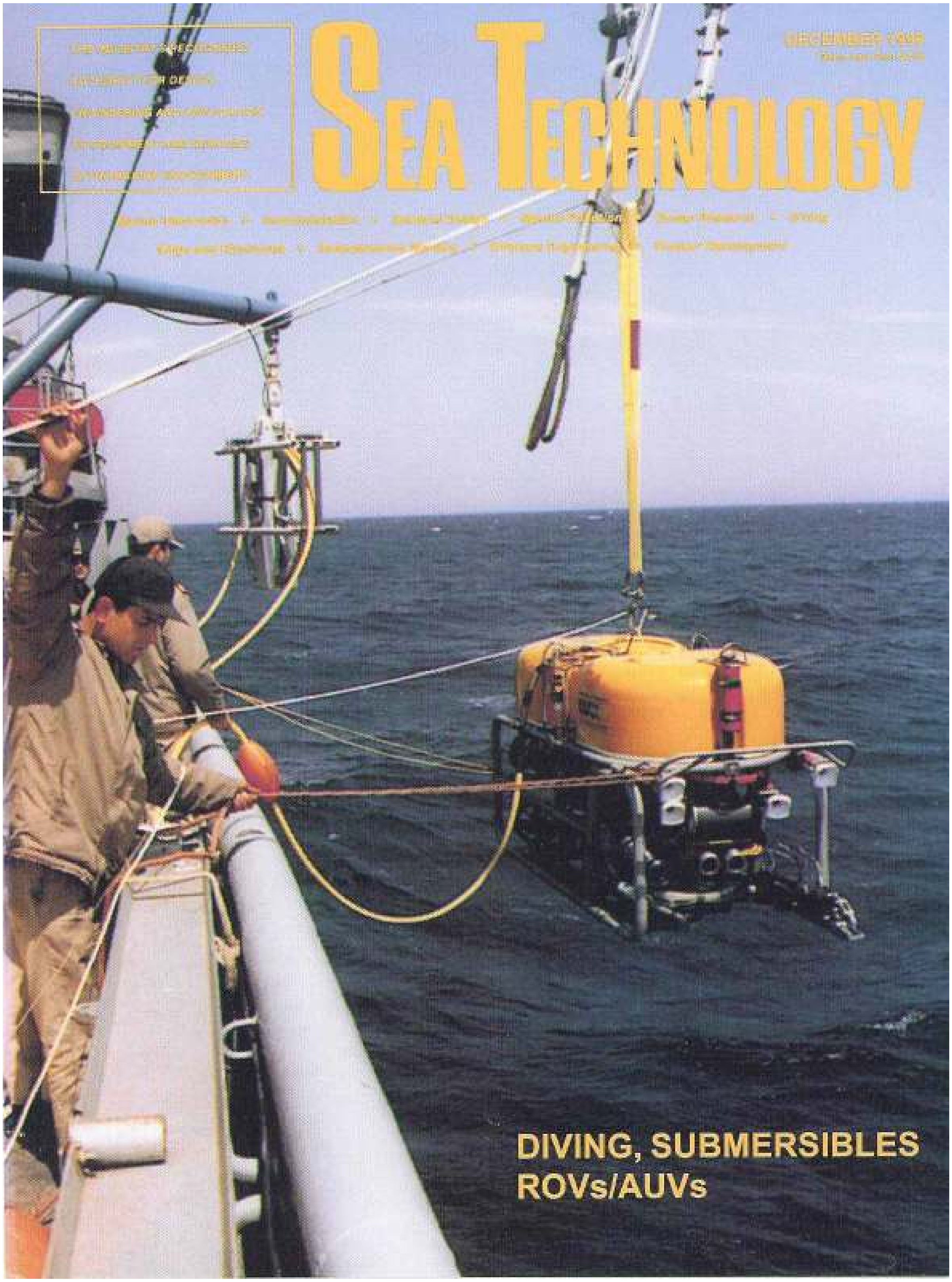
SEA TECHNOLOGY
DIVING, SUBMERSIBLES
ROVs/AUVs

CETUS: Design of a Production AUV

Design Objective: Streamline Development, Manufacturing Steps Towards Task-Specific Vehicles; Approach Seeks to Minimize Design Time, Cost per Unit

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With the growing interest in autonomous underwater vehicle (AUV) applications worldwide, designers and users increasingly must choose between platforms that are specific to a given task and those that accommodate a variety of missions. The former is certainly the most common strategy at present. Isolated objectives such as video survey or water column sampling, for example, involve specialized equipment, and a vehicle capable of adapting to the many variations would be complex and expensive to create.

