



Know the Flow: Flow Sensor Integration for AUV and ROV Applications

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ABSTRACT

A Hall-effect flow sensor was integrated with the pumped sensor and filter systems used on the Autonomous Underwater Vehicle (AUV) and Remotely Operated Vehicles (ROVs) operated by the Monterey Bay Aquarium Research Institute. After preliminary tests, the flow sensor was integrated into the scientific payload section of the AUV and used to support and analyze data collected by the other sensors in the payload section. On the ROVs, the sensor was arranged to transmit data via the onboard science port through the tether to the scientists in the ROV control room. Basic tests and calibrations were performed, but more testing is needed before full operational use can be implemented.

INTRODUCTION

Many Autonomous Underwater Vehicle (AUV)- and Remotely Operated Vehicle (ROV)-based data collection systems involve pumping seawater through sensors or filters to collect scientific data or samples, and would produce better data with knowledge of the rate of water flowing through the system. This paper describes the first steps of the integration of a Hall-effect flow sensor into one AUV and one ROV system at the Monterey Bay Aquarium Research Institute (MBARI).

The AUV currently under development at MBARI is for the upcoming Atlantic Layer Tracking Experiment (ALTEX) mission to study waters beneath the arctic icecap. The scientific payload for that mission, designed and constructed by Nicole Tervalon, includes sensors for the temperature, conductivity, oxygen, and nitrate content of seawater (Fig. 1). To accomplish this, water is drawn into the body of the AUV, routed through each of the sensors in series, and then ejected back into the ocean by a pressure-tolerant pump. This has proven to be a reliable method of making measurements – the same concept is used on many Conductivity/Temperature/Depth (CTD) casts made from ships. However, the separation of the sensors creates issues in post-processing. A single

parcel of water flowing through the tubing takes a non-negligible amount of time to flow between two sensors. Without accounting for this affect, plotting the simultaneous data for two of the sensors at a particular instant produces data for two different pieces of water, perhaps from different depths. This lag time is different between each set of two adjacent sensors, depending on the length of tubing between them.



Figure 1: The scientific payload of the AUV is mounted in the nose section. The space above the components is taken up with syntactic foam when the vehicle is fully assembled.

Sea-Bird Electronics, Inc. manufactures these systems, and has developed data analysis software that takes into account the lag times between sensors as part of post-processing. Sea-Bird, however, designed the software to be used with the specific flow pattern layout (tubing lengths, sensor arrangement, etc.) that they produce. The tight quarters and odd dimensions in the nosecone of the AUV require a different flow pattern layout than the standard configuration, so the Sea-Bird software is functional but not optimized for the AUV configuration.

Scientists have written their own algorithms to better analyze the data from the AUV, but they require a flow rate to run them. The pump data sheet provides a flow rate number based on pump speed setting, but it only offers data for two sensor configurations: one conductivity sensor, or one conductivity sensor and one temperature probe. The data sheet does not offer information for more complex sensor packages. When using the specification sheet data, the scientist must also assume that the flow rate is constant throughout the mission. While the pumps are designed to output a constant flow, this is not necessarily the case for this application.

Integration of a flow sensor would eliminate the guesswork behind this post-processing. Knowing the flow rate through the tubes and the diameter of tubing used, a lag time can be found between each pair of sensors, and then used in the data analysis algorithms to more accurately align the data.

The ROV-based system for this project was built for the radium sampler used by Bill Ussler. This setup consists of a filter that is sensitive to flow rate, which must be limited to 2 L/min. for proper operation. With the expense of dive time and the desire for as large a sampled volume as possible, it is advantageous to keep the flow rate as close to that limit as possible without exceeding it. On previous missions, this was accomplished with the installation of a simple floating-ball flow meter at the outlet of the plumbing system (Fig. 2). While this approach functioned for the project for 43 dives while on the Hawaii cruise of 2001, it required an independent camera and light. In addition, accuracy was diminished since the flow meter was read indirectly via the video monitor in the control room. In contrast, the output from a digital flow meter could be sent directly up the ROV tether, and displayed on a screen in the control room, offering an accurate, easy-to-read flow rate without requiring camera, light, and time resources on the ROV. As an added bonus, the digital flow rate can be easily integrated over the sampling time to find the total amount of water pumped through the system – a valuable piece of information not available using the current methodology.

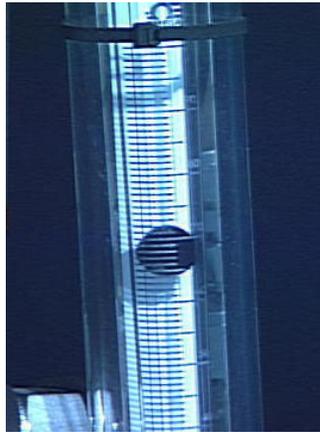


Figure 2: The analog method of reading the flow rate of water through the Radium Sampler is a camera and light trained on a floating-ball flow meter.

