Modular AUV for Routine Deep Water Science Operations

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Abstract – **The original Odyssey vehicle systems established a style of platform that has proven to be extremely versatile and useful for a variety of scientific missions. The Monterey Bay Aquarium Research Institute (MBARI) has carried forward the Odyssey design, now called Dorado.**

Dorado is a mid-sized vehicle in comparison to other AUV systems. Dorado vehicles are 0.5334 m (21") diameter, and are designed for deep water (4500 m) operation.

The Dorado design improves upon the original Odyssey versatility by dividing the vehicle up into modular sections. Specific sections can then be built to carry out each type of mission. A Dorado vehicle can then consist of a nose section, one or several mission-specific midbodies, and a tail section. The main vehicle systems for propulsion, control, data handling, navigation, acoustic sub-systems, and most other standard functions are housed in the tail section.

This paper introduces the history of the Dorado systems, and what has been accomplished to date. This paper further describes the various architectural concepts and operational results. Future planning is also discussed.

I. INTRODUCTION

MBARI is in its sixth year of building and operating AUVs. The engineers and scientists learned many lessons from numerous sea trials and a few scientific oceanographic missions. In the fall of 2000, MBARI deployed Odyssey IIb AUVs from the RV Point Sur during the MBARI Upper-Water-Column Science Experiment (MUSE) cruise. The vehicles, mainly built by the Massachusetts Institute of Technology (MIT) Sea Grant Laboratory, carried silver-zinc rechargeable batteries for energy storage, a PC/104 stack of boards for a main vehicle computer, a CTD, Bathyphotometer, and a forward looking sonar. The software was written and designed at MBARI and deployed initially on these vehicles. The object-oriented, CORBA-like software was a successful improvement over the original single-threaded code from MIT [1]. Missions over the past several years have proven it to be extremely robust.

The most recent vehicle that brought in lessons learned was called the Atlantic Layer Tracking Experiment (ALTEX) vehicle [2]. It was a Dorado class AUV which was deployed in the Arctic Ocean near Spitzbergen in October 2001 to measure ice thickness and perform mid-water analysis and data collection [3]. When the original ALTEX AUV was designed, modularity was a key component. The ability to swap out different energy sections, instrument payload sections, and data transfer sections was a requirement for testing the ALTEX vehicle over the years of development. The Dorado class of AUVs was the result of this design effort.

Other institutions such as Florida Atlantic University recognized the need for modular AUVs. Their Ocean Explorer class of AUVs address the requirement of modularity. Scientists wanting to integrate a payload on one of those vehicles are given a simple electrical and mechanical interface specification. This approach is the same for Dorado.

MBARI is directing its development efforts to create new technologies for AUVs such as autonomous docking. The Monterey Accelerated Research System (MARS) project at MBARI is funded to install a cabled observatory in the Monterey Bay. It will provide a remote, continuous, long-term infrastructure for multidisciplinary, in situ exploration in the deep sea. AUVs are one of the data collectors which will be moored to these observatories. Dorado vehicles will be modified and designed to perform unattended docking in the deep sea.

MBARI has drafted concepts of operations documents based on future missions requested by scientists. These are providing direction for the functional requirements for the next class of Dorado sized vehicles. The functional requirements also include improvements based on experience with the ALTEX vehicle. Engineers have performed trade studies on various topics such as energy sources, cabling/bus architecture, and navigation solutions to meet the functional requirements of the scientific missions.

II. DORADO SPECIFICATIONS

Before specifying the new Dorado vehicles at MBARI, science drivers needed to be in place to direct decisions and trade studies. With help from scientists eager to use the Dorado vehicles to collect their data, engineers developed concepts of operation. Missions studied included deep water (6000 m) seafloor mapping with a multibeam sonar, autonomous low-light organism detection, 50 km yo-yoing

CTD transects without a support ship in the vicinity, upper-water column bioluminescence detection and particle measurement and detection, and deep water docking as a technology to allow the next generation of oceanography.

The concepts of operations spawned trade studies. Some of the topics were navigation solutions, battery chemistry, communication bus architecture onboard the vehicle, offboard communications (satellite/RF/acoustic), and vehicle size. The studies followed the standard engineering practice of trading off cost, size, weight, performance, lead-time, safety, reliability, etc. The study for batteries was the most necessary since there were many options that all seemed to fit the vehicle, and the choice of chemistry was going to have the most significant impact.

