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A Remotely Operated Serial Sampler for Collecting Gas-Tight Fluid Samples*

WU Shi-jun (吴世军)[a], YANG Can-jun (杨灿军)[a, 1],

DING Kang (丁　抗)[b, c] and TAN Chun-yang (谭春阳)[b, c]

[a] *State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*

[b] *Earth Science Department, University of Minnesota, Minneapolis, MN 55455, USA*

[c] *Sanya Institute of Deep-Sea Science and Engineering, Chinese Academy of Sciences, Sanya 572000, China*

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ABSTRACT

This paper describes the design, construction and preliminary test results for a gas-tight serial sampler intended to be deployed at seafloor for long-term operation to take time-series fluid samples from deep-sea environments such as cold seeps, water column and hydrothermal vents. The serial sampler is a modular system that is based on independent and identical sampling modules, which are designed to collect six 160 ml gas-tight fluid samples maintained at high pressure to a depth of 4000 meters. With two working modes, the sampler can be deployed either with seafloor cabled observatory for remote control or as a stand-alone device for autonomous operation. A prototype of the instrument has been constructed and tested on the MARS cabled observatory for two months. The laboratory and field tests proved the success of the design and construction of the serial sampler, and indicated the potential for future ocean sciences.

Key words: *serial sampler*; *gas tight*; *seafloor cabled observatory*

1. Introduction

It is a common sense that the marine environments and activities present spatial and temporal variability. Traditional ship-based explorations are labor intensive and have limited time resolutions. The cabled ocean observatories which provide unprecedented amounts of power and two-way bandwidth communication to access and control scientific instruments deployed in the oceans are regarded as the innovative facilities for future ocean sciences (Chave *et al*., 2004, 2006; Chen *et al*., 2012). Although many kinds of sensors have been developed and used to characterize various ocean environments, these in-situ measurements are often insufficient to fully investigate important scientific questions. Additionally, some extreme environments, such as the deep-sea hydrothermal vents, pose considerable challenges for in-situ measurements. At present the in-situ sensors for high-temperature hydrothermal vents are confined to several specific species, like H_2S, H_2 and pH (Ding *et al*., 2001; Ding and Seyfried,

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1 Corresponding author. E-mail: ycj@zju.edu.cn

2007). Water samples will become important to complement the wide array of sensors and provide ground truth for in-situ measurements.

To date, a variety of samplers have been developed to collect water samples and hydrothermal fluids from seafloor (Edmond *et al*., 1992; Seewald *et al*., 2002; Wu *et al*., 2011). However, most existing samplers for hydrothermal fluids are primarily used with Remotely Operated Vehicles (ROVs) or manned submersibles, and each sampler can only take one sample during each dive. This paper presents the development of a new gas-tight serial sampler, which is designed to be deployed at seafloor for long-term operation to take time-series fluid samples. The sampler is designed based on the idea of modularization to improve the reliability and interchangeability. Currently, the sampler is composed of a control module and six sampling modules, and it is convenient to be upgraded by adding more sampling modules in future. A prototype of the serial sampler has been constructed and tested on the Monterey Accelerated Research System (MARS), which can be remotely accessed and controlled through Internet.

This paper outlines the basic design concept, mechanical and electrical components of the serial sampler in Section 2. The integration of the serial sampler into the Calibrator Linked In-situ Timed Observatory is also described. The water tank and field tests are introduced in Section 3. Conclusions are given at the end of the paper.

2. Design and Construction

2.1 Design Concept

The serial sampler is a modular sampling system that is designed to collect multiple fluid samples from deep-sea environments and seafloor hydrothermal vents. As shown in Fig. 1, the serial sampler is composed of a control module and six sampling modules. The control module consists of a rechargeable battery pack and a circuit board with functions of sampling control, temperature measurement, data storage and communication. Each sampling module has a sampling cylinder, an independent sampling valve and valve actuator, which is electrically connected to the control module via an underwater cable. Since the sampler is based on independent and identical sampling modules, it features some advantages compared with the centralized samplers. First, the fault-tolerant ability of the instrument is greatly improved, as the failure of a single sampling module does not affect the whole system. Second, the sampler is extendible, which means more sampling or measuring modules can be added into the system. Finally, the configuration and assembly of the sampler can be conveniently modified to meet different deployment requirements.

