Development of an Active, Large Volume, Discrete Seawater Sampler for Autonomous Underwater Vehicles

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***Abstract*- Engineers and researchers at the Monterey Bay Aquarium Research Institute (MBARI) have developed a water sampler that rapidly captures a 2-liter sample of seawater. This syringe-like sampler is spring actuated and can acquire a full sample in less than two seconds. This sampler will complement the wide array of sensors currently integrated on MBARI's autonomous underwater vehicles (AUVs). Although many properties of seawater can be analyzed by AUV onboard sensors, these measurements alone are often insufficient to fully investigate important scientific questions. Returning a discrete sample of seawater from the field, via an AUV, for laboratory analysis will expand the spectrum of research possible with AUV platforms. Using AUV onboard intelligence, designated sites and important phenomena can be targeted for acquiring water samples. This paper addresses the development, testing, and initial deployments of this sampler.**

I. INTRODUCTION

This paper presents the development of a new water sampler for 21" science class AUVs. The operational capabilities of AUVs are rapidly expanding, so that unattended surveys of physical, chemical, and optical oceanographic properties may be conducted across large ranges. While our ability to gather high-resolution data increases, we are still dependent on ship-based operations to collect the samples necessary to ground-truth our instruments and to distinguish the species contributing to biological layers we detect. Many applications require a sample of water for analysis. Some of these applications include: plankton and larval ecology, harmful algal bloom (HAB) detection, and sediment transport/carbon flux investigations. The AUV is already capable of triggering control behaviors based on real-time sensor readings, for example oscillating vertically between temperature or density surfaces. Using AUV onboard intelligence, important phenomena can be targeted for experiments requiring water samples. The AUV Gulper, a new payload developed at the Monterey Bay Aquarium Research Institute (MBARI), is designed to rapidly acquire multiple large-volume water samples aboard the AUV.

II. DESIGN REQUIREMENTS

In the first phase of development, the project team, consisting of engineers and scientists, defined a set of functional requirements for the water sampling system. The team decided on a sample volume of 2 liters, which would be large enough to adequately sample sparse microbial populations. Large sample volumes also enable multiple science users to share a single sample. An additional requirement was to sample around and within thin layers of phytoplankton. To accurately sample thin layers, the sampler must acquire a single sample rapidly (in less than 4 seconds) and be able to collect multiple samples in quick succession (3 samples over 10 vertical meters, with less than 6 seconds between sample acquisitions). Due to the large volume and fast acquisition time, the sampler was aptly named the AUV Gulper.

Further requirements included that the sample must be acquired with no ballast change to the vehicle and the sampling system must fit within the available space in MBARI's existing AUV. To meet this requirement we settled on a system comprised of 10 discrete samplers. Although the AUV typically dives to depths of 300 m, each sampler has been pressure-rated to 1500 m to allow their use on other vehicles in addition to the AUV.

The users requested a transparent sampler body because scientists investigating plankton and bioluminescence need to view a sample before it is exposed to the atmosphere. Finally, researchers investigating the iron content of seawater established a requirement that no stainless steel or acrylic parts contact the sample.

III. DESIGN ELEMENTS

A. Concept

The Gulper sampler functions like a syringe—a piston within a cylinder (Fig. 1). The 2-liter sample is drawn into the cylindrical sampler body through a one-way valve from outside the vehicle fairing. The water occupying the volume behind the piston is expelled through outlets in the rear end cap of the sampler and exits the vehicle through vents in the vehicle body. Energy stored in springs drives the piston stroke. This results in low energy consumption and assures rapid sample acquisition. Ten of these 2-liter samplers are configured within the mid-body section of MBARI's Dorado-class AUV. The dimensions and shape of the sampler were driven by the available space within the AUV mid-body, 52 cm in diameter and 108 cm in length. This resulted in a sampler cylinder with an inside diameter of 12.7 cm with a .64 cm wall thickness. The length of the sampler body is 20.32 cm. A compensating

0-933957-35-1

diaphragm allows the samples to be taken at depths up to 1500 meters.