MATERIALS AND METHODS

AVAILABLE FLOW SENSORS

Two flow sensors were tested for use in these applications: one made by Gems Sensors, the other by Cole-Parmer (Fig. 3).

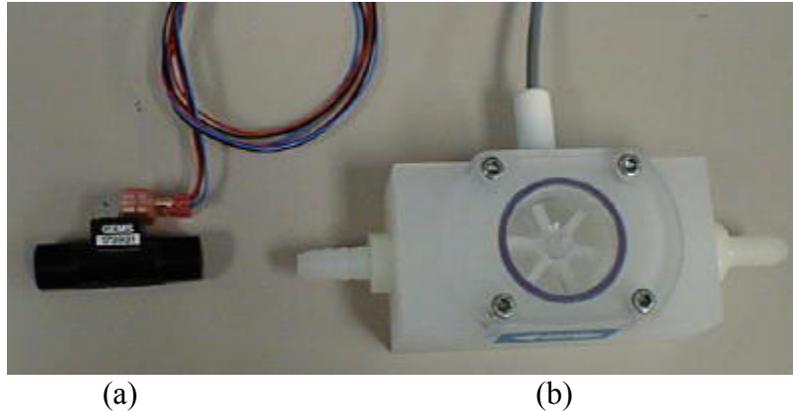


Figure 3: The two flow sensors tested are manufactured by Gems Sensors (a) and Cole-Parmer (b).

Both flow sensors operate using the Hall-effect principle. A paddle or propeller placed in the path of the water is spun by flow passing through the sensor. At least one blade of the paddle (Cole-Parmer) or propeller (Gems Sensors) includes a magnet, which creates a perpendicular current when adjacent to a semiconductor mounted at a fixed point in the path of the magnet. This change in current produces a square wave output signal, which varies linearly in frequency with the speed of the impeller or paddle. In theory (and as will be seen, in practice), this frequency therefore varies linearly with the actual flow rate through the sensor.

FLOW SENSOR CALIBRATION AND TESTING

The flow sensors were pressure-tested and calibration data was taken before either could be incorporated into a vehicle. A calibration was performed on land to find the operating ranges and conversion factors to translate from frequency output to flow rate in liters per minute. Initially, the Cole-Parmer flow sensor was intended for use on the ROV. After the preliminary testing, it was decided to use the Gems Sensors flow sensor for both applications. Not only was the Gems Sensors sensor smaller than the Cole-Parmer sensor, it also provided a higher resolution for the flow rates expected in both applications.

Equipment was not available to allow the flow sensors to be operated while in the pressure tank. The pressure tests served to show whether or not the sensors could handle the pressure at their intended working depths while in a static state, and subsequently function normally at atmospheric pressure on land. Each sensor was tested on land by running water through it and observing the output. It was then placed in the pressure tank and cycled to a pressure of 6000psi for the Cole-Parmer sensor and to 2190psi for the Gems Sensors sensor. The output was observed again at atmospheric pressure, and in both cases was observed to be unchanged from its pre-pressurized output. The difference in test pressures is due to the intended applications for the sensors: the Cole-Parmer sensor was intended to be used on the radium sampler, built for the 4000m-capable Tiburon, and the AUV application for the Gems Sensors sensor is planned to run to only 1500m depth.

To make sense of the frequency output from the sensors, and to compare the usefulness to the AUV and radium sampler applications, calibration data was taken for each sensor. Two water tanks were used to produce a constant flow rate through a sensor (Fig. 4). The large tank serves as a reservoir for the water, which flows through a siphon into the smaller tank. The smaller tank has two outputs. The higher bulkhead is the overflow spout, and keeps the water level in the tank constant. Excess water flows through a tube into a large carboy, which is periodically emptied into the large tank. The lower bulkhead in the small tank leads through tubing to the flow sensor being tested, and then to the bronze outlet valve. Changing the height of this valve adjusts the pressure head of water in the small tank, and therefore the flow rate. Different-length tubes are inserted between the flow sensor and the bronze outlet valve to allow greater range in produced flow rates.



Figure 4: A constant-flow apparatus was assembled to characterize the frequency response vs. flow rate for each flow sensor.

Some practice is required to produce a constant flow through the sensor. The challenge exists in adjusting the flow rate from the large tank to the small tank, using the ball valve at the outlet of the large tank. The flow rate from the large tank must be greater than the flow exiting the small tank through the sensor, but not more than that rate plus the maximum flow rate through the overflow bulkhead.

It should be noted that the tube carrying water from the overflow bulkhead into the carboy should not be long enough to hang below the water level in the carboy. If this should happen, the excess air in the tube has only one exit, which itself may become blocked by the water level at the overflow bulkhead. Sealing of both ends of the tube with water produces a limited oscillating flow rate through the tube (presumed to be caused by the air in the tube being compressed and released by pressure from above). In

any case, this limits the flow rate through the tube, and makes it more difficult to effectively adjust the valve at the large tank.

