Open Source Instrumentation Nodes for the Greater Oceanographic Community

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***Abstract*— The Monterey Bay Aquarium Research Institute (MBARI) has a long history of developing state of the art underwater instruments to support its scientific research. Often these devices are one of a kind, highly engineered pieces of equipment. While MBARI has successfully transferred technology to outside organizations, this generally required extensive training and end users with a specialized skill set. Often times, these instruments require precise machining and come with a high financial price tag. This paper outlines an approach to developing lower cost, easy to use scientific modules that have wide applicability to the greater oceanographic community. With this approach, MBARI is seeking increase access to ocean technology for science.**

The devices covered in this paper grew out of the development of the exportable Free Ocean CO_2 Enrichment (xFOCE) system. The core of this system is a series of modular building blocks which add design flexibility and ease of fabrication and maintenance. Two of the base building blocks are the Gateway Node and Sensor Node. The Gateway Node acts as a central computer which is able to control any underwater experiment. The Sensor Node acts as multi-port interface to a wide range of scientific instruments. Both nodes were designed to be open source, and thus modifiable by the end user.

Keywords- oceanographic; engineering; open-source; underwater; gateway; sensor; node; MBARI;

I. INTRODUCTION

The problem of ocean acidification (OA) due to increased absorption of CO_2 has been known for many years [1]. Scientists and engineers at the Monterey Bay Aquarium Research Institute (MBARI) have been studying it in earnest since 2005. An MBARI Institute Initiative (http://www.mbari.org/rd/projects/2011/initiatives.htm), the Free Ocean Carbon Enrichment experiment (FOCE) was established to study the long term effects of a decreased ocean pH by developing in situ platforms. One such platform was the Deep FOCE (dpFOCE) [2]. dpFOCE was deployed at a depth of 890m in Monterey Bay for 17 months between May 2011 and October 2012[3]. dpFOCE allowed various scientists to perform OA experiments, including the feeding behavior of deep sea urchins under low pH conditions.

Upon the conclusion of the dpFOCE deployment, work began at MBARI on a shallow-water FOCE system (swFOCE). Simultaneously, MBARI began receiving multiple requests for assistance and technical input from various organizations around the world on similar underwater (and often shallow water) FOCE like experiments. These included the University of Queensland, Laboratoire Océanographique Villefranche sur Mer, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). All of these organizations were developing shallow water subsea OA platforms in parallel with MBARI's new swFOCE effort. The FOCE team decided to rethink the approach it was taking in designing the swFOCE experiment. Perhaps significant portions of the swFOCE experiment could be designed in a manner that they could be used by other researchers for use in their experiments. This process led to the development of the exportable FOCE (xFOCE) [4] system.

II. NODE DEVELOPMENT DRIVERS

A broad technical trade study of the modular concept was conducted. Many factors were considered including financial cost, technical resources, deployment location, and ease of use. Multiple use-case scenarios of FOCE experiments were considered. For instance, some experiments may not have access to shore side connections (power, communications, CO_2 enriched seawater). Some experiments may have a moored surface expression connected to the subsea component. Different types of electrical power generation were considered: tether, battery, solar, diesel. Data handling methods vary from wired connections, wireless connections, local storage and physical retrieval, and satellites. CO_2 generation for low pH water is not an easy task; shore side generation, CO_2 tanks on moorings, or even scrubbed CO_2 from the exhaust gases of diesel generators were considered.

An institute level design review of the xFOCE concept was held with potential collaborators from multiple institutions in attendance. The feedback received confirmed the direction we were pursuing regarding our proposed design approach. The result of this trade study was a modular approach to the xFOCE system. The final reference design incorporated aspects which allow it to be compatible with a number of possible deployment scenarios.

The development of general purpose nodes as building blocks for experiments is a novel approach at MBARI. Instead of engineering a one-off experiment for a particular scientist, modular and adaptable sections would be designed. Based on

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the input from potential collaborators, we determined that there would be some functionality that was common to all users while other applications would be uniquely designed for specific researcher needs.

III. Implementation of In-situ Nodes

The first implementation of the modular concept was the design of the swFOCE experiment. The principles that arose from the xFOCE design review could be applied to any type of underwater instrumentation device. However, swFOCE is a perfect candidate for a modular layout due to the large number of instruments utilized.

