Mapping Payload Development for MBARI's Dorado-Class AUVs

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***Abstract* - The Monterey Bay Aquarium Research Institute (MBARI) is developing an autonomous seafloor mapping capability for deep ocean science applications. The MBARI Mapping AUV is a 0.53 m (21 in) diameter, 5.1 m (16.7 ft) long, Dorado-class vehicle designed to carry four mapping sonars. The primary sensor is a 200 kHz multibeam sonar producing swath bathymetry and sidescan. In addition, the vehicle carries 100 kHz and 410 kHz chirp sidescan sonars, and a 2-16 kHz sweep chirp subbottom profiler. Navigation and attitude data are obtained from an inertial navigation system (INS) incorporating a ring laser gyro and a 300 kHz Doppler velocity log (DVL). The vehicle also includes acoustic modem, ultra-short baseline navigation, and long-baseline navigation systems. A single cylindrical pressure housing contains all of the mapping sonar electronics, and the main vehicle control and acoustic communications electronics are housed in a separate glass ball. The Mapping AUV is powered by three 2 kWhr Li-polymer batteries, providing an expected mission duration of 12 hours at a typical speed of 1.5 m/s. The assembled package is rated to 6000 m depth, allowing MBARI to conduct high-resolution mapping of the deep-ocean seafloor. Initial at-sea testing commenced in May 2004 using the subbottom profiler and 100 kHz sidescan. The sonar package will also be mountable on ROV Ventana, allowing surveys at altitudes < 10 m at topographically challenging sites. The MBARI Seafloor Mapping team is now working towards integration of the multibeam sonar and towards achieving regular operations during 2005.**

I. INTRODUCTION

One of the fundamental efforts in oceanography is the use of sonar to map the morphology, character, and structure of the seafloor. MBARI scientists make extensive use of multibeam bathymetry, sidescan imagery, and subbottom profiles for geological research, for ROV dive basemaps, and in support of other science and development projects. Almost all of the existing MBARI seafloor mapping data has been collected from surface ships using hull-mounted multibeam sonars. Although much of this data is very high quality (e.g. 30 kHz multibeam surveys of Monterey Bay and other sites [1,2,3,4]), surveys from hull-mounted sonars lose lateral resolution in the deep ocean because of the large distance between the sonar and the seafloor. Future progress in many MBARI science goals, including seafloor observatories [5], submarine canyon sediment transport studies [6,7], benthic habitat studies [8], submarine volcanism [9], and submarine hydrate deposits [10] require higher resolution seafloor bathymetry and subbottom profiles than conventional sonar platforms can deliver. In addition to meeting existing institute science goals, high-resolution mapping of the deep ocean seafloor is still a novelty, and thus deeply submerged sonar mapping operations are likely to yield new, unexpected discoveries.

In this paper we present preliminary results from an MBARI project to develop an efficient, well navigated, 6000 m rated autonomous vehicle that can operate high-frequency sonars close to the seafloor. The AUV configuration chosen for MBARI's seafloor mapping needs is based on the modular Dorado design [11]. Planning for the Mapping AUV began during 2001, but the design effort did not begin in earnest until January 2003, following completion of two earlier Dorado-class vehicles. The functional requirements and other considerations that guided and constrained the system design are presented in section II. Section III presents the vehicle design, including some sensors and subsystems that are not yet complete or successfully integrated. We discuss the current project status and results from initial sea tests in section IV, and our future plans for this AUV seafloor mapping capability in the conclusions section V.

II. SYSTEM REQUIREMENTS AND SPECIFICATIONS

The functional requirements for the Mapping AUV were developed to satisfy a number of planned and proposed missions. The highest priority goals involve swath bathymetry, but the required resolution varies considerably amongst different uses. For instance, studies of particular seafloor feature types (e.g. vent sites, outcrops, slumps) will often need both lower resolution surveys covering large areas to find the features and higher resolution surveys of the features themselves. Bathymetric surveys intended to support ROV dives, habitat studies, or cable emplacements generally require a lateral bathymetric resolution of 5 m or less. On the smallest scale, MBARI scientists wish to repeatedly map sites in the Monterey Canyon channel to help document the frequency and nature of sediment transport events; these surveys require sub-meter lateral and vertical resolution to detect subtle changes in channel morphology. Sidescan imagery is required to augment the bathymetry with information constraining subtle morphologic features and variations in bottom lithology. A subbottom profiling capability is important to allow high-resolution imaging of shallow sedimentary structures. Finally, a depth rating of 6000 m is required in order to enable the use of this vehicle