Actual flow rate is determined by measuring the time taken to fill a 3-liter beaker. In order to avoid affecting the height of the outlet, and therefore the flow rate, the flow rate is made constant while outputting into a bucket. Once the flow rate is known to be steady, the beaker is slipped into the stream of water, without disturbing the outlet valve, and the timer is started. A small bit of juggling is required to shift the bucket out of the way and set the beaker on a flat, stable surface. The output frequency is observed on the scope while the beaker fills, and then the time is stopped when the water level reaches 3L, according to the graduations on the side of the beaker.

The sensor output, in Hz, is then plotted against this actual flow rate, and a best-fit line found (Fig. 5). The inverse slope of this line is taken to be the conversion factor for finding flow rate from observed frequency.

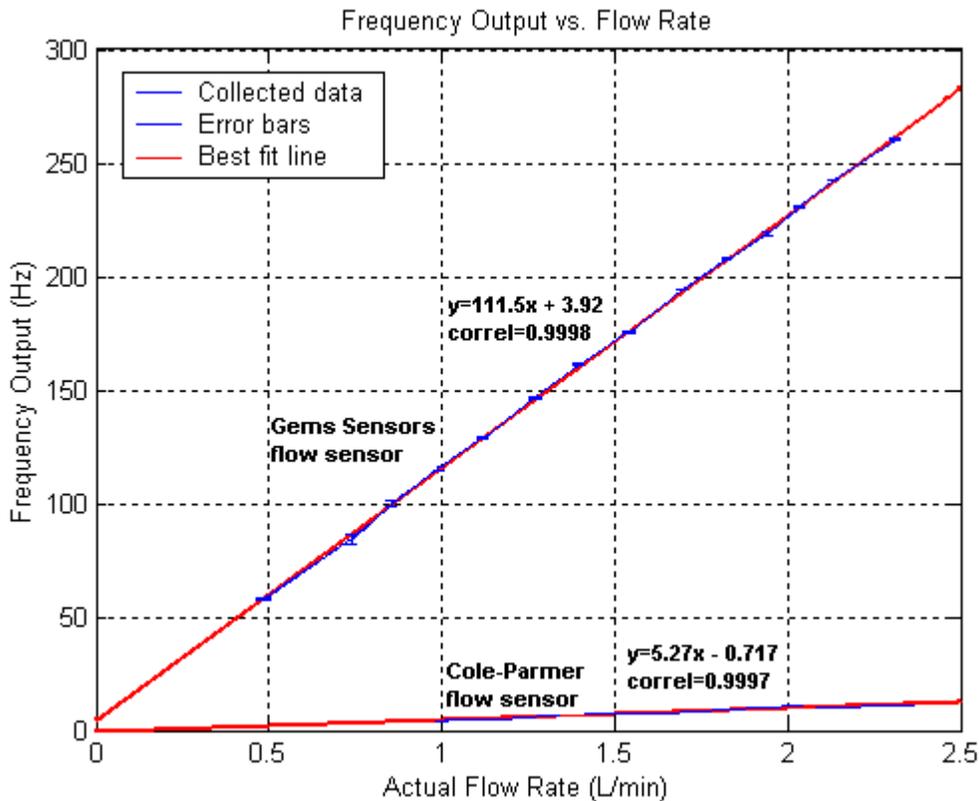


Figure 5: Calibration at atmospheric pressure showed extremely linear relationships between flow rate and output frequency for the two flow sensors tested.

As can be seen in Figure 5 above, the Gems Sensors sensor outputs a higher frequency than the Cole-Parmer sensor, for a given flow rate. However, the Cole-Parmer sensor is

able to handle much higher flow rates. Both the AUV and radium sampler applications operate at no more than 2.5 L/min, so the Gems Sensors sensor was chosen for use in both applications.

FUNCTIONAL INTEGRATION

The Gems Sensors flow sensor arrives with three metal contacts sticking out of the top of the housing (see Fig. 3). In order to be used at depth, each sensor must be potted to a cable or connector to avoid shorting of the contacts by seawater. (Fig. 6) Molds were built for the potting compound and, as more sensors were potted through the summer, experience produced more durable iterations.