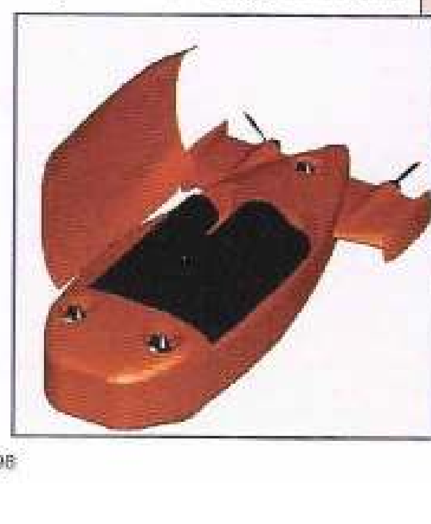
Lockheed Corp. requested a flatfish-shape autonomous underwater vehicle for mine countermeasures. In response, the CETUS vehicle was designed and built at MIT Sea Grant's Autonomous Underwater Vehicles Lab. We relied on our experiences with other Sea Grant vehicles, including Odyssey IIb (*Sea Technology*, December 1995) to produce a vehicle that was not only inexpensive to manufacture but also durable and easy to service. The typical approach involving exhaustive iterative hull testing and component development was not possible due to limited time and budget. Instead, we were compelled to rely on theoretical data from existing vehicles, in-house expertise, and our finite resources. The resulting design

Left; CETUS production AUV.

met or exceeded the original performance criteria and was within the apportioned budget. Our final design has a single-piece HDPE (high density polyethylene) hull, formed using a rotational molding process. We employ two propulsive thrusters and three hovering thrusters, with no active control surfaces.

In this paper, we will demonstrate some of the approaches employed that allowed for a rapid vehicle design and development project. Our design process exploited our existing familiarity with AUV design to develop

Below: Rotationally molded fin with integral stainless steel tubing. The tube provides structure, allows for fin adjustment, and acts as an electrical conduit for thruster motor power and control wiring. Plastic shrinkage during the molding and cooling process provides substantial torsional and axial rigidity.



Lower left: CETUS vehicle and its three vertical and two horizontal thrusters. Note the payload bay, which accommodates the main pressure vessel, up to four battery housings, motor controllers, and user-provided payloads. A simple single-layer hatch made from 1/4-inch-thick polyethylene covers the bay and provides hydrodynamic streamlining.

techniques allowing us to quickly arrive at a final design that met Lockheed's needs. The first step in this process was an analysis of the imposed constraints and careful consideration of the desired performance objectives. Once these were understood, an initial hull shape was proposed, drawn up, critiqued, and reiterated. This design spiral process was accelerated considerably using mathematical analysis tools and solids modeling software.

The majority of the limitations (such as power requirements as related to hull size and shape) were addressed in this early software-based design stage. In this manner, we minimized costs while working towards a suitable solution. Once the preliminary hull shape was determined, thrusters selected, and payload space allocated, a one-fifth-scale model was built and tested in the MIT towing tank. Initial hull drag coefficients were determined and used to "close the loop" on the power requirements and propulsion components.

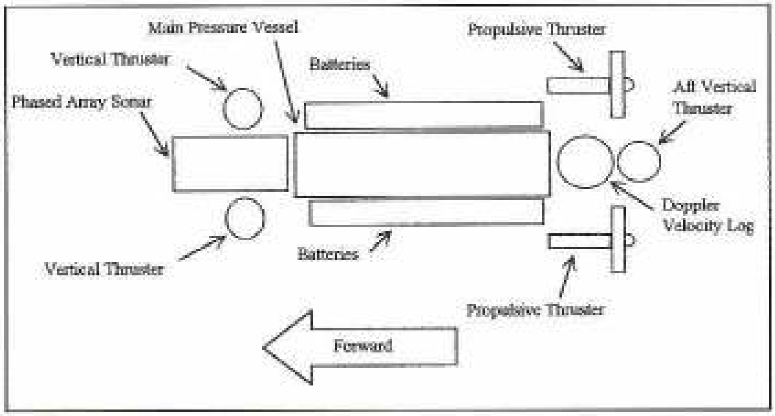
Next, a full-scale fiberglass model was built and tested in order to arrive at the static stability solution and to verify hull drag calculations. Finally a set of molds were constructed and the production quality hulls fabricated, detailed, assembled, and delivered to Lockheed. This entire process was completed from concept to delivery in nine months.