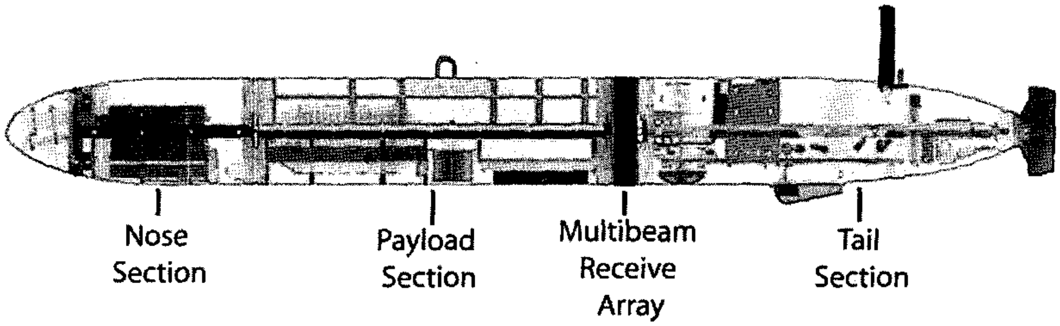

Figure 1. MBARI Mapping AUV design. The vehicle is 0.53 m (21 in) in diameter and 5.1 m (16.7 ft) long.

for seafloor mapping through most of the world's oceans.

Multibeam sonar was selected as the primary mapping sensor in order to provide the best possible swath bathymetry. The resolution and swath width achieved by a multibeam depends on the beam-widths, the sonar altitude, and the angular swath width. It is thus possible to achieve very high resolution by operating the sonar close to the seafloor, and also to achieve efficient surveys of larger areas at lower resolution by operating at a higher altitude. Although current generation multibeams generate backscatter imagery, the resolution and quality is limited relative to sidescan sonars, and so a separate sidescan sonar capability is also required.

The system design is constrained by two end-member conceptual surveys, one intended to cover the greatest area possible with lateral resolution < 5 m, and the second intended to cover small areas in sub-meter resolution by surveying at altitudes of just a few meters. The typical high altitude survey is conceived as mapping a 3 km by 6 km region with 500 m line spacing in a single, 55 km trackline dive. Since Dorado vehicles run at about 1.5 m/s, this survey requires survey duration of 10.5 hours plus time for the descent and ascent. The 500 m swath coverage must be accomplished within a 120° angular swath in order to achieve the lateral resolution requirement (footprints of outer beam soundings stretch out on the seafloor, lowering resolution), implying a 150 m vehicle altitude. In turn, this maximum altitude led to the selection of 200 kHz as the highest feasible frequency for the multibeam. The near-bottom, highest resolution surveys are not achievable in extreme topography (e.g. the Monterey Canyon channel) because of limitations in the AUVs maneuverability. Consequently, the mapping package is intended to be mountable onto one of MBARI's ROV toolsleds.

Swath surveys require navigation with a precision similar to the bathymetric resolution; otherwise the resulting maps will show artifacts where bottom features mismatch on overlapping swaths. Although correlation of seafloor features on overlapping swathes can be exploited in post-processing to improve navigation, the realtime navigation must be sufficiently accurate to ensure that the target region is properly and fully surveyed and that vehicle safety is not compromised by unexpected extreme topography. These requirements impose a need for inertial navigation aided by both a bottom tracking Doppler sonar and by external navigation (e.g. USBL from a surface vessel or LBL from bottom transponders).

In addition to simply meeting the survey requirements, the deployment of mapping sonars on an AUV involves several additional engineering challenges. Autonomous vehicles are power limited for both propulsion and sensors by the battery payload. The 0.53 m (21 in) diameter Dorado AUV also imposes constraints on the shape and volume of the electronics packages, and the amount of buoyancy compensation required. Operational realities (the vehicle must be deployed and recovered at sea) dictate that any protuberances from the cylindrical Dorado vehicle will tend to be damaged. Consequently, another very desirable design feature for Dorado systems is to keep all sonar elements internal or conformal to the cylindrical AUV.

III. SYSTEM CONFIGURATION

MBARI's Dorado AUVs are made out of modular sections with yellow ABS plastic fairings 0.53 m (21 in) in diameter that are split both horizontally and vertically. The sections are held together with joining rings and band clamps. Currently the Mapping AUV has three main sections plus a multibeam sonar receive array (Figures 1 and 2). Each section is slightly positively buoyant due to the addition of machined, 6000 m depth rated syntactic foam modules.

