Precision Underwater Positioning for *In Situ* Laser Raman Spectrographic Applications

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Abstract- **The Monterey Bay Aquarium Research Institute (MBARI) has developed and deployed a laser Raman spectrometer system (DORISS - Deep Ocean Raman In-Situ Spectrometer) for oceanic geo-chemical measurements of sea water specimens. Quality spectra have been obtained on standards carried to the seafloor. The next stage of this development involves the ability to obtain spectra from natural targets of interest in the deep ocean and to maximize signal return from the sample. To accomplish maximum signal return the DORISS probe head must be properly positioned and focused. In addition the probe head must be held steady for several minutes while spectra are being acquired. This is in contrast to laboratory work in which the sample is precisely positioned with respect to the probe head. This requirement has been the driver for a new device, the Precision Underwater Positioning system (PUP).**

The positioning system has strict requirements for motion about the target. The DORISS requires very exact and repeatable motions with positional accuracies in the < 1 mm range over a large workspace. The device must also let the user see where they are focusing, be able to move without disturbing the base position, and to stay stable over a variety of terrains. In addition, the system must be adaptable to other vehicles. Another requirement is to return relative position from a known home position once the PUP is set in place. Moreover, the device has several operational constraints that impacted the design and operation of the system.

This paper outlines the science drivers, the operational considerations, and the engineering trades that were made to build the first two stages of the PUP. The test results of this system are also included demonstrating the device's actual performance against the specifications. In conclusion the paper outlines the next tasks and the direction the program is taking to fulfill the complete precision underwater positioning system requirements.

I. INTRODUCTION

The need for ocean chemical sensors that probe the geochemistry of solid phases in the ocean leads to increasing demands on sensor positioning. Previously, oceanographic applications for high precision motion on the order of 1 mm or less have not been treated as a general requirement. When precision of this magnitude was required with very fine resolutions, custom devices were integrated as part of the instrument and usually not as a completely independent piece of equipment. The Precision Underwater Positioner (PUP) is a different approach to solving the precision motion problem for ocean science. PUP is a stand-alone system deployable by a remotely operated vehicle (ROV) and capable of delivering precise motion to a series of devices that fit within specified limits of weight, size, and power. PUP is designed to satisfy requirements derived from several of the newest instruments under development at the Monterey Bay Aquarium Research Institute (MBARI), but one device is recognized as the main driver of the current systems being considered.

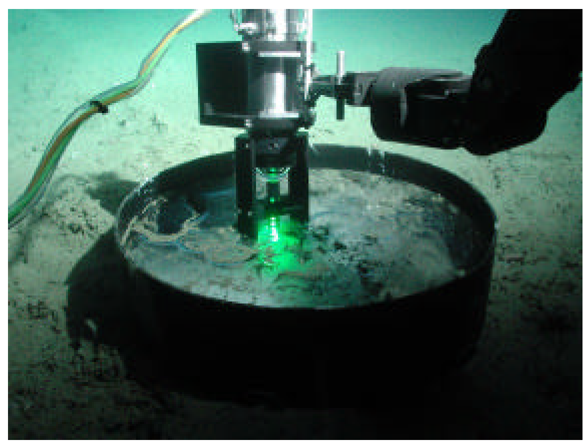

Figure 1 - DORISS Probe Head

The PUP system, although intended to address a series of instruments, has been developed under a key instrumentation program (DORISS – Deep Ocean Raman In-Situ Spectrometer) for *in situ* laser Raman spectroscopy [1], see Figure 1. Due to the small laser spot size (on the order of tens of microns) and focal depth (~0.3-3 mm) of the DORISS system, high precision movements and stability are required to collect Raman data from solid and opaque objects *in situ*. The DORISS requirements for accuracy, resolution, and repeatability are much more difficult than requirements from other intended uses, such as *in situ* microscopic cameras, and were thus the driving factors in the development of the PUP system.

II. FUNCTIONAL REQUIREMENTS

The PUP must be a ROV deployable platform that can mount a sensor head (up to 30 kg) in either a horizontal or vertical orientation, and move it with a precision of 0.1 mm within a range of 15-20 cm in each axis and hold that position for minutes. The performance specifications are listed in Table 1. Other requirements include having one external camera mounted to the sensor mount and two crossing lasers for positioning reference. External lighting is also needed.

