

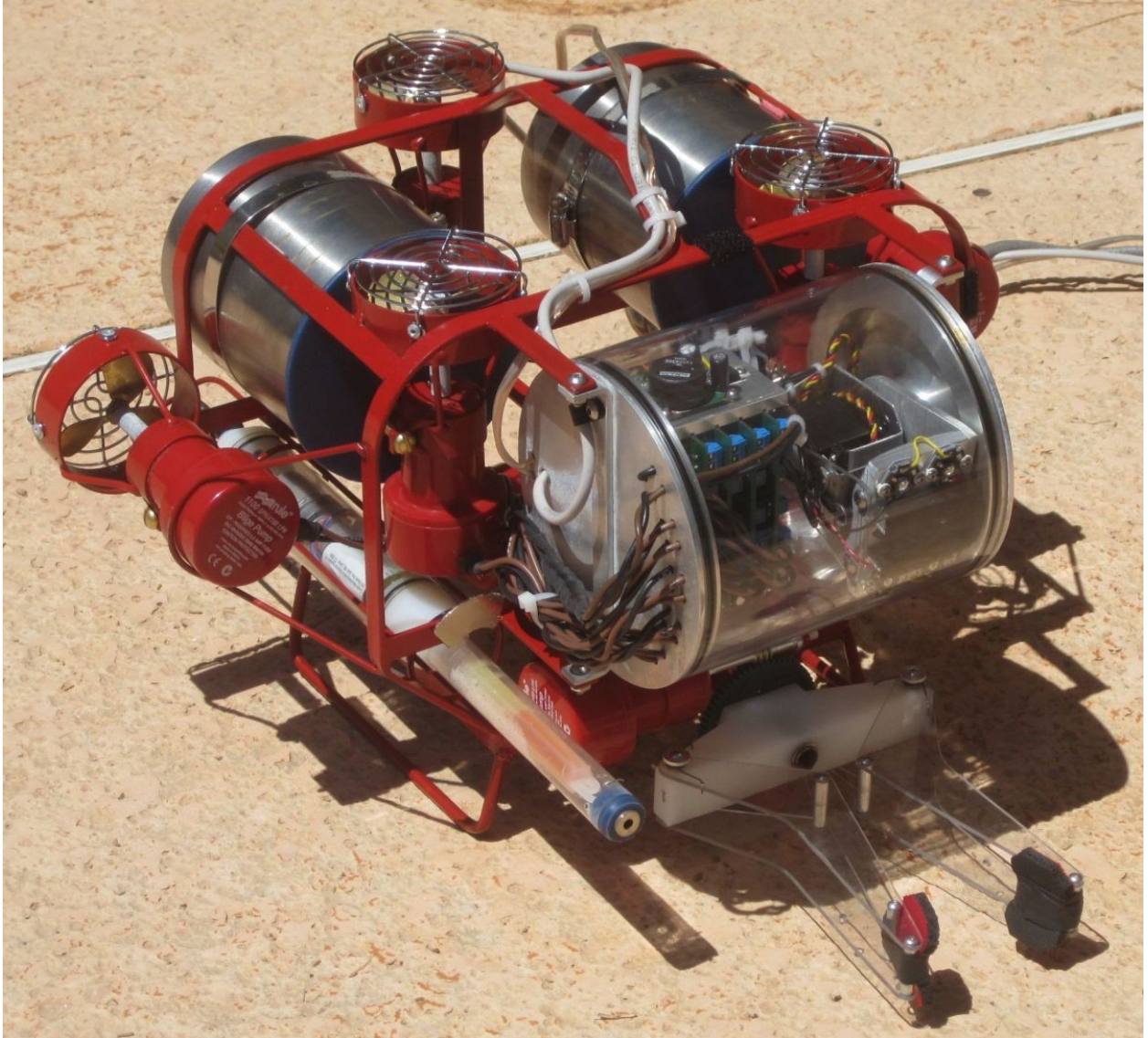
The Typewriter Repairmen

Technical Report

2010 National Underwater Robotics Challenge

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Sierra Vista and Tucson, AZ



"Babs"

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Abstract

This is the second year that The Typewriter Repairmen, a family team from southern Arizona, has entered the National Underwater Robotics Challenge. By putting to use the knowledge gained from last year's ROV, we have designed, built, and tested our 2010 entry, "Babs". We again used a systems engineering approach, which includes defining and prioritizing requirements, brainstorming, prototyping, testing, and iterative redesign. The result is a smaller, lighter, more powerful ROV with an integrated, configurable control system. During the entire design, building, and testing process, we maintained a blog, posting many photographs and videos on the Internet.

ROV System Design

The Typewriter Repairmen had a great time competing in the 2009 National Underwater Robotics Challenge, so we decided that we had to do it again this year. Last year's ROV "notBob" (Figure 1) was very capable, but far from perfect. This year we had to decide whether we could modify notBob to use again, or start over with a new ROV.

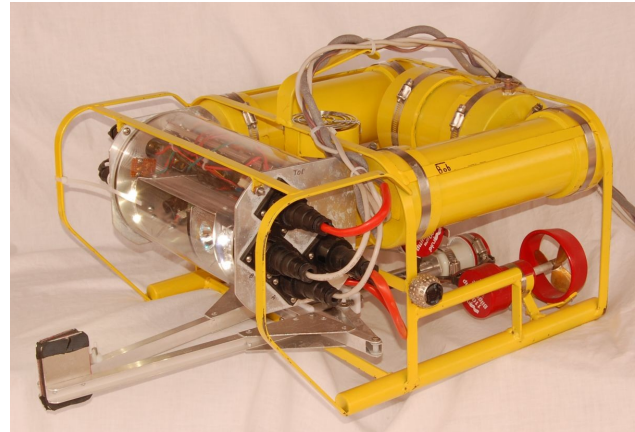


Figure 1 - notBob, the Typewriter Repairmen's 2009 NURC ROV

After reviewing the game rules, we put together a list of basic requirements for the ROV:

- Very good visibility—camera and lighting, in all directions
- Very good maneuverability—full control in all directions, with fast ascent/descent
- Manipulator that can grasp and rotate
- Instrumentation including live audio and depth measurement
- Untethered payload delivery system, with aiming ability

Looking back on notBob's performance last year, we came up with a list of issues that we thought needed to be improved to fulfill the new mission:

- Insufficient vertical thrust
- Restricted camera movement (cannot see up)
- Manipulator cannot rotate
- ROV is too heavy—inconvenient to carry, sluggish performance
- Wire connections leak
- Clunky control system requiring two operators

Although notBob could be made to satisfy the new mission requirements, we decided that his existing problems warranted designing and building a new, more versatile ROV.

