Design of a gas tight water sampler for AUV operations

Chris Roman
University of Rhode Island
Graduate School of Oceanography
Narragansett, RI, USA
cnr@gso.uri.edu

Richard Camilli
Department of Applied Ocean Physics and Engineering
Woods Hole Oceanographic Institution
Woods Hole, MA, USA
rcamilli@whoi.edu

***Abstract*— This paper presents the design and preliminary test results for a small gas tight water sampler intended to work on scientific AUVs. In recent years AUVs have developed into reliable platforms capable of carrying a wide variety of environmental sensors for in-situ chemical measurements. Physical sample collection however remains difficult, due to the combination of space, power and complexity constraints inherent in working with autonomous platforms. The AUV sampler is a small (12 cm x 85 cm) cylindrical package designed to collect eight 20 ml gas tight volumes of water, with each sample maintained at high pressure to depths of 2000 meters. The motivation behind this device is to provide high quality autonomous water sample collection and return for accurate analysis of dissolved chemicals without degassing. Additionally the system can be used to ground truth in-situ chemical measurements**

***Index Terms*— water sampling, water chemistry, AUV**

I. Introduction

Reliable sample collection from Autonomous Underwater Vehicles (AUVs) represents a new advancement that will offer increased scientific utility. A wide variety of in-situ chemical sensors can be carried by AUVs and used to characterize various environments with high spatial resolution. As in-situ chemical measurements become more sophisticated, water samples will become important to provide ground truth for the real-time measurements. Currently, water sampling is primarily done from hydrocasts on a ship's wire that has limited position accuracy or with complex samplers than require manipulation to operate and need to be used with Remotely Operated Vehicles (ROVs). Only a small subset of these samplers offer gas tight samples [1] [2]. Bringing water from depth to the surface can release dissolved gases from the water and make quantitative measurement of the actual in-situ gas concentrations difficult and unreliable.

The limitations of the existing gas tight samplers have motivated the design of a new small multi-chamber sampler that can be used on an AUV, carrying a suite of environmental sensors. The diagram in figure 1 shows how the water sampler will be used with a set of chemical sensors. The arrangement allows for samples to be taken after any of the in-line sensors have analyzed the water parcel and detected an "interesting" event. The eight 20 ml sample volumes provide enough fluid to perform most standard laboratory analyses. This new sampler is a self contained instrument controlled through a serial interface and requires no physical manipulation.

This paper outlines the major design criteria for the sampler in section II. Section III presents the mechanical and electrical components of the sampler. The operational steps for sample collection and extraction are also outlined. Test results presented in section IV show the amount of cross contamination between samples as a function of the valve and pump timing.

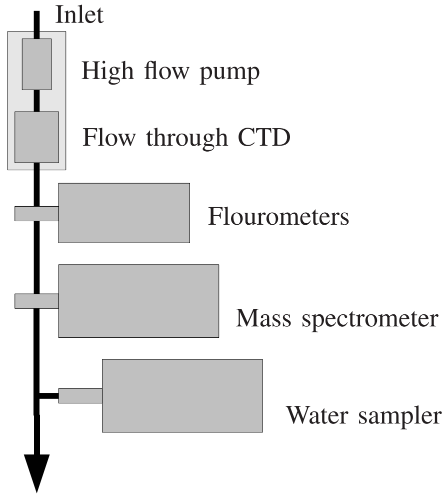


Fig. 1. Overall chemical sensing system. The AUV water sampler fits into a system of chemical sensors and will take physical samples to ground truth the in-situ measurements. A high flow pump will flow water continuously through a CTD, flourometer package, mass spectrometer and to the inlet of the water sampler. When a sample is taken an internal high pressure pump in the water sampler will turn on briefly.

II. Design Objectives

The design of the water sampler followed from the following list of objectives that dictate both its own internal operation and its use in conjunction with additional sensing systems.

- **Size:** The total size of the sampler should be small enough to make it portable for typical AUVs and ROVs.
- **Power:** The standby power should be minimized to make the sampler appropriate for AUV use. Any higher power draw for pumping should be required for a short time only.