B. Rev 1.0

Although a spring-loaded syringe is simple in concept, executing this design proved to be difficult. Due to the rather large cylinder diameter (12.7 cm), not many seal types were available to seal between the piston and the sampler body. At this phase in the development, two seal systems were identified and tested. The first seal configuration was a standard loaded lip seal (PolyPak), and the second was a quad O-ring. The PolyPak sealed well, with minimal drag forces (< 7 kg). However, given the large stack height of the piston and seals (27 mm), a significant portion of the sample size was lost. This seal also required extremely tight tolerances between the cylinder body and the piston. The quad O-ring provided an excellent seal, but with much higher drag forces (>9 kg). The stack height of the piston with the quad O-ring was less than 12 mm, and there was considerably more compliance in the cylinder/piston fit. It became apparent that to meet the requirement of a 2-liter sample size, the quad O-rings were the right choice. However, there was still the problem of overcoming the higher drag forces associated with the quad O-ring.

The original sampler concept was configured with a single compression spring mounted on the guide shaft (Fig. 1). Although this design proved functional, a single spring of a reasonable size could not generate sufficient force to overcome the drag force of the quad O-ring with the necessary reliability. Switching to a more robust spring would increase the size of the spring wire and thus the solid length of the spring. This affected the overall length of the sampler, since the length was constrained by the vehicle diameter, and became a factor limiting sample size.

C. Rev 1.1

The issue of insufficient force to drive the piston was eventually solved by redesigning the spring assembly. The single-compression spring located on the outside of the sampler body was replaced with two extension springs mounted in tandem on either side of the guide rod (Fig. 2, Fig. 3). The springs were mounted directly to the piston and were anchored to a bridge assembly on the rear end cap. These two springs generated at least 18 kg of force, cycling the piston reliably with a fill time of under 2 seconds. In mounting the springs directly to the piston, the loaded spring can now be stored inside the sampler body as opposed to the outside. This decreased the overall length of the sampler, thus achieving the goal of a full 2-liter sample, and still fit well within the 52 cm vehicle diameter. The only penalties associated with this design were an increased part count and a slightly higher weight, both of which were deemed acceptable.

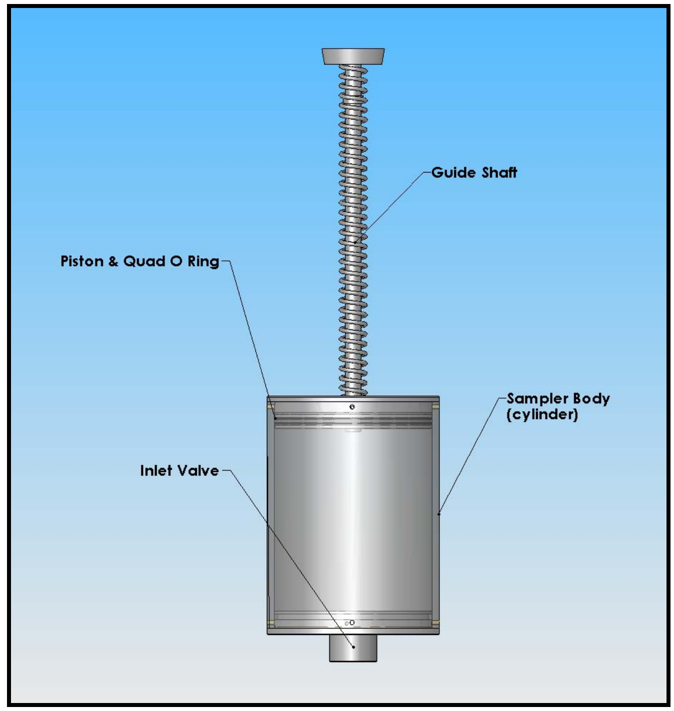

Figure 1. Rev 1.0 of Gulper sampler: The compression spring is mounted on the exterior of sampler. The sampler is in open, un-armed position.