There were many good design features of notBob that we applied to the new ROV. These include the gimballed camera/light assembly, steel frame construction, bilge pump motor thrusters, surface mounted power, custom made speed controllers, and the horizontal Sealed Compartment for Underwater Lights and 'Lectronics (SCULL) housing the camera, lights and electronics.

Our new ROV, affectionately named "Babs", features new improvements including use of O-rings to seal wires, more vertical thrusters, fabricated propellers, lightweight steel frame with standardized thruster motor mount/shroud assemblies, worm gear driven manipulator, electric torpedo subsystem, and a fully integrated and configurable control system.

Mobility System

We modeled the ROV using SolidWorks 3D CAD software, so design changes were relatively easy to make, and we could view the design from any angle. The design goals were to make Babs as compact and light as possible, with a lot of thrust in all necessary directions and minimal drag. The basic layout of Babs evolved over the course of a few months from early rough concepts to the final design, as seen in Figure 2.

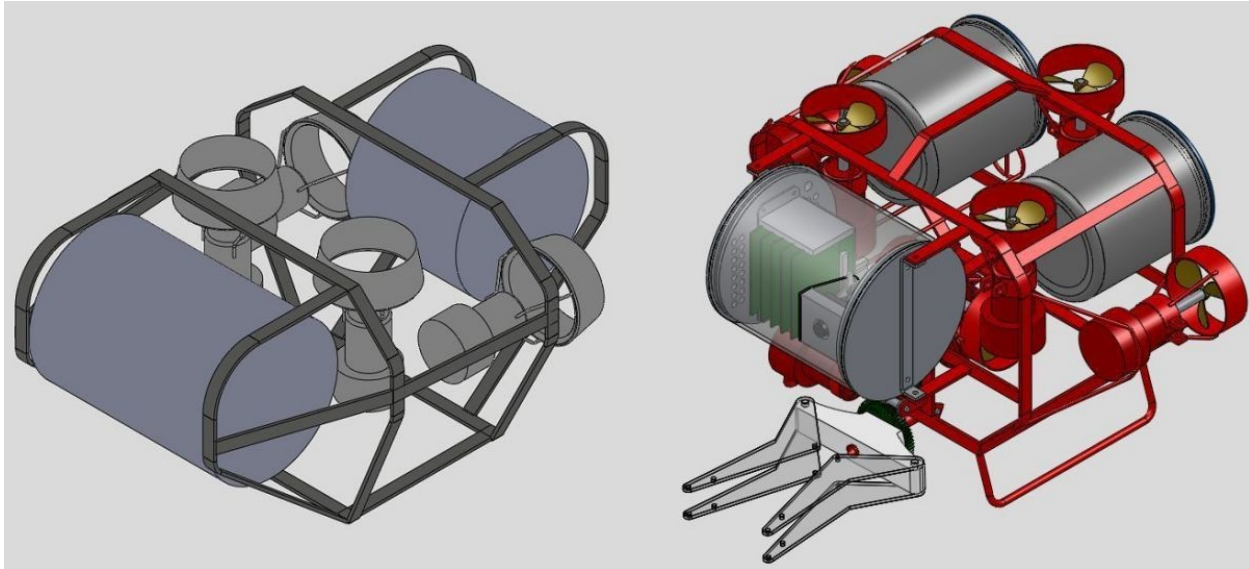


Figure 2 - Evolution of ROV from original concept to final design



Figure 3 - Thruster welding jig

We finally settled on a total of six thrusters: three vertical thrusters, two forward thrusters, and one side thruster. The flotation chambers on each side allow a rear vertical thruster to sit between them, giving pitch control for torpedo aiming. The entire configuration gives Babs five degrees of freedom: translation in all three dimensions, turning on a horizontal plane (yaw), and pitch.

Since we needed six thrusters, we decided to make them as identical integrated assemblies. By making the motor clamp and the propeller shroud of steel, we could weld them together and have a single steel part that could be welded to the frame. Alignment between motor and shroud is critical, so we made a jig to hold the pieces for welding (Figure 3).

We liked how the purchased brass propellers worked on notBob, but they are expensive and we needed six. Another team in last year's competition (the N.E.R.D.S.) made their own brass propellers from nuts and sheet brass, so we decided to copy the idea. Making the propellers accurately requires a jig, so we made one of steel (Figure 4).

This made it easy to silver solder the blades to the center nut at the proper angle. After attaching the blades, we used pliers to form them into their final shape.

The frame is the central structure of the ROV. We were satisfied with the thin strap steel frame of notBob, so we decided to use the same material on Babs. Having relatively common equipment such as an abrasive chop saw, MIG welder, and vise already, it was easy to build the frame. We were careful to make sure all the parts were the correct size and properly aligned before welding (Figure 5).

The flotation tanks on notBob are large and heavy, thus they are not very efficient. We wanted Babs to be as compact and light as possible, so we knew that we had to figure out a better way to make the tanks. We found the solution in the kitchen section of a local store, in the form of thin wall, stainless steel storage containers. We made new plugs for them using thick plastic sheet, with O-ring seals.