The following Dorado specifications have resulted from the trade studies. The vehicle has a depth rating of 4500 m with a capability of going to 6000 m with special payloads like the multibeam sonar. The minimum and maximum speeds are 0.5 m/s and 2.0 m/s respectively. The outer diameter of the torpedo shaped-hull is 0.5334 m (21”). Lengths of the vehicle can vary between 2.36 m (93”) and 5.56 m (219”). Energy storage is met with multiple 2 kW-hr battery packs, which are paralleled onto the bus. Main vehicle navigation sensors include a Doppler velocimeter log (DVL) and a compass with gyro stabilization. For mapping missions with stricter navigational requirements, an inertial navigation system (INS) with an integrated DVL and ring laser gyro is used. The modular vehicle sections are joined together mechanically and electrically so payloads and energy modules can be swapped easily.

III. DORADO CONCEPT

MBARI’s AUV development focuses on building a modular, easily reconfigurable vehicle that can be modified out at sea for different missions. The vehicle has a power and communications backbone that allows sections and payloads to tap off of it as long as bandwidths and power consumption values are within the specification. Every vehicle has a Tailcone section which contains the main vehicle computer and propulsion system, and various sensors and beacons. These items will be explained in detail in the next section of this paper. The next vehicle section forward of the Tailcone could be a Nosecone with batteries or any parallel mid-body with instrumentation or energy storage. The modular sections attach to each other by means of 0.5334 m (21”) bicycle rims, which provide the structural support for joining the vehicle together. Bandclamps are then clasped around the rims to hold the sections together.

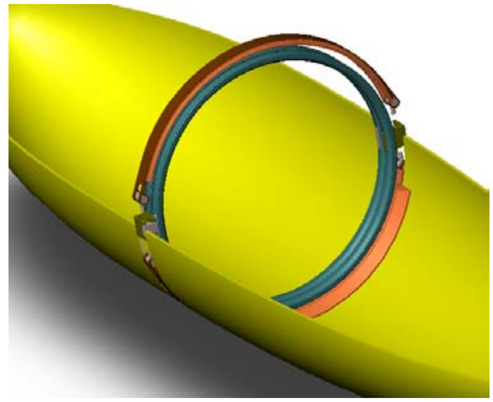

Fig. 1. Joining Ring and Two Bottom Hull Sections

In each section payloads need to conform to the vehicle specification of deep water operation. This includes providing enough flotation to provide adequate buoyancy for its own section to the specified depth, which is currently 4500 m. Interfacing to the bus is done through the standard bus connector, a Seacon MIN-K-10. This connector has raw DC power from the energy source, 100 Base-T Ethernet, and 1 Mbps CANbus. Each section must pass these signals on to the sections joining to it.

Fig. 2 depicts the vehicle bus and main housings for a typical mid-water vehicle. A tether can be attached to the power/comms tether whip for data transfer at speeds up to 100 Mbps and for shore power. When in situ rechargeable batteries are installed (September 2002) the tether will also act as the charging means for a medium-rate charge.

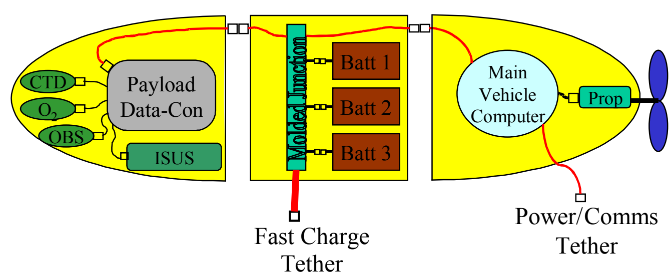

Fig. 2. Typical Dorado Configuration

A standard bus cable and interconnect, plus proper ballasting, make the sections modular. Some software reconfiguration is also required. Ballasting is first performed in the MBARI seawater test tank. The software is easily modified by editing configuration text files which describe the sensors attached to the vehicle bus. While testing in the summer of 2001 for the upcoming ALTEX trials, the AUV was reconfigured multiple times to test a semi-fuel cell section, a buoy section, a science payload, and battery sections. In the arctic on the ALTEX mission in October 2001, the vehicle was reconfigured shipboard multiple times to attach the buoy section for testing from the USCGC Healy. A block diagram of the ALTEX vehicle is shown in Fig. 3. This vehicle was built with the older style bus cables which actually broke out the power and communications conductors over two connectors.