In the current design, the serial sampler has two working modes. In the remote operation mode, the sampler is controlled by the computer. A software is designed to display the data from sampler and sent commands to control each sampling module. In the autonomous mode, the sampler works as a stand-alone device, which takes samples according to the preset time.

2.2 Mechanical Structure

The structure of the sampling module is illustrated in Fig. 2. It is composed of a sampling valve, an electric motor actuator used to control the sampling valve, and a gas-tight sampling cylinder. The sampling cylinder consists of a 160 ml-volume sample chamber which is coaxially connected with an accumulator chamber through a threaded coupling. A high-pressure stop valve integrated in the accumulator chamber is used for gas precharge. Each sampling module is 40 cm long, 8 cm wide, 17.5 cm high, and weighs about 5 kg in air. It is designed to collect a gas-tight sample maintained at high pressure to a depth of 4000 meters.

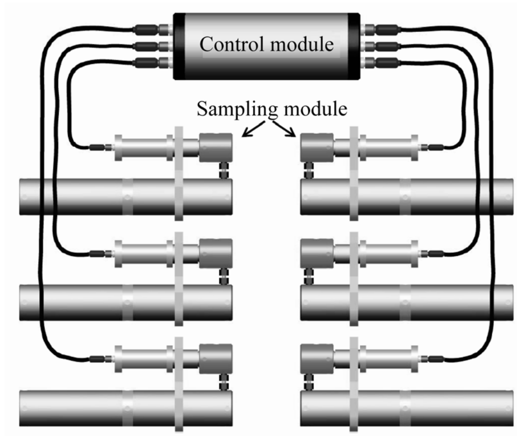


Fig. 1. Schematic illustration of the gas-tight serial sampler.

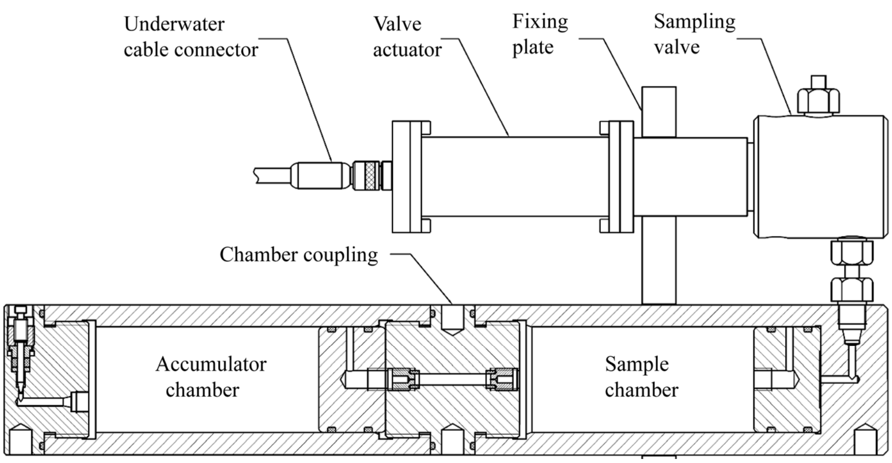


Fig. 2. Structure of the sampling module.

The working principle of the sampling module is similar to the previous gas-tight samplers (Seewald *et al*., 2002; Wu *et al*., 2011). Before deployment of the sampler, the sampling valve is closed, and the accumulator chamber is filled with compressed nitrogen gas, the pressure of which is adjusted to about 10% of the pressure at the sampling depth. The volume between the sample piston and accumulator piston is filled with local bottom seawater (or deionized water). When taking a sample, the actuator is energized through the underwater cable to open the sampling valve. Fluid sample fills the sample chamber, forcing the sample and accumulator pistons to move accordingly. After the sampling process is completed, the actuator is energized again to close the sampling valve. During recovery of the sampler from seafloor to surface, the compressed nitrogen in the accumulator chamber is used to compensate the pressure fluctuation caused by volume expansion and temperature change. So the collected fluid sample is kept at nearly in-situ pressure.