Electronics Housing

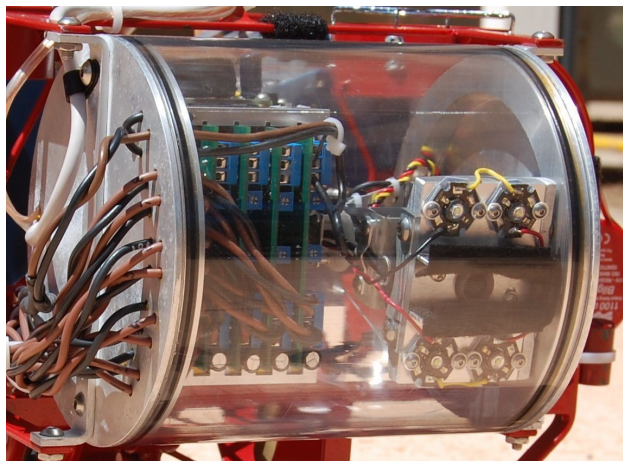


Figure 6 - "SCULL" Electronics Enclosure

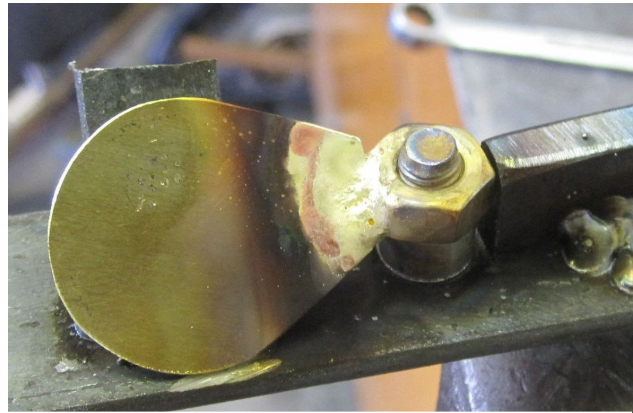


Figure 4 - Propeller blade soldering jig

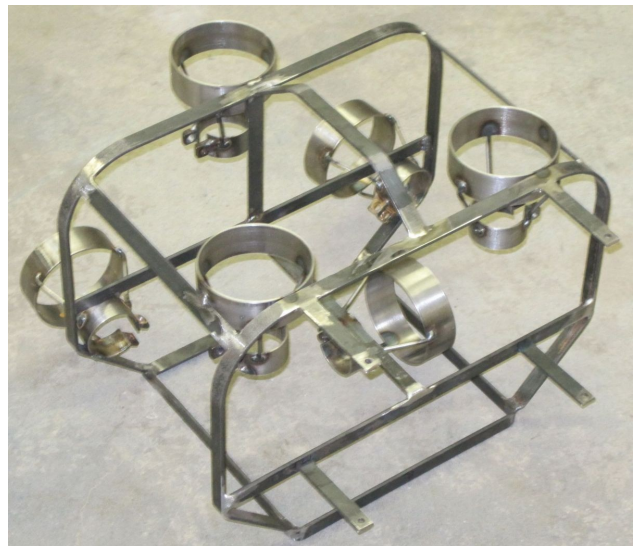


Figure 5 - Welded frame

We made new plugs for them using

As we did last year, we used a transparent, horizontal tube to house the electronics, lights, and camera. This design configuration provides the ability to see in all directions, using only one axis of camera motion. The entire ROV is "panned" to see to the side, and the camera and lights are tilted to see up or down. Besides making the ROV very capable, this method of building the housing is relatively easy to seal. The tube has a metal plug at each end, sealed with an O-ring. The plugs are round, so they can be made with a lathe. The tether and motor wires have to pass through the plugs, and be sealed

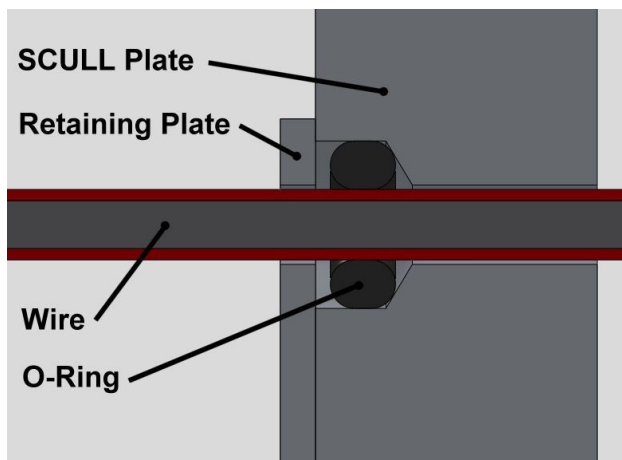


Figure 7 - Wire sealing with O-ring

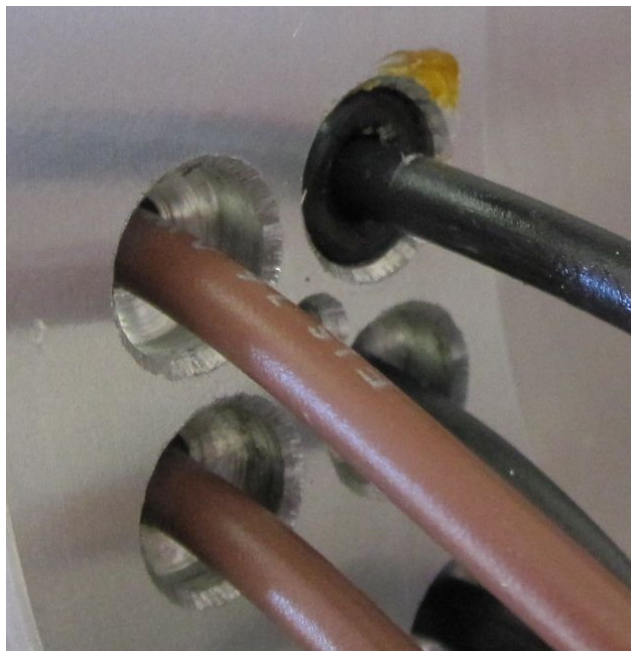


Figure 8 - Wires with and without O-ring seals

did not leak, so we decided to use the method on Babs. We drilled holes for each motor and tether wire, and counter drilled them to accept the O-rings. Each set of four motor wires has a retainer plate held in with a screw. A silicone-based grease is used to lubricate all the O-rings, to make assembly easier (Figure 8).