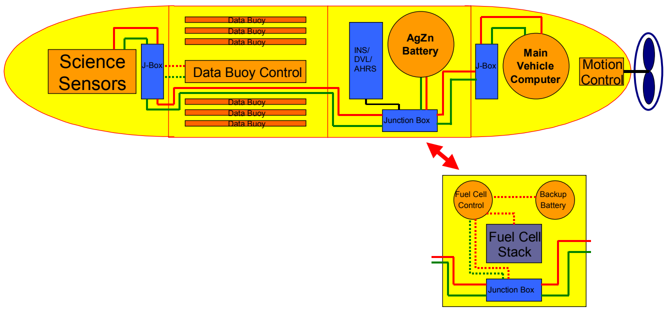

Fig. 3. ALTEX Vehicle Configuration

IV. DORADO MODULAR DESIGN

The vehicle is fundamentally comprised of several sections: the nose, the midsection(s), and the tail. Although the external appearance of the nose and tail will remain relatively the same, there is substantial space to vary much of the internal equipment (i.e. add/delete instruments and batteries). The middle portion of the vehicle can exist as one or two midsections depending on mission requirements. The hull sections consist of a top section and a bottom section. The top and bottom sections are joined together using two methods. The first method involves longitudinal "toothed" rails that run along the interior edges of each side. The tops and bottoms then have vertical fasteners to secure the top and bottom rails together. These toothed sections are placed in shear when the vehicle is lifted and assist in providing longitudinal stiffness. The second method uses an ABS semi-ring that is radially bonded to the interior end(s) of each hull section, an aluminum stiffening hoop that is secured between each semi-ring, and a stainless steel band clamp that secure all of these together. These items not only connect each of the hull sections, but also secure the modular sections together to comprise the total vehicle length.

The syntactic foam used for flotation in the various modules is rated to 4500 meters. This foam provides the necessary flotation to assure slightly positive buoyancy.

A. TAILCONE

The Dorado tailcone contains the mechanical equipment necessary to provide steering and propulsion to the vehicle. The tailcone currently used was the result of a joint development between MBARI and Bluefin Robotics. The items in the tailcone include: propulsion motor and gearbox, propeller and ducted control surface, linear actuators, motor micro-controller, pressure compensator, and syntactic foam flotation. Initial testing helped us to arrive at the following design criteria:

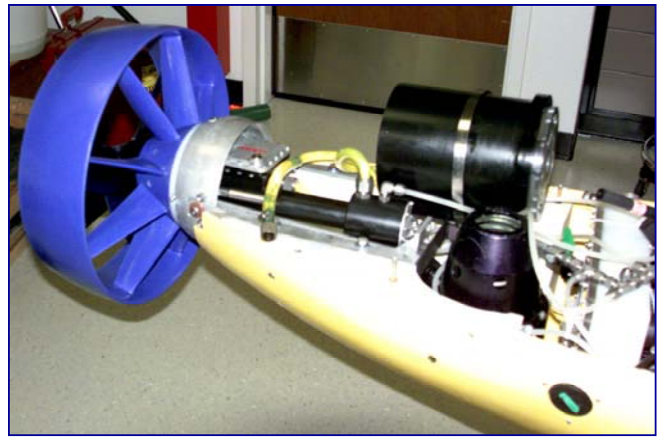

Fig. 4. MBARI Tailcone

- Minimum of plus/minus 15 degree range of duct movement
- Linear actuator Torque of at least 5Nm
- Linear actuator accuracy of at least 0.5 degrees
- Robust design capable of high impact resistance during launch and recovery

The propulsion motor chosen for the propeller is a brushless DC motor, controlled by an amplifier and motion control chipset. The motor is connected to a 10:1 planetary gearbox allowing an operational propeller speed of 100 RPM to 400 RPM. The propulsion system is compensated and lubricated with Shell Tellus 22 oil.

The design of the ducted control surface and propeller screw was done at MIT. This integrated system was chosen to enable the vehicle to have several important features. Foremost among these features is increased efficiency. An additional genesis of the duct concept was the requirement to protect the propeller and control surfaces from damage occurring from natural and operational sources. The duct substantially protects the propeller from entanglement by lines, seaweed, ice, and other hazards. The inherent strength of a ducted ring will also minimize the potential damage that can occur during launch and recovery in high sea states.