Initial Design Issues

The CETUS platform was developed in order to allow the U.S. Navy to upgrade existing mine countermeasure assets. Currently, using ROVs equipped with phased-array sonar systems, the Navy is capable of performing near-shore mine detection surveys (depth rating of approximately 200 meters). Covert capability is compromised when using ROV technology, however, due to the limits imposed by a tether and requirements for nearby surface vessels. The deployment of a similarly equipped AUV (CETUS) significantly enhances operational capability by eliminating both of these inherent limitations.

The following specific constraints, provided by Lockheed-Martin, drove the vehicle design:

- Single-piece hull to be flat and stackable
- Total vehicle length less than 200 centimeters
- No movable control surfaces.
- Payload is one 90- x 25-centimeter-diameter pressure bottle, one 12- x 15-centimeter-diameter doppler current profiler, and one 20- x 20- x 80-centimeter, box-shaped sonar package in the nose
- Operational speed of 1.5 meters/second, with a maximum vertical transit rate of 0.5 meters/second, for a one-hour duration
- Hover capability
- Low vehicle unit cost
- Durable structure, easily handled and transported
- All thruster motors and controllers identical.



Top view of payload layout. Size and weight of the forward-facing phased array sonar, the main pressure vessel, and the doppler velocity log were imposed constraints. Thruster size (diameter and length) was designed to meet performance objectives while simultaneously imposing drag and performance penalties.

These requirements have several implications. First, a flat vehicle has increased pitch instability, making it susceptible to surface-wave disturbances. In the absence of movable fins, vertical thrusters are needed for depth control, although it is not obvious whether these same thrusters should, or could, be used to stabilize pitch motions. If not, then passive aerodynamic stability is crucial during forward flight; this can be achieved with large fixed fins aft. In either case, the vertical thrusters and their orifices add to the vehicle's forward drag, as does the square bow implied by the sonar package. To achieve low-cost manufacturing, we decided very early in the design process to fabricate the hull using rotationally molded HDPE. Polyethylene is a very durable thermoplastic that offers acoustic impedance near that of seawater, low cost, and neutral buoyancy.

Design and Analysis

AUV technology is relatively new and thus limited literature is available on the subject of general AUV design. With AUVs, mission requirements translate into specific geometry, size, and energy budgeting, which must be carefully balanced if a solution is to be obtained. As one simple example, a length maximum and a payload minimum may categorically preclude the most streamlined hull shapes.

In the earliest stages of the project, we prioritized the constrains to give some overall shape to the vehicle. An initial analysis then assisted in confirming the basic hydrodynamic stability properties. We addressed the many issues associated with packaging internal components, thrusters, and supplemental equipment; this step in particular required a number of iterations and often a reassessment of the hydrodynamic effects. Increasing the working diameter of a tunnel thruster, for example, may cause the vehicle profile to expand, thereby increasing vehicle drag and compelling more powerful horizontal propulsors.

To speed the design cycle, we used MATLAB software to simultaneously define hull, fin, and propeller geometry; make hydrodynamic and weight/balance calculations; and write computer aided design (CAD) macros. Within this framework, all of the geometry was mathematically dependent on a few parameters; we obtained instant hydrodynamic predictions and CAD files as we explored different configurations. For visualization, interference checks, tool drawings, and rapid-prototyping electronic files, we employed the IDeas CAD package.