The main object of the current serial sampler is to analyze the chemical components (including the gas components) of the time-series fluid samples, so we did not consider the thermal insulation of the sampler. For the study of deep-sea microbial, the temperature may be an important factor affecting the viability of the psychrophiles and thermophiles.

According to the working principle of the sampling module, it may be seen that the sampling valve must have bidirectional sealing capability under high pressure. A custom-made sampling valve is applied here. As shown in Fig. 3, the sampling valve mainly employs two sliding O-ring seals and a cone seal comprising of a valve poppet and seat (Wu *et al*., 2010). A spring is employed to produce an initial sealing force between the valve poppet and seat. A special feature of the sampling valve is the pressure-balanced valve poppet. Because the two sliding O-ring seals and the valve seat have the same diameter, the pressure forces on the valve poppet are always equal and opposite no matter which port is subjected to high pressure. That is to say, the valve poppet is always pressure-balanced. One benefit of using a pressure-balanced valve poppet is that the sealing force does not vary with operation fluid pressure. Therefore, the valve actuator only needs to overcome the spring force and a little friction force to move the poppet and open the valve. Once the external actuating force is released, the valve becomes closed again automatically. In order to achieve good repeatability of contact seal, an alignment pin is used to prevent the rotation of valve poppet, ensuring the same contact surface with the valve seat each time.

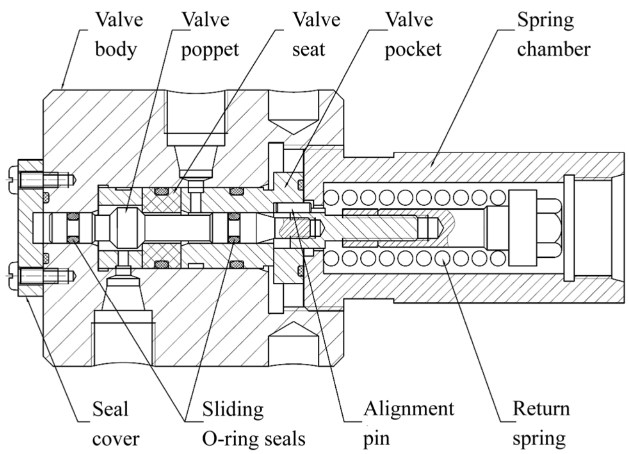


Fig. 3. Structure of the sampling valve.

The current prototype of the serial sampler (with one control module and six sampling modules) is shown as Fig. 4. All of the sampling chambers and valves are made of titanium alloy (TC4) for corrosion resistance and temperature tolerance. Therefore, the serial sampler can be used to collect samples from a variety of deep-sea environments such as cold seeps, water column, and hydrothermal vents. In previous studies, we demonstrated that the sampler designed based on the similar structure of the sampling module had been successfully used for deep-sea high-temperature hydrothermal vents (Wu *et al*., 2010, 2011). The whole instrument is about 80 cm long, 30 cm wide, and 30 cm high. It weighs approximately 50 kg in air. The compact structure and acceptable weight make it possible for the serial sampler to be mounted in the basket of the ROV or manned submersible during deployment.

2.3 Electronic Control

Power consumption and size are two major concerns for the circuit design of serial sampler. The MSP430F149 Micro Controller Unit (MCU) from Texas Instrument is adopted as the core of the sampler's control circuit, as it is one of the new generation of ultra-low power microcontrollers. MSP430 MCU is widely used in battery-operated instruments like data loggers, hand-held meters and medical equipments (Zhao *et al*., 2009; Wang *et al*., 2009). In addition to extremely low power consumption (ranging from several microwatts in active mode to less than 0.1mW in sleep mode), it has a series of models with abundant on-chip peripherals, such as Analog-to Digital (AD) converters, digital I/Os, timers and Universal Synchronous/Asynchronous Receive/Transmit (USART) interfaces. So it can significantly simplify the circuit design as well as reduce the size.