Additionally there are general requirements the PUP system must meet such as operating in a stand-alone mode (in air or water) for in-lab use and testing. PUP must maintain stability over full range of motion on uneven ocean floor while accommodating a variety of seafloor surfaces (e.g., rocks, sediment, mud). The PUP must allow placement in any appropriate location (with the sensor head facing the target). The target must be within the operational work space of the sensor head as positioned by the ROV manipulator and the seafloor must not exceed an angular slope of 30 degrees. The PUP must also be capable of positioning the laser beam normal to some optimal plane associated with the target.

One key requirement of PUP is that it must be "user friendly" (controllable by a shipboard scientist without expert experience). This requires the user interface software to be capable of control and displaying the position feedback. Since the positioning is a fairly slow operation the PUP must also have dual speed positioning to let scientists move quickly from one target to another within the operating area. The last requirement is expansion capability to accommodate other instruments (including serial instruments) as yet undetermined.

III. CONCEPT OF OPERATION

Operating the PUP system requires a special set of conditions and capabilities from the ROV and the pilots who fly the missions. The ROV platform must have a balanced buoyancy margin to carry the system and still be capable of holding position after off-loading a large amount of in-water weight. MBARI has two ROV systems that are capable of carrying the DORISS and PUP integrated package, ROV *Tiburon* and ROV *Ventana*.

The ROV *Tibruon* is a 4000 meter rated vehicle. ROV *Tiburon* has a variable buoyancy (VB) system which enables it to offload the PUP and adjust for the in-water buoyancy change associated with that operation. The other vehicle platform, ROV *Ventana*, does not have a VB system at this time making the problem more difficult.

Minimum position travel of the beam spot	15 cm
Minimum travel increment of the beam spot	0.1 mm
Maximum time to travel full range	1 minute
Relative precision	0.1 mm
Relative accuracy	1 mm
Pan and tilt range (for either horizontal or vertical orientation)	+/-45 degrees
Maximum sensor weight allowed on mounting surface (in air)	30 kg
Maximum sensor size allowed on mounting surface	60 x 20 x 20 cm
Maximum weight of complete system (in air)	100 kg
Maximum stowed size	122 cm W x 61 cm H x 61 cm D
Input power (based on in-house ROV platforms)	240 VDC, 5 kW (Tiburon) 110 VAC, 2 kW (Ventana)
Operating depth	4000 m
Operating temperature (ambient)	0 to 50 degrees C
Operating current (water velocity)	0 to 0.5 knots

Table 1. Performance Requirements

The challenge of the operation is not only to deliver the PUP and DORISS to predetermined science coordinates, but once there to avoid perturbations while the device is in use. *Ventana* must apply thrusters to overcome the buoyancy change, yet avoid kicking up detritus that might interfere with the measurements. The system must only use the laser excitation light since vehicle lighting adds spectral lines to the Raman signals DORISS is capturing. To accomplish this task the prescribed method of operation is to place the PUP in position and move the ROV *Ventana* down current. Once the vehicle has let out the PUP tether and the pilot gets the vehicle in position, the imaging sonar is used to see the PUP. The PUP camera and crossing lasers are used to perform the final positioning of the system while the pilot monitors the available aids for relative position. The PUP lighting aids are turned off, the pilot uses the cameras and acoustic images to hold the ROV *Ventana* in position, and spectra are acquired with the DORISS system. MBARI ROVs do have limited but reliable automated positioning systems available, but the pilot must be constantly aware of any changes in current that might disturb the PUP, its tether, or kick up sediments into the sampling area.

IV. SYSTEM SPECIFICATION

The final design of the PUP system was accomplished through a series of trade studies. Several platform concepts were considered, including pure Cartesian systems and 6 degree of freedom Stewart platforms. Once the functional specifications and the use scenarios were completely worked out it became clear an X-Y-Z positioning method alone would not yield the versatility needed for the various instruments PUP is expected to carry. It also became apparent that systems like the Stewart platform had limitations of size and weight to meet the working envelope specifications. A compromise of various system elements eventually proved to be the answer.

Deployment of the system from MBARI's ROVs is necessary for placing the PUP & DORISS system near a target measurement site. The use of the ROV vehicle places a restriction on the overall system weight, the in water weight of the system and the deployed package size.

The final PUP design is a 5 degree of freedom (5 DOF) mechanical positioning stage for *in situ* instruments is shown in Figure 2. Gross planar positioning is provided by the ROV since the requirements call for them to be within a 15 cm by 15 cm working area.