Control System

The control system that we designed for notBob last year performed quite well. We used a 48V power source on the shore and a set of synchronized PWM motor controllers to drive 12V motors. The main shortcoming of the system was the limited interface of the Vex control transmitters, requiring two operators: one to drive the ROV and the other to manipulate the camera and claw.

We decided early on that Babs would have single operator control, using a commonly available video game controller. Some Internet research revealed that the Sony PlayStation2 controller had been reverse-engineered by the robotics community, and interface software was

against water leakage. The electronics, camera, and lights are also mounted to the plugs, and dissipate heat through the contact of the plugs with the water (Figure 6).

Last year we had problems with the wiring connections leaking. We used multi-conductor, waterproof connectors. The problem was sealing pairs of motor wires into the single round grommets of the connectors, which required carefully gluing the wires into another tube with epoxy. The connectors also make the ROV rather wide, as they have to stick out the ends of the enclosure. To eliminate these problems, as well as to save money (connectors are expensive), we decided to try a new approach. Since O-rings work so well to seal the housing ends, we thought they might work to seal the wires. The idea is to drill a hole for each wire, then drill part way through with a larger drill, leaving a cavity for the O-ring to sit in. The holes would be sized so the O-ring is compressed. A plate is needed to retain the O-ring (Figure 7). One disadvantage is that the motors and tether cannot be quickly disconnected from the housing, but our experience last year showed us that this would not be a significant problem.

We tested this idea using a small hollow container, with a single wire looped out one hole, and into another, each sealed with an O-ring. We put it under water for a while, and it

freely available. The Sony controller uses an SPI serial interface that is widely implemented in common 8-bit microcontrollers.

The control system that we designed for notBob used the standard pulse modulation scheme found on radio-control devices. We decided that it would be better to use a serial data transmission method, since we could also send telemetry data up to the shore from Babs on the same serial interface.



Figure 9 - ROVotron configuration menu

Since we had no clear idea which controls on the PlayStation2 controller should be assigned to each control function on Babs, we decided to make the assignment of controller buttons and joysticks to ROV functions entirely configurable, using the controller itself to navigate a set of configuration menus displayed on a four-line text display (Figure 9). The display shows the telemetry data while operating.

Since only onboard video may be used to drive the ROV, we worked to make the video

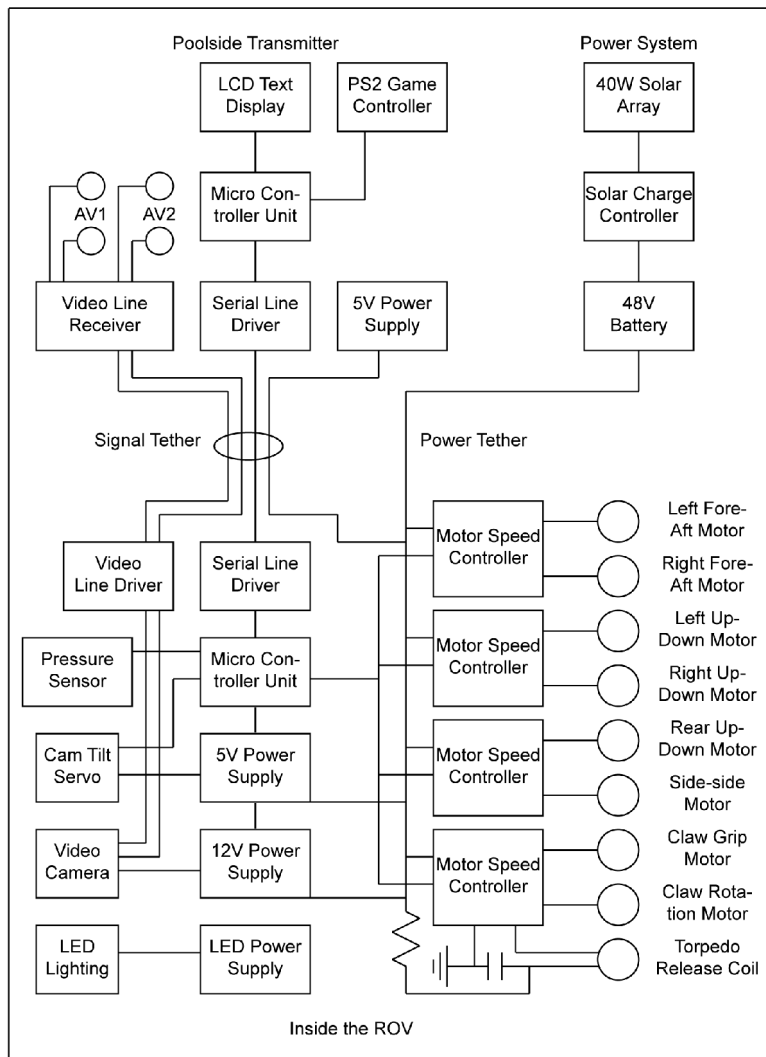


Figure 10 - ROV system diagram

signal as clean as possible. A pair of balanced differential signal drivers on the backplane drive the video and audio signals up the signal tether cable, and matching differential receivers are used to convert these signals back to single-ended form for connection to both the officials' and the driver's displays.

The other shortcoming of notBob's control system was the packaging of the electronics in the SCULL. The long circuit boards precluded movement of the camera above the horizon. We decided that the circuitry should be packaged in a more compact, cubical space. Designing a backplane that could hold up to five two-channel motor controllers solved this packaging problem. An aluminum card cage was designed to conduct heat from the motor controller transistors, through heat sinks to one side of the card cage, then to the SCULL end plate.

The control system has been integrated into a set of three circuit

boards: the RTXA transmitter, the RRXA receiver/backplane, and the RSCA dual motor speed controller (figure 10). The transmitter resides in a plastic box on the shore. It has a signal tether connector, a controller connector and two pairs of audio/video connectors. A four-line LCD display shows the telemetry data while operating, or the configuration menus while modifying the controller parameters. A microcontroller programmed in C communicates with the PlayStation2 controller via an SPI serial interface and with the ROV using an RS-485 bidirectional differential serial interface.