The two linear actuators are manufactured by Ultra Motion and are used to control the duct that steers the vehicle. A parallel driven stepper motor coupled with a 0.083 pitch ACME lead screw drives the actuators. This configuration results in a 2" linear stroke. Each actuator is housed in a pressure-balanced oil filled case. Each of the actuators is responsible for one direction of vehicle control. One is responsible for providing movement of the duct in a vertical component (Pitch) while the second actuator provides movement in the horizontal component (Yaw). The actuators are capable of working simultaneously to provide plus/minus 15 degrees of duct movement. This equates to a controlled turn of nearly 10 degrees per second.

The rest of the tail cone is filled with a 0.4318 m (17”) diameter glass sphere housing the main vehicle computer (MVC) and other one atmosphere electronics, navigation instruments, and tracking devices. An RDI Workhorse Navigator DVL is rigidly mounted to the MVC sphere plate so that only a one-time calibration to the compass is needed. Other instruments in this section include transducers for long baseline navigation and ultra short baseline tracking, strobe and radio beacons, RF and GPS antennas, and a pressure sensor.

B. Battery Mid-Body Section

The next Dorado vehicle being built as this paper is written will use Bluefin’s pressure tolerant lithium polymer Smart Batteries. The initial configuration will be a short mid-body section designed to hold three 1 KW-hr batteries, wired in parallel, which should store 3 KW-hr of energy.

C. Science Nose Section

One of the Dorado nose sections has been configured with a suite of oceanographic instrumentation that enables the AUV to collect substantial water-column data.

The instrumentation carried in the nose includes several SeaBird instruments including dual FastCAT SBE-49 CTDs for measuring conductivity, temperature, and water pressure, and one SBE-43 for measuring dissolved oxygen. Several SBE-5T pumps are used to assure adequate water flow to the sensors. One Hobie Labs Hydroscat-2 is used for measuring turbidity and chlorophyll fluorescence. Sensors that may accompany this core suite are: MBARI ISUS for measuring and analyzing nutrients through UV absorption spectra, the Sequoia Scientific LISST-100 for measuring particle sizes in the water, and a bathyphotometer for measuring bioluminescence. For cold weather missions an ASL IPS4 ice profiling sonar can be used for measuring ice thickness [4]. An alternative to placement of the IPS is to use the RDI Workhorse Navigator DVL for determining distance to the underside of the ice. Fig. 5 shows the nose cone configured for Arctic, under ice data collection.

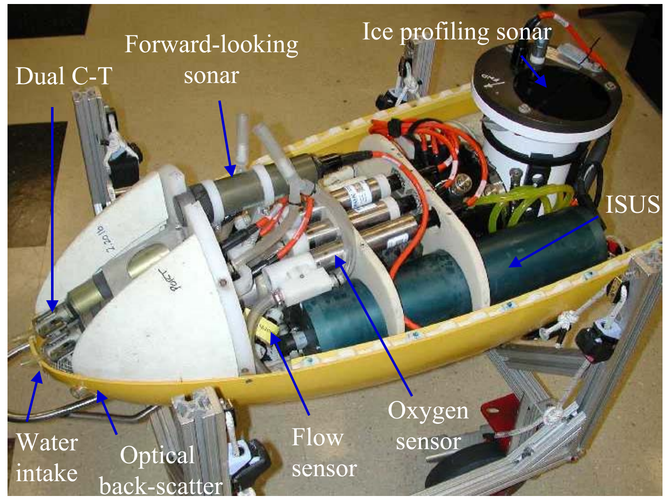

Fig. 5. ALTEX Science Payload Nose Section

V. DORADO MISSIONS

The Dorado AUV development effort at MBARI in 2000-2001 was directed towards long endurance high latitude under-ice operations during the ALTEX cruise aboard the USCG Ice Breaker *Healy* in October and November of 2001. Integration of an advanced power source (Fuel Cell Technologies semi fuel cell), remote data transfer system (Scientific Solutions International buoy launcher), high latitude capable navigation system, and a configurable data acquisition system were emphasized [5]. Fig. 6 shows the full length vehicle being deployed in the icy waters of the Arctic.