The swFOCE experiment is located just off the coast of the Hopkins Marine Station (HMS) in Pacific Grove, Ca. An existing seawater pump house structure at HMS serves as the shore station for both swFOCE and the Kelp Forest Array (KFA) (Figure 1). The KFA is a subsea cabled observatory administered by the Center for Ocean Solutions (COS). An electrical tether supports both experiments; it contains copper conductors for power and optical fibers for communication. The swFOCE experiment consists of three major assemblies: the subsea experimental and control chambers, the shore side power and communications rack, and the shore side enriched seawater (ESW) system. The ESW and power and communication systems are housed in the HMS pump house. The electrical tether and a pair of reinforced hoses run from the pump house out to the subsea swFOCE site. The actual swFOCE site is approximately 300 meters from shore at a depth of about 15 meters of water. It is completely diver serviceable.

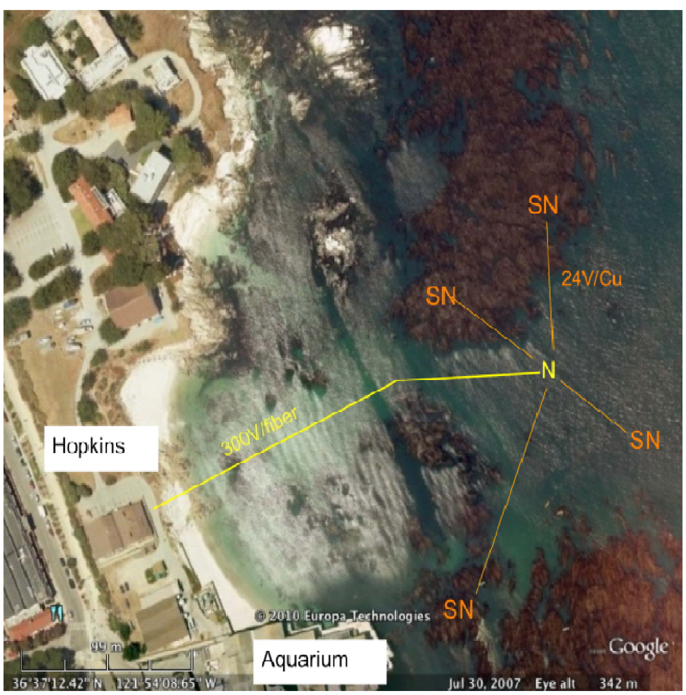

Figure 1: swFOCE/KFA site at Hopkins Marine Station. N is the location of the Kelp Forest Array Node in 15 meters of water. SN represent the KFA subnodes. The swFOCE array is adjacent to the KFA.

A. *Subsea System*

The subsea swFOCE node is fed from a Central Node which distributes power and communication to the individual swFOCE chambers. The Central Node currently supports two chambers, but can be upgraded to support six. The three primary housings on the swFOCE chambers are the Main Electrical Housing, the Gateway Node, and the Sensor Node (Figure 2). The Gateway Node and Sensor Node were designed to be open source while the Main Electronics Housing was designed around swFOCE specific instrumentation.

The Main Electronics Housing supports swFOCE specific equipment which required custom electronics. These include motors and associated drivers, an HD camera interface, and a custom relay board to control lights and power to the Gateway Node. The input to the Main Electronics Housing is the main cable from the Central Node which carries 48Vdc and Ethernet communication.

