizontal, two vertical
Major Components	
Computer	Kontron J-Rex
Thrusters	VideoRay ROV thrusters
Batteries	ThunderPower TP6000-4S3PL
Underwater connectors	Seacon Hummer connectors
Power	
Bus voltage	29.6V
Energy capacity	355.2 Wh
Typical pack runtime	2 hours
Communications	
Tether	Ethernet, 802.11a
Peripheral	RS232
Sensors	
Orientation	MicroStrain 3DM-GX1
Depth	Sensotec GW-420/F747-01 pressure transducer
Altitude & range	Tritech PA500/6-PS altimeters
Hydrophone	Custom
Heading	Honeywell TCM-250 compass
Forward & downward cameras	Logitech Quickcam for Notebooks Pro
Software	
Serial drivers	C/C++
Vision	OpenCV library
Mission	Python

2 2007 Innovations

The Cornell University Autonomous Underwater Vehicle team (CUAUV) has built 6 generations of autonomous underwater vehicles (AUVs) since 1999. In past years' designs, we've established a competency in vehicles based on a four-thruster, twin hull architecture. Past vehicles have also emphasized structural modularity and adaptability to different mission profiles. The Proteus draws upon that experience and extends the philosophy of a flexible architecture. The primary innovations this year have been three features at the architectural level that shape the fundamental characteristics of the vehicle.

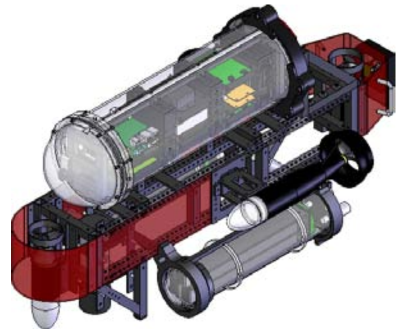


Figure 1: CAD model of the Proteus AUV

2.1 Cantilevered Rack

In the primary pressure vessel, the electronics rack is cantilevered from an endcap mounted permanently to the vehicle. Rather than needing to remove the rack to access the electronics, the hull slides off of the rack, exposing the electronics. This allows us to probe and test the electronics after recovering the vehicle without a system shutdown. See Sections 4 and 6.

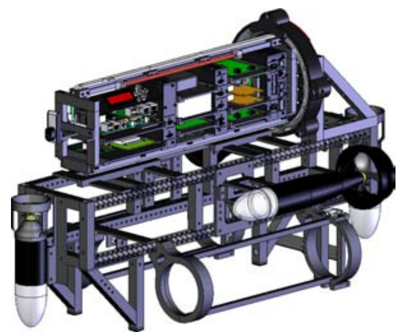


Figure 2: Model illustrating the cantilevered rack

2.2 Power Distribution System

Two self-contained battery pods power the vehicle. The dual pod structure allows the batteries to be replaced without shutting down the sub. A ubiquitous power distribution system manages the power from the pods. It not only provides regulated power to all the other boards, but also performs transparent safety monitoring. See Section 5.

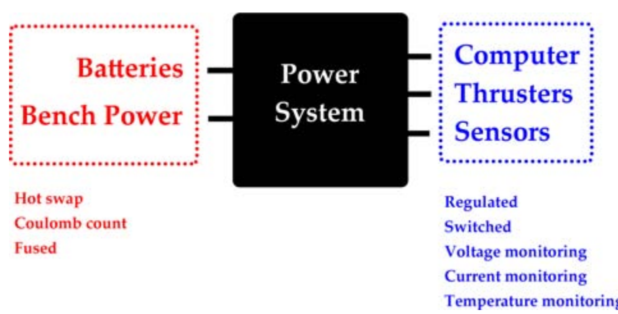


Figure 3: Black box view of power system

2.3 Vehicle Abstraction Layer

A software vehicle abstraction layer (VAL) acts as a bridge between the low level hardware interface and high level algorithms. Changes made to a sensor only requires updating a single driver; the control loop is not affected at all. The VAL also contains pre-programmed mission snippets that allow a full mission to be quickly scripted and tested. See Section 7.