Overall Layout. Some critical relationships between vehicle stability, control, and power requirements were investigated and the results drove the overall vehicle design. Munk moment calculations indicated that any allowable vertical thrusters would be largely ineffective in stabilizing the pitch mode of the proposed hull. Large thrusters would only increase the hull width, exacerbating the pitch stability problem and creating a larger frontal area. Another consideration is the thrust reversal effect (Beveridge, 1975), which can be minimized by using small, fast jets. Even a low duty cycle for water jets, however, presents a significant power drain, and thruster tunnel diameters reach a practical size limitation due to required shafting, motor bodies, hubs, and so on.

We decided to place no stabilization requirements on vertical thrusters but instead to rely on fixed horizontal fins aft, which exert a strong aerodynamic moment on the vehicle during forward motion. This leaves the vertical thrusters responsible only for low-speed maneuvering and to achieve static pitch ("pointing") during forward motion. In this latter case, the differential thrust between two vertical thrusters in the bow and one in the stern is offset by the static C_g-C_b (gravity-buoyancy) separation and not a destabilizing pitch moment. If the C_g-C_b separation were brought close to zero, the vehicle would of course be able to remain stable while pointing in any orientation, however, at the probable cost of roll/pitch/yaw coupling.

Hull and Fin Geometry. The hull shape is a modified form of Gertler's Series 54 polynomial body with very attractive pressure profile and drag coefficient. In essence, we started with a body of rotation and inserted a wedge from the nose to provide the flattened bow with a pointed stern. This wedge tapers to a point when viewed from above but to a line when viewed from the side, leaving more space aft and adding yaw stability.

The hull deviates from the smooth Gertler form in several important ways. First, the addition of a flat nose is certain to cause a drag penalty as is the presence of three cross-body thruster openings. The hull also has localized, smoothed protrusions. One is located at the forward thrusters' outer curve, required to allow plastic flow in that area. Another bulge is located at the station 70 percent along the vehicle's long axis, again allowing plastic to flow in the area where the battery tubes are nearest the outer skin.

The fins extend 50 centimeters from vehicle centerline to tip and have an aspect ratio of 0.8. The taper ratio is 0.7 and the cross-section follows a NACA 15 profile. In the prototype vehicle, these fins are fixed in location. However, in some applications, employing them as moveable control surfaces would lead to extremely effective pitch control. Thus, our design leaves open the opportunity for driving the fins (in tandem or differentially) through motors within the hull.

Putting It All Together

Rotational molding provides for the ability to create complex multiwall geometry out of a variety of thermoplastics. In the rotational molding process, a female mold is filled with a precise amount of powdered plastic and then rotated within a large oven. Through uniform and tightly controlled heating of the mold, the powder inside becomes a viscous liquid and flows freely according to the motions of the mold. The plastic ideally forms a sheet of uniform thickness on all surfaces in the mold; the temperature is reduced slowly and eventually the mold is opened to allow for final cooling. This process allows for the incorporation of structural elements and fasteners to be cast in place, thereby reducing post-casting machine operations and resulting in a more efficient design.

One of the most crucial elements of the paper design is ensuring the uniform flow of plastic through the heated mold. First, the plastic will shrink during the post mold cooling stage by approximately 3.5 percent, making it necessary to oversize the mold by this amount. The shrinking that occurs during cooling may not be uniform due to geometry and variations in plastic volume at different stations. It is common to employ a cooling fixture that clamps the part in place once it is removed from the mold. This fixture is used to reduce warping and distortion caused by internal stresses that may develop during the cooling stage. Second, as the viscous plastic material is flowing throughout the mold, adequate clearance between mold wall surfaces is required to allow full coverage of all mold surfaces. This assures generation of the minimum wall thickness specified.

We used rotational molding for the hull, for a separate box mounting the DVL, and for the horizontal fins. The hull was formed with ten embedded threaded inserts and a number of "kissoffs" (locations where inner and outer plastic surfaces bond together over a small area) on the floor of the main bay for strength. Each fin was molded with an intrinsic stainless steel tube and a cylindrical cavity for a horizontal thruster motor. The tube is the main structural connection between the hull and the fin and carries wiring to the motor. The lid was fabricated using 6-millimeter (nominal 1/4 inch) HDPE sheet stock, employing a vacuum forming process. Lids as molded were oversized and required post processing in order to secure to the hull. Special care was taken in the selection of both the raw plastic powder stock material and the sheet stock material in order to provide Lockheed with the requested color match and surface finish desired.