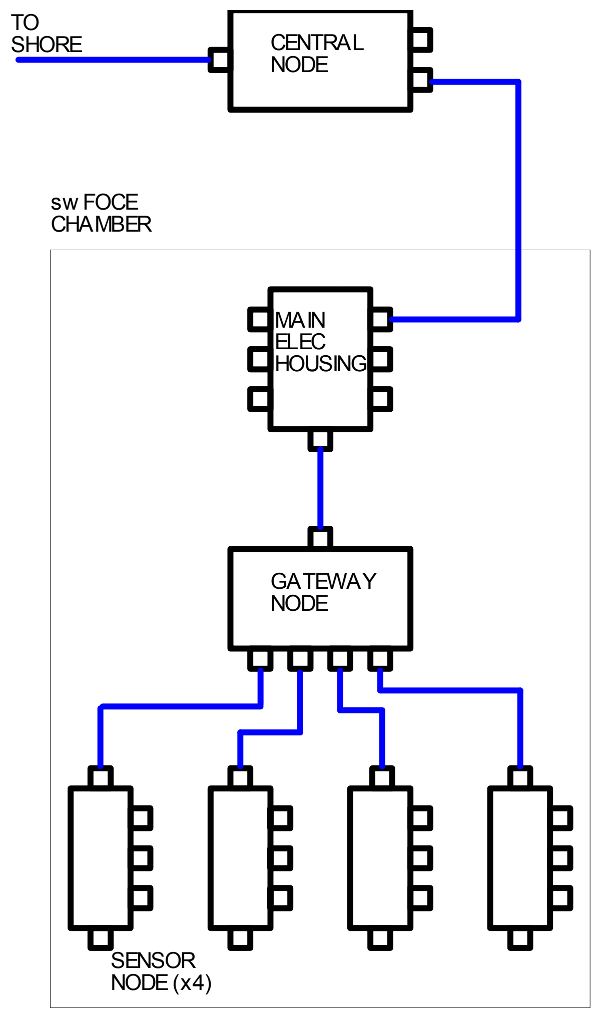

Figure 2: Block diagram of swFOCE Implementation

The Gateway Node serves as the main embedded computer in swFOCE. While it contains custom code, the computing power is sufficient to operate a wide range of experiments.

The Sensor Node is the primary interface to the instrumentation on swFOCE. As with the Gateway Node, the Sensor Node was designed to be general enough to support a wide range of instruments.

IV. Gateway Node

The Gateway Node is a modular housing that serves three primary purposes in the swFOCE experiment. It collects data from all of the subsea instrumentation, disseminates data to the shore station and peer nodes, and acts as the central computer in the experimental control loop. It communicates to the shore station and peer nodes through the Main Electronics Housing via Ethernet communication. It interfaces up to four Sensor Node modules via RS-232 serial communication. The Gateway Node also provides individual load switching of the 48Vdc bus to the Sensor Node modules.

A. Mechanical Design

The housing for the gateway node is a 25 cm (ten inch) diameter schedule 40 PVC tube. This material meets our depth requirement of 40 meters and is readily available for purchase. The diameter was chosen for two reasons: using a common size as other housings on swFOCE and to provide ample room for the enclosed electronics.

To minimize the machining requirements we decided to install a flange style fitting to the housing. This lipped flange is glued to the housing and allows the end cap to be bolted to it instead of the housing itself (Figure 3). The end caps are made from PVC and contain a single o-ring groove.

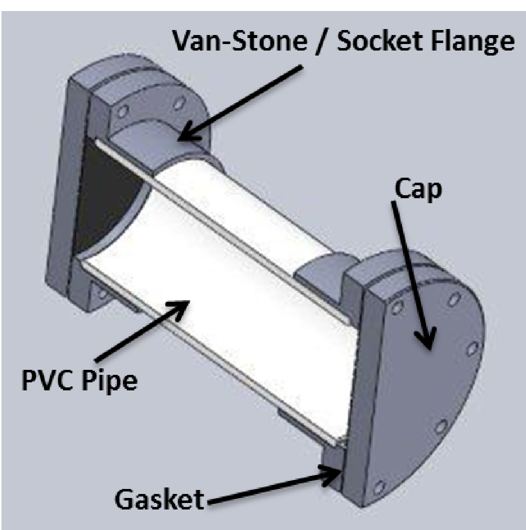

Figure 3: Mechanical housing for the Gateway Node

B. Electrical Design

The Gateway Node module consists of a Gateway Node carrier board, four chassis mount relays, and a DC-DC converter board. The four relays are used to switch DC power to the attached Sensor Node modules. Due to the 48Vdc bus and the current level involved, higher power rated off board relays were selected. The DC-DC converter is an isolating 48V:48V converter which is used to supply the Sensor Node modules only. The Gateway Node carrier board is powered directly from the input 48Vdc from the Main Electronics Housing.

The Gateway Node carrier board (Figure 4) houses a BeagleBone computer board. The BeagleBone uses a TI AM3358 720MHz ARM Cortex-A8 based microprocessor. It has an Ethernet interface, USB port, microSD card slot, four serial ports, and multiple analog and digital pins. The BeagleBone acts as the central computer for its associated node.

The Gateway Node carrier board is powered directly from the input 48Vdc from the Main Electronics Housing; this allows the full 250 watts from the isolating DC-DC converter to be shared among the four Sensor Node modules. The Gateway Node carrier board has individual load switching and power monitoring for each of the Sensor Node modules. The 48Vdc bus is split into four identical load paths; one for each of the Sensor Node modules. Current monitoring is provided by a current sense amplifier. It outputs a representative voltage of the Sensor Node load current. The signal is scaled to 1.8 volts for use with the built in 12-bit ADC on the BeagleBone. The signal is sent through a passive first order low pass filter prior to application to the ADC. Individual load switching is handled by an electromechanical relay and a coil driving mosfet. The load switching relays are chassis mounted dual coil latching 2 Form C relays; they can be activated using low side switching. Individual on and off signals from the BeagleBone drive a dual N-channel MOSFET for coil activation. Relay state feedback is also provided to the BeagleBone from the second set of poles.