Fig. 6. Full Length ALTEX Configuration

Initial testing in the year 2000 was conducted using Odyssey IIb hardware from the MIT Sea Grant Laboratory, shown in Fig. 7. The Odyssey IIb vehicle was controlled with new software in an object-oriented framework running on a PC-104 based main vehicle computer. The new software was qualified in sea trials during January 2000 aboard the NOAA ship *MacArthur* in Monterey Bay. An additional Odyssey vehicle was converted and in August of 2000 10 days of hydrographic survey missions were run with the two vehicles during MUSE cruise.

Fig. 7. Odyssey IIb AUV

The prototype Dorado class AUV was deployed at sea on 35 days in 12 different configurations during the course of 2001. The bulk of the testing was carried out in Monterey Bay in water depths less than 100 meters but the vehicle was operated on several occasions to a depth of 500 meters. 10 days of operations were conducted at latitudes as high as 82 degrees North. Several kilometers of under-ice data were acquired in the arctic.

Dynamic control testing was successful in 5 different vehicle lengths ranging from 2.36 m to 5.56 m, with a majority of the operations conducted with the vehicle in a 3.89 m configuration. Five different navigation suites were deployed using combinations of GPS, magnetic based compass, Doppler velocimeter log, long baseline navigation system, fiber-optic gyro, and ring laser gyro based inertial navigation system. The vehicle was powered during two sets of sea trials with a semi-fuel cell built by Fuel Cell Technologies and at all other times by a 3 KW-hr silver-zinc battery pack.

Mission statistics and outcomes for the set of operations to date have been compiled in a database and analyzed for trends. Resources in 2002 have been targeted towards high return areas in order to enhance system performance and reliability. The two vehicles currently in production are designed to be working science assets supporting MBARI scientists and the broader community.

VI. DORADO PLANS

With the success of the MUSE and ALTEX experiments, plans for future Dorado vehicles include missions that will require new and improved capabilities and infrastructure. These experiments will generally require more autonomy, longer duration missions, and increased usability.

A. *Expanding Dorado Mission Objectives*

MBARI is currently outfitting the ALTEX Dorado vehicle with new science sensors for the Spokes cruise in August, 2002. The sensors are located in the nose, with the exception of the LISST and the Bathyphotometer, which are in the midbody section, and the ADCP, which resides in the tail section.

The sensor set for the Spokes cruise consists of:

- LISST: Laser In-Situ Scattering Transmissometer. Measures particle size distribution.
- Hydroscat: Optical backscattering, measures excitation-emission fluorescence.
- Bathyphotometer: measures bioluminescence distribution.
- CTD – Conductivity, Temperature, Depth
- ISUS - Nitrate sensor
- O_2 - Oxygen sensor
- ADCP - measures water velocity as a function of depth. This sensor has been present previously, but has provided only velocity over the bottom for navigation.

MBARI is working to build an Ocean Observation System in Monterey Bay, CA., where Dorado AUVs will be deployed at docking stations [6]. From there, the AUVs can run routine observation missions as well as provide scientists timely response to periodic or unusual events detected by benthic devices or moorings. The docking stations will provide communication and power services for the AUVs to remain deployed far longer than before.

MBARI scientists are planning for seafloor mapping missions that will employ a Dorado integrated with a multibeam sonar imaging system. The AUV will survey around 20 km^2 areas of the seafloor to depths of 4500m. For this mission, the Dorado will have to push the envelope of navigation capabilities to obtain the required data precision.

AOSN II (Autonomous Ocean Sampling Network) is a program that will demonstrate an adaptive coupled observation/modeling system by integrating multiple observation components such as AUVs, gliders, drifters, and moorings [7]. Scheduled for the summer of 2003 in Monterey Bay, CA., the experiment will use multiple Dorado AUVs for quick event response and surveying tasks. The AUVs will have to communicate acoustically with the other components of the experiments to accomplish the missions.

In 2004 the Dorado/ALTEX vehicle is expected to return to the arctic to run the proposed 1000km, 10 day mission. The vehicle will collect CTD, nitrate, and ice-draft data.

B. *Expanding Dorado Capabilities*

MBARI plans on incorporating a docking capability to the Dorado AUVs where the vehicles will navigate and attach itself to a docking station. The docking station could be part of a mooring, a benthic node, or simply a pole lowered from a surface vessel. Once safely docked to a station, the AUV can recharge batteries, offload data, receive new mission instructions, run diagnostic tests, etc. A docking capability will greatly enhance the usability of Dorado by eliminating the need for a surface vessel to launch and recover the vehicle after a mission to recharge batteries, etc.