Motors. The motors and housings were developed by colleagues at Woods Hole Oceanographic Institution. Identical windings to the ABE (autonomous benthic explorer) vehicle are used, but the housing is somewhat smaller, measuring 7.4 centimeters in diameter. These motors have 135-watt peak shaft output, at a nominal 48 DC voltage. The main horizontal thrusters use a 5.5:1 reduction gearbox, while the through-body thrusters are direct-drive. All of the motor housings are oil-filled and pressure-compensated.

The vertical thrusters are held in place within the tunnels by an aluminum collar with spider-like legs that bolt directly to the hull. Two electrical connectors depart from the side of these three motors, occupying the space inside one of the legs, and so passing into the hull. The horizontal thrusters fit inside pre-formed tubes in the aft fins. In this case, the connectors depart the motor on its forward circular face, pass through the main structural post of the fin, and into the main hull. Each of the five motors connects electrically to a matched controller card, which has been packaged in a rugged plastic box (also oil-filled and pressure-compensated). These controllers are mounted variously inside the hull, completing connections to the power bus and thruster control system.

Propellers. For the vertical thrusters, we settled on 15-centimeter-diameter propellers in tunnels. We used propellers designed for model airplanes having ducts; this assures that replacements will be easily found. Initial tests suggest that the vehicle develops 30 newtons of force per unit when installed.

Since the horizontal thrusters consume by far most of the electrical power on this vehicle, we designed right- and left-handed propellers matched to the motor and gearbox. The propellers operate without ducts and are based on a blade element approach that allows the chord to follow a third-order polynomial with radius. These propellers are 35 centimeters in diameter and are therefore prime candidates for rapid-prototyping techniques. The blade geometry, along with performance and strength characteristics, was computed using MATLAB, which automatically generated a script file for the IDeas CAD software. Within IDeas, we simply merged the blade with an existing hub design. When the design was complete, we generated ASCII files for stereo-lithographic forming and electronically mailed them to contractors.

From the STL generated part, we produced female RTV molds (faithful for about 20 casts) of right- and left-handed props and cast polyurethane filled with 10 percent chopped glass. The casting process is carried out within a vacuum chamber in order to minimize part porosity.

Pressure Vessels. A total of five pressure vessels fabricated out of aluminum are used to house the main vehicle electronics and power distribution system. All five cylinders are secured within the main vehicle payload cavity using a non-metallic nylon fastening system. The main electronics pressure vessel is 26.7 centimeters in OD and 80 centimeters long and is mounted on the vehicle's centerline. The battery cylinders are 14 centimeters in OD and 80 centimeters in length. All five pressure vessels are designed to operate down to 200 meters and were tested to 240 meters to assure a minimum 20 percent overpressure rating. The desired operating depth for the AUV is 200 meters, so any additional safety factor would only penalize the overall vehicle weight and cost.

Power Systems. Lead acid batteries in two or four 14-centimeter-diameter aluminum bottles provide power to the vehicle for propulsion, navigation, and control electronics as well as user-specified payload. The power system was designed to provide a range of options to accommodate a broad range of payload and mission duration objectives.

The wet wiring harness accommodates battery bottles in sets of two, all of which may be filled with an appropriate number of cells, depending on desired operating voltage. A practical minimum configuration would use two bottles with 12 cells in each, and the maximum packing would allow four bottles with 15 cells in each. The first alternative would provide a nominal 48 VDC with approximately 600 watt-hours of energy. Using the four full bottles, these values increase to a nominal of 60 VDC for roughly 1,500 watt-hours.

Each battery module houses a very compact, custom-designed electronic circuit that continuously monitors module voltage and charge rate. Each monitor is individually serialized and addressable by the main vehicle computer using standard SAIL protocol. This design allows the user to maintain continuous records of battery life and quickly determine charge status and anticipated battery life.

Cyclon "J" series batteries were selected, based on energy-density, cost, and packaging considerations. This design loop was initiated with the projected duty cycle and power consumption of thrusters and electronics. Total system power was based on a 100 percent duty cycle for horizontal propulsion and 50 percent vertical (using all three through-hull thrusters), 100 percent hotel and payload electronics load. A 50 percent factor of safety was used as a maximum duration excursion.