The Gateway Node carrier board contains a seawater ground fault measuring circuit for monitoring the 48Vdc output bus to the Sensor Node modules. The circuit is bipolar and can monitor both the positive and negative rails of the 48Vdc. The circuit utilizes a separate isolated DC supply to minimize interference from neighboring circuits. Because the four Sensor Node modules use a common bus, the initial detection of a seawater ground fault could be in any of the four modules. The user can then manually power down the Sensor Node modules sequentially to isolate the fault.

The Gateway Node carrier board also houses various environmental sensors. The ambient humidity and temperature of the Gateway Node housing is monitored by an onboard sensor which converts the measurements to digital signals and communicates to the BeagleBone via the SPI bus. The temperature of the off board DC-DC converter is measured with a K-type thermocouple and an associated conditioning circuit. A water presence detection circuit is also included.

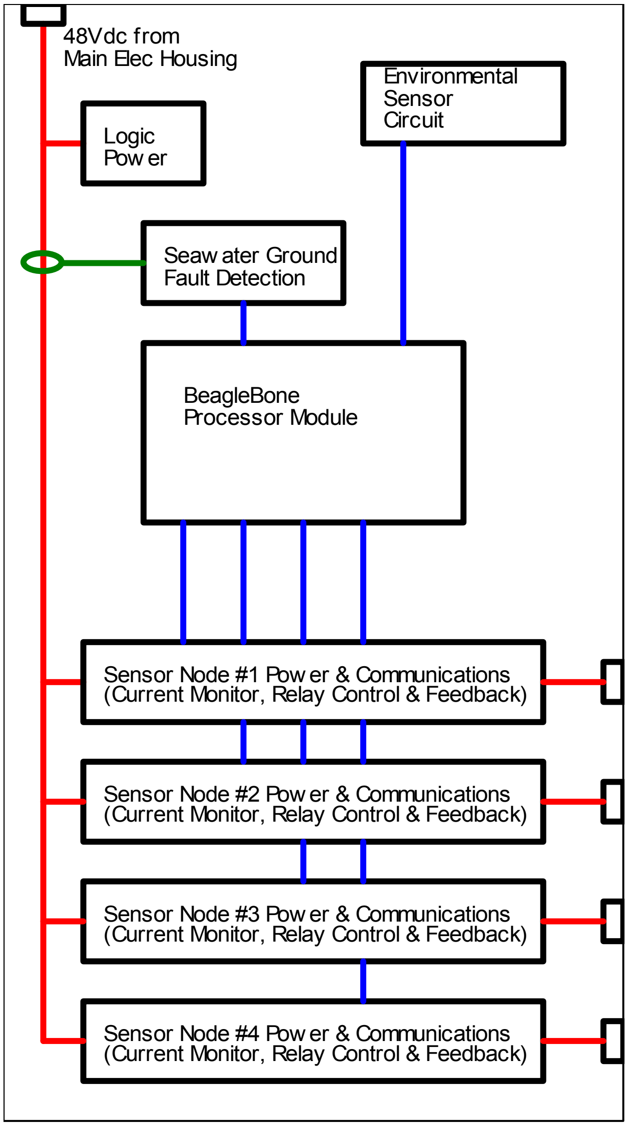

Figure 4: Block diagram of Gateway Node carrier board

C. Software Design

The core activities of FOCE software are to control pH within experimental chambers, measure conditions in and around FOCE chambers using various sensors, and enable users to observe organisms housed within chambers. The software architecture is primarily concerned with collecting scientific and contextual data, distributing and archiving it, and using the data to control the experimental process. The FOCE software design reflects the core xFOCE principles of robustness, modularity, and ease of use.

Among the design strategies for implementing these are to minimize feature and component count, use consistency and symmetry in application programming interfaces (APIs), and provide both examples and documentation that are easy to follow. Though many users will not want or need to understand the software internals, the software should be easy for developers to understand and extend. To that end, we limit the number of programming languages, use standard and portable open source libraries, choose well-established third-party libraries only when necessary, and try to enable users to use the development tools they are most comfortable with.

In general, FOCE experiments need to be operated remotely, and involve at least two sets of related observations (e.g., a control and an experiment). In the context of xFOCE, a modular and distributed architecture is used to provide the necessary flexibility and ease of use (Figure 5). The major software components for swFOCE exist in the gateway, sensor nodes, and shore side clients, and are connected by a messaging bus.