- **Re-sampling:** The sample chambers should be reusable during a single deployment. Contamination from the previous sample should be minimized.
- **Pressure:** The depth rating of 2000 meters allows coverage of coastal regions and several know seafloor vent sites while minimizing weight and size.
- **Interface:** A simple serial interface should operate the sampler.
- **Speed:** Samples should be taken quickly, on the order of seconds, to maximized spatial resolution when using a moving vehicle.

III. Design

The design description for the sampler is broken down to cover the mechanical, electrical and operational aspects in the following sections.

A. Mechanical

The sampler is built around a central titanium billet bored to include eight cylinders and an electronics cavity. In each cylinder a sliding piston is used to divide the cylinder into a sample side and a pump out side. Each cylinder is 4.5 inches long and 0.625 inches in diameter. The pistons are 0.75 inches long and have 2 radial o-rings each to create a sliding seal. An internal pump and plumbing system routes fluid into the cylinders from each end. At each end the cylinders are capped by plates acting as cylinder heads and held on by high strength bolts. Each individual cylinder is sealed against the plates with o-rings at each end. On one side of the billet an aluminum bell shaped housing is used to create a one atmosphere volume to house electronics and a 5000 psi high pressure Vici Valco multiport valve [1]. On the other side of the billet a plastic housing is used to create a fluid compensated volume which contains a brushless motor, peristaltic pump and two solenoid valves. A sketch of these pieces is shown in figure 2.

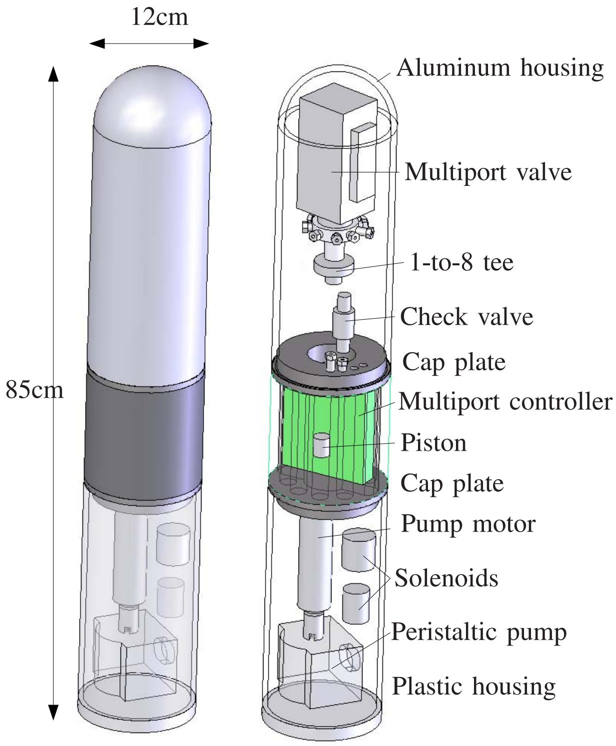
The overall length of the sampler is 85 cm and the diameter is 12 cm. The central billet and cap plates are made from grade 4 titanium for low corrosion, chemical inertness and high strength. The complete sampler weights approximately 27 lbs in air and 5 lbs in water.

The internal plumbing of the sampler is diagramed in figure 3. The low pressure fluid compensated side of of the sampler contains mostly 1/8 inch plastic Tygon plumbing. In operation this plumbing will see approximately 40 psi generated by the Masterflex peristalitc pump and relief valve. A peristaltic pump was chosen to eliminate possible mixing of the seawater samples and the pressure compensation fluid. The pump produces 1.8 ml per revolution and is run between 200 and 300 rpm. Fluid from the pump is filtered prior to entering the sampler to avoid damage to the downstream valves. The two solenoid valves are configured to allow several different flow paths. The high pressure side of the sampler in the one atmosphere housing is plumbed with 1/8 inch stainless tubing.