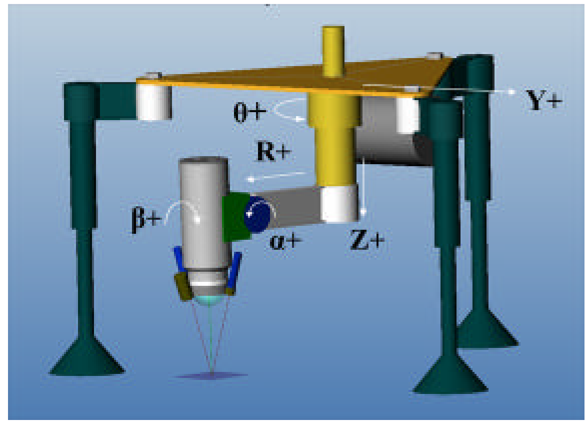

Figure 2 - PUP 5 DOF Concept

The electrical architecture of the PUP is designed around keeping the bottom side complexity as simple as possible, minimizing umbilical complexity, and long sensitive cable runs. To support this design, motion control was designed as close as possible to the motors in an effort to decrease the number and length of sensitive control cables. This also enables a much simpler umbilical from the ROV to the PUP, consisting of only communications and power. The main factors in the design selection process are the following:

1. Stand alone operation
2. OEM parts with no packaging
3. Ethernet interface
4. 8 axis control
5. Analog input
6. Digital IO
7. MBARI knowledge
8. Quadrature encoder inputs

The software specification for PUP has a number of objectives in mind. The primary objective is to control the motion of the instrument and place it in a specific position with the required precision. Secondly, the software design must accommodate iterative development as the platform evolves from 2 degrees of freedom to the planned 5 degrees of freedom. Additionally, the design has to be a relatively simple one and a proven design with a high-level of code reuse. Finally, the design of the user interface software must emphasize simplicity and easy access to the most important features for the science users.

V. SYSTEM BUILD

Early trade studies of motion components to meet the system specifications resulted in the selection of Exlar™ electric linear actuators. These were then modified for deep-water operations. The contact area for the selected roller screw design is larger than comparable ball screw units which deliver longer life and the ability to handle heavier loads. These actuators can also move at higher speeds. The functional requirements defined a horizontal axis to drive the DORISS probe head parallel to the seafloor. This required the addition of structural ways to accommodate side loading the linear actuator will see during normal operations. The ways are made from stainless steel and run in Delrin polymer mounted to the actuator housing.

There are two weight requirements driving the PUP system design. The first is an "in-air" maximum weight restriction limit of 100 kg. The second is the "in-water" weight restriction that is determined by the ROV payload carrying capacity. The package size is controlled by the open volume of the structural support area in front of the vehicle, and the deployment capability of the robotic arm.

The PUP pressure housing contains the power and communications interfaces to the ROV. In addition the pressure housing also accommodates the PUP electronics. The electronics components include the power amplifier, servo controls, environmental sensors, tilt sensors, and camera interface. The final selection for the main pressure housing is a borosilicate glass instrument housing manufactured by Benthos. The housing easily meets the depth requirements and it meets the weight restrictions, weighing in at 39 lbs. in air.

The use of an oil compensation system for the actuators eliminated the need for large structural housings and therefore reduced weight significantly. The compensator spring force introduces approximately 6 to 10 psi of pressure over ambient, insuring any leakage will move external to the housing and no water will ingress into the system. Because the system is filled with oil a resolver, rather than an optical encoder, is used for control feedback.

To keep the architecture complexity in line with the design, a Galil™ motion controller is used as the main interface and controller for the remote portion of the PUP. With the purchase of an AMC Digiflex™ servo drive a complete amplifier/feedback loop has been built. The Digiflex™ amplifier incorporates a resolver drive and input circuit, that is used as the commutation feedback to the amplifier, and therefore generates virtual quadrature encoder pulses for the motion control. Using a resolver in the commutation feedback loop has the added advantage of sinusoidal commutation to smooth torque ripple in the actuators.

To allow for remote viewing of the probe head placement, a camera system has been incorporated in the design. With the original design specification of minimizing the umbilical complexity, using standard video as the primary path back adds more conductors and is not an attractive solution. However, since not many deep-sea network enabled cameras are available, a small four-channel video web server has been implemented. This allows command and control along with video to be passed over the same Ethernet communications link, keeping the umbilical simple.

Two other issues involve remote lighting and probe focal point location. The first problem has been resolved with the use of a 100 Watt incandescent light. The light is easily secured during DORISS sampling when ambient light is required to be a minimum. Locating focal point of the DORISS is accomplished with two crossing lasers as a rough indicator to get the system close prior to fine adjustment.