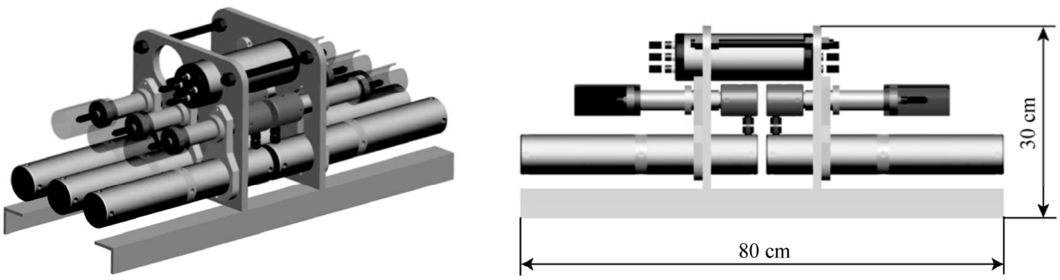


Fig. 4. 3D illustration of the serial sampler.

According to the functions of the serial sampler, the circuit is broken down into five major functional blocks. As shown in Fig. 5, the power conversion module draws electric energy from a 12V power source (battery or seafloor observatory) and distributes the electricity to other circuit modules. Except for the MSP430 MCU, power supply for all of the other components can be switched off to preserve electricity. As mentioned above, the serial sampler has six sampling modules, and each of them uses a Direct-Current (DC) motor to actuate the sampling valve. So the motor control module employs three dual full-bridge drivers (L298) to drive six DC motors. A thermistor and thermocouple is used to measure the temperatures of seawater and hydrothermal fluid. The outputs of the temperature sensors are filtered and amplified by the signal conditioning module. A current-sense amplifier (MAX471) is selected to measure the total current, which is used as the feedback to determine whether the circuit board is functioning well. The signals of temperature sensors, current and voltage are digitized using the MSP430's built-in 12-bit AD converter. In addition, the circuit board also integrates a real-time clock (PCF8563), a flash memory (ATD45DB321), and a RS232 serial communication (LTC1385) module.

The serial sampler is designed to be deployed either with seafloor cabled observatory for remote control or as a stand-alone device for autonomous operation. Therefore, the control program has two working modes. In the remote control mode, the serial sampler can be accessed and controlled through Internet using the laboratory computer. The ability with human intervention will greatly increase the scientific utility of the serial sampler since we can decide when to take a fluid sample based on the comprehensive analysis of the collected data and information. In the autonomous mode, the program is running without human intervention. A simple way for the sampling control is that the sampling modules are triggered according to the preset time. In the future, appropriate control algorithms will be added into the program to realize smart sampling based on in-situ measurements, so as to capture the episodic or abrupt oceanic processes.

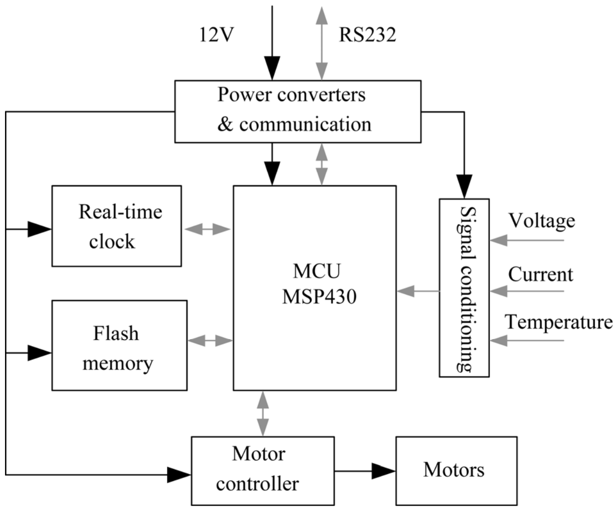


Fig. 5. Schematic diagram of the sampler control circuit.

2.4 System Integration

For the convenience of field test of the serial sampler on MARS cabled observatory, the sampler was integrated into the CALLISTO (Calibrator Linked In-situ Timed Observatory) system that was built in the hydrothermal lab of University of Minnesota. The major subsystem of the CALLISTO is the pH calibrator for precise in-situ measurement of pH in deep-sea environments (Tan *et al*., 2010, 2012). The serial sampler and pH calibrator are using 12 V power supply and RS232 communication protocol, while the MARS observatory only offers 48 DC voltage and network communication, so a junction box with DC-DC power conversion and serial-to-Ethernet conversion modules was developed for the CALLISTO (Fig. 6).