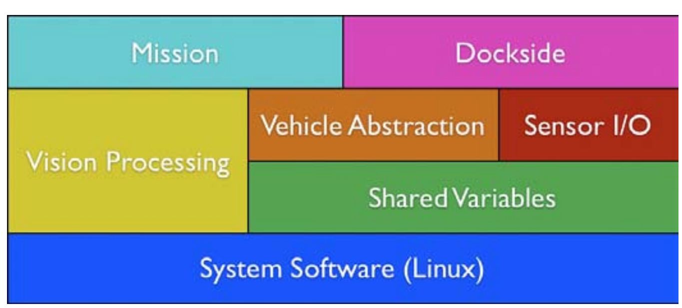


Figure 4: Software architecture overview

3 Mechanical Structure

All components on the Proteus mount to a single frame (Figure 3, **A**). Above the frame is the electronics hull. Below the frame to each side are battery pods (Figure 3, **B**). Four thrusters (Figure 3, **C**) are mounted on each side of the frame. Underwater cables are routed along the insides of the frame and panel fairings (Figure 3, **D**) serve both as an aesthetic as well as physical enclosure. Below the frame are four support skids (Figure 3, **E**). All structural components are built using 6061 or 6063 aluminum, finished with a black anodization.

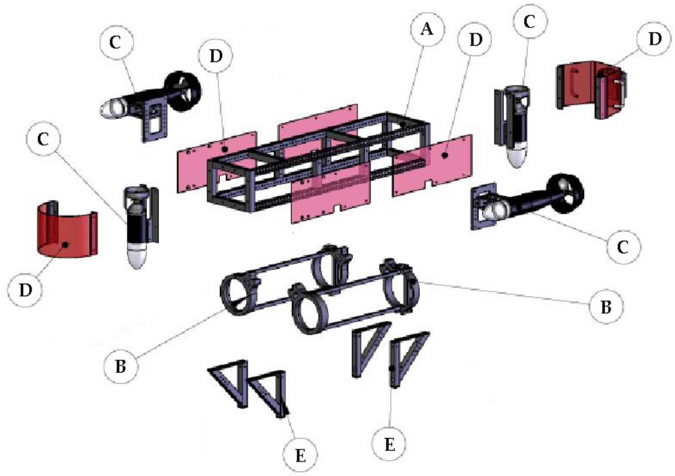


Figure 5: Exploded view of Proteus structural elements

Frame

The box frame is welded using 3/4" wide square aluminum tubing with 1/16" thick walls. Along each of the 4 long bars are mounting holes spaced at 1/2" increments. This mounting system allows precise positioning of each element, be it hull, sensor, or thruster. The welded aluminum frame is also strong enough to withstand any torque from the thrusters.

Underwater Cables

Seacon's Hummer line of connectors and cables form the bulk of Proteus' underwater cabling. Hummers' small form factor not only reduces cable mass, but also allows for a greater number of external connections. The only exceptions are the power lines which use Seacon's more rugged Micro Wet-Con series instead.

Battery Pods

Two pod holders are suspended from the bottom of the frame. A rail along the bottom of the holder guides the battery pod in along the correct alignment. A rear latch locks into place, as internal padding ensures the pod is firmly in place. To remove the pod, the latch is popped open and a single connector disconnected. This physical configuration allows the battery pods to be quickly and safely inserted and extracted. Refer to Section 5 for details on the batteries.

Figure 6: Battery pod holder

Thrusters

Each thruster is mounted using a custom bracket. Two vertical thrusters control pitch and depth while the two horizontal thrusters control heading and forward speed. This thruster configuration has proven successful for us in the past. The four degrees of freedom (yaw, surge, pitch, and heave) are enough for the vehicle to complete all competition tasks, including hovering. The simple geometry reduces complexity in the control algorithm. Refer to Section 8 for technical details on the thrusters.

Skids

Instead of building a separate stand for the vehicle while it's out of the water, four triangular skids are built directly onto the frame. Not only are the stands functional, they also protect the vehicle from inadvertent damage. Being able to lift the vehicle out of the water and immediately set it down on any flat surface is another way to make the debugging and testing process faster. The small triangular configuration was chosen over full skids because they are lighter and leave a clear field of view for the downward facing sensors.