To monitor the internal health of the system an environmental monitor has been developed. This system includes the following sensors:

1. Water Sensor
2. Absolute Pressure
3. Temperature
4. 2 axis Tilt
5. Relative Humidity

The tilt sensor allows the monitoring of the attitude of the PUP on the seafloor. This also allows the pilot to ensure stability and provides an indication if the PUP is sinking into the bottom. The absolute pressure and water sensors allow monitoring of leaks on deck during closing procedures or initial entry into the water. The humidity sensor assists with the possibility of a slow leak where the water sensor is not tripped but ever increasing humidity is detected. Ambient temperature monitoring indicates the electronics temperature. On deck the system dissipates 50 watts through the glass without surrounding seawater and this imposes a limited power on time in air.

Early on, the PUP team decided to reuse a software design and code framework from the Environmental Sample Processor (ESP)[2], a successful MBARI project with similar precision motion control requirements. The software was developed using object-oriented techniques and implemented in C++, using Microsoft's Visual Studio. More importantly, the code has been tested and in use for a number of years, providing a capable and reliable foundation for the PUP software to build upon.

The PUP framework includes a number of core C++ classes intended to work within a variety of applications. The code implementing these classes has been re-used and virtually unchanged for the PUP project. Reusing the code from ESP allowed the project team to focus on the particular motion and control requirements of the PUP, saving significant software development hours.

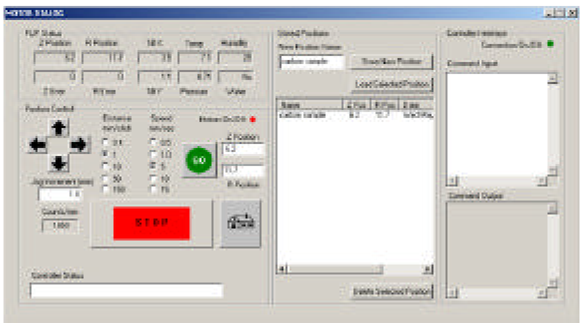

Figure 3 - PUP GUI

Often in oceanographic applications, user interfaces are designed for a small set of users that become experts in making the best use of the features in that application. Conversely, the PUP graphical user interface (GUI) has been designed to be used by the occasional science user. As a result, the real-time information from the PUP is always in view and the motion control features are displayed at all times, shown in Figure 3.

The updated position and environmental data from the PUP onboard controller is displayed in the PUP Status area of the GUI. The data is continuously updated by the interface software, providing the scientist with the available environmental data. The Position Control section of the GUI allows the user to place the PUP in a desired location within the control plane. The controls are divided into two modes: incremental positioning and direct positioning. The Stored Position, located in the middle of the GUI, is useful for logging interesting locations and later returning to that location. Finally, the Motion Control dialog provides a command line interface to the onboard controller on the right side of the GUI.

VI. SYSTEM TESTING

Preliminary tests were performed on the two-axis PUP instrument to characterize the functionality of the system (Figure 4). Limited test tank availability constrained these initial tests to be simple boundary conditions in-air and in-water. As a result, first round tests were designed to quickly determine whether the system met the relative precision and basic functional requirements for the project. Specific elements investigated in these tests included actuator positioning precision/repeatability (0.1 mm. / 1 mm., respectively) for both the horizontal (R) and vertical (Z) axes and axis arm deflection measurements under load.

