MARS Benthic Rover: In-Situ Rapid Proto-Testing on the Monterey Accelerated Research System

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***Abstract* – The Benthic Rover is an autonomous, bottom-crawling vehicle being developed at the Monterey Bay Aquarium Research Institute (MBARI) to conduct long-term deep-ocean ecological research. In 2009 MBARI researchers deployed the Rover on the Monterey Accelerated Research System (MARS) cabled observatory for component and operational testing. MARS is located near-shore in the Monterey Bay near Monterey, CA, at a depth of approximately 900 meters, providing the power reliability and network accessibility similar to an on-shore laboratory. By enabling immediate feedback and the ability to quickly re-program control software and re-configure mission scripts, MARS facilitates a kind of "*in-situ* rapid proto-testing". MBARI researchers were able to run numerous experimental procedures and analyze results in a relatively short timeframe, converging on desired operational profiles quickly and at very low cost. This paper will cover recent development work on the Benthic Rover with emphasis on the deployment and testing on MARS.**

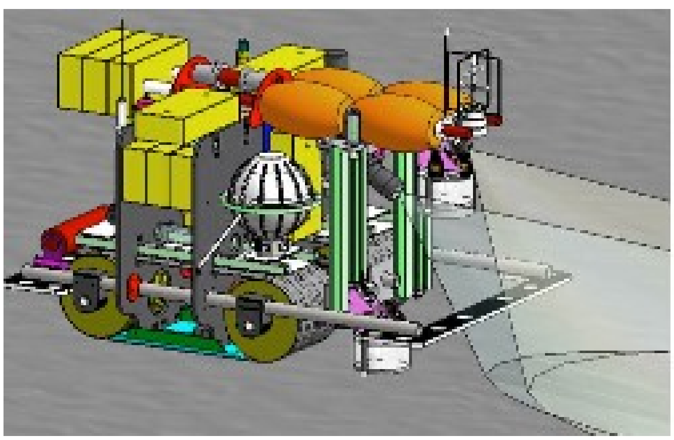

Figure 1. Solid model drawing of the Benthic Rover.

I. Introduction

The Rover is a tracked, bottom-transecting vehicle capable of making long-term time series measurements at abyssal depths up to 6000 m. Two lithium-ion battery packs enable autonomous deployments of six months. The vehicle is equipped with instruments developed to study sediment community activity and biogeochemistry. Two respirometer chambers, rack-mounted on the front of the vehicle, can be lowered into sediment to measure community oxygen consumption. A fluorescence imaging system is installed to detect phytopigment fluorescence from fresh phytodetritus on the sediment surface [1]. Four other cameras are employed to provide images of the sediment experiment area, wide-angle frontal images to record transects, and rear-view images to monitor the cable connected to the MARS node. Power management electronics minimize energy consumption by enabling the vehicle to hibernate but still maintain power to required components. The control system is then able to resume the mission where it had left off before hibernating.

The Monterey Accelerated Research System (MARS) is a cabled observatory located in the Monterey Bay off the coast of central California. The primary objective of MARS, as part of the United States Ocean Observing Initiative, is to provide a near-shore cabled facility for researchers to test instruments, systems and equipment in a deep-water environment. MARS supplies full-time power and high-speed data connection from a main science node located 25 km from Monterey, California at a depth of almost 900 meters. Science equipment is attached to the node using wet-mate connectors to cables up to 4 kilometers in length. Access to instruments is similar to a dry laboratory setup. MARS has been operational since 2008.