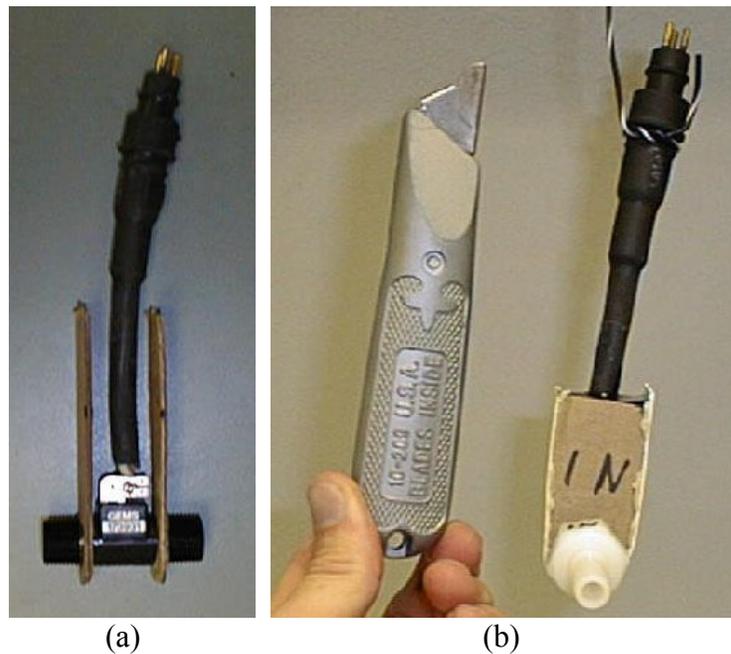


Figure 6: To avoid shorting due to seawater contact, cardboard molds (a) are made around the electrical components of each flow sensor and potted with epoxy (b).

FUNCTIONAL INTEGRATION – AUV

The AUV's scientific payload section consists of two independent pumped sampling paths, each controlled by its own Sea-Bird Electronics SBE25 CTD data collection boardset. These boards include seven extra channels for auxiliary data inputs. One channel on each board is dedicated to the output from the flow sensor mounted in the sampling path from which that board collects sensor data. The available voltage inputs, each sampled at a rate of 4 Hz, are analog inputs (0-5V DC). To accommodate this, a small circuit board was constructed to convert the frequency signal from the flow sensor into an analog voltage that can be read by the voltage-input on the CTD board. Fortunately, this circuit board was small enough to fit in the 1-atmosphere housing in the scientific payload section of the AUV (Fig. 7). Mounting the circuit board on the 1-

atmosphere housing chassis with the two CTD boards prevented the need for an additional oil-filled or pressure-tolerant housing specifically for the frequency-to-voltage converter board. See Appendix A for circuit diagram.

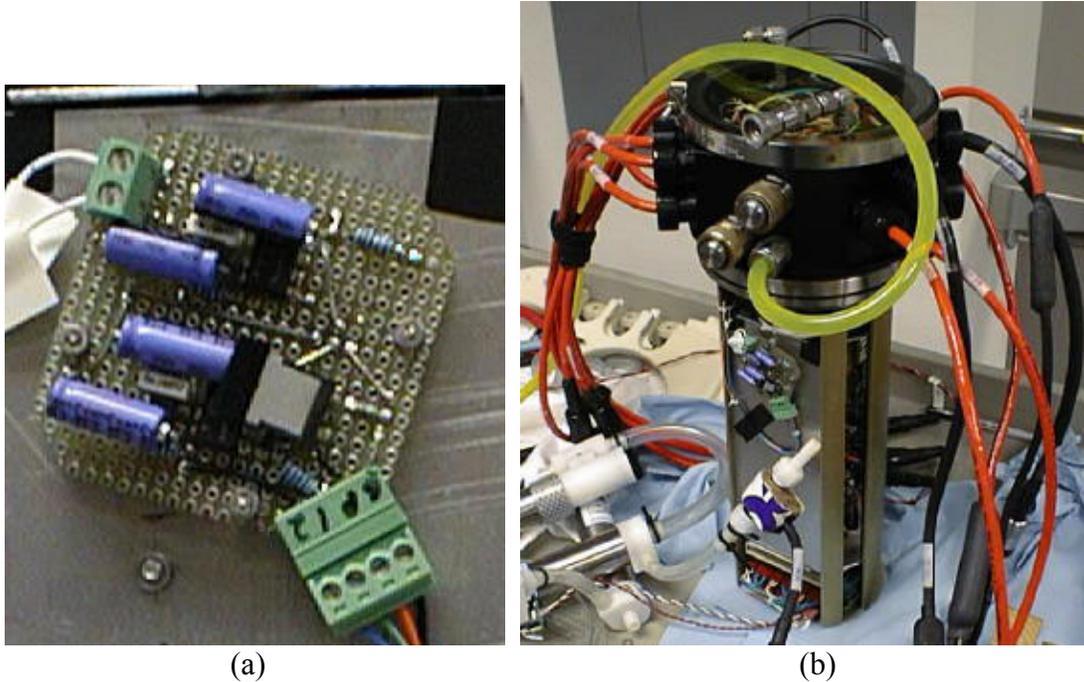


Figure 7: Two frequency-to-voltage converters are mounted on a circuit board (a) and placed with the CTD boards on the chassis of the 1-atmosphere housing (b). The chassis is connected directly to the housing end-cap and junction box for the science payload.