Performance will ultimately be based on mission, payload, and operating environment, but it is reasonable to anticipate a 1-1/2 hour survey mission at 1.5 meters/second (3 knots) between charges.

Initial Hull Testing

We constructed a full-size fiberglass prototype and performed preliminary tests in Sebago Lake, Maine. These tests identified two critical performance parameters: the frontal drag coefficient of the vehicle and the minimum fin areas required for pitch and yaw stability.

Preliminary non-powered flight tests with the fiberglass prototype led to better understanding of the AUV's dynamic stability. These tests indicated that pitch stability could be readily achieved with a reasonable amount of horizontal fin area aft and that yaw stabilization would also be needed. Early tests with a sailboard fin mounted on the vehicle's centerline proved that a small amount of well placed vertical control surface could produce sufficient passive yaw stability, but this solution might preclude the design requirement for stackability.

However, as the yaw instability is much slower than in pitch, there are several solutions.

First, the horizontal thrusters have adequate bandwidth and power to regulate the heading through differential thrust. Additionally, we found that adding small wingtips to the horizontal fins also leads to a hull that is passively stable. The final fin design reflects this solution that satisfies both the passive stability requirements and the ability to easily stack vehicles. Note that the vehicle does not have sway control because it has no athwart-ship thrusters.

Frontal Drag. We towed the fiberglass prototype behind a small pleasure boat, calibrating speed with a handheld global positioning system (GPS) unit. The vehicle nose was attached to a submerged load cell, which we monitored from the boat. This test confirmed a drag coefficient of 0.17 based on frontal area.

Stability. Because the thrusters were not available at the time of these tests, we simply towed the vehicle and then released it into free flight. Divers equipped with underwater video cameras were able to easily identify unstable flight. For studying the pitch mode, we constructed disposable fins of glassed foam that could be cut off in steps between tests. As the tests progressed, we reached the minimum fin size necessary for protecting the propeller tips well before the vehicle showed pitch instability. We then attached simple wingtip foils to stabilize the slow yaw mode. After delivery of the vehicle, Lockheed engineers fitted the aft thrusters with small shrouds. We calculated that this alone is probably enough to achieve yaw stability.

Summary

Using an efficient integrated analysis/design system comprising high-end mathematical and CAD packages, we were able to deliver a task-specific vehicle in nine months. Polyethylene has proven to be a highly desirable material in the construction of low-cost, robust AUVs. Along with the material's physical properties—such as neutral buoyancy and acoustic attenuation—polyethylene is easy to manufacture and machine. Rotational molding techniques allow for creative placement of both structural and streamline features and user-specified mechanical inserts can be integrally molded into the part to provide fasteners and structural members as desired.

The use of mathematical and design software significantly reduces the lead time and man-hours required to close the design loop and generate a set of working drawings that are readily used by fabricators. Designs are easily checked for efficiency and anticipated performance within the mathematical software tools, thereby catching inefficiencies early on in the theoretical stage of development. Once drawings are produced, manufacturing considerations are addressed and necessary changes are quickly incorporated. Should major design changes be necessary at this step, the mathematical tools prove very useful for predicting the impact proposed design changes will have on the vehicle's performance. /st/

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Joseph A. Curcio received his bachelor of science in mechanical engineering from The University of Vermont in 1985. He was previously employed as engineer aboard two historic America's Cup sailing vessels, Endeavour and Shamrock V, before receiving a master's of science in ocean systems management and the master's of engineering in ocean engineering from MIT in 1995. Curcio has worked in the Sea Grant AUV lab since completion of his master's degrees, focusing on vehicle design and operation as well as developing an AUV with hovering and station-keeping capability.

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Dr. James G. Bellingham received his doctorate in physics from MIT in 1988. He has led the design of several vehicles, perhaps the most successful of which is Odyssey. The Odyssey vehicles, five of which now exist, have been extensively used by Bellingham in the field, including the arctic and antarctic. His most recent expedition brought the Odyssey to the Kaikoura Canyon off the coast of South Island, New Zealand, to explore the benthic habitat of giant squid. Currently, Bellingham leads a multi-institutional effort to develop and demonstrate autonomous ocean sampling networks (AOSNs), a concept in which groups of cooperative AUVs operate from network stations to provide a long term reactive ocean presence.

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