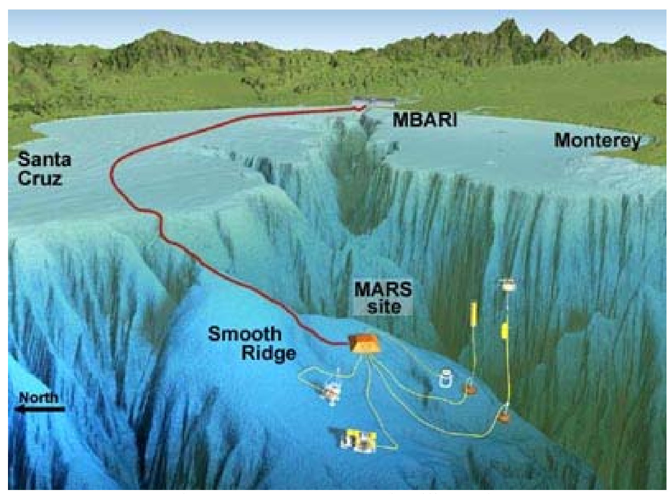

Figure 2. MARS perspective illustration.

In 2009 Monterey Bay Aquarium Research Institute (MBARI) conducted two test deployments of the Benthic Rover on the MARS node. The first deployment began on July 10th and lasted 34 days, while the second began on October 1st and went on for 79 days. The research team took full advantage of the reliable power and high-speed networking provided by the MARS facility, which enabled:

- Full-time video from the two chamber cameras mounted on the front of the vehicle

- Monitoring of the cable tether at 10 frames per minute
- Real-time analysis of engineering logs
- Easy modification to mission procedures
- Low-level control system software additions and corrections

II. Monterey Accelerated Research System

MARS was designed and built as part of the Ocean Observing Initiative to provide an easily accessible, deep-ocean test facility for ocean observation systems and experiments. The main node is installed at a depth of 890 m in the Monterey Bay near Monterey, CA. Power and data is carried through 52 km of telecommunications cable anchored in Moss Landing, CA. The two main MARS electronics housings are contained within a trawl-resistant frame measuring 3.7 m by 4.6 m, and 1.2 m tall. The housings contain data communication and power converting equipment required to convert the high voltage from the main cable to voltages suitable for science instruments.

Figure 3. MARS Trawl-resistant frame.

Experiments and instruments are connected to one of eight science ports on MARS. Each port provides both 375V and 48V DC power. The ports are individually switched and, with the addition of a Science Instrument Interface Module (SIIM), can support extension cables up to 4 km in length. The science ports support 100 megabit/sec Ethernet communications, allowing researchers to interact with instruments in real-time.

MARS has hosted a variety of instruments and experiments since it became operational in 2008. Research teams have been conducting a Free-Ocean CO_2 Experiment, collecting seismometer data, testing cutting-edge acoustic communication equipment, and capturing images of deep-ocean animals.

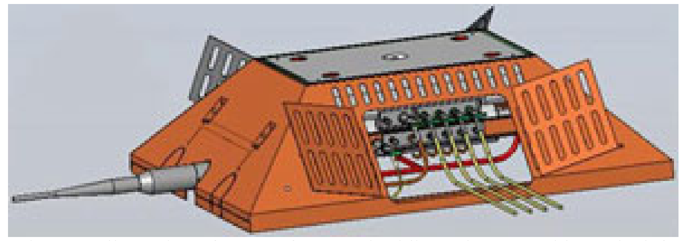

Figure 4. Illustration of MARS frame and cabling. The grey cable on the left is the main cable. The yellow cables in the midsection are instrument connectors.

III. Benthic Rover

The Benthic Rover is an important tool to help address questions about biogeochemical cycling in the ocean. Specifically, the Rover is designed to help resolve the coupling between pelagic and benthic systems by monitoring the arrival and residence of organic matter on the seafloor in spatial and temporal resolutions appropriate to the phenomenon [1]. The autonomous bottom-transecting vehicle is equipped to image the fluorescence of organic matter on the seafloor as well as measure the biogeochemical activity in the sediment community.

Much of the design of the Rover was driven by the requirement for autonomous deployments lasting up to 6 months at depths of 6000 m [1, 2]. Design trade-offs tended to favor reliable and redundant systems, power efficiency, and simple mechanisms that would be more likely to survive and remain functional over an entire deployment.