To satisfy the design objective of re-using a sample chamber a sliding piston design was chosen. The piston allow for a sample to be ejected from a chamber prior to re-sampling the chamber while minimizing contamination from this sample. Initial tests indicated that a prohibitively long washing time was required to completely rinse a chamber of the previous sample when a piston was not used. In this design samples are contained in between the multiport valve and a 5000 psi Swagelok check valve for each cylinder. The use of passive check valves eliminates the need for a second multiport valve and controller. Each individual sample chamber can be filled in approximately 10 seconds during an initial filling. The valving topology allows for each of the sample chambers to be emptied and refilled during a dive in less than 20 seconds. The sliding piston also enables the samples to be extracted from the sampler at high pressure (i.e. the ambient collection pressure).

To account for the pressure of the samples in the chambers and the thermal expansion of water when the sampler is brought to the surface, hard o-rings are used as compliant members on the pump out side of the pistons. These 90 durometer o-rings require large compression forces and will not be compressed by the internal sampler pump or when the sampler is submerged. A temperature change of $40°C$ was accounted for as a maximum differential between the ambient bottom temperature and hot on deck conditions.

[1] http://www.vici.com/



(a) Assembled (b) Partial component view

Fig. 2. Simplified renderings of the water sampler. (a) The sampler assembled and ready for in water use. (b) Sketch with the major system components labeled. The plumbing is removed for clarity. The aluminum housing creates a one atmosphere space for the electronics, multiport valve and multiport controller. The plastic housing is filled with a dialectic compensating fluid.

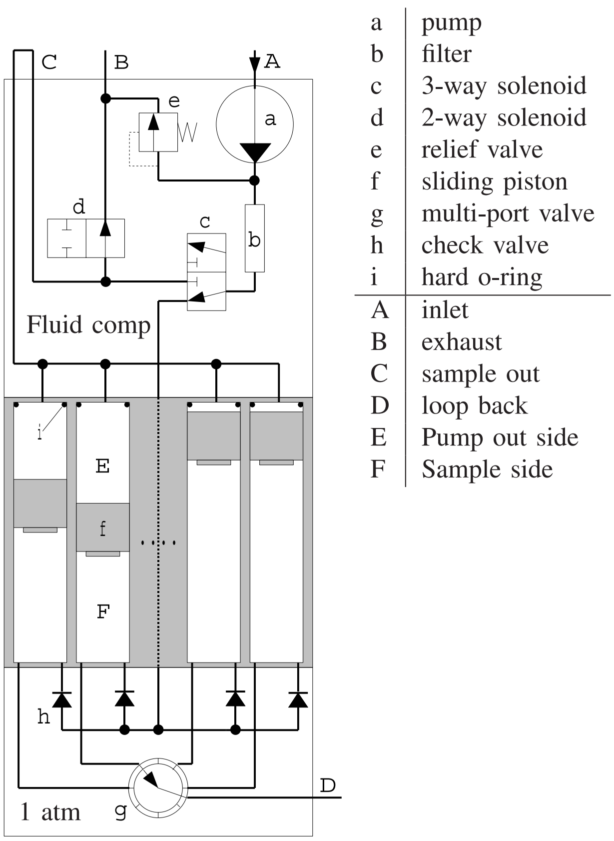


Fig. 3. Diagram of the internal plumbing. The figure shows a slice through the sampler. The pump and solenoid valves operate in a fluid compensated housing. The multiport valve is in the 1 atmosphere pressure housing. The dash line indicates tubing passing through the center of the main sampling body.

Using $2.8 \times 10^{-4} \frac{1}{^{\circ}C}$ as the mean coefficient of volumetric expansion over this temperature range and $4.5 \times 10^{-6} \frac{1}{dBar}$ as the compressibility of seawater, the resulting pressure for a fixed volume of water would become approximately 3500 psi. The compliance of the o-rings ensures that this thermal expansion in combination with the ambient pressure will not allow the internal cylinder pressure to exceed 5000 psi.