To understand the data output by the frequency-to-voltage converter board, one additional conversion factor is needed. Before installation into the 1-atmosphere housing, a calibration from input frequency to output voltage was obtained for the converter board. The input frequency was produced and varied using a function generator, and measured with an oscilloscope. The output of the circuit board was then monitored using a digital multimeter, and recorded for later analysis. A best-fit line was found (Fig. 8), and the equation from that line used to further convert the data collected by the AUV.

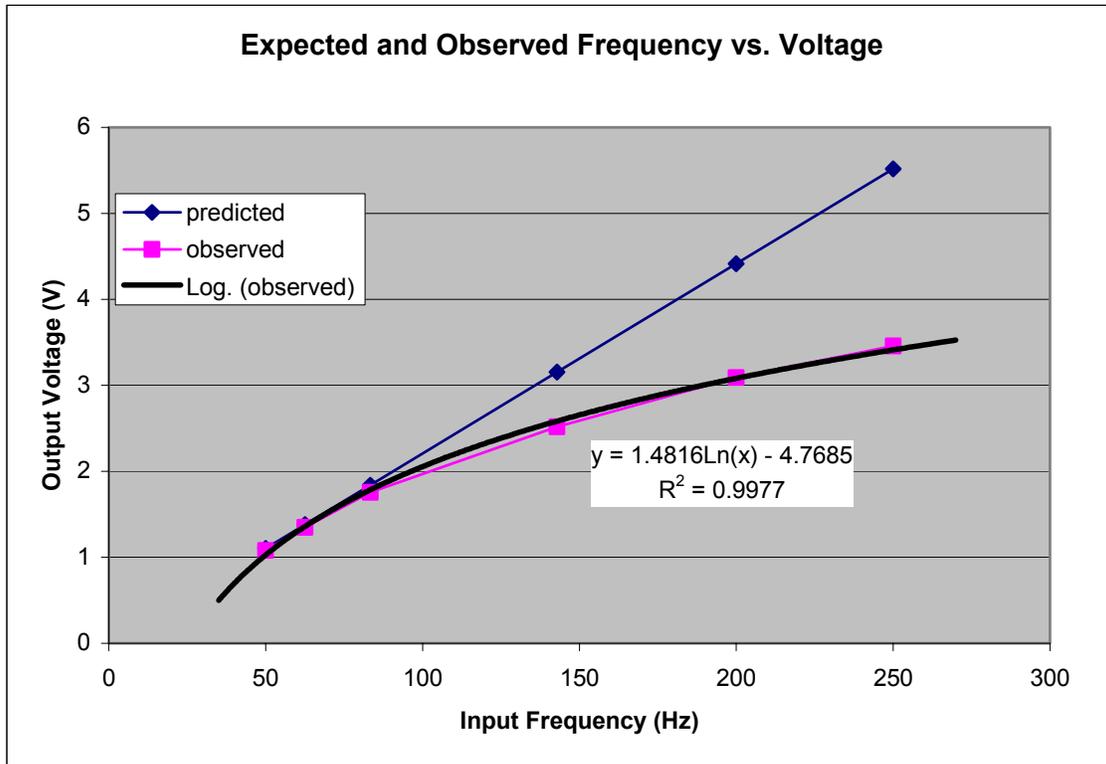


Figure 8: Unexpectedly, the frequency-to-voltage converter produces a logarithmic response to frequency.

While the voltage response of the frequency-to-voltage converter circuit board is not linear, the conversion can still be used in the analysis of the AUV data.

FUNCTIONAL INTEGRATION -- ROV

Both the ROV *Ventana* and the ROV *Tiburón* include science ports through which control and data signals can be passed to or from the scientific apparatus mounted on the vehicle. These data ports present the most convenient channel through which to send the data from the flow sensor. To accomplish this, a PIC microcontroller-based circuit board was constructed to convert the square-wave output of the flow sensor into the RS-232 signal required for transmission through the science port and up the ROV's tether. See Appendix A for circuit diagram.

While the flow sensors in the AUV application are contained in the 1-atmosphere data acquisition housing of the scientific payload section, the flow sensors in the radium-sampler system cannot depend on another part of the vehicle for mounting or containment. There are no 1-atmosphere housings available in the radium-sampler apparatus, so a different method was devised to contain the electronics for the ROV application.

Two possibilities were considered for the circuit board housing: a small 1-atmosphere housing built specifically for the circuit board, and a compensated oil-filled housing.

Due to time and machining constraints, in addition to a desire for simplicity, an oil-filled housing was chosen as the best option. The circuit board requires three conductors leading to the flow sensor and four connections to the ROV science port. To make physical installation as simple as possible, the housing was designed to effectively be an in-line piece of the cable that runs from the flow sensor to the science port. In this configuration, three conductors exit one side of the housing, and four pass through the endcap in the other end. A piece of 2"-diameter flexible TYGON® tubing was chosen for the body of the housing. End-caps were designed and machined to both be clamped into place on either end of the TYGON® tubing, and to accommodate dorn fittings to allow a cable to pass through the end-cap (Fig. 9). The housing is filled with oil because it is non-conductive and nearly incompressible. The flexibility of the TYGON® tubing compensates for the oil's small compressibility by decreasing in volume slightly with depth (the sides of the tube simply cave in).

