Results from MBARI's Integrated Mapping System

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Abstract **– The Monterey Bay Aquarium Research Institute (MBARI) has developed an autonomous underwater vehicle (AUV) for deep ocean seafloor mapping. The MBARI Mapping AUV is a 21" diameter, torpedo-shaped *Dorado* class vehicle equipped with a 200 kHz multibeam sonar, 110 kHz and 410 kHz chirp sidescan sonars, and a 2-16 kHz sweep chirp subbottom profiler. The multibeam sonar incorporates a circular receive array conformal to the vehicle hull, providing 1 degree X 1 degree beam resolution over a 150 degree swath. Navigation and attitude data are provided by an inertial navigation system integrating a laser ring gyro, accelerometers, and a 300 kHz Doppler velocity log (DVL). The vehicle is tracked during missions using an ultra-short baseline navigation system. The vehicle will also include acoustic modem and long-baseline navigation capabilities. A central cylindrical pressure housing contains all of the mapping sonar electronics. The main vehicle control and acoustic communications electronics are housed in a separate pressure housing in the vehicle tail section. Propulsion and steering are provided by a tailcone including an articulating propeller. Li-ion or Li-polymer battery packs allow for a 12 hour mission duration. The assembled package is rated to 6000 m depth. The mapping payload is also designed for ROV mounting, enabling low altitude (< 20 m) high precision missions in topographically challenging sites. The Mapping AUV has now been operated in both autonomous and ROV modes in and around the upper Monterey Canyon, successfully collecting high-resolution multibeam bathymetry and subbottom profile data. Near bottom surveys of the canyon axis achieve bathymetric coverage with a lateral resolution of 1 m and a vertical precision of 0.3 m. The subbottom profiler images subsurface structure to depths of 60 m in soft sediments.**

I. INTRODUCTION

Acoustic mapping of seafloor bathymetry, character, and subbottom structure is a fundamental activity in oceanography. In general, the resolution of seafloor mapping data improves as sonars approach the seafloor and as larger sonar array apertures (compared to the acoustic wavelength) are used. Consequently, high-resolution seafloor mapping in the deep ocean is best accomplished by operating high frequency sonars near the seafloor on depth-

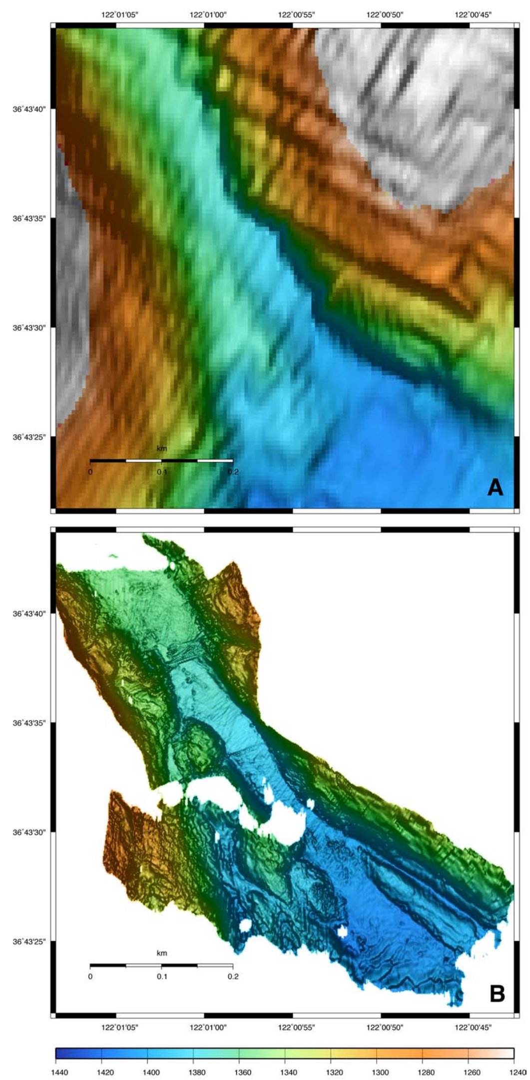

Fig. 1. Comparison of multibeam bathymetry resolution achieved in water depths of 1000-1400 m using (A) a hull-mounted 30 kHz multibeam and (B) the MBARI Mapping AUV operated at an altitude of ~60 m. Both maps show the same area at the same scale; the location is indicated on Fig. 12.