The nose section holds the energy for the vehicle that is comprised of three pressure-tolerant, 2kWhr Lithium Polymer batteries manufactured by

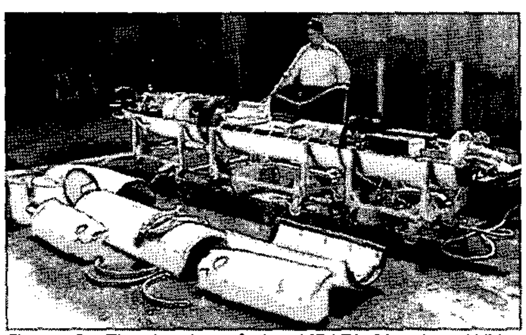

Figure 2. The interior of the MBARI Mapping AUV revealed by removing the upper fairings and syntactic foam blocks.

Bluefin Robotics. A Sea-Bird SBE 49 FastCAT CTD sensor is mounted in the foremost position to sample the water just outside of the vehicle's boundary layer. A single-beam, 225 kHz ranging sonar (Benthos PSA-916D) is mounted up front as well for obstacle detection up to 50 m away. A custom epoxy-filled junction box provides Ethernet switching, Ethernet-to-serial communications, voltage bussing, and multi-drop serial communications to the subsystems mounted in this section.

The mapping sonar payload is mounted in the mid-section, and incorporates a Reson 7100 200 kHz multibeam sonar and an Edgetech FS-AU system, including 100 kHz and 410 kHz chirp sidescan sonars and a 2-16 kHz sweep chirp subbottom profiler. The Reson 7100 achieves 1° by 1° resolution in each of 349 beams forming a 150° swath. The multibeam projector, subbottom projector, and subbottom receiver staves are mounted along the bottom of the section, inside the fairing. The dual-frequency sidescan staves are mounted along both sides, 20° from vertical. The circular multibeam receive array makes up its own modular 0.53 m (21 in) section mounted closest to the tail section. All of the active sonar elements are electrically connected to a cylindrical titanium pressure vessel which houses power supplies, an Edgetech FS-AU control computer (Windows 2000), a Reson payload controller and data logging computer (Windows XP), and both Reson 7100 and Edgetech FS-AU sonar electronics.

The tail section is where the guidance, navigation, and control of the vehicle take place. In the fore-most part of the tail section, a Kearfott SEADeViL inertial navigation system (INS) is mounted in a cylindrical pressure housing. The INS integrates a ring laser gyro and a mechanically coupled Doppler velocity log (DVL) with additional information (e.g. pressure depth and external position fixes from USBL or LBL navigation) through an embedded Kalman filter. The navigation accuracy specification of the INS/DVL, not including external aids such as USBL or LBL, is 0.05% of distance traveled (DT), circular error probable rate (CEPR) [12,13,14]. The roll accuracy of the INS gyro is 0.05°, meeting the roll precision requirement of the multibeam sonar. Mechanical coupling to the multibeam receive array is achieved through custom plates to maintain roll alignment between the two components. Transducers for acoustic communication, long baseline navigation, and ultra short baseline navigation are mounted aft of the INS inside the fairing. Aft of the transducers is a 0.43 m (17 in) diameter borosilicate glass pressure housing, which holds the main vehicle computer (QNX), wireless Ethernet modem, Iridium satellite modem, ARGOS satellite tracking unit, power converters, and various other electronics to run the strobe light and 10 kg drop weight. Mounted at the aft end of the tail section, is the MBARI-patented propulsion system, with a brushless DC motor and gearbox connected to a ducted propeller and two linear actuators which turn the duct as a control surface [15].

The vehicle navigation system combines autonomous, DVL-aided inertial navigation with the potential for both surface-aiding and bottom-aiding. During descent and ascent, the vehicle must navigate without the aid of a bottom tracking Doppler. Accumulated errors are on the order of 800m/hour for high quality INSs. Tracking data from a surface ship is provided via ultra-short baseline (USBL) tracking, and can be transmitted to the vehicle via a low-frequency acoustic modem. In water depths or operating conditions where surface tracking is not feasible, the AUV is capable of interrogating spread spectrum and tone-burst transponders anchored to the seafloor. Acoustic synchronization requirements limit modem operation to the turning portions of the survey. The INS is capable of navigating with DVL aiding with an accuracy between 0.05% and 0.1% of distance traveled (DT), allowing the AUV to navigate a 6 km trackline without external aiding.