D. One way inlet valve

The one-way inlet valve was required to allow a seawater sample to be drawn into the sampler body and then dependably seal. A simple spring loaded plunger mechanism was designed to accomplish this function. All valve parts were commercially pure titanium. It was necessary to employ the minimum spring force required to adequately close and seal the valve, as this force worked in direct opposition to the springs cycling the piston. A custom spring of titanium 6al4v, with < 1 kg of force, was manufactured for this purpose.

E. Pressure Compensation

Each sampler must be pressure compensated because a typical AUV run involves up to 70 yo-yos, a flight pattern during which the vehicle dives to a fixed depth and then resurfaces. This is a different sampling regime than encountered when doing routine water sampling off a surface ship with Niskin bottles and a rosette. With Niskin bottles, the sample is collected at depth and brought to the surface, so compensation is only needed in one direction (the sample is always at higher pressure than the external seawater.) This pressure imbalance can be easily compensated for with a one-way valve. However, the Gulpers need to compensate for both when the internal (sample) pressure is greater than the external pressure (as with the Niskin example) and when the external pressure is greater than the internal (sample) pressure.

The pressure compensation of the sampler was accomplished with a diaphragm 22.3 mm in diameter. The material is a low durometer (20) silicon rubber 1.6 mm thick. The diaphragm is mounted on the inside of the front end cap.

When a sample is taken at depth, the diaphragm expands outward to allow depressurization as the sample is brought to the surface. For samples taken near the surface, followed by a descent behavior, the diaphragm must expand inward with a lower constant than the spring in the one-way inlet valve. This prevents seawater at depth from being forced into the sampler, contaminating the sample. Compliance in the diaphragm prevents pumping and assures a discrete sampling even when the vehicle's mission calls for a series of depth changes.

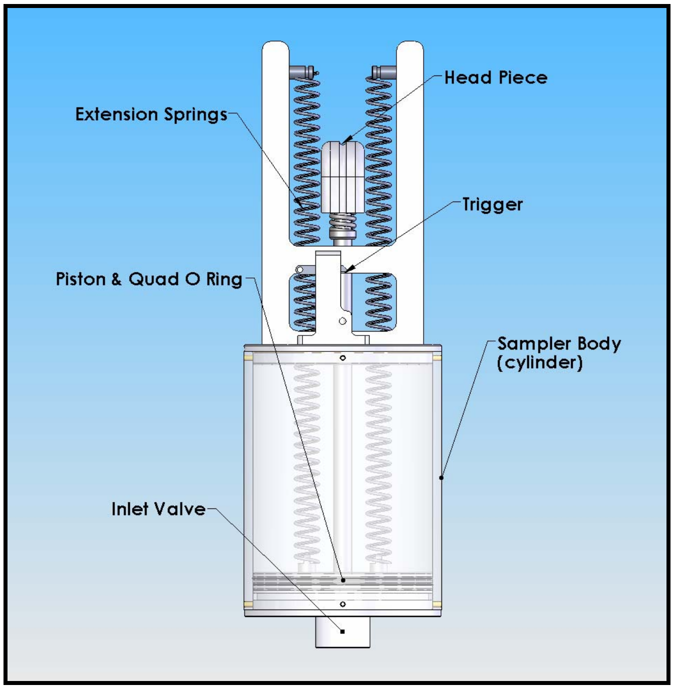

Figure 2. Rev 1.1 of Gulper sampler. Extension springs are mounted on interior of the sampler. The trigger cable passes over the head piece engaging the trigger. The sampler is closed, in armed position.