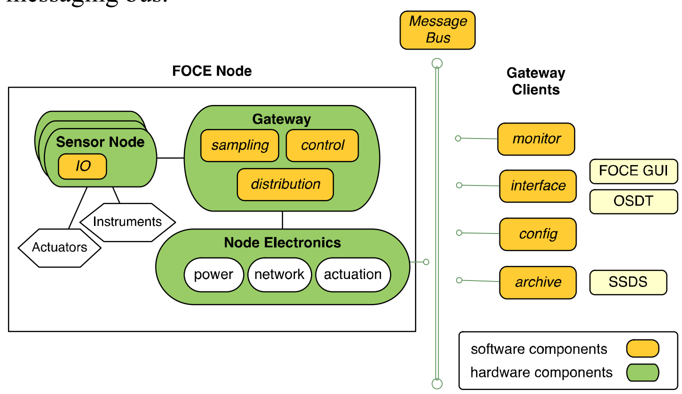

Figure 5: xFOCE software components

The gateway node sampling modules are responsible for acquiring data from instruments. A supervisor thread periodically activates a number of worker threads, which in turn evaluates a schedule and other conditions to determine whether to perform its assigned task. Sample workers may acquire a measurement from a device using an instrument module, or supervise a group of workers to coordinate or aggregate measurements (Figure 6).

Measurements are time-stamped, marked with stream ID information, and passed to a data handler module. Each data stream has an associated policy, indicating how it is to be handled: it may be logged, parsed, published, or provided. Logged data are stored in an archive (data file) on disk. Published data are broadcast on the message bus using a traditional publish subscribe mechanism. Provided data are posted to a shared data server, a sort of virtual whiteboard that stores data under named topics, and pushes updates to registered clients as they arrive from providers. Parsed data are sent to an appropriate module for parsing. The parser can generate new data streams, which are given to the data handler for further processing, per the policies for those streams. Shore side clients, for example user interfaces and configuration tools, use the message bus to access measurements and send configuration and control via node proxies.

The control modules are responsible for maintaining a specified pH (offset relative to the external environment) in the FOCE chamber. The main control module uses measurements from the pH, enriched seawater (ESW) delivery system and flow sensors obtained via the message bus and shared data server. It determines the appropriate rate for adding ESW, and adjusts the flow rate and ESW delivery by operating the associated valves and thruster motors.

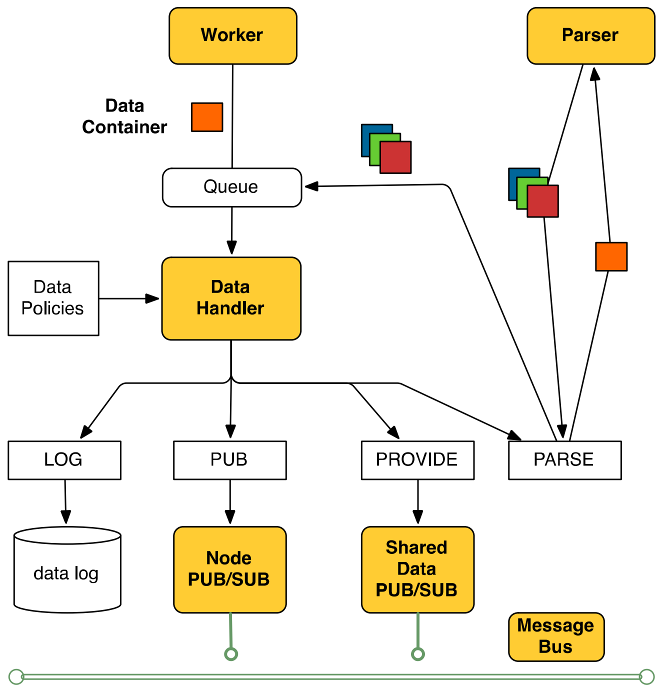

Figure 6: xFOCE Gateway data stream processing

The gateway software is a C application for the Linux operating system; the gateway reference implementation uses Beaglebone ARM hardware and uses the Angstrom Linux distribution. The message bus for FOCE is built using ZeroMQ, a lightweight and robust broker-less messaging library. The implementation language and hardware were chosen because of their broad use and portability, making them familiar and easy to implement on similar hardware platforms. Mainstream open source software is used throughout to minimize cost and provide a wide technical support network.