The modular design of the Mapping AUV results in a large number of electrical connections between the vehicle sections, each representing a potential failure point [16]. To reduce the risk of failures, the team chose to use a titanium metal shell connector with only 10 pins. Two large gauge pins are used for the 26-34 VDC bus, four pins are used for 100 Base-T Ethernet, two pins are used for an RS-485 multi-drop communications bus, and the other two are for shields and enable lines. The cable is custom made, with a polyurethane jacket extruded around twisted-shielded pairs. To date, no failures have been associated with these cables and connectors.

The MBARI Mapping AUV incorporates a single lift point, allowing operation from any ship with an appropriate lifting capability and adequate laboratory and deck space (e.g. blue water UNOLS vessels). At MBARI the vehicle is operated from the R/V Zephyr, which is equipped with a specialized Launch and Recovery System (LRS) built for Dorado AUVs built by Brooke Ocean Systems [17]. As shown in Figure 3, the Zephyr LRS uses a system of pneumatic hoses to capture the vehicle as it is pulled toward the fantail on a tag line, and then lifts it with three straps. The entire assembly then pivots up and forward to bring the vehicle on deck.

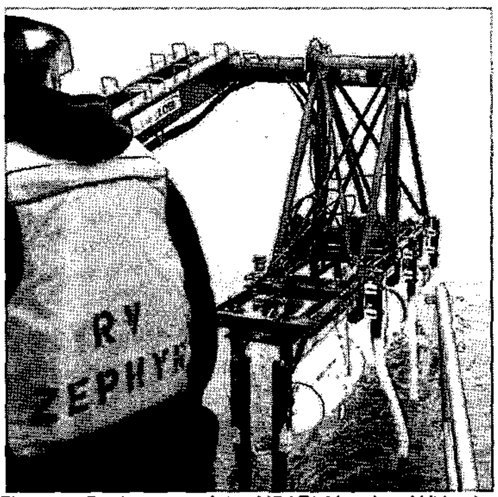

Figure 3. Deployment of the MBARI Mapping AUV using the AUV Launch and Recovery System (LRS) [17] on the R/V Zephyr.

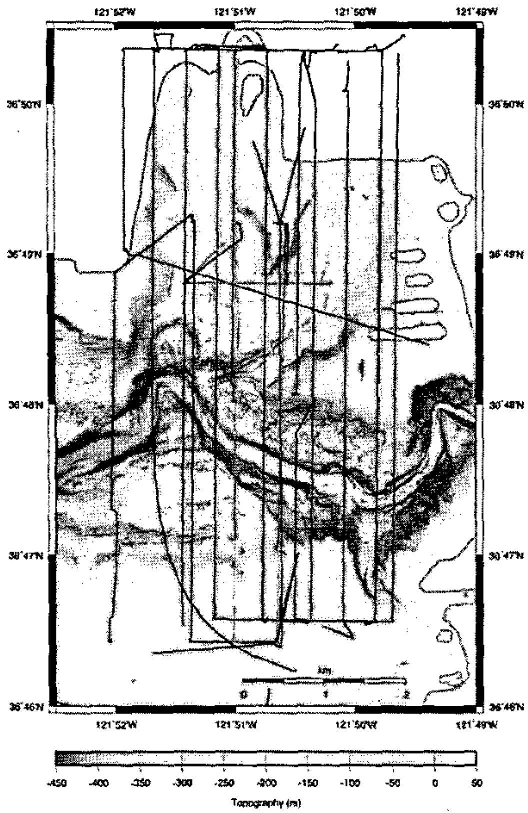

Figure 4. Location map of the Spring 2004 Mapping AUV sea tests. Subbottom profile data was collected along 140 km of tracklines across the upper Monterey Canyon. The red track shows the mission displayed in Figure 4. The thick red track is the location of the subbottom profile displayed in Figure 5.

IV. VEHICLE STATUS AND TESTING RESULTS

The initial sea tests of the MBARI Mapping AUV occurred in April 2004, followed by more extensive testing with a partial suite of sensors through the spring and summer. The function of critical vehicle systems and basic vehicle operation were verified during the first four days at sea. The subbottom profiler and sidescan systems were then tested during eight days of survey operations in and around the upper Monterey Canyon (Figure 4). Further tests of the AUV and the initial tests of the ROV-mounted configuration are planned for Fall 2004.