4 Electronics Hull

Since a single hull houses the majority of Proteus' electronics, its reliable operation and consistent sealing is very important. The additional requirement of making the hull clear to mount cameras inside of it makes design even harder. Early in the process, we agreed to undertake the risk of a novel sealing method on the hull in exchange for the ability to remove the hull while keeping the electronics running. Thus a lot of Proteus' functional advantages come from a well-built electronics hull.

Figure 7: Sealed electronics hull

Clear Hull

The clear acrylic hull is assembled from two separate parts: the front dome and the hull proper.

The forward looking camera sits inside the clear acrylic dome. A "dome flange adapter" is epoxy sealed to the flat surface of the dome. The flange adapter ensures a perfectly flat sealing surface, something not possible with dome's flange directly.

Two "hull sealing collars" are similarly epoxied to each end of the hull. The collars have o-ring glands on its sealing face for the dome and endcap seals. The hull collars and the dome flange adapters have matching holes for screws to create the pressure seal. This face sealing method has proven reliable as long as the collars and adapters are correctly epoxy sealed to their respective hosts.

The flange adapter and both sealing collar have key notches cut out. These align along an external aluminum key beneath the hull to ensure the correct insertion orientation.

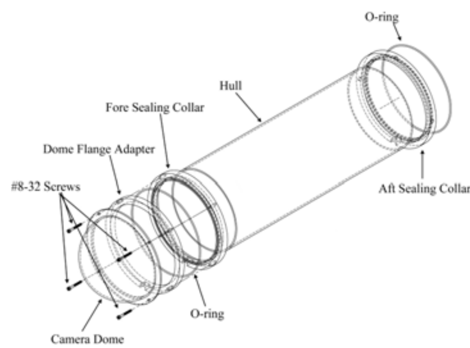


Figure 8: Exploded hull assembly

Hull Materials

Hull & Dome

Length	23.75"
Diameter	7"
Material	1/8" thick cast acrylic

Sealing

O-ring size	#167
Sealing screw	#8-32

Endcap

Material	Black anodized aluminum

Rack

Length	20.5"
Bulkheads & trays	Static Dissipative ABS/PVC
Rack frame	Black anodized aluminum
Guide rails	Clear extruded acrylic

Endcap

The electronics rack is cantilevered from the rear endcap. To seal, the hull slides into the endcap to form a face seal. Therefore, opening and closing the hull has no effect on the electronics.

Previous vehicle designs have mounted the electronics hull directly to the frame. The bore seal endcaps used by this design required a substantial amount of force and angular movement to install and remove. We chose a face seal method, because unlike a bore seal, face seals only require on-axis force to compress the o-ring.

The o-ring gland on the sealing collar is fastened against a flat face of the endcap to seal the electronics hull. Latching of the sealing collar to the endcap is achieved through a unique two-part fastening system that accepts screws driven between the two pieces to clamp the sealing collar to the endcap. The face seal and latching system design benefits the Proteus by supporting the cantilevered rack, allowing for low-force installation of the hull, and shortening assembly time through supporting power-driven installation of the latching screws.

5 Power

The power system supplies power to all the electronics on Proteus. As the central distribution system, it controls hot swapping of power sources, performs power switching, and ensures that everything receives clean and safe power. Referring to Figure 5, there are three sets of boards that comprise the power system. The pod board governs the batteries in each battery pod. The merge board combines the various power sources and provides the main bus to the distribution board and thrusters. The distribution boards supply power to all the other electronics while collecting monitoring information.