Code development is done using GNU automake and compiler tools, and the mercurial source control management system. For development, we use a cross tool chain running on an Ubuntu virtual machine. Gateway API documentation is generated using Doxygen, and additional documentation will be made available via the xFOCE website [5].

Much testing and debugging can be done on the virtual machine using tools such as Valgrind and gdb. The virtual machine used for development also hosts OpenEmbedded and Bitbake, which are utilities used to package a binary Linux kernel and root file system that include pre-installed FOCE gateway software. Users will be able to download a complete SD card image, making it trivial to configure a FOCE gateway node.

Users wishing to extend the Gateway code (for example to add new drivers) may use a simpler development environment. They may use their favorite development tools, making it easier to adopt and use. For example, they may build directly on the Beaglebone target, or cross compile and debug remotely using Eclipse.

V. Sensor Node

The Sensor Node is the final link in the chain of modular devices attached to the swFOCE experiment. The Sensor Node modules connect to the Gateway Node and provide a serial expansion bus for interfacing scientific instruments. The Sensor Node provides power switching and communication to three individual instruments. The output voltage is determined by the user and has a total capacity of 75 watts. Communication from the Gateway Node to Sensor Nodes is handled using the Modbus protocol over RS-232.

A. Mechanical Design

One of the primary difficulties in deploying underwater instrumentation is the design of mechanical housings. Depending on the depth rating and size, housings can easily become expensive and mechanically complicated. The design and fabrication of end caps and o-rings for even simple housings made of PVC can prove daunting. In order to make the Sensor Node housing easy to manufacture, we decided to reduce the number of underwater connectors and avoid a housing design with removable end caps.

The depth rating of the Sensor Node module is 40 meters, the nominal maximum depth for divers using air or nitrox. The relatively shallow operating depth eases some of the restrictions on housing design and material. However, we wanted to choose something that would be simple enough to build by a researcher having average skills and tools. The solution was to use a commonly available rectangular project box, and filling it with a potting compound. In place of external connectors and standard cables, we chose to use unterminated whips held in place by compression fittings. The rectangular shape coincides with the form factor of the Sensor Node circuit board, thus reducing overall volume. The rectangular form factor also helps with module placement on the actual swFOCE frame. Multiple Sensor Node modules can be stacked side-by-side, much like books on a library shelf.

There are a total of five whips extending from the housing: one input from the Gateway Node, three primary science ports, and one high power port. The whips are fabricated by Subconn using their standard Micro connectors attached to a Falmat cable section. The Subconn Micro connectors can be mated underwater, making it possible for divers to change instruments, or even the Sensor Node itself.

B. Electrical Design

The Sensor Node (Figure 7) performs two main functions for the attached scientific instruments: providing DC power and communication. The input to the Sensor Node from the Gateway Node is 48Vdc for power and RS-232 serial communication. The Sensor Node has three primary instrument output ports and one high power port. The three primary ports can deliver up to 2 amps each at the selected bus voltage and serial communication. The high power port has no communication, but can provide up to 6 amps at the selected bus voltage. Instrument port #3 has a user selectable option to accommodate a 4-20ma instrument. Other functions include individual port power switching, load current monitoring, and state feedback. Serial communication is handled by individual RS-232 transceivers. The heart of the Sensor Node is a PIC24 microcontroller; it is programmed with a Modbus interface which handles all internal and external I/O. An onboard 16-bit ADC is used for all analog measurements.

The Sensor Node circuit board (Figure 8) was designed with cost effectiveness and parts availability in mind. Inexpensive parts were used whenever possible and only currently available parts were chosen. The same parts were used where appropriate to minimize the number of different components. Power usage was also a primary design consideration. The background power usage with no instruments on is less than two watts.

Because the Sensor Node was built to interface a wide range of peripherals, the DC output voltage level and available power can be selected to meet the individual science user's needs. The Sensor Node board houses a single DC-DC converter, but will accept five families of converters, in two separate packages. The converters range in output power from 10 watts to 75 watts and the fixed output voltages range from 12Vdc to 48Vdc. Optional trim up and down resistors can be added if a non-standard voltage is desired. The selected bus voltage, however, is common to all four output ports. The ability to select a lower power DC-DC converter was added in the event that the Sensor Node is used on a system with limited power, such a battery powered experiment. Using a lower power converter reduces efficiency losses. The input and output filters for the DC-DC conversion stage were designed to accommodate any of the converters. After the output filters, there is a voltage and current sensing circuit. This reports back the total amount of power being consumed by all of the attached loads. It is up to the user, however, to verify that the maximum power rating of the converter is not exceeded when selecting instruments.