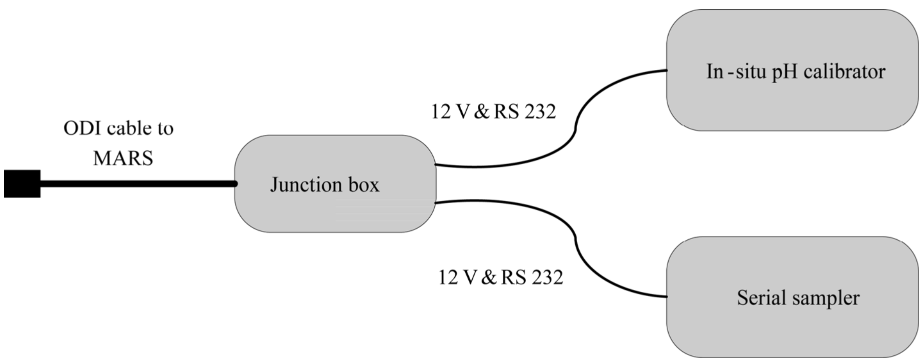


Fig. 6. Schematic diagram of the electrical connection of the CALLISTO.

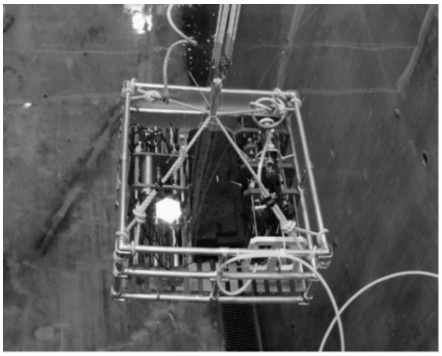
All the components of the CALLISTO are mounted inside a frame that was built using aluminum alloy pipes and structural slip-on pipe fittings (Fig. 7). This design is very cost effective because it requires the least amount of machining work and the materials are reusable. The whole system is 96 cm long, 96 cm wide, 50 cm high, and weighs about 104 kg in air.

Fig. 7. Integration of the serial sampler into the CALLISTO.

3. Tests and Results

3.1 Tank Test

Prior to field test, the serial sampler was tested in the water tank of Monterey Bay Aquarium Research Institute (MBARI). During the tank test, the serial sampler was set to work in the autonomous mode. Six sampling modules were automatically triggered according to the preset time as indicated by the current record (see the right panel of Fig. 8), which was further confirmed by the water samples collected in six sample chambers. After the tank test, all the sampling modules were disassembled, cleaned and put together again for the field test. Unfortunately, because of uncareful operation, the thread coupling between the actuator and sampling valve of one sampling module was damaged. As there were no replacement parts for the serial sampler at that time, only five sampling modules were used during the following field test.



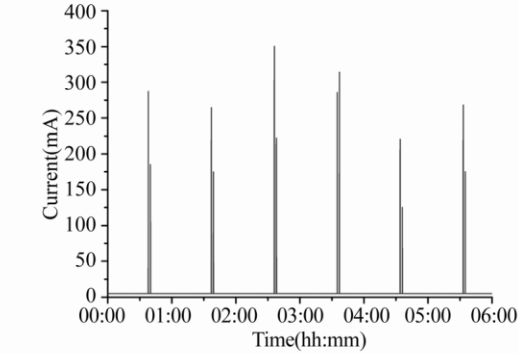


Fig. 8. Test of the serial sampler in the water tank (left) and the record of current during tank test (right).

3.2 Field Test

As a part of the CALLISTO system, the serial sampler was tested on the MARS cabled ocean observatory from November 11, 2012 to January 15, 2013. During the sea trial, the research ship *Rachel Carson* and ROV *Ventana* of MBARI was used for the deployment and underwater operation of the instrument. In consideration of the size and weight of the CALLISTO system, the instrument was lowered from the ship and free fell to the seafloor (as shown in Fig. 9). In order to acquire a suitable descending velocity in the water, a pack of buoyancy was attached to the CALLISTO to reduce its weight in the water. As a result, the instrument was nicely deployed at the place 55 meters away from seafloor main node of MARS (36°43'N, 122°11'W). Then, the wet-mate cable connection between the CALLISTO and MARS was completed by the ROV *Ventana*.