The Dorado vehicle is currently transitioning from an engineering prototype to a routinely operable vehicle. Design changes to improve reliability include:

- Mechanical design improvements to the tailcone structure by Bluefin Robotics - This design is now supported by Bluefin and is employed on many different vehicles. MBARI is able to incorporate improvements resulting from many users' experience.

- Improved tailcone electronics - Dorado uses electronics specifically designed for pressure-tolerant under-sea applications.

- Reduction of underwater connectors and junction boxes - Elimination of the oil filled junction boxes is being done in an effort to increase overall reliability. As can be seen in the differences between Figs. 2 and 3, the vehicle architecture is simpler without the junction boxes. Instruments simply "tap" off of the main bus by means of a molded junction. The dual communications and power cables are being married into one cable to also cut down on the number of O-rings and other connector hardware which is prone to failure.

These design improvements are the result of experience gained from many AUV missions over the past several years.

MBARI is taking steps to upgrade the standard CTD science payload in the nose section of the Dorado vehicle. In addition to modernizing the sensor payload, the objective is to increase the extensibility of the science payload to allow more flexibility in sensor deployment and mission capability.

MBARI is also planning to integrate software developed by Bluefin Robotics which enables mission planning to proceed more quickly and with less error. Other Bluefin software will be used to graphically display vehicle status in real-time whether the vehicle is in the lab (Ethernet), on the surface (wireless Ethernet), or submerged (acoustic modem).

C. Upgrading Dorado Infrastructure

Dorado vehicles are designed for easy reconfiguring to meet the needs of specific science missions, now and in the future. Reconfiguring for science missions usually means swapping various instruments and sensors to and from the sections of the Dorado vehicle. An effort was made recently to study the tradeoffs of speed, cabling, volume, etc. between a number of communication technologies, including RS-232, Ethernet, CAN 2.0B, and LonTalk. From that study, MBARI decided to employ CANbus for most of the instrument communications in future Dorado vehicles. CANbus offers a multi-drop capability with a low power profile that can handle the relatively small data packets from science sensors.

Most of the interesting tasks for AUVs last longer than a few hours, sometimes more than 24 hours. In order to support missions of that duration MBARI is planning upgrades in battery technology and power management. Dorados will soon transition to Lithium Polymer batteries with power budgets approaching 6 KW-hr. The new batteries are able to be recharged in-situ which will decrease the turnaround time between missions as well as support the docking capability mentioned earlier.

VII. Conclusion

In October of 2001, the Dorado/ALTEX vehicle proved itself sufficiently autonomous and reliable to conduct missions in the hostile arctic environment of late fall. Several missions took the vehicle over 1 km away from the support ship, under relatively thick multi-year ice. The vehicle was out of tracking range and was able to autonomously navigate back to relatively small leads in the ice, and surface in water next to the ship.

During the arctic cruise, the AUV team ran the vehicle with both a single midbody, and with two midbodies, depending on mission requirements, thus demonstrating the benefit of a modular AUV. On several occasions, the team was able to reconfigure the vehicle in an overnight shift, and was ready to run by the next day.

After the Spokes cruise, MBARI will finish the final design work and assembly of the newest Dorado vehicle. This vehicle will be able to carry the current science payload nose cone, as well as different noses specifically designed for CTD transect missions. Sea trials will occur later this fall. Deep water operations will commence next year during seafloor mapping missions.

Because of Dorado's modular style, the MBARI marine operations staff running the day to day AUV operations will not require much time in between missions to swap payloads.

Acknowledgments

The ALTEX and Dorado projects at MBARI are supported through the Packard Foundation. The National Ocean Partnership Program provided the funding necessary to initiate the multi-disciplinary and multi-institutional development project that resulted in the ALTEX AUV under contract N00014-98-1-0814, administered by the Office of Naval Research. The ALTEX development is currently being supported by the National Science Foundation under grant number OPP-9910290. The Dorado design and build would not be possible without the dedicated efforts of the authors and fellow MBARI employees James G. Bellingham, Thomas C. O'Reilly, Robert Fuhrmann, Nicole Tervalon, Ed Mellinger, and Doug Au.

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