The three primary instrument ports are operated independently from one another and are identical with the exception that number three has a user defined option for utilizing a 4-20ma instrument. The load current of each science port is measured by a circuit utilizing a current sense amplifier which has a fixed gain of eight and it outputs a voltage which is representative of the measured current. The scaling is such that slight over current conditions can still be measured. The output goes through a passive first order low pass filter prior to the octal 16-bit Successive Approximation Register (SAR) ADC which uses SPI bus for communication. Load switching is handled by an electromechanical relay and a coil driving mosfet. To save power, a dual coil latching relay was selected; separate 20msec pulses turn the relay on and off. State feedback is monitored through the second set of poles.

Each of the three instrument ports has two lines for serial communication. On port #3, jumpers allow the transceiver to be bypassed and instead, a 4-20ma interface circuit is accessible. The 4-20ma signal is converted to a 0 to 3 volt signal. This signal is routed to the octal ADC. If not utilized, these parts can be no-stuff without affecting the remaining board operability.

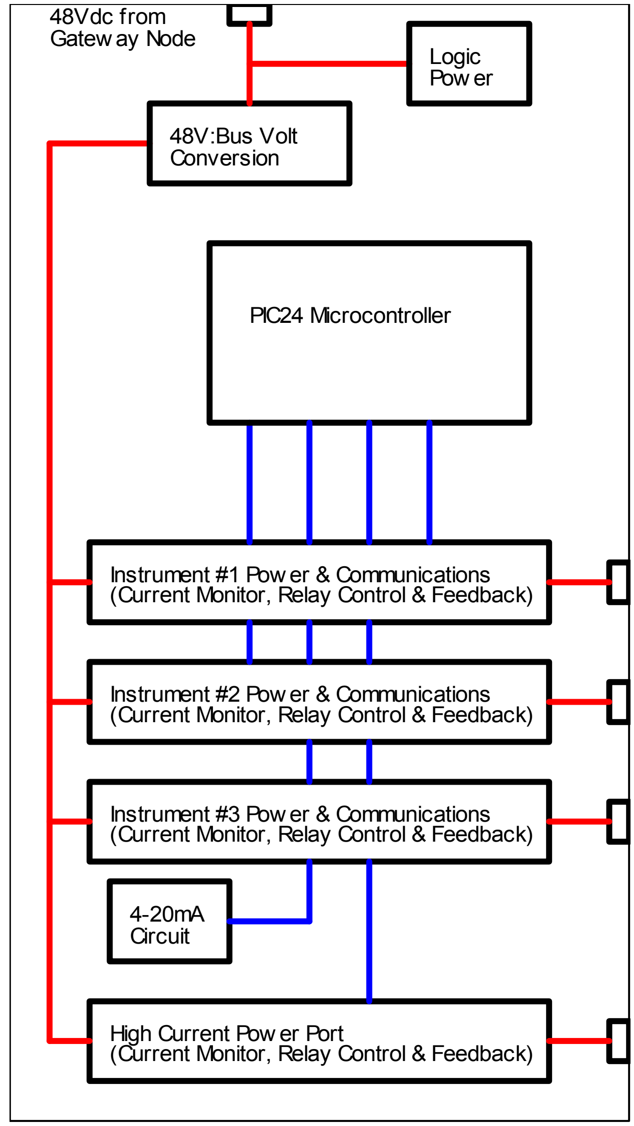

Figure 7: Block diagram of Sensor Node board

A fourth, high power port provides the user the ability to drive a simple device such a motor or pump; it can handle a maximum of 6 amps. Like the primary instrument ports, the load current is monitored and load switching is handled via an electromechanical relay of MOSFET driver.

The onboard microcontroller is a 16-bit PIC24FJ256GA106. The Sensor Node board is populated with a programming connector and a serial port that connects to the Gateway Node can be used a debugging port. An LED, which is brought out to the housing, can also be used as an optional heartbeat signal.

Due to the number of possible configurations for the Sensor Node, the user has the option of setting an 8-position dip switch. This allows a query at a later time to verify the configuration. These eight bits are read directly by the microcontroller.