After the successful deployment of the CALLISTO, the serial sampler could be accessed and controlled by the laboratory computer through Internet. During the remotely operated sampling process, the current of the control circuit board was used as the indicator to determine whether the sampler was functioning well. As shown in Fig. 10, there was a rapid current rise when opening and closing the sampling valve. During this field test, four sampling modules have been successfully remotely triggered as indicated by the correct current feedback. However, there was no current rise (remained unchanged at about 5 mA) when the sampling module #5 was triggered, suggesting a malfunction occurred.

The CALLISTO system was recovered on January 15, 2013 after two months deployment. Except that the sample chamber #5 was empty, four seawater samples were obtained and kept at in-situ pressure (Table 1), which coincided with the judgment according to current feedback. Through the examination of the sampling module #5, it was found that the actuator chamber was full of seawater due to the leakage caused by the failure of the O-ring seal between the actuator chamber and sampling valve. As a result, the sampling valve was not opened.

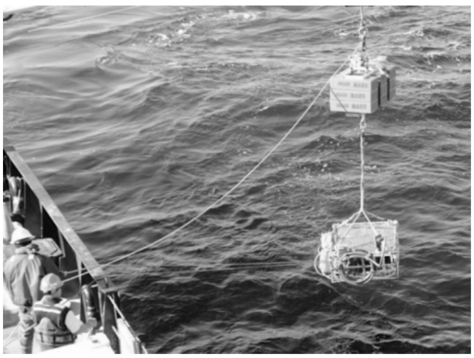


Fig. 9. Deployment of the serial sampler with CALLISTO in Monterey Bay, California.

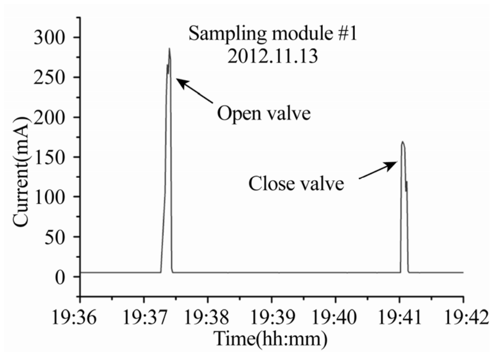


Fig. 10. Current feedback of the serial sampler when the sampling module was remotely triggered through Internet.

Table 1 Records of the recovered fluid samples

Sampling module	Date	Sample volume (ml)	Recovery pressure (MPa)	In-situ pressure (MPa)
1	2012.11.13	163	8.3	8.9
2	2012.11.17	162	8.4	8.9
3	2012.11.19	160	8.5	8.9
4	2012.11.26	163	8.4	8.9

In summary, this is the first deployment of the serial sampler on a cabled ocean observatory. The main purpose is to verify the function of the sampler, and the remote operation through Internet. The sea trial demonstrated the success of the development of the serial sampler and its effectiveness for collecting time-series gas-tight fluid samples during long-term deployment.

4. Conclusions

A new serial sampler has been designed and built for long-term deployment to collect gas-tight time-series fluid samples. It can be used in stand-alone mode for taking fluid samples in pre-programmed schedule or be connected onto the cabled observatory for remotely controlled operation. Based on the modular design principle, the serial sampler can be conveniently adapted into in-situ sensor system (like CALLISTO) for fast response from the sensor measurement and be upgraded in the future. The laboratory and field tests proved the success of the design and construction of the prototype of the serial sampler. In the remote operation mode, the electric current feedback was demonstrated to be an effective method to determine whether the sampling module is successfully triggered. Quantitative chemical analysis of time-series fluid samples is essential for studying the temporal changes in hydrothermal vent chemistry and surrounding biological communities. Combined with in-situ sensor system, the gas-tight serial sampler has great potential for long-term monitoring of the deep-sea hydrothermal activities.

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