B. *Electrical*

The connections between the electrical components of the sampler are shown in figure 4. A custom PCB board conditions and directs the input power to four subsystems, each of which is a commercially available product. The sampler is controlled using a Gumstix [2] Linux computer running a single software application. Two serial ports are used to communicate with the host system externally and the Valco multiport valve internally. The solenoids and the pump motor are controlled using the Gumstix digital IO lines. The controlling software consists of a simple serial command interpretor and a set of action commands. The valving and pumping sequences for sampling,

ACTION	POWER	DURATION
Hotel load baseline	2.4 W	Mission duration
Solenoids switched	25 W	$< 10sec$ per sample
Pump motor running	20 W	$< 20sec$ per sample
Multiport valve moving	50 W	$< 1sec$ per sample

TABLE I
SAMPLER POWER REQUIREMENTS

re-sampling and filling the sampler during pre-dive are enabled as simple macro commands.

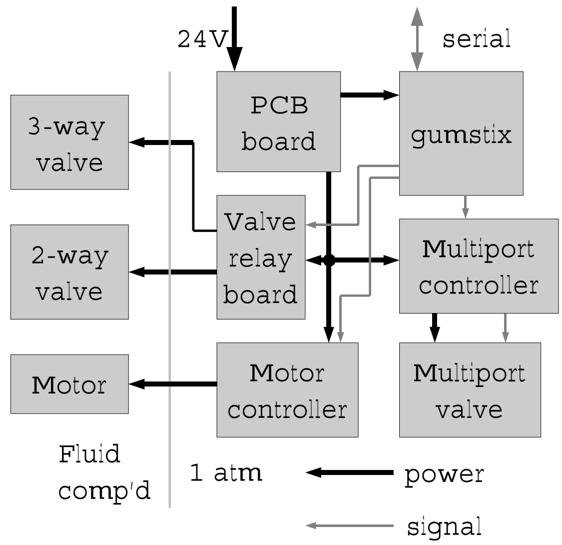


Fig. 4. Diagram of the sampler electrical connections. The solenoid valves and pump motor run in the compensation fluid.

The Vici Valco multiport valve is supplied power from the PCB board and receives serial commands from the Gumstix computer. The eight port valve is configured to have sixteen positions; eight which flow into the chambers and eight which dead end the flow and close of the sample chambers. A Neptune Research Incorporated COOLDRIVER[3] solenoid valve controller board is used to switch the 24V solenoids. The brushless pump motor is controlled by a Maxon DEC 24/1 digital brushless motor controller. A brushless motor was selected to run in the pressure compensate side of the sampler at ambient pressure. The motor is controlled using a ground referenced enable line.

The various power requirements for the sampler are shown in table III-B. The hotel base line power is required to run the Gumstix and power the valve controller in a quiescent state. The solenoids and valve motion only require power during sampling.

C. *Operation*

The basic operation of the sampler involves preprogrammed sequences of pump and valve actuation that can be triggered