The vehicle control and dynamics has been a focus of the early sea testing. Although the Mapping AUV is a different length and has several minor shape differences compared with the previous Dorado vehicles, the missions so far indicate no noticeable change in vehicle dynamics. The measured rate of ascent and descent is 30 meters/minute, although the AUV will likely go faster if commanded to. The vehicle travels at 1.5 m/s when going straight and level, but slows to as little as 1.0 m/s when in a tight turn. The maximum turn rate is 8 deg/s, implying a turn radius of less than 10 m. In steady straight and level flight the depth control error is about +/- 30 centimeters. The vehicle can travel as slow as 0.7 m/s in straight and level flight, but depth control error increases to +/-1 m. The transient response of the depth control loop has an oscillatory and lightly damped mode, which has a time constant of several minutes. This is consistent with the previous Dorado type vehicles, and is not a problem, although it is under investigation.

The simplest AUV guidance scheme uses setpoints, where the vehicle navigates using only heading, time and depth. The operators select heading durations before the mission by dead reckoning predictions. This mode was used successfully for the early test missions.

In general, the Mapping AUV is operated using waypoint missions, in which the vehicle travels between sets of geo-referenced waypoints. The control algorithm uses the navigated position to compute the perpendicular distance of the AUV from the track line connecting the previous waypoint to the next. The algorithm then trims the vehicle heading to null this cross-track error. Each waypoint has an associated depth command and also includes minimum altitude and abort altitude parameters. The vehicle will fly at the commanded depth unless that takes it below the minimum altitude, as measured by the DVL. Whenever the minimum altitude is reached, the vehicle attempts to follow the seafloor at that altitude. The mission is terminated if the altitude becomes smaller than the abort threshold. Although this altitude following technique is convenient for following the seafloor over relatively smooth topography, mission aborts due to violating the abort altitude occur when slopes exceeding the vehicle's ascent capability are encountered.

Figure 5 shows along-track profiles of a sub-bottom mapping survey done with waypoints; this mission is shown by the red tracklines in Figure 2. The vehicle surfaced after each long leg to obtain a GPS position fix to null the accumulated navigation error. The vehicle demonstrated altitude following between 2555 and 4450 seconds on this mission.

The navigation error after the 5 km north-to-south leg was 0.85% DT, and on the return leg it was 0.66% DT. The integrated navigation system error is specified to be less than 0.05% DT, CEPR [12,13,14], under good conditions where the DVL maintains continuous bottom lock. However, during this mission the vehicle passed briefly over terrain

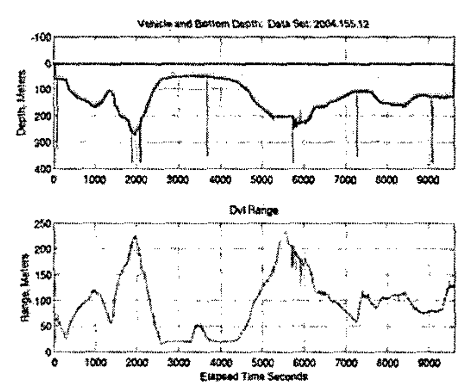

Figure 5. Depth and DVL range (altitude) profile along the mission track shown in red on Figure 3.