F. Triggering

To minimize entrained water from other than the sample site, the design was modified to ensure the piston bottom out against the front end cap. The manufacture of precision parts to accomplish this would prove difficult and unreliable. To address this requirement, a spring-loaded head piece is located on the outer end of the guide rod. This head piece contains a robust die spring with a higher constant than the two extension springs at full extension. As the piston bottoms out against the end cap, the die spring in the head piece is compressed. A trigger cable passes over the head piece engaging the trigger (Fig. 3). The piston is now set, (spring loaded), against the end cap. A small detent (.18 mm) in the trigger assures the sampler will not misfired, but does release dependably with 3.7 kg of pull. For initial testing the samplers were triggered either manually with the ROV manipulator or by a submersible solenoid on the AUV.

Figure 3. Rev 1.1 Prototype of Gulper sampler. Two extension springs drive the piston. The trigger cable passes over the head piece engaging the trigger. The sampler is open in unarmed position.

IV. MANUFACTURE

The manufacture of the majority of the individual parts was routine. However, the cylinder body offered a particular challenge for several reasons. The material chosen for the cylinder was polycarbonate; unfortunately precision bore polycarbonate tubing was not available. This required oversized stock to be machined to precise dimensions, which further required the development of tooling dedicated for this purpose (Fig. 4). Further, the bore dimension was unknown. Certainly a number of sources offer the proper sizing for typical quad O-ring applications, but these sizes are based on high-pressure applications and assume the piston is driven by hydraulics or pneumatics or are mechanically actuated. In the Gulper sampler application, all that is required is a reliable seal, with only a negligible pressure differential. Also, the piston is driven only by a modest spring that can easily and safely be armed by operations or science personnel. The development procedure was to machine a staged set of cylinder blanks at incremental sizes above and below the theoretical dimension. These blanks were then chemically vapor polished using Trichloroethylene to restore the clarity and finish required for this application (Fig. 4). The staged sets of cylinder blanks were tested to check for sealing and drag forces. Results of these tests yielded the dimensions for a functional sampler.

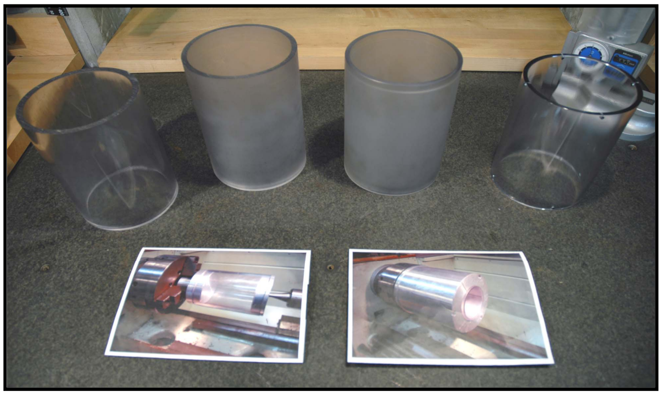

Figure 4. The Gulper sampler cylinders and dedicated tooling. Polycarbonate tubing has been machined and TCE vapor polished smooth and clear. The cylinders, from left to right, show the progressive stages in this process.

V. INTEGRATION WITH AUV

Ten of the Gulper samplers are configured diagonally within the mid-body section of MBARI's Dorado-class vehicle (Fig. 5). The samplers are arranged at an angle of 120 degrees opposed to each other, 60 degrees off the vertical in a V-10 assembly. The overall length of the sampler is 50 cm, which allows for a comfortable fit within the 52 cm diameter mid-body. Each sampler is mounted in a cradle with a retaining strap that securely holds it in place. The samplers protrude through very precise holes in the vehicle fairing; this assures the sample is drawn from outside the vehicle.

VI. TESTING AND PRELIMINARY RESULTS

Extensive testing took place in MBARI's 1.5-million-liter (400,000 gallon) test tank. Field testing was accomplished by triggering the prototypes aboard MBARI's remotely operated vehicle (ROV) *Ventana* (Fig. 6). This provided video footage of each test and allowed for comparisons between different seal, valve, and spring configurations. For ROV dives, samplers were triggered manually with the manipulator arm. The fill time of the sampler was measured by reviewing the video. With our double-spring sampler, design the fill time was consistently less than two seconds, well within the system requirements.