A. Mechanical Design

The mechanical design of the Benthic Rover was based around 4 main mission requirements: 1) 6 month deployments at an operating depth up to 6000 m; 2) the ability to move over soft and sticky sediment; 3) the capability of changing buoyancy by over 100 kg during recovery; 4) the ability to insert and remove respirometer chambers in and out of the sediment [2].

To meet the mission duration and depth requirement, the frame and chassis components are made of titanium and UHMW plastic. All one-atmosphere housings are made of titanium. Pressure-tolerant equipment is contained in Delrin plastic housings filled with Shell Tellus T-15 oil maintained by positive-pressure compensation systems.

The vehicle transits the seafloor on two lugged, spring-tensioned, polyurethane tracks, each measuring 46 cm wide. The tracks support the 68 kg in-water weight of the Rover over a 0.94 m^2 footprint. Two brushless propulsion motors, mounted at the rear of the chassis in oil-filled housings, rotate gear-head output shafts connected with belts to the rear 44 cm drive wheels.

Rectangular and football-shaped syntactic foam packs provide buoyancy. Before launch, the vehicle is trimmed to weigh approximately 68 kg in water while carrying a 113 kg lead weight. When the lead weight is released, the vehicle buoyancy becomes positive and the vehicle floats to the surface for recovery.

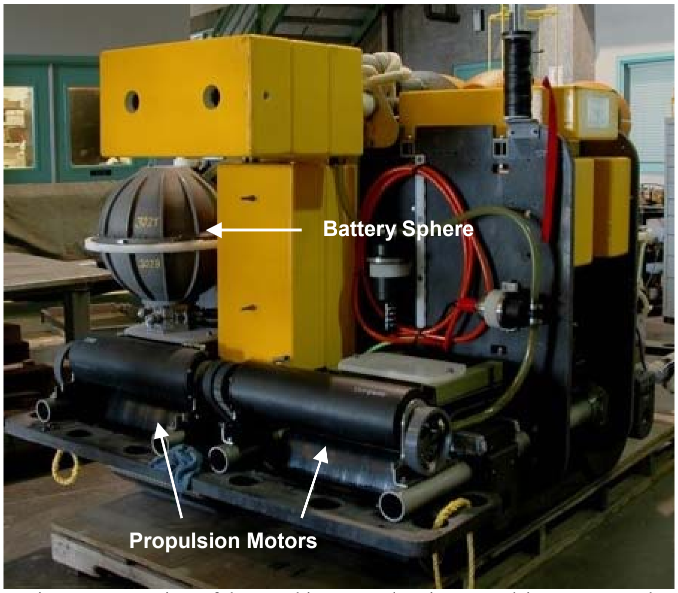

Figure 5. Rear view of the Benthic Rover showing propulsion motors and battery sphere.

Specially designed racks on the front of the Rover insert and extract two respirometer chambers used to measure sediment community activity. The chambers are attached to vertically-aligned lead screws in the racks. Using motors to turn the screws, the chambers can be lowered and raised to the desired level.

B. *Electrical Design*

The electrical design for the vehicle was driven primarily by the power budget. The Rover can carry two titanium battery spheres containing lithium primary batteries, for a total of about 20 kW-h of energy [2]. Therefore, many components were chosen based on the amount of power required to operate them.

The main vehicle computer (MVC), housed in a third titanium sphere, is built around an ARM9-based processor board from Technologic Systems, Inc. The PC/104 format card delivers adequate processing power while consuming only 2 W peak, and 0.5 W while idling. The card comes pre-loaded with a Linux 2.4-based operating system and tools for modifying the kernel as needed.

The propulsion and rack motors are controlled using small and efficient EZServo-23 controllers boards from All Motion. The MVC communicates with the controllers through an RS-485 multi-drop bus. A power management board from Tri-M Engineering is installed on the Rover to aid energy conservation. The device, called a HESC-SERD card, can cut virtually all power from the MVC for an adjustable amount of time. After that time has elapsed, power is restored, the MVC reboots, and the mission continues.