The power tether is a 16 AWG zip cord that carries 48V DC power from the battery box to the ROV. The signal tether that connects the ROV to the transmitter box is a standard Cat-5e Ethernet cable. One pair carries low-current 48V DC power up to the transmitter. Another pair has bidirectional RS-485 asynchronous serial data. The last two pairs carry audio and video signals from the camera to the display.

The receiver/backplane card is bolted to an aluminum card cage. It connects to the signal tether, the 48V power tether, the video camera, the camera LEDs, the camera rotation servo, and the telemetry signal transducers. The motor speed controller boards connect to the backplane power and signals via a special right-angle plug-and-socket connector and to the motors via screw terminals (Figure 11).

The motor speed controllers are nearly identical to last year's design. This system operates multiple motors in a time-sharing mode, modulating each with from zero to 25% duty cycle to permit operation of four 10 Ampere, 12V motors at once with a 10 Ampere, 48V power supply. This system is described in detail in an article that we wrote for the February 2010 edition of SERVO magazine.

A PIC 18F4523 microcontroller is used in each of the transmitter and receiver boards to perform all necessary tasks by executing programs written in the C language. The schematics and software that is running on the microcontrollers is available in source code form on the ROVotron website: <http://www.rovotron.com/>

Vision

The stereovision attempted last year was not found to be useful, since it requires an extended training period with a 3D viewing system, which we did not have. As a result, Babs has only one video camera (as seen in Figure 6).

The camera used last year was a low-cost surveillance unit with insufficient resolution to see details under water. We decided to spend more money on a higher quality camera, and purchased a 520-line unit.

NotBob had four LEDs and a halogen lamp, but we found that the halogen lamp was not necessary, as the LEDs provided plenty of light. This led us to use only LEDs on Babs, but we designed the camera mount to allow conductive cooling of the LEDs, eliminated the need for a cooling fan. The control receiver board was outfitted with a switching LED current regulator to provide for up to eight LEDs wired in series at 700 mA current.

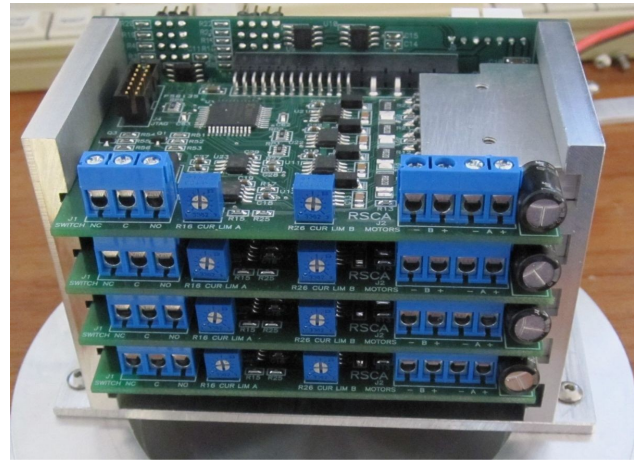


Figure 11 - ROVotron receiver with motor controller boards

Power

Babs runs on solar power, stored in four 7-Ah sealed 12-volt lead-acid batteries. A 40-watt solar panel is mounted to the robot cart, and can be tilted as needed for full sunlight (Figure 12).

A plastic box holds the batteries, charge controller, charge/run switches, and system fuse. The batteries are connected in parallel when the switches are set to “CHARGE”, and they are wired in series when switched to “RUN” (Figure 13). The solar panel and ROV are connected to the battery box wiring with paired Anderson connectors, which are keyed differently so they cannot be connected wrong. The batteries provide nominal 48-volts and the fuse is rated at 15-amps, so the maximum power the ROV can use is 720-watts, well under the 1700-watt maximum allowed.

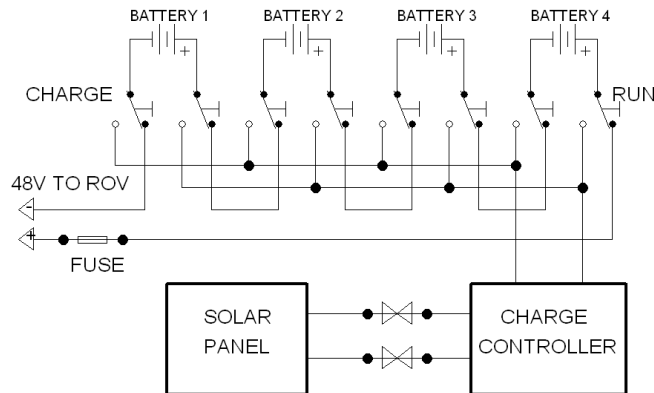


Figure 13 - Power system schematic

Manipulator

To meet the requirements of the mission, we figured out early on that a somewhat sophisticated manipulator was needed. While notBob had great success with the simple opening and closing gripper, releasing the bait would be extremely difficult with such a manipulator. We decided that Babs needed a manipulator that could both grip, and rotate. To make it easier to control, we wanted to be sure that the gripper could rotate freely without having to worry about tangling wires. This added functionality meant that a completely new manipulator assembly had to be designed and built.

Several approaches to the new design were considered. Initially, the design concepts focused around a fully sealed module

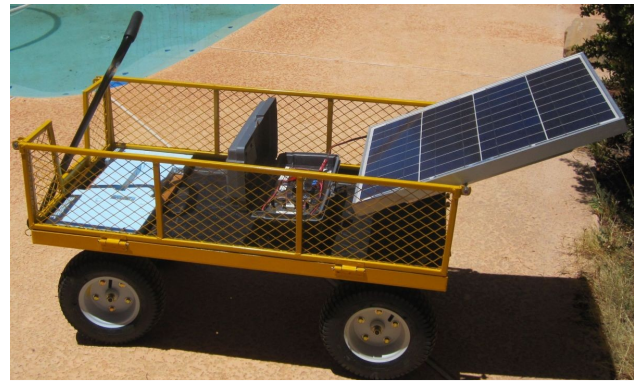


Figure 12 - Power system on robot cart

paired Anderson connectors, which are keyed differently so they cannot be connected wrong. The batteries provide nominal 48-volts and the fuse is rated at 15-amps, so the maximum power the ROV can use is 720-watts, well under the 1700-watt maximum allowed.