capable platforms. Fig. 1 demonstrates the resolution advantage sonars on submerged platforms have relative to hull-mounted sonars. Towed systems have long been used to map in the deep ocean, but are cumbersome and slow. Recent mapping work from both autonomous and remote operated vehicles (e.g. [1][2][3]) has demonstrated the feasibility and utility of these vehicles as mapping platforms.

The Monterey Bay Aquarium Research Institute (MBARI) has developed a *Dorado* class Autonomous Underwater Vehicle (AUV) to map the deep-ocean seafloor efficiently in high-resolution. The MBARI Mapping AUV combines a complete mapping system, a high performance inertial navigation system, and efficient propulsion in a vehicle that can be easily operated from a variety of vessels. The mapping and navigation components can also be mounted on MBARI's ROV Ventana, allowing near-bottom surveys in areas of extreme bathymetry such as the depths of submarine canyons.

The primary mapping sensor is a 200 kHz multibeam sonar that provides swath bathymetry and acoustic backscatter intensity. Dual 110 kHz and 410 kHz chirp sidescan sonars image the seafloor character with greater fidelity than the multibeam backscatter, augmenting the bathymetry. A 2-16 kHz sweep chirp subbottom profiler images subsurface structure.

Additional acoustic devices include a Doppler velocimeter log (part of the navigation system), ultra-short baseline (USBL) positioning, acoustic modem, and an obstacle avoidance sonar. All of the acoustic systems other than the USBL beacon and the acoustic modem are externally triggered to avoid interference between sonars. The triggering is designed so that the sonars all end their ping cycles simultaneously, and thus no sonars are in a receive cycle as another sonar pings.

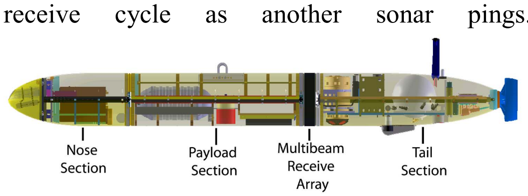

Fig. 2. Mapping AUV modular layout.

The central component of the vehicle navigation system is an inertial navigation system (INS) incorporating a ring laser gyro and accelerometers. The INS is integrated to the DVL in a commercially available package from Kearfott© called SeaDevil™. The real-time navigation error is 0.05% of distance traveled, CEPR, assuming the DVL has continuous bottom tracking.

Dorado class AUVs are 21” diameter variable length vehicles that have been developed and operated at MBARI. Dorado vehicles are constructed from multiple modular sections. A nose section and tail section are required at a minimum to provide the power and propulsion. This modular approach allows many different custom payloads to be inserted and deployed from the same core vehicle.

The Mapping AUV is constructed from three sections: a nose containing batteries, a midbody containing the mapping sonar payload, and a tail section including navigation, communications, main vehicle control, and propulsion (Fig. 2). The design also allows the mapping AUV to be quickly reconfigured into a remotely operated vehicle (ROV) payload. Figure 3 shows the mapping AUV vehicle in the ROV mode mounted to the ROV *Ventana*. The ROV operational mode allows a human to teleoperate the system at a low altitude in dangerous terrain that may include outcrops, canyon walls, or other hazards.