Testing of a single sampler aboard the Institute's AUV was conducted to assure the sampler would not leak or pump water during repeated pressure cycling. To verify that the pressure compensation diaphragm was effective, we filled a sampler with deionized water and sent it out on a 15-hour AUV mission, which included over 70 yo-yos to a depth of 100 m. Upon completion of the mission, the salinity of the water in the sampler was measured using a salinometer. The two sub-samples taken had an average salinity of 0.0372 ±0.007 PSU. This very small amount of salt is most likely due to salt water on the exterior of the one-way valve encountered during the sample extraction.

ROV tests were also used to validate that the Gulper was collecting the expected water mass (i.e. not misfiring or sticking while filling). The salinity of the seawater collected by the Gulper sampler was compared to measurements from a CTD mounted on the ROV and the salinity of seawater collected concurrently with a Niskin bottle. Samples collected in the Niskin bottle and the Gulper sampler were sub-sampled, and the salinity was measured using a salinometer. The Gulper water mean salinity was 34.1325 ± 0.000 PSU, and the Niskin water mean salinity was 34.1354 ± 0.001 PSU. The on-board CTD (Seabird SBE19Plus) measured 34.122 PSU. The tight correlation between the Niskin bottle, the CTD, and the Gulper provided reassurance that there was not leaking or misfiring.

We have begun validation tests using multiple samplers on the AUV, and we will compare the salinity of these captured samples to the salinity measured with the two CTDs in the nose of the vehicle.

Figure 5. Dorado-class mid-body section with one Gulper sampler set in place. Samplers are secured in the individual stations with retaining straps.

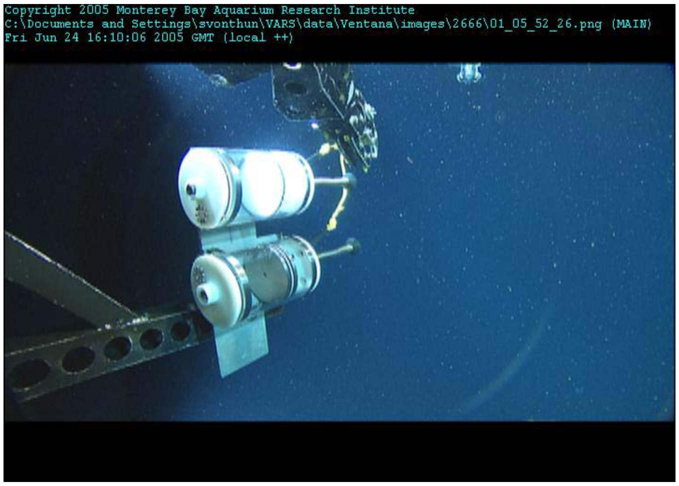

Figure 6. Gulper samplers were regularly tested on MBARI's ROV *Ventana*. Different seal, valve, and spring designs could be easily tested and evaluated.

VII. Conclusion

Several successful engineering missions have taken place with the full complement of 10 samplers. The validation of the water samples collected is ongoing. Science missions are scheduled for early fall 2007. MBARI researchers are hopeful that coupling rapid, large-volume water sampling with the autonomy of an AUV will provide a better observational platform for diverse research areas in oceanography.

Acknowledgment

This project was funded by the David and Lucile Packard Foundation through MBARI project number 900403, AUV Gulper. Special thanks go to the Gulper project team: Farley Shane, Brian Kieft, Andy Hamilton, Chris Scholin, Steve Haddock, Joe Jones, and Bob Vrijenhoek. Additionally we would like to thank Hans Thomas, Duane Thompson, and Douglas Conlin of MBARI's Marine Operations AUV Team for aiding in the development, integration, and testing of this system.