[2]http://www.gumstix.com/

[3]http://www.nresearch.com/

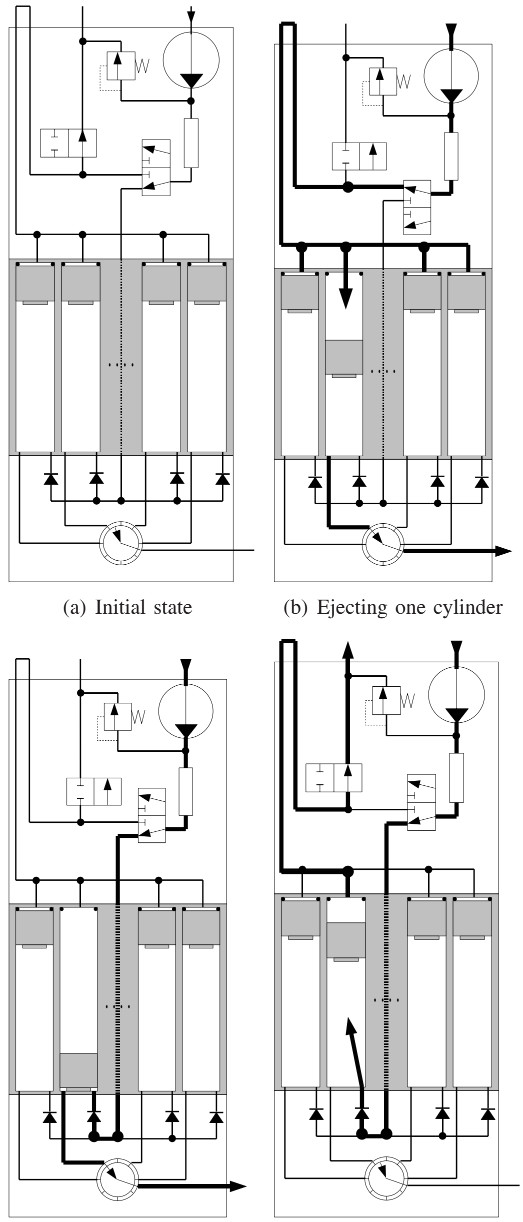
through the serial interface. Prior to deployment the sample side of the cylinders are filled with water and the pistons slid to the end of the their travel. A pre-programmed routine will cycle through the cylinders, remove all of the air from the cylinders and, fill them to this position.

1) Sampling and re-sampling: The basic sampling sequence is completed in three steps (figure 5). Starting from the initial state with all cylinders filled, a single chamber is emptied. The chamber is selected by the position of the multiport valve and the pump is run for a preset amount of time. Next, a washing step is used to flush the system tubing of any old water that would contaminate the new sample. The sliding pistons are designed with a raised section on one end to create a low volume flow path in and out of the top of the cylinder. The length of the washing time is preset. Finally, the sample chamber is filled by dead-ending the multiport valve and forcing fluid into the chamber. The water on the pump out side of the piston is allowed to exit via the two way solenoid. The filling step requires that at least one chamber has been emptied since all of the cylinder inlets will be pressurized but only one will allow fluid in.

If the chambers are being filled for the first time on a dive this filling sequence is modified to empty the next cylinder immediately after one is filled. This speeds up the sampling for a first time use as time is not needed to empty the chamber at the time of sampling.

2) Sample extraction: The sample extraction step is shown in figure 6. Fluid is extracted from the sampler using a bench top high pressure pump and relief valve setup to reproduce bottom pressure. For extraction the loop back is removed and a high pressure liquid chromotgraphy (HPLC) pump is connected to the pump out side of the pistons through the only piece of high pressure tubing used in the fluid compensated end of the sampler. All of the low pressure plastic tubing is left unused by removing the external loop-back. A high pressure metering valve is attached to the multiport valve exhaust line and used to control the extraction. A gas-tight syringe is used to capture the samples.

Extracting the samples at bottom pressure ensures that the correct ratio of dissolved gas to fluid is maintained when the pressure is reduced to one atmosphere and prevents gas partitioning within the sample volume. This method of sampler extraction also allows a single sample to be subdivided while maintaining the correct gas to fluid ratio.



(a) Initial state (b) Ejecting one cylinder

(c) Pre-sample washing (d) Sampling

Fig. 5. The sampling sequence is shown here for a single chamber. The emboldened lines indicate the flow of water for that step. (a) In the initial state either samples or waste water fill each chamber. (b) To eject a sample the pump is turned on and multiport valve is used to select which sample chamber to empty. (c) The washing step allows contamination from previous samples to be removed by flushing the tubing with sample water. (d) The new sample is taken when the multiport valve is moved to a closed position and fluid is forced into the cylinder. In any configuration flow can occur across the relief valve once the sliding piston reaches the end of the sample chamber.

IV. Testing

Testing of the sampler was completed to characterize the sources and amount of contamination in the samples. Two main sources of contamination exist. The first is related to the residual fluid volume remaining in the plumbing leading to the sample chamber that is not associated with the current sample. This can be reduced by adjusting the length of washing time used prior to filling a cylinder, shown as step three in figure 5(c). The plot in figure 7 shows the how level of contamination will drop to approximately 1 ppt after seven seconds of washing time. This test was completed for a single cylinder by sampling a salty solution and then re-sampling that cylinder with fresh deionized water. The fresh sample was then measured for conductivity.