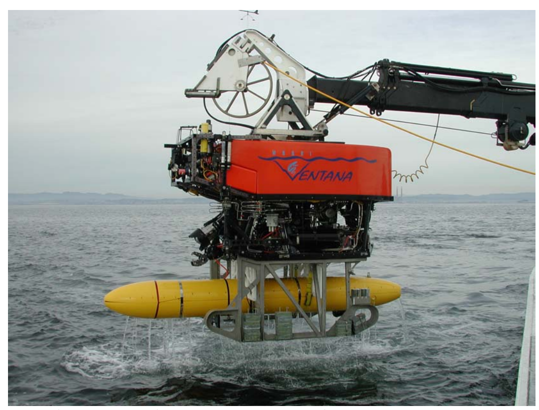
Fig. 3. Mapping system mounted on ROV Ventana.

II. SYSTEM SPECIFICATIONS

As noted above, MBARI’s Mapping AUV is based on the previously proven AUV platform *Dorado* [4, 5], and many of the system specifications follow from that basic design plan. Compared to other seafloor mapping capable AUVs, this vehicle has several unique features. In particular, the 200 kHz multibeam receive array is circular and conformal to the vehicle hull. This allows for a large (21”) sonar aperture in a relatively small vehicle, improving the beam resolution. The circular receive array is also a better geometry for wide swath bathymetry than the flat or slightly curved arrays that must be mounted on larger vehicles. All components of the vehicle are rated to 6000 m, allowing high resolution mapping operations through fully 90% of the oceans. The Mapping AUV is also smaller than most similarly capable vehicles, allowing it to be operated from small vessels by a limited staff. For example, the vehicle is most often operated autonomously by a two-person science party from *R/V Zephyr*, a 26 m boat with a three-person crew.

A. Vehicle Specifications

- *Dorado* Class AUV
  - Torpedo shaped with no fins
  - 21” diameter, 17.2’ length
  - Typical speed 3 kts
- Special Features
  - Rated to 6000 m depth
  - Can be operated from vessels of opportunity
  - Can be attached to a suitably equipped ROV
- Power
  - Two Battery Options:
    - 6 kWhr Li-polymer pressure tolerant
    - 5 kWhr Li-ion battery pack in glass housing
  - 12 hour mission duration
- Other Features
  - Radio modem at surface (56 kbps)
  - Emergency drop weight
  - Argos satellite communication & shipboard locator

B. Mapping Sonar Specifications

- Reson 7100 Multibeam Sonar
  - 200 kHz
  - Circular receive array
  - *Currently using 7125 model with flat receive array*
  - 0.94 deg X 0.94 deg beams
  - Nadir footprint:by altitude:
    - 30 cm at 20 m
    - 1.5 m at 100 m
- Edgetech 110/410 khz chirp Sidescan Sonars
  - Images seafloor character & fine-scale features (~10 cm resolution)
- Edgetech 2-16 kHz chirp Subbottom Profiler
  - Images subsurface sediment structure

III. APPLIED TECHNOLOGY

The main hull sections of the vehicle are acrylonitrile butadiene styrene (ABS) plastic. This material has properties that are beneficial to the mapping AUV system. The plastic skin acts as the main structural strength member of the vehicle and carries the vehicle loads in air as well as in water. It also provides a low-drag body shape, thereby increasing the speed and mission duration.. ABS has the additional benefit of approximating an acoustic window over the breadth of frequency spectrums used on the mapping payload, removing the need to cut holes for many of the sonar transducers Consequently there are only a few small holes in the mapping payload, thus avoiding the drag caused by large openings in the hull, which increases vehicle range.

The MBARI Mapping AUV has two principle modes of operation: autonomous and ROV-assisted. The autonomous mode operates as one would expect, running the mapping mission from the main vehicle computer without human intervention. In ROV-assisted mode, the Mapping AUV is carried beneath the ROV Ventana, Fig. 2. A small electrical interface housing temporarily mounted in the AUV's nose contains a 100 Mb/s Ethernet switch for data communications and a 450 Watt power supply to convert the ROV's 110 VAC to the 28 VDC required by the AUV. This mode provides two important capabilities not possible in autonomous mode. First, it allows engineers to adjust sonar gains and to evaluate system performance interactively in real time; performing this work with multiple autonomous AUV missions would be much more time-consuming and much less effective. Second, ROV-assisted mode provides the ability to take the mapping sonar into extreme ocean-bottom terrain such as submarine canyons. Such regions are scientifically interesting, but pose an unacceptable navigational risk to the Mapping AUV without human guidance.