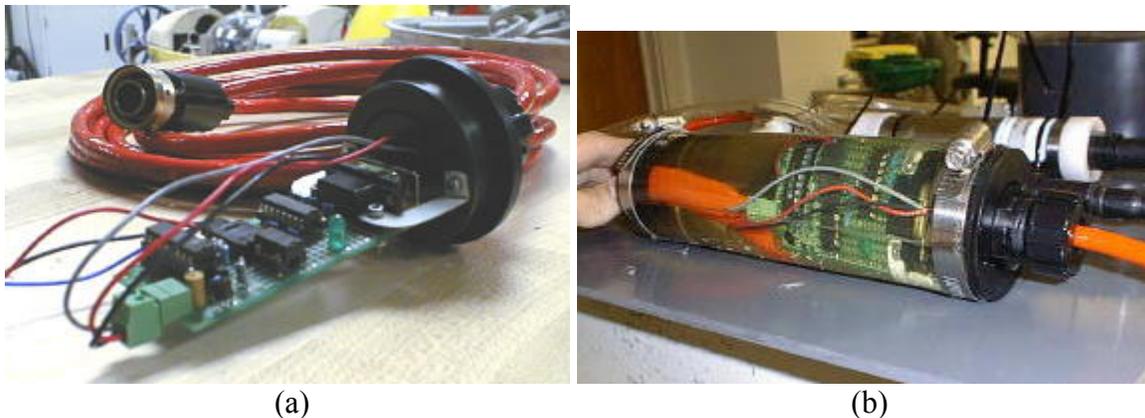


Figure 9: A PIC-based circuit board (a) converts the frequency signal from the flow sensor to an RS-232 signal for transmission up the ROV tether. The assembled housing protects the board from the corrosion and conductivity of saltwater (b). Dorn fittings allow the cables to pass through the walls of the housing.

Because the housing must withstand only ambient pressure at depth, each electronic component was chosen because it had been shown previously to be pressure-tolerant.

AUV TESTING

Once the flow sensors and circuit board are mounted in the science section of the AUV, flow rate data is automatically recorded any time other science data is being taken. The data is then easily downloaded from the vehicle and analyzed on a lab computer. As long as the CTD boards were not deactivated, data was recorded during navigation, buoy section, and propulsion test cruises this summer.

ROV TESTING

The testing performed on the ROV was also important for the AUV application of the flow sensor. A system was designed to allow the same type of 'actual flow rate'-to-'flow sensor output' calibration *in situ* that was performed on land early in the project. The

apparatus could be operated on either ROV, but ease of access and cruise schedules dictated the use of ROV *Ventana* for the test.

In air, filling a rigid container with water and timing the process is quite straightforward. Beneath the ocean surface, the task takes on a new level of difficulty. Due to the pressure at depth, no air can be present in the system. An apparatus consisting of a rigid flask connected to a flexible bladder was constructed to solve the problem. In its initial state, the flask is filled with colored mineral oil, and the bladder is evacuated. Water is pumped into the flask through a bulkhead in the base of the flask. Since oil is lighter than water, it is displaced upward by the water and forced into the bladder. The change in the volume of water in the flask can be observed by watching the interface between the oil and water. Using a video camera, light, and two marks on the side of the flask, an average flow rate can be found by determining the volume between the two marks and measuring the time needed to displace the oil from one mark to the other.

The ideal solution to the question of actually pumping water through this system would be an adjustable, reversible, pressure-tolerant underwater pump. Unfortunately, these pumps do not appear to exist within the flow rate range of 0.5 – 2.5 L/min. In a slightly less desirable but more reasonable approach, two Sea-Bird Electronics SBE 5T pumps, set to different speeds, were used. By utilizing a pilot valve and the ROV's pilot oil system, it is possible to switch back and forth between the pumps. If the two pumps are reversed in relation to each other (they are arranged to pump water in opposite directions), then one can be used to pump water into the flask, and the other to draw water out. Since flow direction does not matter in the measurement of the actual flow rate (timing the movement of the water/oil interface in the flask), the same two marks on the side of the flask are used to measure the flow rate produced by both pumps.

One final complication in the implementation of this apparatus is the fact that the flow meter is unidirectional. To ensure accurate flow measurement, the water must always flow through the sensor in the same direction. With two more pilot-operated valves, this can be achieved for the two-pump system described above (Fig. 10).