The power system is very convenient to use. Last year, we used an older, larger solar panel that one of the team members had on hand. We purchased the smaller, new panel to make the system user-friendlier, and plan to put the solar panel to use on another project after the competition. It is a bit too small to be worth installing as part of a home power system, but would be appropriate for a powered gate, shed lighting, RV battery charging system, or similar use.



Figure 14 - Gripper assembly

that would contain both motors required for actuation and the appropriate mechanical reductions to achieve the desired motion. This approach was abandoned due to the projected cost and difficulty involved with sealing moving components. Instead, we wanted to find a design that used the same pre-sealed motors that were used on the thrusters. While this meant any mechanical reductions would be submerged in water, it eliminated the need to construct reliable seals.

The final configuration for the manipulator is shown in Figure 14. Rotation of the gripper uses a worm gear reduction from the motor shaft to a 60-tooth gear attached to the main body. Clamping force comes from a winch, which is driven by a worm gear reduction using a 36-tooth gear. Fishing line connects the winch to both gripper arms. Because this line is concentric with the gripper rotation, the gripper may be rotated many times without affecting gripping ability (although the line may become twisted, it will still function properly). When the line is let out, the gripper arms are forced open by torsion springs at the base of each arm.

Torpedo System

“Quest for Nessie” has a very challenging element, requiring sticking a radio tag onto Nessie, using an untethered device. The point reward for this task is not very high, but the technical challenge was enough to convince us that we had to try it. We thought of several ways to power a torpedo to deliver the radio tag, including compressed air jet, compressed air powered motor, rubber band powered motor, and electric motor. We decided to use an electric motor, mainly because it is relatively easy to control it, and we can store a lot of energy in a battery.

We did a lot of prototyping to test our ideas. We all know that “real” torpedoes have fins, but they also have guidance systems. Our plan for aiming is to point the ROV at the target, and shoot the torpedo in a straight line. All that this requires is a torpedo that is mounted parallel to the camera on the ROV, and that flies straight. We tried using spin-stabilization, and discovered that it works pretty well, as long as the torpedo is neutrally buoyant, and balanced in all planes. The spinning happens because without fins on the torpedo, the body of the torpedo rotates the opposite direction of the propeller, due to the reaction of the motor.

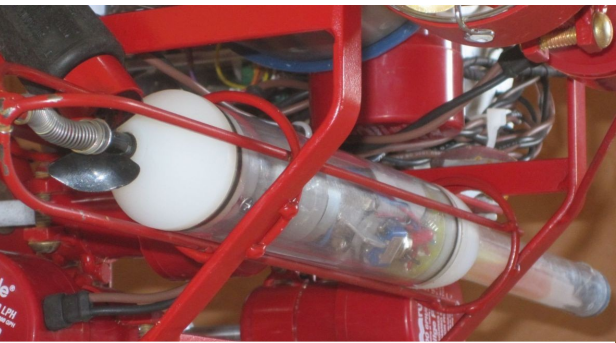


Figure 15 - Torpedo assembly in launcher



Figure 16 - Torpedo control circuit

The torpedo body is made of the same type of tubing as the ROV electronics enclosure, and sealed with the same O-ring method. The motor shaft is also sealed with an O-ring (Figure 15).

We designed and built a control circuit that turns the motor on when a magnetic switch is activated, and turns the motor off after about ten seconds. If the torpedo hits something reasonably solidly, a mechanical switch (mounted between battery and nose cone) makes the

circuit stop the motor for moment, then run it in reverse for a second or two. The control circuit uses surface mount logic chips and resistor-capacitor timing components, mounted to a round printed circuit board (Figure 16).

The launching method is a bit roundabout, but it ensures that the torpedo will not cause an unsafe condition if it is accidentally released, such as in the pits at the competition. The torpedo is loaded into the launcher from the front, the propeller seats against a soft spring, and a solenoid pin locks into the rear torpedo housing (Figure 15). An electronic switch in the ROVotron receiver discharges a capacitor into the solenoid, causing it to retract the lock pin suddenly. The spring pushes the torpedo forward, so the magnetic switch on the torpedo controller board passes by a magnet mounted on the ROV frame, and turns on the motor. When the torpedo strikes the target the motor reverses, driving the torpedo off the payload tube, leaving just the payload tube and “radio tag” stuck to the target. The logic for the circuit can be found in Appendix E.

Testing and Revisions

Mobility

We tested Babs in various stages of completion. First testing was done before the manipulator was installed, so we could get a feel for how she handled. Most aspects were fine, and the ascent/descent speed was amazing. However, she did have a bad tendency to “kick up” when driving forward. This was because the forward thrusters were mounted below the flotation chambers, thus below the centers of mass and volume. We did not anticipate the problem being this bad, although we knew it would exist. The fix was to relocate the forward thrusters outside of the frame, between the vertical center of mass and volume. After making this change, she is quite a bit wider, but handles much better (Figure 17).