The vehicle navigation system combines a DVL-aided inertial navigation with both surface and bottom-aiding. The same system is used for both AUV and ROV operations. At the surface, the INS is aided by GPS fixes. During descent and ascent, the vehicle must navigate without the aid of the bottom tracking DVL. Accumulated errors for the INS in unaided or free inertial operation are on the order of 800m/hour. Tracking data on the surface ship is provided by a Sonardyne™ ultra-short baseline (USBL) sonar. 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.

A. *Software Architecture*

The hardware and software making-up the main vehicle computer (MVC) of the Mapping AUV is a derivation from previous *Dorado* vehicles [6]. An object-oriented framework, running with the QNX operating system on a PC-104 stack, provides the foundation for all the vehicle software, including guidance and control functions, data logging, and interfaces to any payload devices. The framework provides a useful layer of functionality that can be included in user- defined classes and used to quickly create desired control sequences and communication paths.

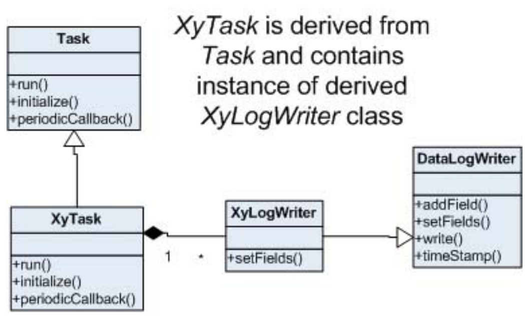

Fig. 5: Sub-classing *Task* and *DataLogWriter* in Software Framework

Each logical function in the system, navigation for example, is abstracted as a sub-class of the *Task* class from the framework. Objects of type *Task* operate independently and at a user-defined frequency that is appropriate for the function. After initialization, the framework controls the operation of each *Task* by invoking object methods at the specified frequency. On the Mapping AUV, a *Task* object is created for navigation, mission control, and all device drivers controlling payload hardware.

Data logging is an important function of the Mapping AUV that is also handled by the software framework. Normally, a log file is produced for each *Task* that runs in a mission to record science and engineering data, and control settings. To enable data logging, a *DataLogWriter* object is associated with a *Task* object to write user-defined data records to a log file. What, when, and how often records are logged is determined by the user when the run-time code for the *Task* object is written.

System tasks often require actions and information from other system tasks to perform their functions. The software framework relies upon the CORBA (Common Object Request Broker Architecture) distributed object model to control abstracted interaction between software tasks running in the system, as shown in Fig. 6. An interface description language is used to specify interfaces between *Tasks*, then proxies are written to implement those interfaces. The abstracted interactions de-couple software units, providing more flexible arrangements between *Tasks* in the system.

B. *Guidance and Controls*

During straight and level flight the vehicle makes small motions in orientation angles as well as rudder and elevator angles. Consequently, separate linear models for sway/yaw and heave/pitch may approximate the dynamic control behavior. The heave/pitch dynamics and control have proved to be the most challenging and thus are discussed here.