A second source of contamination exists in the extraction process when the remnants of a previously ejected sample mix with the newly ejected sample in the exhaust line of the multiport valve. To minimize this the first three ml of the

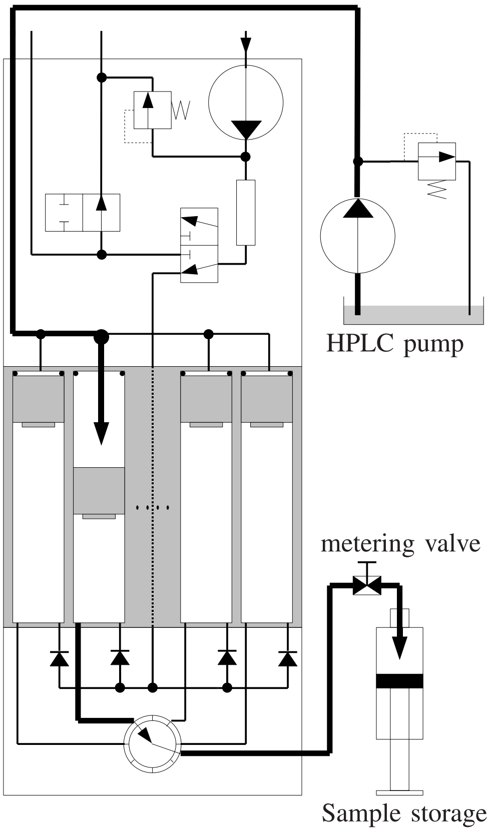


Fig. 6. The sample extraction is completed using a high pressure pumping system and a metering valve. After the equivalent depth pressure is created with the High Pressure Liquid Chromotgraphy (HPLC) pump, the multiport valve for the sample cylinder is opened and the metering valve is then used to release the sample into a one atmosphere gas tight syringe.

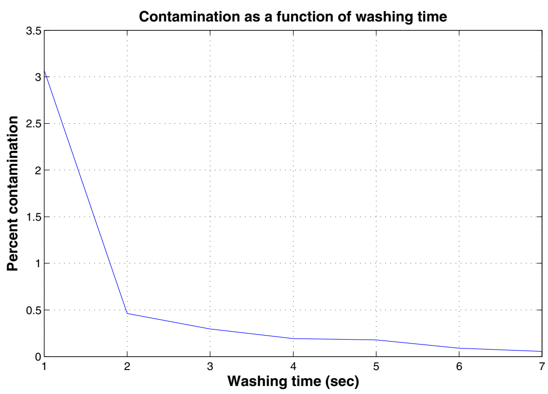


Fig. 7. Relation between the washing time and contamination by the previous sample.

new sample can be released and discarded. The volume of the exhaust line is 0.35 ml and this discarding will reduce the contamination to approximately two ppt. If required by samples with expected chemical concentrations that vary by several orders of magnitude, the aluminum bell house can be removed and a new exhaust line with lower volume can be attached directly to the multiport valve. The existing exhaust line is 1/8 inch stainless tubing. Smaller tubing would restrict the flow significantly and require a much longer washing time when samples are taken.

V. Conclusions

This paper has presented a design and preliminary test results for a water sampling device designed for scientfic AUVs, (figure 8). The sampler is small in size and has a low hotel power requirement. Eight samples of water can be collected and returned to the surface in a gas tight manner to make quantative measurements of dissolved gas concentrations possible with laboratory equipment. This sampler can be used in conjuction with a suite of in-situ chemical sensors on AUVs and triggered by a simple serial command. The authors will use this device to ground truth in-situ chemical measurements and expand the sampling capabilities of AUVs.

VI. Acknowledgements

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References

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Fig. 8. Photo of the sampler with the aluminum and plastic housings removed. The maxon motor controller and PCB board are not visible behind the multiport valve motor.