C. *Instrumentation*

The Benthic Rover carries a variety of instruments for the science mission as well as recovery and control. During autonomous, non-tethered tests and deployments, communication with the vehicle is achieved using an acoustic modem. The Benthos ATM-887 modem is used primarily to query the status of the vehicle, abort running missions, and start new missions. The modem is also equipped with a burn-wire feature used to release the 113 kg drop weight for recovery. Once on the surface, recovery is aided by an Argos satellite beacon, a VHF radio beacon, and a Xenon flasher.

The science mission of the Rover centers around measuring the sediment community oxygen consumption (SCOC) on the seafloor. The SCOC measurements are made using a pair of benthic respirometer chambers mounted on the front of the vehicle that are inserted into the sediment and sealed. Aanderraa Data Instruments model 3830 optodes are used to measure the oxygen concentration of the water inside the chambers for periods of 24 to 48 hours. A third optode is mounted outside the starboard chamber to measure the ambient water during the chamber experiments.

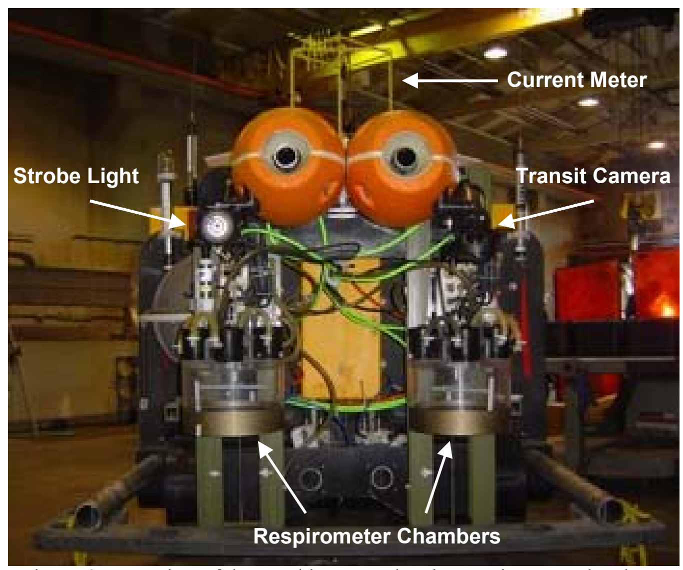

Figure 6. Front view of the Benthic Rover showing respirometer chambers, transit camera and strobe, and current meter.

Mounted on top of the Rover is a model 2D-ACM acoustic current meter with integrated magnetic compass from Falmouth Scientific, Inc. The current direction and velocity is recorded during measurements. Current information and compass data is used for navigation during seafloor transits.

A number of cameras are installed on the vehicle to capture images during a standard autonomous mission. Two Nova video cameras from Insite Pacific Inc. are used to image the sediment measurement area before, during, and after the respirometer chamber experiments. A circle of white LEDs are integrated around the camera lens to provide lighting. Images from each measurement site are analyzed after recovery for the presence of macrofauna in the sediment, and to ensure the chambers were properly sealed.

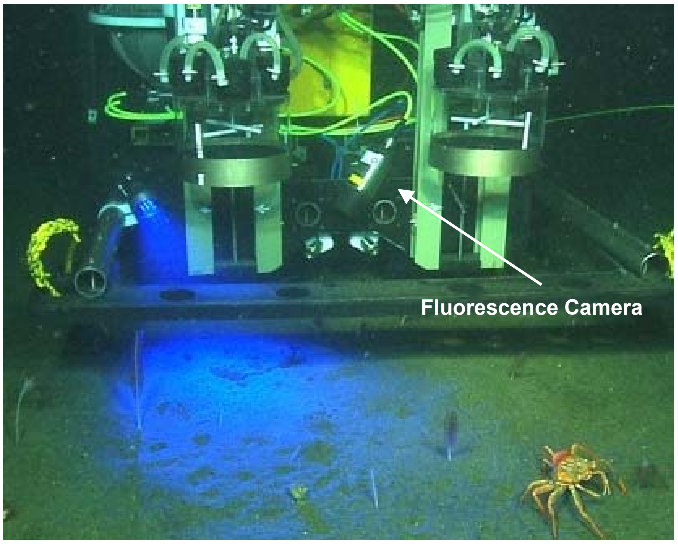

Figure 7. Front view of the Benthic Rover capturing a fluorescence image on the seafloor.