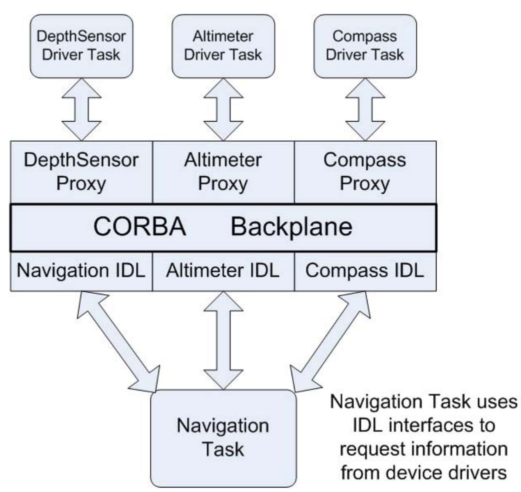

Fig. 6. Using CORBA to de-couple run-time software units.

The depth control algorithm consists of two Proportional-Integral-Derivative (PID) loops, one nested within the other. The inner loop moves the elevator to achieve a desired vehicle pitch angle. The elevator angle is computed from the vehicle pitch angular error and angular rate. The outer loop computes a desired vehicle pitch angle based on the error between commanded and measured depth, Fig. 7 shows this structure.

The depth control performance was improved recently by the addition of a depth rate term and gain redesign. The depth rate is easily extracted from the Kearfott INS/DVL navigation system, and was not previously available directly. Also, the pitch integrator has been removed from the depth control loop. Figure 8 shows the step response after the redesign.

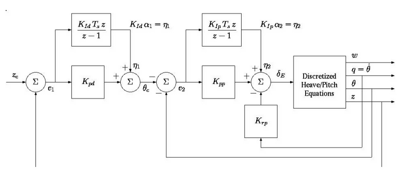

Fig. 7: AUV Pitch and Depth Control Algorithm

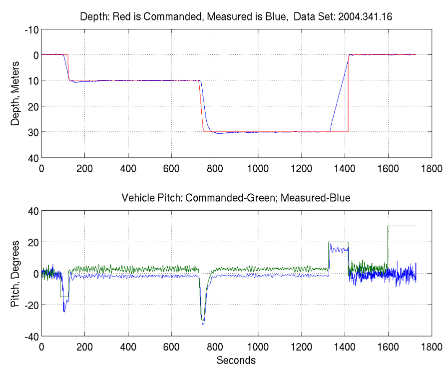

Fig. 8: AUV depth step response after control redesign.

All of the mapping sonar, navigation, attitude, and CTD data are logged in a single data format. The open source software package MB-System [7,8] is used to process the multibeam, sidescan, and subbottom data and then produce data products such as maps, grids, mosaics, images and GIS coverages.

One MB-System [7,8] feature that is particularly important for the Mapping AUV is a capability to adjust navigation so that features observed in crossing bathymetry swathes. Figure 9 shows a screen dump of the program Mbnavadjust, an MB-System tool that identifies crossing swathes and allows users to interactively match features in contours or in a cross-correlation plot. Once the navigational offsets required to match features are known, the program solves for an optimal navigational model satisfying those offsets while minimizing perturbations to speed and acceleration. The resulting navigational precision approaches the lateral resolution of the multibeam bathymetry.

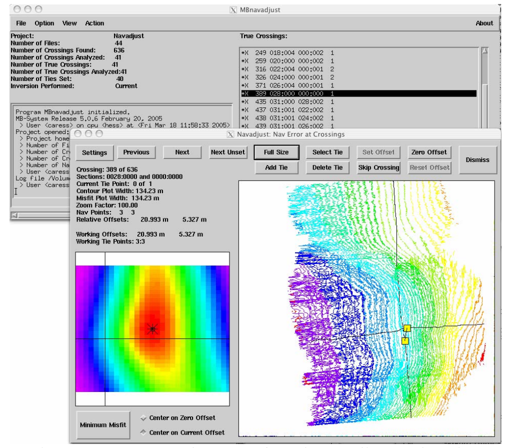

Fig. 9. Screen dump of Mbnavadjust showing interactive navigation analysis of crossing multibeam bathymetry swathes. In this case the relative offset required to match bathymetric features is 21 m E-W and 5.3 m N-S.