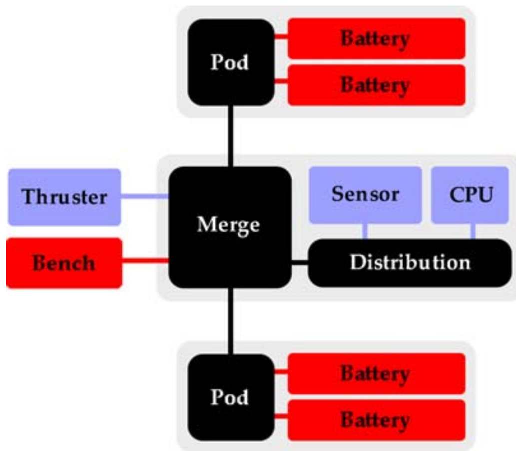


Figure 9: Block diagram of the power system

Battery Pods

Each battery pod contain two lithium polymer packs in series. Each pack is built from 12 cells. Since lithium chemistries are extremely dangerous when handled improperly, the pod board is responsible for regulating charge and discharge to the batteries. This is the initial layer of safety that prevents overdraw on the batteries and ensures a balanced charge on all cells. The pod board also performs routine monitoring of voltage, current, temperature, and coulomb counting.

Merge Board

The merge board literally merges the power it receives, be it batteries or bench power. As long as a single port on the merge board receives power, the entire vehicle stays powered on. Since the merge board controls power to the entire vehicle, the vehicle on/off switch and motor kill switch are connected to it. This single central control ensures safe power switching.

All voltage, current, temperature, and safety data collected from any power system device are sent to the merge board, which responds to queries from the computer. As such, the entire power system can be treated as one unit by the software. The merge board also relays power on/off commands from the computer to any power port on the vehicle.

Distribution Boards

Fore and aft power distribution boards provide ready access to power for any electronic device. Since the distribution boards draw from the same power line as the noisy thrusters, DC-DCs exist on the boards to provide regulated power to each port. Each of its ports is monitored for safe current draw. Overdraw on any port results in an immediate fault on the port and power being cut. The distribution and merge boards both follow an LED color standard that report vehicle health at a glance.

Power at a glance

Battery Specs

Manufacturer	Thunder Power
Model	TP6000-4S3PL
Cell configuration	4 series, 3 parallel
Pack voltage	14.8V
Pack capacity	6Ah
Pack max current	60A
Pack max burst current	108A

System Specs

Pod configuration	2 packs in series
Bus voltage	29.6V
Regulated outputs	13 ports
Regulated voltages	+5V, +12V

LED colors

Heartbeat	Blue
Power on	Green
Fault / alert	Red

6 Electronics Rack

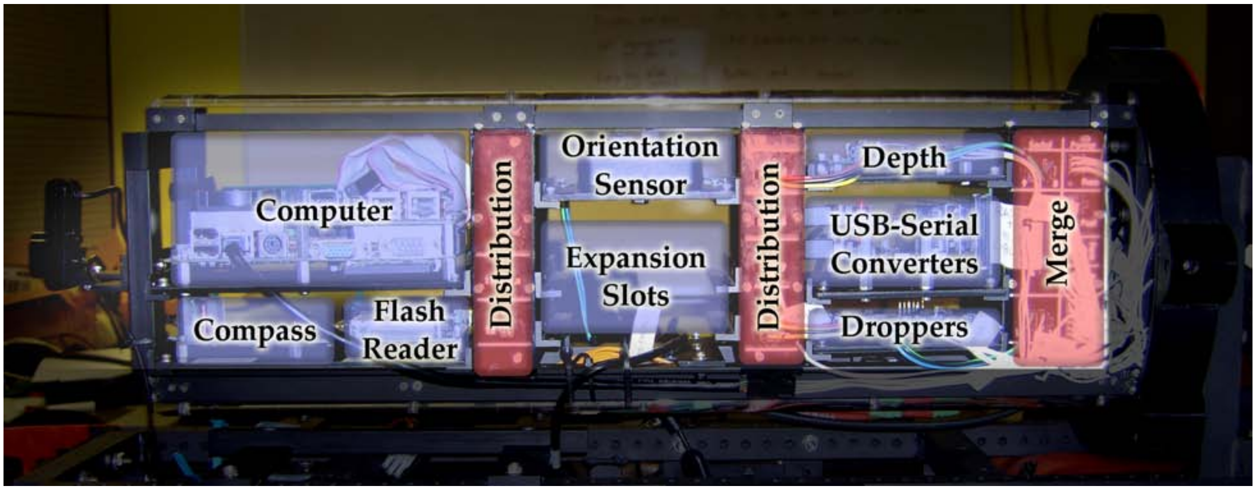


Figure 10: Proteus rack with various segments highlighted

Overview

Aluminum beams that form the frame of the rack are mounted to the inside of the endcap. Power boxes along the beams hold the frame together. Mounted upright inside these boxes are the power merge and distribution boards. These power boxes then serve as the mounting points for the other internal electronics.