A Prosilica model GC2450 camera from Allied Vision Technologies is installed in a titanium housing and mounted high on the front of the vehicle. The camera is used to capture high-resolution color images of the seafloor during transit between measurement sites. Lighting is provided by an AquaFlash deep-sea strobe light triggered by the Prosilica camera. A second Prosilica camera, with a 675 nm low-pass filters installed, is mounted low on the front of the vehicle to map the chlorophyll fluorescence of the respirometer measurement area while exposed with a blue LED light.

D. Early Tests and Deployments

The first at-sea testing took place near the future MARS site in Monterey Bay in early 2006. The vehicle was launched by crane over the side of the R/V *Pt. Lobos*, allowed to freefall to the seafloor, and observed running propulsion motor tests using the ROV *Ventana*.

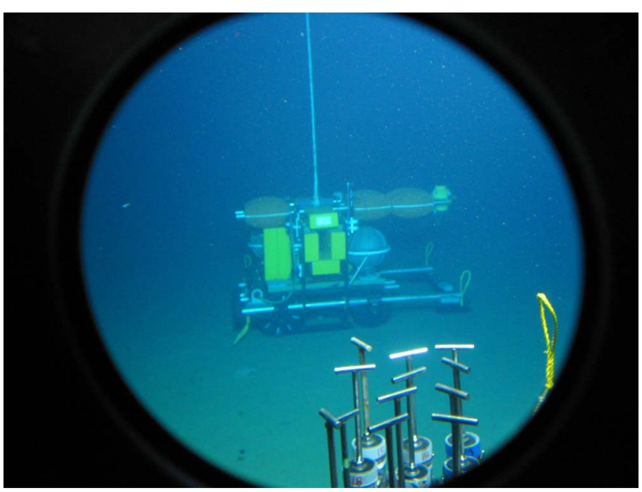

Figure 8. View of Benthic Rover from window of DSV Alvin at 4200 m

Test results lead to modifications to the track drive mechanism to eliminate interference with chassis bulkhead hardware. Improvements to the launch and recovery procedure were also made.

In the summer of 2006, the first deep-sea tests were conducted from the R/V *Atlantis* with observations made from the DSV *Alvin* at Station M 220 km west of the central California coast at a depth of 4200 meters. Test results verified the propulsion system modifications and motor control software, as well as the depth rating of the MVC and battery spheres.

The vehicle was tested again at Station M in the winter, spring, and fall of 2007 from the R/V *Western Flyer* and accompanied by the ROV *Tiburon*. Tests were conducted on the respirometer chambers to confirm modifications and improvements, control system upgrades, and camera systems.

Figure 9. Rover being launched from R/V *Pt. Lobos* in Monterey Bay

In the summer and fall of 2008, the first extended vehicle tests were carried out in the Monterey Bay off the R/V *Pt. Lobos* consisting of three separate deployments lasting between 7 and 8 days. Besides testing hardware and electronic components, one of the primary objectives of these deployments was to verify the mission control system for correct function and fault-recovery. Although quality science data was collected during each deployment, the tests exposed several weaknesses in the mission programming and control system that required major upgrades in preparation for the upcoming MARS deployments in 2009.

IV. Rover Modifications for MARS

Since the Benthic Rover was designed for long-term, untethered, autonomous deployments, several significant modifications were necessary for the vehicle to operate as a tethered vehicle on the MARS node.