IV. PERFORMANCE / RESULTS

The MBARI seafloor mapping team began designing this vehicle in January 2003, following the completion of two earlier *Dorado* class AUVs. The initial sea tests of the vehicle began in April 2004, and autonomous subbottom profiler surveys in and around the upper Monterey Canyon began in May, 2004. Multibeam sonar testing commenced in November 2004 with a series of near-bottom, ROV-mounted surveys at sites along the Monterey Canyon axis.

Fig. 10 summarizes the survey tests of the Mapping AUV through May, 2005. The vehicle has operated autonomously for a total of 36 hours along a total track length of 170 km. Subbottom profiler data have been collected during all these missions, and autonomous multibeam data acquisition commenced in early 2005. Near bottom ROV-mounted multibeam surveys have been conducted at four sites along the upper Monterey Canyon axis at depths of 300 m, 520 m, 1000 m, and 1400 m (Fig. 10); these surveys have totaled 30 hours of data collection covering 98 km of tracklines.

The multibeam sonar has been operated to date with incomplete functionality, both in terms of firmware (crude beamforming and bottom detection algorithms) and hardware (a flat Reson 7125 receive array instead of the circular 7100 receive array). The subbottom profiler works well during autonomous surveys, but acoustic interference from the hydraulic systems on ROV Ventana precludes the collection of good subbottom data during ROV-mounted surveys.

The sidescan sonars are functioning, but the data are marred by noise, and are not usefully imaging the seafloor. We think that the noise source is electrical rather than acoustical, and are presently working to identify and remove the source(s) of the interference.

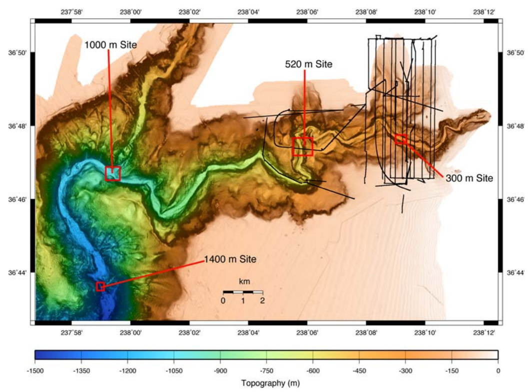

Fig. 10. Summary of the MBARI Mapping AUV survey tests. The black lines show tracks of autonomous surveys in and around the upper Monterey Canyon. The red boxes indicate locations of near-bottom ROV-mounted multibeam surveys. The 1400 m site is shown in Figure 1, and the 520 m site is shown in figures 11-14.

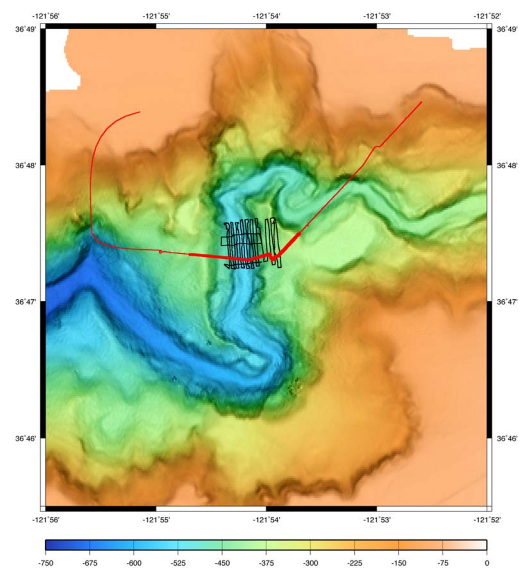

Fig. 11. Vehicle tracks of autonomous (red) and ROV-mounted surveys (black) at the 520 m survey site. The thick red line shows the location of the subbottom profile of Fig. 12.