As signal cables come in from underwater connectors through the endcap, they are routed to a pair of USB-serial adapters. Though the computer has only one serial port, it can communicate with up to 16 serial devices through these adapters.

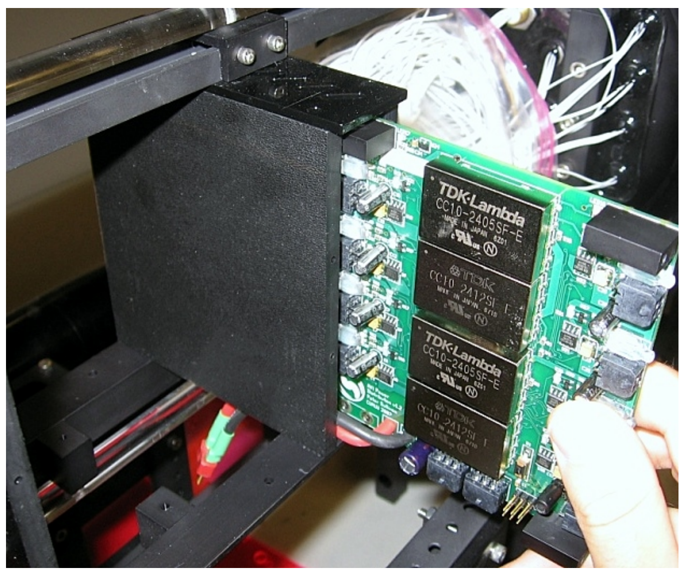


Figure 11: Power distribution board being inserted into its power box

Board Mounting

A series of mounting braces are built into the power boxes. All electronics inside the hull are first mounted to a removable tray, and then screwed down into the brace. Since each section is independently mounted, only four screws need to be removed to remove an entire component.

Compact Flash Reader

A compact flash card logs all sensor data during a run. After recovery, the flash card can be swapped with a blank one. Not only can another logged run immediately commence, but this allows for concurrent software and hardware debugging.

7 Software

Our computer's operating system is based on Debian GNU/Linux. Heavy modifications result in dramatically decreased boot time and power consumption. All onboard storage use vibration resistant flash memory, again decreasing power consumption and increasing speed.

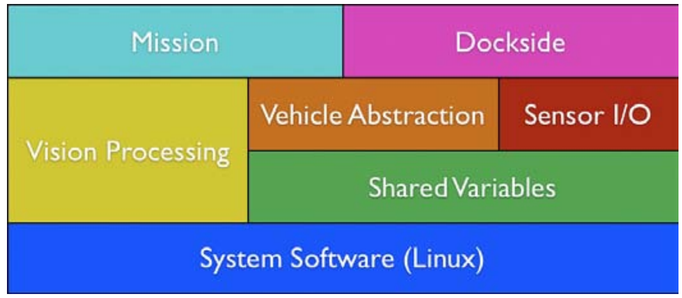


Figure 12: Software architecture overview

Shared Memory

The software architecture is built in three broad layers. The shared memory architecture based on existing Linux code stores all of the vehicle's status data (sensor readings, thruster commands, etc). The next layer of code interacts solely through this shared memory.

At the hardware end, serial drivers interact with the various peripheral electronics like sensors and thrusters. Data from these devices are written to shared memory, and outgoing commands to those devices are read from shared memory. This simple interface allows code reuse and simplifies the process of writing drivers.