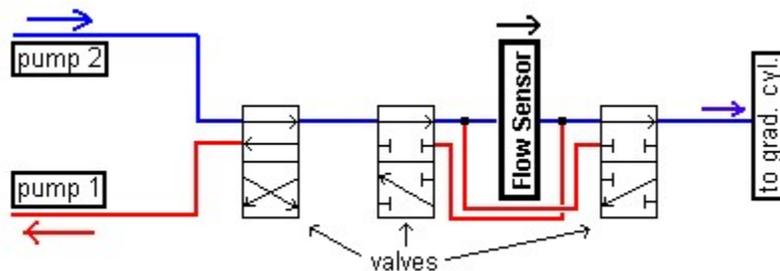


Figure 10: Three valves allow two pumps to be used to fill and empty the flask or graduated cylinder, while always maintaining the same flow direction through the flow sensor.

The final device was tested to ~500m during midwater dives with ROV *Ventana* on 7 and 8 August 2001 (Fig. 11).

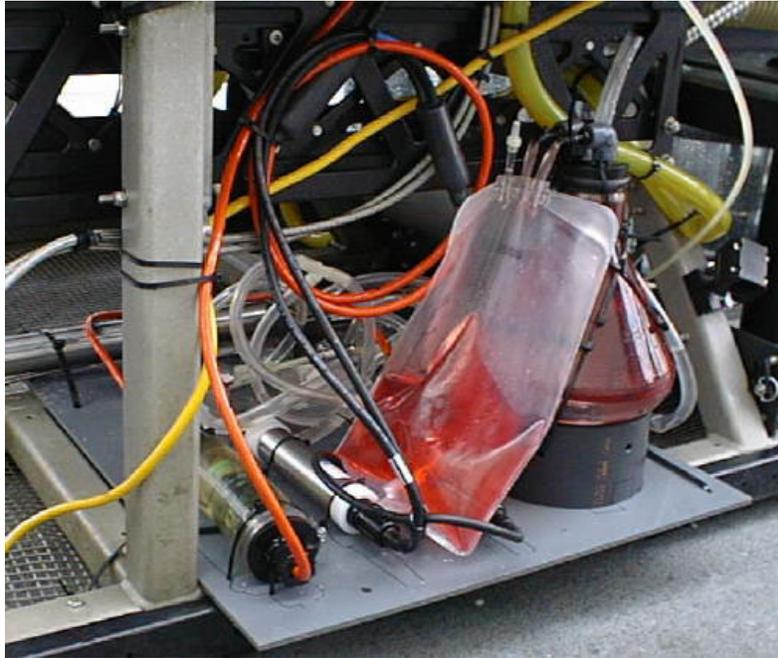


Figure 11: The *in situ* flow sensor calibration apparatus is mounted on ROV *Ventana*.

RESULTS

AUV RESULTS

The frequency-to-voltage converter mounted in the AUV was shown to produce a non-linear response to frequency input. Since the frequency-to-voltage integrated circuit is designed to produce a linear output, this raises a question as to the accuracy of the conversion. For initial analysis, the data was kept in its analog voltage form. However, the data in its raw form has still shown to be useful in verifying anomalies in other data taken by the AUV at the same time (Fig. 12).