Results of both autonomous and ROV-mounted surveys of the canyon axis 520 m site are presented in Figs. 11-14. The subbottom profile in Fig. 12 is typical of data acquired by flying the vehicle close to the seafloor than to avoid sea surface reflection interference. This profile images subsurface structure to a depth of about 40 m and demonstrates that sediments drape the inner canyon walls (the implications of these observations are discussed in [9]). Subbottom penetrations of up to 60 m have been observed in soft sediments near the Monterey Canyon head.

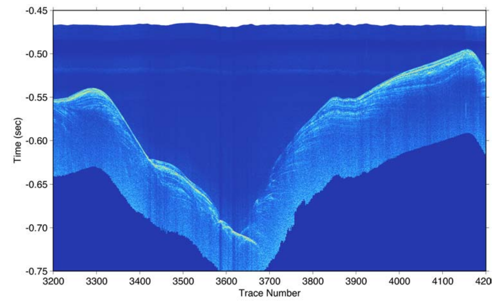

Fig. 12. Subbottom profile collected over the inner canyon at the 520 m survey site. See Fig. 13 for location.

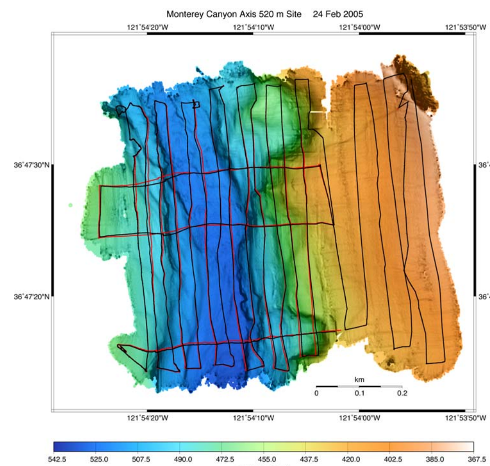

Fig. 13. Bathymetry and navigation of the 520 m site ROV-mounted multibeam survey. See Fig. 13 for location. The grid spacing is 1 m. Red tracks show the initial inertial navigation; black lines show navigation corrected by correlating bathymetry of crossing multibeam swathes.

The multibeam bathymetry from the 520 m site ROV-mounted survey is shown in Figs. 13-14. This survey was conducted using 30 m line spacings and a vehicle altitude of about 20 m. The maximum navigation correction required to match features in crossing swathes is 15 m, amounting to 0.1 % of the 15.6 km tracklength. The multibeam survey achieves a lateral resolution of 1 m and a vertical precision of 0.3 m, with the largest component of the error budget deriving from the vehicle pressure depth measurements.

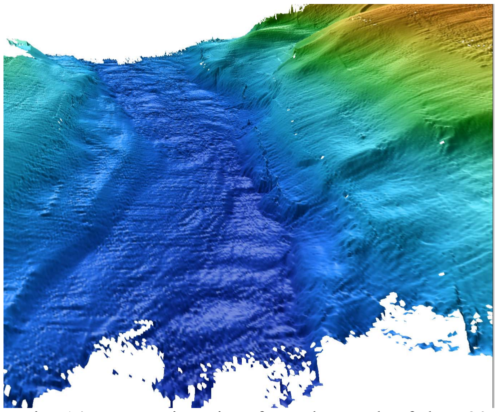

Fig. 14. Perspective view from the south of the 520 m site canyon axis with illumination from the north. The apparent sand waves in the active channel (foreground center) are 0.75 m to 1 m high.

Overall, the Mapping AUV sea testing has been remarkably successful. The vehicle itself has proven to be quite robust, and the operational team is now adept at designing and executing missions that fly the Mapping AUV into the challenging, extreme topography of Monterey Canyon. The subbottom profiler is performing to specification, and is being used to investigate recent sedimentation in and around the Upper Monterey Canyon [9]. Despite the incomplete state of the multibeam sonar, the processed bathymetry data are meeting the science requirements for the mapping system, and we expect to achieve considerably improved performance when the final firmware and hardware upgrades are installed.