Vehicle Abstraction Layer

The vehicle abstraction layer builds a Python language wrapper around all of the shared variables, creating an abstract "Vehicle" object in Python. This Vehicle not only has access to physical sensors which write data to shared memory, but can also create virtual hybrid sensors that combine data from multiple real or simulated sources. This feature allows us to create a new virtual sensor like "water depth" by combining data from the real depth and altitude sensor. It also allows mission code to be tested using data from a simulator which writes data to virtual sensors.

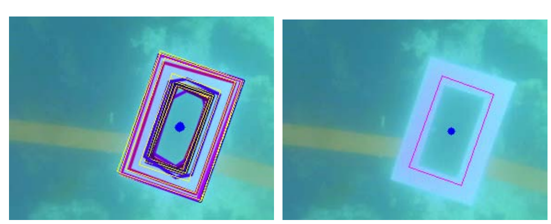
The vehicle object has a collection of behavioral abilities that dramatically simplify high level algorithms. For example, the vehicle object can be given a command like "drive forward" along with a hook to another process called "find bins". When the bin detection code triggers, the movement command is interrupted. This allows individual commands (like movement and vision) to be tested without worrying about mission-level integration. Conversely, after building up a repertoire of abilities, writing mission code through the VAL layer is easy and produces reliable missions.

Vision

Our vision processing system this year is built on top of the OpenCV library. This library contains an extensive collection of image transformation algorithms and has been highly optimized.

Separate code exists for bin, buoy, and recovery object detection. The bin detection code is a representative algorithm and explained here. First, the image is thresholded to identify regions of interest (Figure 13(a)). Contours are detected (Figure 13(b)) and then filtered for ones that are rectangular (Figure 13(c)). The filtered rectangles are statistically averaged to result in the final probable bin location (Figure 13(d)).

(a) After thresholding (b) After contour detection



(c) After filtering for rectangels (d) After averaging rectangles

Figure 13: Box detection algorithm

8 Thrusters

Our thrusters this year are from VideoRay, an ROV manufacturer. The vertical thrusters are their standard model while the horizontal thrusters are their GTO (Greater Thrust Option). Since these thrusters were originally designed to operate on VideoRay's vehicles, we built custom motor controllers for them. Our two board stack is mounted inside of each thruster. They receive serial-based commands directly from the computers and provide performance and safety feedback.

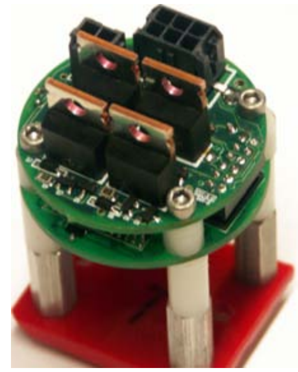


Figure 14: Motor controller stack

9 Switch Box

A new switchbox this year simplifies vehicle control for safety divers. The left LED button is green when the vehicle is unkilled (on) and red when killed (off). The right LED button turns blue when the vehicle has been commanded to start its autonomous run.

Figure 15: Switchbox with motors unkilled and mission started

10 Printed Circuit Boards

A lot of important custom PCBs have not yet been mentioned. A depth board reads analog data from the external pressure transducer and communicates filtered data to the computer. A similar board mounts to the top of the orientation sensor and provides a more stable connection. Two serial boards break out the lines from the USB-serial adapters to more convenient locations inside the power boxes. A marker dropper board allows the computer to turn on power to three separate 1A lines to activate the dropper.

11 Acknowledgments

Corporate Sponsors
We'd first like to recognize all of our corporate sponsors this year who made tremendous donations of time, resources, and funding. We'd first like to recognize the 2007 Diamond corporate sponsor - Nexlogic. The Proteus is officially now the Cornell-Nexlogic Proteus! Special thanks to our Platinum sponsors this year: AMD, Seacon, and Cornell University. We'd also like to thank our other generous sponsors: Videoray, Molex, Exxon-Mobil, Industrial Metal Finishing, Keithley, CentralDesktop, Alpha Metal Finishing, Deep Sea Power and Light, Hi-Tech, Advanced Circuits, MS Technology, Digikey, and Mouser.

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