A. *Benthic Rover Tether and Tether Management*

First, a suitable tether was required to support the power and data communication to the Rover as the vehicle moved about the MARS node. Researchers chose to install 300 meters of MOOS Benthic Copper cable from Falmat Technologies. The cable length necessitated a system to manage the payout as well as equipment to support Ethernet over that distance.

Rather than design a traditional cable management system on the vehicle, engineers chose to wrap the cable around a rear-mounted mandrel. A moderate adhesive held the cable securely to the aluminum mandrel, while still allowing it to unwind in a predictable manner. The simple cable system restricts the range of motion to a single direction away from the MARS node to avoid entanglement. A rearward facing Prosilica camera and blue light were used to monitor the cable during the deployment. The camera and light were remotely controlled from shore to periodically check and ensure the cable had not fouled during transit.

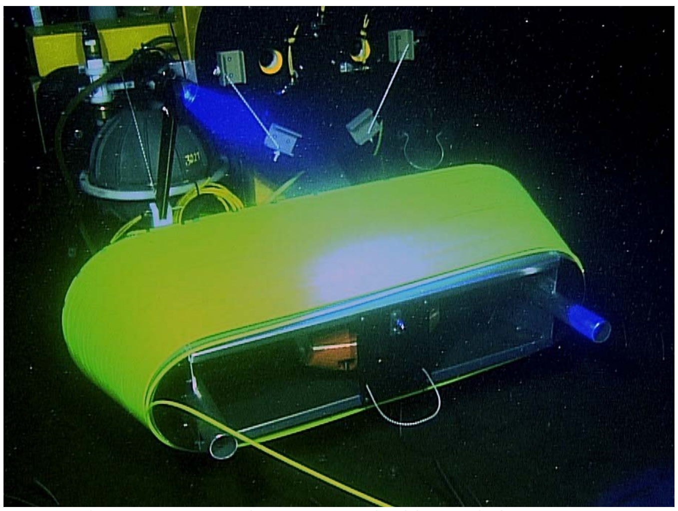

Figure 10. Rover tether camera and cable mandrel on MARS.

B. *Enabling Ethernet over the Rover Tether*

To support high-speed communications over the cable, DSL modems were installed in the battery sphere and in the SIIM near the MARS node. A SIIM is used in MARS applications to interface the power and communication capabilities of MARS to the specific requirements of instruments being tested on the facility. Since Ethernet cannot be pushed through 300 meters of cable, the modem in the SIIM can provides a communication path from the MARS network to the DSL modem on the Rover. When power is supplied to the Rover port on MARS, the DSL modems boot and establish a high-speed Ethernet connection from shore networks to the main vehicle computer on the Rover.

During early development of the Rover, a straightforward mission control script, directing a fixed sequences of tasks, was adequate for testing instruments and mechanical components [1, 2]. However, over time it became clear a more flexible mission control system design was needed in order to support the type of incremental development and test sequencing researchers required during the MARS deployment and beyond. Engineers designed a new system to retain the instrument interfaces tested over the previous deployments, but replaced the closed sequencing algorithm with an open and more transparent mission planning system.

C. *Improved Planning and Control System*

Mission plans are human readable ASCII files containing ordered lists of cohesive, single-objective elements called *behaviors*. When executed, the control program loads a desired plan file and translates the behavior elements into the known units of action. The system enables researchers to create a library of test plans of arbitrary length and order, and then arrange those into a kind of overall mission-narrative.

V. Rapid Proto-testing

The availability provided by a cabled observatory such as MARS enables an operational pace quite different from that of the normal test and deployment cruise. The researchers on the Rover team normally would begin the day reviewing science and engineering data from an overnight test experiment looking for equipment and instrument anomalies, interesting images and results, and expected outcomes. After a thorough review, the team would address equipment problems and unexpected results and conclude with a 1 or 2 day experiment plan designed to tease-out potential errors and attempt different experiment measurement strategies or altered instrument configurations.