V. CONCLUSIONS AND FUTURE WORK

The MBARI Mapping AUV has completed initial tests and is now being used for science missions, though the overall system is not yet complete. The system will be considered fully operational once the final multibeam upgrades are installed, the sidescan noise issues are resolved, and underwater communication via the acoustic modem is implemented. We expect to achieve these milestones during 2005.

This new capability is already contributing to existing research projects and driving new research at MBARI. The four ROV-mounted near-bottom surveys along the Monterey Canyon axis will be repeated tri-annually during coming years to monitor changes in the canyon morphology associated with the frequent sediment transport events that are known to occur in the upper canyon [10][11]. We expect to conduct the first large-scale autonomous survey on Smooth Ridge, north of Monterey Canyon, during the latter half of 2005.

The Mapping AUV operational schedule will be fully subscribed during 2006. In addition to surveys studying sediment transport and mass wasting in Monterey and other nearby submarine canyons, the system will be used to study offshore seamounts, hydrate deposits and gas seep sites, to support benthic biological research by mapping deep-water habitats, and to support the emplacement of seafloor observatory infrastructure. These efforts will likely include the first operations outside Monterey Bay. We expect this new deep-ocean, high-resolution seafloor mapping capability to contribute substantially to MBARI science in the coming years.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Yoerger, D.R., Bradley, A., Cormier, M.H. Ryan. W.B.F., Walden, B. High Resolution Mapping of a Fast Spreading Mid Ocaen Ridge with the Autonomous Benthic Explorer, Proc. 11th UUST, AUSI, Durham, NH, Aug. 1999.

[2] Yoerger, D.R., Kelley, D.S., Delaney, J.R., Fine_scale Three Dimensional Mapping of a Deep-Sea Hydrothermal Vent Site Using the ROV Jason System, Proc. Field Service Robotics 99, Carnegie-Mellon University, 1999.

[3] Belknap, D. F. (et al), Mapping Lobster Habitat with Sidescan Sonar and ROV - A Geologic and Benthic Oceanographic Collaboration,Geological Society of America, Vol. 36, No. 2, p. 137

[4] Podder, T. K., M. Sibenac, H. Thomas, W. Kirkwood, and J.G. Bellingham (2004) "Reliability Growth of Autonomous Underwater Vehicle - Dorado." *MTS/IEEE Oceans 2004*, Kobe, Japan. MTS/IEEE #563, 2004.

[5] Sibenac, M., W. Kirkwood, R. McEwen, F. Shane, R. Henthorn, D. Gashler, and H. Thomas, "Modular AUV for Routine Deep Water Operations", Oceans Proceedings, , Boluxi, MS, 2002.

[6] T. O'Reilly, "An object-oriented approach to AUV software development", UUVS Conference at Southampton Oceanography Centre, Southampton, I.K., 2000.
[7] Caress, D.W., and D. N. Chayes, "Improved processing of Hydrosweep DS Multibeam Data on the R/V Maurice Ewing", *Marine Geophy.Res*., *18*, 631-650, 1996.
[8] Caress, D. W., and D. N. Chayes, "MB-System: Open source software for the processing and display of swath mapping sonar data", http://www.mbari.org/data/mbsystem/ , 2005.
[9] Paull, C.K., W. Ussler III, P. J. Mitts, D. W. Caress, G. J. West, "Discordant 14C-Stratigraphies in upper Monterey Canyon: A Signal of Anthropogenic Disturbance?", submitted, GSA Bull., 2005.
[10] Paull, C.K., Greene, H.G., Ussler, W. III., and Mitts, P.J., Pesticides as tracers of sediment transport through Monterey Canyon: Geo-Marine Letters, v. 22, p. 121-126, 2002.
[11] Xu, J.P., Noble, M.A., and Rosenfeld, L.K., In situ measurement of currents structures with turbidity currents: Geophysical Research Letters, v. 31. P. L0911, 2004.