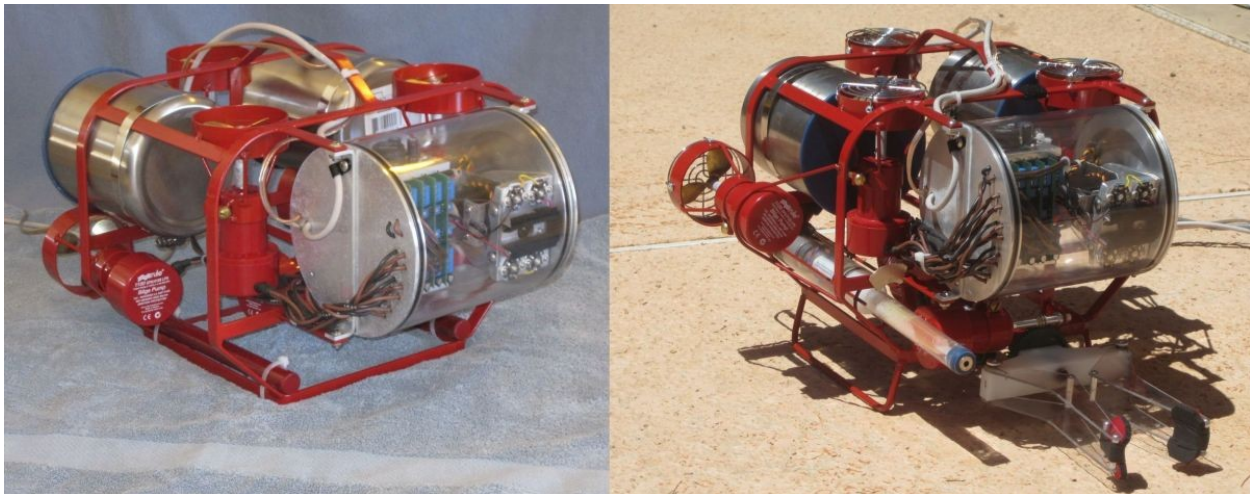


Figure 17 - Forward thrusters before and after relocating

Before adding the manipulator, we had added extra weight to the bottom, to keep the ROV stable, and counteract the buoyancy of the tanks. After we made and installed the manipulator, less weight was required, and we decided to see if less stability would be acceptable, so we moved the ballast weight further up. The result was that Babs could do an inside loop maneuver, such as done by aerobatic airplanes. Stability is still adequate, as it takes careful driving to complete the maneuver without the ROV self-righting part way through.

Manipulator

Testing of the manipulator proved it to be more than adequate to meet the mission requirements. A total gripping force of 42 Newtons, compared to the gripping force of notBob's claw of 2 Newtons, shows a great improvement in manipulator strength. The rotation torque of the manipulator was also demonstrated to be more than strong enough to release the bait containers.

Several small improvements were made to the claw during testing phases. We found that during night missions it was difficult to see objects in the water due to the immense glare produced by the aluminum gripper arms. To alleviate this, new gripper arms were built out of transparent polycarbonate. These not only eliminated the glare issue, but also allowed the camera to see downward through the claw (Figure 18). This made navigation while handling



Figure 18 - Aluminum gripper vs. transparent gripper, and egg hoops
objects substantially easier.

An additional improvement was made to the manipulator for handling Nessie's egg. While the manipulator could simply grab a large object, it proved difficult to hold onto it. To fix this problem, we made removable hoop attachments (Figure 18).

Vision

We first mounted LEDs on a square 10mm thick aluminum plate surrounding the camera. However, the glare from the LEDs was too intense, so we made a larger plate to permit baffling the reflections with aluminum channel, with felt wipers (Figure 6).

We also found that the cooling bracket (the piece that supports the LED mounting plate) was too thin to adequately lower the LED temperature, so we made a thicker, wider plate to replace it. Thermal calculations revealed that a heavier cross section material would lower the LED temperature by 10C, enough to lengthen the lifetime of the LEDs substantially.

Torpedo

We learned a lot while developing the torpedo system. Our original design concept seems to be successful, but every part of the system has required a lot of tweaking. We had a lot of trouble getting the reversing switch to work reliably, until we realized that the time constant on its de-bouncing circuit was too long. Removing a capacitor fixed that problem. The balance of the torpedo greatly affects its aim, and getting it just right has been a constant battle. Most recently

we discovered that not all glow sticks have the same buoyancy, so we need to make an adjustable system that we can use at poolside just before loading the torpedo.

Operation

The entire system is shown in Figure 19. The only components needed for operation are the ROV, the surface control box (transmitter), PS2 controller, battery box, and television monitor. Once all of the components are set up properly, Babs can be powered up and start running immediately.

As mentioned earlier, the configuration of the controller can be changed quickly on the fly to suit the preferred driving style of the operator. After testing several controller configurations, we concluded that the configuration shown in Figure 20 gives a good level of control to the driver. Having all operations on a single controller allows all maneuvers to be performed by one person (this is preferable to last year's entry, which required two drivers to be coordinated with one another to control the ROV). To prevent any accidental launches, the torpedo-firing button is located on the transmitter box and is actuated by another person.

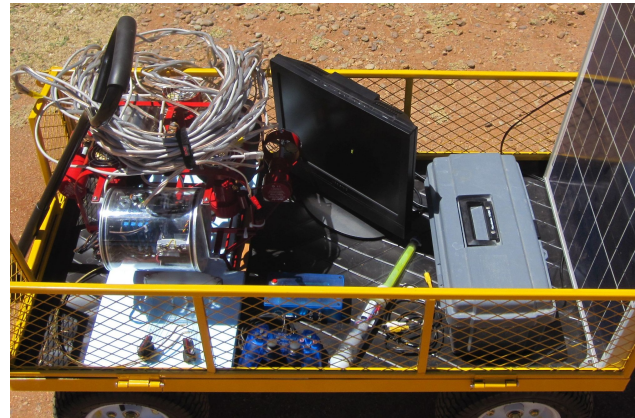


Figure 19 - Complete ROV system



Figure 20 - Controller configuration for Babs

Acknowledgements

We would like to thank the Jones family and the Moeller family for the generous use of their swimming pools, and APASE for sponsoring this competition. We would especially like to thank the many volunteers that make it possible.