A. *Transit Camera Setup*

Cameras can be challenging instruments to configure correctly for deep-ocean applications due primarily to the difficulty of simulating the seafloor optical environment in on-shore test facilities. The network-accessible Prosilica transit camera used on the Rover has many options available to help obtain just the right image in different environments. The MARS facility allowed the research team to readily try numerous configuration combinations and converge on a suitable setup in a single day instead of weeks or months of traditional hit-and-miss test deployments. Most of the effort involved adjusting the gain and exposure time of the cameras. Images from the camera are used to create mosaics of the seafloor transected during a deployment (Fig. 11).

B. *Stirring Duty Cycle*

A key design theme of the Benthic Rover concerns power management and optimization in order to efficiently utilize the available battery energy and maximize the duration of deployments. Close to 70 percent of a science deployment is spent gently circulating the water volume inside the respirometer chambers during measurement cycles (Fig. 12). Therefore, researchers dedicated a dozen overnight runs attempting to discover a strategy that closely approximated constant stirring while minimizing the energy required by the stir motors. Tests indicated that stratification of the water volume would begin to occur without stirring after less than 30 seconds. The optimum trade-off was determined to be at a 50 percent duty cycle with 10-second intervals.

Figure 11. Mosaic created from Rover transit images on MARS.

C. Sediment Transport

When the vehicle transits to a fresh measurement area, it is important that the amount of sediment transported by the propulsion tracks is minimized. Part of the mission profile is dedicated to detect when the ocean current is moving in a direction that can help carry disturbed sediment away from the target measurement area. Using the respirometer chamber video cameras, the research team was able to visually confirm that a significant amount of disturbed sediment is carried along during transects, and that the amount can be greatly reduced by simply waiting for favorable current conditions.

Figure 12. Rover respirometer chamber shown inserted in sediment.

D. Control System Modifications

Most of the vehicle control system and data management software was developed and tested before deployment on MARS. However, having network access to the MVC allowed engineers to fix problems discovered during tests and significantly modify the system *in-situ.* Problems that would prove "fatal" during an autonomous test could be addressed quickly and testing could resume.

One minor problem that was addressed early-on involved controlling the insertion of the respirometer chambers into the sediment. Normally, a switch is used to detect when a chamber has been inserted to the desired depth. While viewing the inserted chambers, researchers noticed one chamber was much deeper into the sediment than usual, indicating that the switch had failed. Engineers made a small modification to the motor control code to include a software limit as a backup to the hardware limit switch.

A significant development project that was completed *in-situ* was the hibernation capability that enables the vehicle to shutdown the MVC for long periods of time to save energy. As a safety measure, engineers installed a web-relay switch into the battery sphere. The relay can be triggered in case the MVC does not wake-up as scheduled.

E. Summary

When planning the Rover deployment on MARS, the MBARI team sought to take advantage of the provided uptime, accessibility, and bandwidth. The network-ready cameras and video servers on the vehicle proved to be a very valuable investment for troubleshooting problems as well as for public outreach. The flexible mission planning and control system gave researchers many different methods to acquiring data and discover subtle interactions between the equipment and the environment. And finally, a simple software development tool-chain enabled straightforward *in-situ* development and testing.

VI. Future Work

MBARI is planning the first long-term deployment of the Benthic Rover late in 2010. The vehicle will be deployed at Station M from November 2010 until May of 2011. Several modifications are currently underway.

For the respirometer measurements, a simple PIC microcontroller board is being developed to switch the stir motors on and off at 10 second intervals while the MVC is hibernating. A second reference optode will be mounted outside the respirometer chambers on the front of the vehicle for redundancy. The engineering team is also planning improvements to the control system with better fault-tolerance and recovery as the main objective.

References

[1] P.R. McGill, A.D.. Sherman, B.W. Hobson, R.G. Henthorn, A.C. Chase, K.L. Smith, Jr., "Bottom-transecting instrument platform for long-term measurements in deep benthic environments", *Oceans 2007 MTS/IEEE proceedings*, October 2007.

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