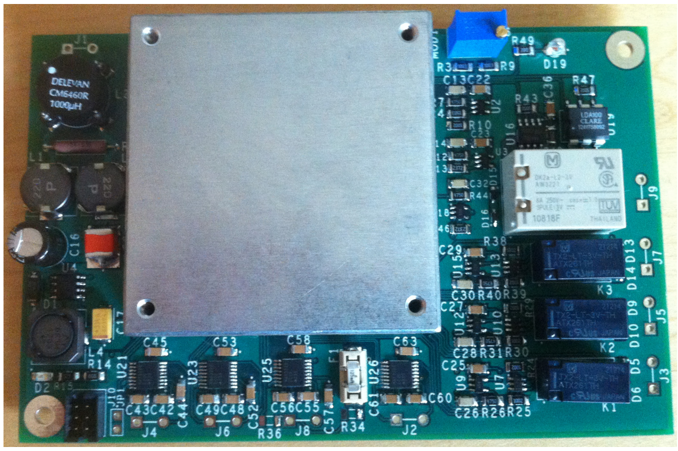

Figure 8: Sensor Node circuit board

C. *Software Design*

In order to provide the most general and accessible interface to the Sensor Node, we decided to implement the interface using Modbus over Serial Line [6].

Modbus Protocol is a messaging structure developed by Modicon in 1979. It is used to establish master-slave/client-server communication between intelligent devices. It is a de facto standard, truly open and the most widely used network protocol in the industrial manufacturing environment. It has been implemented by hundreds of vendors on thousands of different devices to transfer discrete/analog I/O and register data between control devices. It's a lingua franca or common denominator between different manufacturers. One report called it the "de facto standard in multi-vendor integration". Industry analysts have reported over 7 million Modbus nodes in North America and Europe alone [7]. There are numerous tools and software packages for interfacing to Modbus devices, including National Instruments' Labview and the open-source project libmodbus. There are also many useful software and hardware tools for debugging. We did our initial debugging by using Modbusview, shareware software from Ocean Controls.

The embedded code on the Sensor Node is built on freemodbus, an open-source implementation targeted specifically for embedded systems. This was ported to the PIC24J CPU on the Sensor Node board. We then wrote higher-level modules to expose the Sensor Node hardware capabilities (instrument serial ports, power switches, A/D) via Modbus Holding Registers and Coils.

We also wrote an interface library, called snLib, for the Gateway node, to provide easy and convenient access to the Sensor Node resources. SnLib provides convenience functions for actions such as: open and close Sensor Nodes, open and close serial ports, serial read/write/flush/init/etc, control of power relays, A/D conversions, etc. SnLib was written using libmodbus.

VI. Open Source Resources

The Gateway Node and Sensor Node were developed to be general enough to be used in a wide range of applications. In keeping with the open source concept, modifications to our original design are to be expected and welcomed. A full set of documentation will be available on the xFOCE.org community site. This will include all pcb fabrication files, bills of material, mechanical drawings, written instructions, and technical notes. A user's forum is also available for technical help and to post user specific designs.

VII. Conclusion

A modular approach to underwater instrumentation has been demonstrated by the design of the swFOCE experiment. This approach was undertaken due to the many requests for assistance from external organizations. A lengthy trade study and design review resulted in a widely accepted modular approach to the swFOCE experiment. The design of the modular pieces, however, lends their use to a wide range of underwater experiments. The xFOCE.org website has been established to help support this effort. It is hoped that this work will be enthusiastically embraced by the greater oceanographic community.

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References

[1] Caldeira K, Wickett ME 2003 Anthropogenic carbon and ocean pH, NATURE 425 (6956): 365-365 Sep 25, 2003

[2] Walz, P.M., Kirkwood W.J., Peltzer E.T., Hester K.C., & Brewer P.G., 2008. Creating controlled CO_2 perturbation experiments on the seafloor - development of FOCE techniques. Proceedings of the Marine Technology Society / Institute of Electrical and Electronic Engineers Kobe Techno-Ocean 1:1-4.

[3] Monterey Bay Aquarium Research Institute. (2011). *First controlled experiments on ocean acidification in the deep sea* [Press release]. Retrieved from http://www.mbari.org/news/homepage/2011/foce-bio/foce-bio.html

[4] *xFOCE Systems: Present Status and Future Developments Workshop*, UPMC - Observatoire Océanologique de Villfranche-sur-Mer, Villfranche-sur-Mer, France, Dec 10 to 12, 2012.

[5] Monterey Bay Aquarium Research Institue. (2012, Nov 1). Title (edition) [Online]. Available: http://www.xFOCE.org

[6] Modbus-IDA.org (2006, Dec 6). MODBUS over serial line specification and implementation guide (V1.02) [Online]. Available: http://www.modbus.org/docs/Modbus_over_serial_line_V1_02.pdf.

[7] Modbus-IDA.org (2006, Dec 6). MODBUS Frequently Asked Questions [Online]. Available: http://www.modbus.org/faq.php.