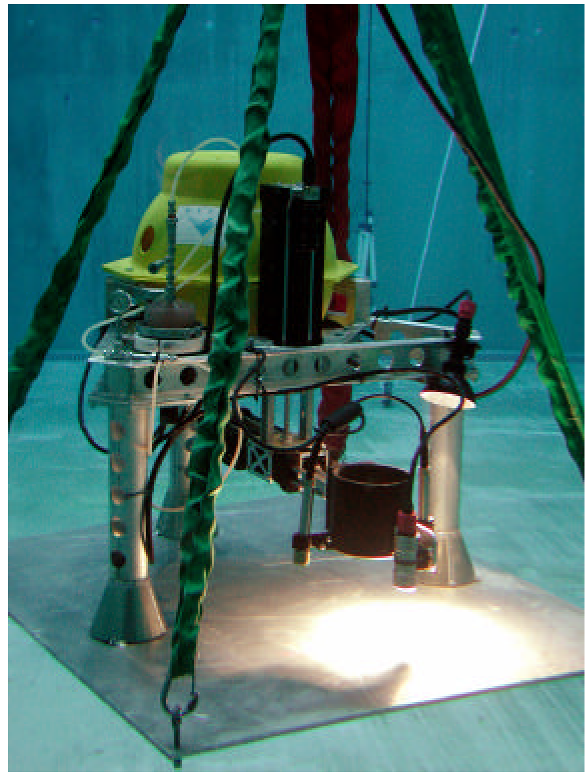

Figure 4 - PUP Assembly in Test Tank

Actuator tests were performed to determine performance of the system when commanded to move a small amount along both axes. Small, 0.001 inch (0.025 mm) incremental commands were input to the controller and actual movement (mm.) was then measured with a dial indicator. All measurements fell well within the error of the dial indicator, thus exceeding the 0.1 mm. requirement. More over, the range of extension for both the R and Z-axis actuators was determined to be 20 cm overall, with 15 cm being the “set maximum” for testing purposes thus this also met project requirements.

Extension tests of the slide mechanisms were designed to determine single axis deflection under various loads. The load tests were conducted for 1-cm extensions of the slide mechanism up to 15 cm along the R axis. The loads were increased by 4.6 kg (10 lb.) increments starting at 11.3 kg. (25 lbs.) up to 20.4 kg. (45 lbs.). The results showed that for a 20.4 kg. load the deflection of the R axis slide mechanism was 0.11 mm., which is extremely close to the required value of 0.1 mm. These results indicate that a load under 11.3 kg. (e.g., DORISS probe head) would be within the allowable deflection error for each axis on the PUP system.

Integrated axis deflection measurements were taken in both air and water for the system with a load of 9.2 kg. (in-air weight; the equivalent to the in-water weight of the DORISS probe head). Deflection tests involved extending the R axis in 1-cm increments from 0 to 15 cm while holding the Z- axis either at a position of "no extension" or "full extension". The tests indicate a 0.36 mm. increase in deflection of the system with both axes at full extension (heaviest load point; HLP) versus just R fully extended. At the HLP, the deflection along the R axis in water was 0.483 mm while in air it was 1.575 mm resulting in a difference of 1.092 mm. This offset is due to buoyancy effects and the load deflection trends observed during in air testing. Since buoyancy slightly influenced the test equipment all water test data was normalized. It should be noted that although the in-water integrated deflection values are not system requirements, the deflection is relatively linear (R^2 = 0.87) and can thus be characterized. Therefore, it is believed that the actuator can move in fine enough increments to compensate for deflection effects.

Repetitive motion tests were performed to determine whether the PUP instrument met the required relative system precision. Overall, local (<1 cm.) increments along a particular axis were determined to be precise to within +/- 0.02 mm., which was well within the 0.1 mm. requirement for the system. During these tests, however, it was discovered that reversing the system motion along the Z-axis tended to produce an initial backlash of 0.013 mm. This error is not highly significant but will require further testing to ascertain its source.

VII. CONCLUSIONS

Precision positioning within a relative area of operation is necessary to obtain quality Raman spectra from solid and opaque targets on the seafloor. The PUP positioning system is the first attempt to meet the positioning requirements of obtaining Raman spectra and the DORISS system. PUP holds the probe head in position, in focus, and allows relative motions (scanning) on the sea floor. PUP also meets the requirements of a number of other new analyses tools and techniques from the science user community.

The PUP system has met the science requirements of positional control to sub-millimeter accuracy for relative motions. Testing has indicated that PUP is capable of much higher accuracy and repeatability than requested. New test plans are being developed to accurately confirm the resolution and repeatability limitations of PUP. The repeatability is of particular interest to MBARI science since characterization that can be trusted would allow for more advanced automation and features in the system.

Although the full-up PUP system is not complete due to resource constraints for the 2003 project year, the 2004 project year will complete the PUP. The PUP system currently has tilt sensing, video feedback, crossing lasers for visual feedback, remote lighting, and 2 of the 5 axes along with the supporting electronics for all axes. The PUP software is easily extensible to include the new features. Mechanical design and component builds are the next phase of the program. The completion of the other 3 axes and the addition of functional legs that allow operations on the specified slopes will occur in 2004. PUP will also be deployed with DORISS in August of 2003 in deep ocean field trials.

Overall the Precision Underwater Positioning system has met or exceeded the goals for 2003. Based on early test results PUP will meet the complete set of requirements from the science users at MBARI.

ACKNOWLEDGMENTS

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