References

ROVotron Control System <http://rovotron.com>

Microchip Microcontrollers <http://microchip.com>

Xilinx Programmable Logic Devices <http://www.xilinx.com>

Parker O-ring Handbook <http://www.parker.com>

Freescale Pressure Sensors <http://www.freescale.com>

Sony PS2 Controller Interface <http://store.curiousinventor.com/guides/PS2/>

Appendix A: Bill of Materials

Section	Part	Material	Source	Total Cost
Electronics	Connector	DE 9 pin connectors	Elliott	\$ 2.00
Electronics	Connector	Molex 8 pin KK shells	Digi-Key	\$ 2.65
Electronics	Connector	Molex pins	Digi-Key	\$ 2.00
Electronics	Controller	Sony Play Station 2	WalMart	\$ 20.00
Electronics	Controller	RSCA Dual Speed Controller	Cathode Corner	\$ 308.76
Electronics	Controller	RTX ROVotron Transmitter	Cathode Corner	\$ 128.13
Electronics	Controller	RRX ROVotron Receiver	Cathode Corner	\$ 105.72
Electronics	Controller	Card cage metalwork	Precision Tool	\$ 175.00
Electronics	Seal	104 O Ring	McMaster Carr	\$ 4.82
Electronics	Torpedo	Capacitor 2200uf 63V	Digi-Key	\$ 3.41
Electronics	Velcro	Industrial 2" x 4' Black	Ace	\$ 10.99
Float	Clamp	Hose Clamp Stainless #72	Lowe's	\$ 3.66
Float	End cap	UHMW Plastic 1/2" thick	McMaster Carr	\$ 13.10
Float	O ring	EPDM 245 16 pk	McMaster Carr	\$ 9.56
Float	Tube	2 Qt Storage Container	WalMart	\$ 13.94
Frame	Paint	Krylon Banner Red 12oz can	WalMart	\$ 2.97
Frame	Structure	Steel strap 1/2" x 1/8"	Aztec Welding	\$ 2.40
Gimbal	Base	Aluminum 3/16" x 4" x 4"	Online Metals	\$ 13.97
Gimbal	Camera	Defender 82-12836 color camera	MCM Electronics	\$ 89.99
Gimbal	Light	Luxeon LED 3W Star White	Dan Bolin	\$ 14.40
Gimbal	Pivot	Spring, wave, 26mm ID	McMaster-Carr	\$ 0.42
Gimbal	Servo	HiTec HS-645MG	Hobbytown USA	\$ 39.50
Gimbal	Structure	Aluminum Sheet 5052 0.050"	Online Metals	\$ 4.19
Gimbal	Top	Polycarbonate Sheet 1/8"x6"x12"	McMaster Carr	\$ 6.64
Manipulator	Arms	Polycarbonate Sheet 1/8"x6"x12"	McMaster Carr	\$ 6.64
Manipulator	Body	UHMW Plastic 1-1/2" x 1"	McMaster Carr	\$ 6.70
Manipulator	Hoops	Brass Rod 1/8"	Lowe's	\$ 2.17
Manipulator	Motor	Rule 1100 Bilge Pump	Amazon	\$ 73.44
Manipulator	Screw	Aluminum Rod 1/2"	Ace	\$ 4.49
Manipulator	Spacer	Aluminum Rod 1/4"	Ace	\$ 2.99
Manipulator	String	Monofilament 20#	WalMart	\$ 2.50
Power	Batteries	SLA 12v 7ah rechargeable	Radio Shack	\$ 139.96
Power	Connector	Anderson Power 4pk	Elliott	\$ 11.43
Power	Controller	Morningstar SunSaver10 Charger	Affordable Solar	\$ 48.00
Power	Enclosure	Tool Box, Plastic 17800	techni-tool	\$ 21.05
Power	Fuse	10 A Blade 3 pk	Radio Shack	\$ 1.99
Power	Panel	40 W Solar Panel	UL Solar	\$ 78.84
Power	Switch	DPDT 20A Center Off	Radio Shack	\$ 15.96
Power	Wire	18 gage red/black zip 8m	Radio Shack	\$ 5.99
SCULL	End Plugs	Aluminum Plate 1/2" x 6" x 12"	Online Metals	\$ 16.32
SCULL	O ring	EPDM 253 10 pack	McMaster Carr	\$ 9.27
SCULL	Tube	Polycarbonate Tube 6"x1/8"x12"	McMaster Carr	\$ 33.22
Sensor	Pressure	MPXA4250AC6U	Digi-Key	\$ 14.96
Tether	Float	Foam Backer Rod 7mm x 6m	DKHardware	\$ 15.80
Tether	Power	Speaker Wire #16 x 2	HomeDepot	\$ 23.51
Tether	Signal	Cat5 Network Cable	SWS	\$ 25.00
Thruster	Clamp	1-1/2" Steel Tube 16 ga	Aztec Welding	\$ 1.38

Thruster	Motor	Rule 1100 Bilge Pump	Amazon	\$ 187.38
Thruster	Prop Blade	0.032" x 1" x 12" Brass	Ace	\$ 5.97
Thruster	Prop Hub	1/4"-28 Brass Nut	Sutherlands	\$ 0.90
Thruster	Shaft	Aluminum Rod 3/8"	Ace	\$ 6.99
Thruster	Shroud	3" Steel Tube 16 ga	McMaster Carr	\$ 36.62
Thruster	Support	1/8" Steel Rod	Lowe's	\$ 2.58
Torpedo	Battery	2CR5	WalMart	\$ 29.88
Torpedo	Controller	PC Board, bare	Advanced Ckts	\$ 24.00
Torpedo	Controller	PC board components	Digikey	\$ 19.50
Torpedo	Ends	1-1/2" UHMW Rod	McMaster Carr	\$ 3.36
Torpedo	Housing	1-1/2" Polycarbonate Tube	McMaster Carr	\$ 11.37
Torpedo	Launcher	Solenoid, lawn sprinkler	Ace	\$ 12.45
Torpedo	Magnet	1/2" x 1/4" Rare Earth	McMaster-Carr	\$ 20.76
Torpedo	Motor	6v 4350 RPM	AmSciSurplus	\$ 2.97
Torpedo	Nose	UHMW Plastic 1/2" thick	McMaster Carr	\$ 6.55
Torpedo	O ring	EPDM 123 25 pk	McMaster Carr	\$ 7.85
Torpedo	Payload	Plastic Tube 7/8" x 36"	Aztec Welding	\$ 9.99
Torpedo	Shaft	Aluminum Rod 3/16"	Ace	\$ 1.39
Torpedo	Support	Aluminum Strap 1/16" x 3/4"	Ace	\$ 6.99

TOTAL: \$ 1,937.33

Appendix B: Torpedo Controller Schematic