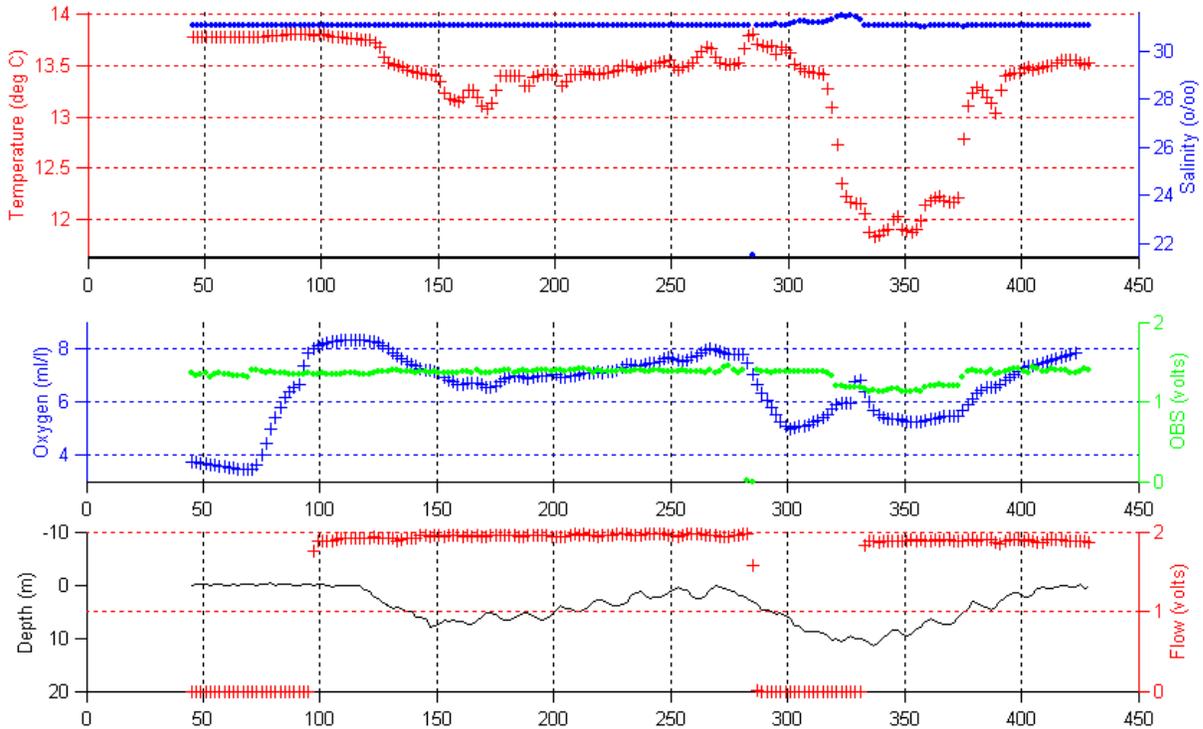


Figure 12: Data from ALTEX AUV mission 2001.221.14 illustrates how raw flow sensor data can be used to verify or debunk anomalies in other data. The x-axis is in seconds from the start of the mission.

ROV RESULTS

Results from the tests run on the ROV *Ventana* were qualitative, but not quantitative. It was shown that the PIC-based data-conversion circuit and the oil-filled housing functioned properly to 500m depths. The test also showed that, with some tweaking, the apparatus can be used to measure a flow rate by measuring the time needed to fill a rigid container. More quantitative results were not attainable, due ultimately to time limitations.

DISCUSSION

AUV RESULTS

In the data set depicted in Figure 12, notice that the flow sensor data is displayed as volts on the bottom plot. Note that at around 280 seconds, the flow data goes to zero. At the same time, data from the other sensors also show some interesting changes. If the flow data is not present, the changes in oxygen, temperature, and salinity might be interpreted as evidence of a significant change in the environment through which the AUV swam while collecting the data. However, the fact that the flow data jumps to zero near that time points to an internal change in the flow system on the vehicle (pump malfunction, controller error, or simply an obstruction in the path of the sensor plumbing), rather than a necessary change in its environment. With this information, the other data from that time period can be said to be questionable, and thrown out, saving time and effort on the

part of the scientists in trying to understand the otherwise unusual changes in the oxygen, temperature, and salinity data.

There is also an as-yet-unexplained behavior in the flow rate data, present in almost every dataset analyzed so far. While generally constant for the entire mission, the flow rate output appears to have a very slight positive slope for the first ~50 seconds of pump activity. An explanation has not been found for this behavior, but it is hoped that further tests will shed some light on the subject.

CONCLUSIONS/RECOMMENDATIONS

While there has not yet been sufficient testing to ensure that the sensors are ready for full operational use, enough was done that they could be ready for deployment with a small amount of additional work. Depending on the application (AUV or ROV), different tasks must be carried out before deployment.

AUV RECOMMENDATIONS

1. The characteristics of the frequency-to-voltage converter circuit board should be better understood. With adjustments to the RC pull-up circuit, the response should become linear, and produce a conversion factor that is easier to work with than the present logarithmic conversion.
2. A full flow rate to voltage calibration should be performed. This would involve the constant flow rate assembly, the flow sensor, and the frequency-to-voltage converter circuit board. A single conversion from flow rate directly to voltage, or vice versa, would increase the accuracy and reliability of the data collected by the AUV.
3. More tests should be run with the ROV to verify consistent flow sensor operation at different depths, and to calibrate the flow sensor *in situ*.

ROV RECOMMENDATIONS

1. More tests should be run to verify consistent flow sensor operation at different depths, and to calibrate the flow sensor *in situ*. The first part of this item will be performed on a Radium Sampler dive in September 2001. The Gems Sensors flow sensor will be inserted in series with the floating ball flow meter (Fig. 2) on this dive, and then the outputs from the two sensors during the mission will be compared.
2. To make the most use of the available PIC technology, additional functionality will be added to the RS-232 conversion circuit. This may include built-in flow integration, direct output of flow rate (rather than frequency), and simple control functionalities (start/stop/clear for flow integration).

CONSTANT FLOW SETUP RECOMMENDATIONS

1. To minimize the amount of adjustment needed to keep the small tank from overflowing, a larger overflow bulkhead and tubing should be installed. Alternatively, a simple open-channel spout at the top of the container would allow for greater overflow flow rates. This increases the possible range of flow rates from the large tank, making it easier to adjust the ball valve at the outlet of the large tank.
2. A simple sliding tray would make it easier and cleaner to shift between the bucket and beaker. A small plastic tray holding both containers, that can be easily slid with one hand, and which would catch any excess water spilled between the containers, leaves the operator's other hand free to start the timer.

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