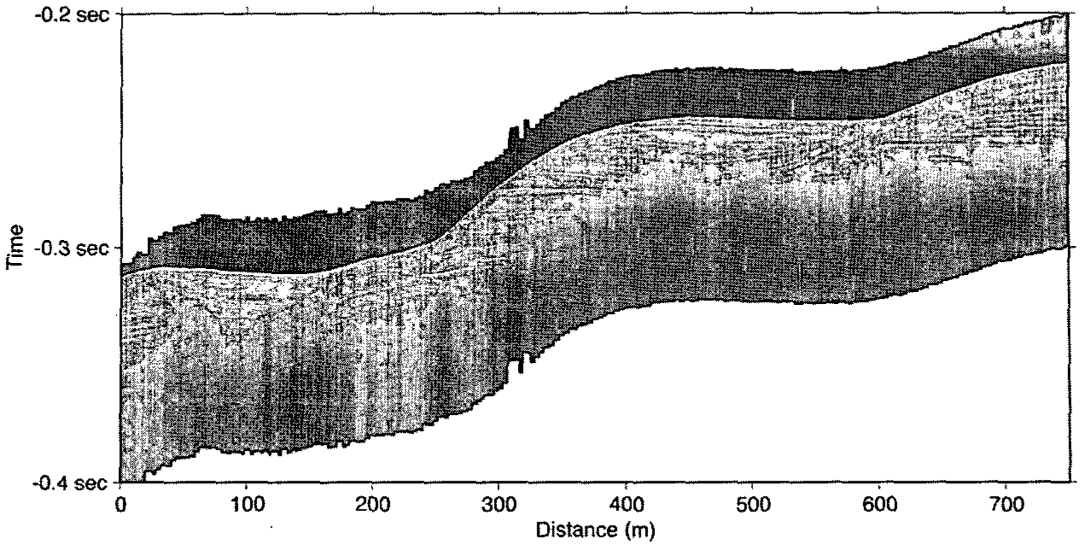

Figure 6. Subbottom profile data collected over the north wall of the upper Monterey Canyon. The location is shown by the thick red track in Figure 3.

that was beyond the DVL range, which is about 200 meters. During these periods, the navigation system accumulated free inertial drift error, which ranges from 0.8 to 1.6 km per hour. Thus, the navigation errors are consistent with expected system performance, and emphasize the importance of flying the vehicle within DVL bottom lock range throughout missions, even in regions of extreme topography.

In fact, a number of "altitude aborts" were experienced during the first attempts to operate the Mapping AUV in and around the upper Monterey Canyon, which features near-vertical walls. A new operational method has been devised in which existing bathymetry data (from hull-mounted multibeam surveys) are used to preplan the vehicle depth profile in detail throughout a mission. This new approach holds great promise for enabling near-bottom surveys of challenging terrain.

Figure 6 presents a sample of the subbottom profile data collected during the Mapping AUV sea tests. The system is clearly successful at imaging subsurface structure in and around the canyon, with typical imaged penetrations of 0.05 seconds (corresponding to roughly 50 m penetration if the mean sediment sound speed is 2000 m/s). To date, 140 km (Figure 2) of well navigated, good quality subbottom profile data have been collected on lines crossing the upper Monterey Canyon.

Although the initial tests have been quite successful, a number of integration tasks and problems remain to be resolved before the Mapping AUV has the full designed capability and can be operated routinely. In particular, delivery of the Reson 7100 multibeam has been delayed, although the multibeam projector and much of the required electronics and software have already been integrated into the vehicle. Testing of the full multibeam system will commence as soon as it arrives. The 100 kHz sidescan sonar is operational, but the data are excessively noisy due to electrical interference. Throughout the initial tests the Mapping AUV was limited to operations at depths less than 250 m due to pressure-related failures in the battery packages used in both this vehicle and the other MBARI AUVs. We expect to resolve the battery depth limitation by early 2005, allowing MBARI to proceed with deep-ocean testing. The acoustic modem and LBL systems are also not yet performing to specification, and must be successfully debugged and integrated for deep-ocean missions. The Mapping AUV team is actively working to resolve all of these issues, and expects to achieve operational status during 2005.

V. CONCLUSIONS

The MBARI Mapping AUV project has designed, constructed, and completed initial sea testing of an autonomous vehicle for conducting high-resolution bathymetric, sidescan, and subbottom profile surveys of the deep ocean seafloor. The core vehicle has proved to be reliable, with operational characteristics as designed and expected. Over 140 km of good quality subbottom profile data have been collected during tests in and around the upper Monterey Canyon. A number of important subsystems remain to be integrated and debugged, including the primary sensor, a 200 kHz multibeam. We expect to complete the integration and debugging process and to proceed with science survey operations during 2005.

The surveys planned for 2005 are located in the Monterey Bay region and will be conducted from the MBARI vessel *R/V Zephyr*. These initial science operations include both AUV and ROV-mounted surveys within the Monterey Canyon and on the Monterey Fan to study sediment transport, mass wasting, and to support benthic biological studies. Surveys are also likely on Smooth Ridge to support the planned deployment of a submarine cabled observatory and proposed IODP drilling. Seafloor surveys in the Gulf of California are being planned, and may be conducted in conjunction with ROV dives during an MBARI expedition proposed for 2006. Ultimately, MBARI plans to operate the Mapping AUV from appropriate "vessels of opportunity", allowing this high-resolution mapping capability to be used anywhere in the world's oceans.

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