A sensor network platform to study impact of ocean acidification in deep water environments.

Tom O'Reilly[†], Kent Headley[†], Bob Herlien[†], Karen A Salamy[†], Sameer Tilak[‡], Duane Edgington[†], Tony Fountain[‡], Peter Brewer[†], Bill Kirkwood[†]

[†] Monterey Bay Aquarium Research Institute Email: {oreilly,headley,bobh,salamy,duane,brpe,kiwi}@mbari.org
[‡]University of California, San Diego Email: {stilak,tfoundain}@ucsd.edu

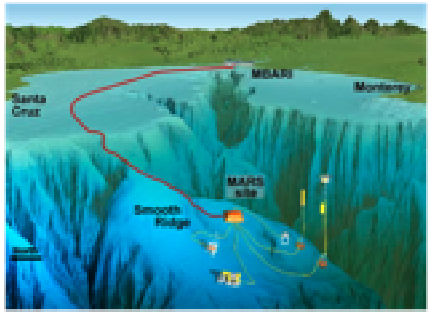
Scientists and engineers at the Monterey Bay Aquarium Research Institute (MBARI) are developing sensor network technology to better understand anthropogenic ocean acidification. Burning of fossil fuels has produced cumulative CO2 emissions on the order of one trillion tons since the beginning of the Industrial Revolution. While approximately half of this CO2 remains in the atmosphere today, the ocean is the main repository for the balance. Experiments and observations suggest that CO2 ocean enrichment and the resulting acidification will inhibit formation of calcium carbonate exoskeletons, and may have major impacts on marine ecosystems. To study these effects on marine ecosystems in situ, MBARI has developed the Free Ocean Carbon dioxide Enrichment (FOCE) system [1]. In contrast to laboratory experiments, FOCE directly measures effects in the ocean environment, and is designed for deployment in deep locations such as the Monterey submarine canyon.

FOCE consists of a flume that is open to the ocean on the bottom and ends (see Figure 1b). CO2-enriched seawater is injected into either end of the flume (depending on the direction of ambient currents) and flows into a central chamber, which holds biological specimens, cameras, and sensors. The flow may be driven entirely by natural ambient currents or regulated using fans and baffles. The control loop will have several modes of operation, but typically will be used to maintain a constant pH offset from the surrounding environment. In this way, the conditions in the chamber simulate ocean acidification conditions corresponding to projected future atmospheric CO2 levels. FOCE sensors include pH, temperature, salinity, and current sensors inside and outside the flume as well as lights and cameras. These sensors are connected to a PC-104 style embedded computer with 500 Mhz CPU, 1 GB memory, and 160 GB notebook drive for persistent storage. The FOCE system is now full scale and installed in deep waters in the Monterey Bay Canyon. FOCE is connected to Monterey Accelerated Research System (MARS: http://www.mbari.org/mars) deep-sea cable-to-shore observatory node in Monterey Canyon in 900 meters depth at the end of the 52 kilometer cable (Fig. 1a). The MARS cable provides Gigabit Ethernet communications over optical fiber, and hence supports sensors with very high data rates. To the best of our knowledge, this is the first deep water sensor network deployment aimed at understanding impact of ocean acidification on marine life. The FOCE equipment is designed with a goal of deployment cycle of 1-2 years duration.

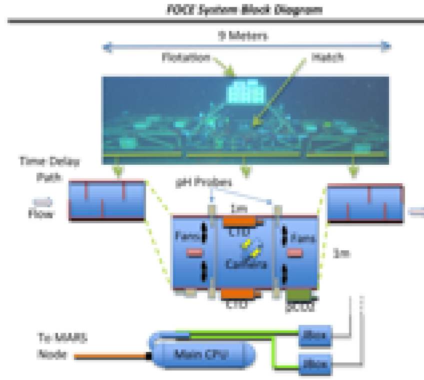
Designing and deploying the FOCE testbed presented several research and engineering challenges including provisioning of electric power and networking capabilities, engineering of the FOCE tube, integration of a broad range of sensors, and design of development of software infrastructure for the data plane (for data acquisition) and control plane (to remotely command and control sensors), and sustainability of the testbed (e.g., upon deployment, FOCE testbed will be visited by an ROV on a periodic basis for CO2 replenishment). FOCE is a technology concept with potentially many different implementations ranging in size and complexity. For example, a version of of FOCE developed in collaboration with University of Queensland is designed for use in a few meters of water on a coral reef. It requires much less infrastructure, and may be installed and operated without a vessel. The software framework is designed and developed in a modular fashion such that it is applicable to other projects at MBARI. Our goal is to make the hardware and software technology freely available to the oceanographic community world-wide.

MBARI team members have collaborated with University of California (UCSD) team to design and develop data plane and control plane software framework for FOCE experiments. MBARI has developed network middleware known as SIAM to operate sensors deployed on TCP-IP network-based ocean observatories [2]. Each physical sensor in an observatory can be accessed through a corresponding SIAM instrument service. The instrument service interface defines generic methods to configure, control, and acquire data, while the service implementation maps between the generic interface and specific sensor protocols. Thus diverse non-standard sensor protocols are hidden by the uniform SIAM instrument service interface, resulting in an instrument network that can be accessed and managed in a straightforward way. This architecture also provides a foundation for more sophisticated science applications with remote control and autonomous operation requirements. SIAM is designed for use on oceanographic observatories that are connected to shore through low-bandwidth satellite links, as well as systems that are connected to shore via power/communication cable.

SIAM service network interfaces are implemented with Java RMI, which provides object-oriented remote procedure



(a) FOCE deployment.



(b) FOCE testbed and its schematic .

Fig. 1: FOCE Testbed

calls through which a client synchronously invokes the service's RMI methods to interact with the corresponding physical sensor. This synchronous interaction style was sufficient for initial deployments of SIAM on low-bandwidth-to-shore moored observatories, but now SIAM is being used on the Monterey Accelerated Research System (MARS) deep-sea cable-to-shore observatory. In this context, an asynchronous data "push" mechanism would be much more efficient that SIAM's synchronous data "pull" methods.

To effectively utilize the available available bandwidth, we've now integrated SIAM with Open Source Data Turbine (OSDT) middleware [3]. OSDT middleware provides asynchronous communication links between distributed components, and is particularly well-suited to streaming sensor data. OSDT provides a subscribe-publish API, and also supports discovery of data sources at run-time. Combined with the existing synchronous SIAM framework, these features enable efficient architectures for applications such as event detection and distributed control loops. SIAM and OSDT will be used to implement closed-loop control of pH in the test chamber. This will allow us to do in-network processing thereby allowing us to command and control the sensors in real-time without having to communicate with the shore side data center. We are currently investigating in-network processing capabilities that can work well in our resource- constrained environment.

The goal of this demonstration is to describe how the FOCE application software can be implemented in an efficient manner with SIAM and Open Source Data Turbine and we will show "live" human interaction with the deep sea deployed FOCE system that uses that uses SIAM-OSDT for its data acquisition at transport. We believe the lessons learned and experiences gained in design, development, and deployment of this deep-water sensor network (both hardware design and software framework) will be invaluable to the sensor network community. In addition, the demonstration will give us a chance to get feedback from the sensor network community and help us refine our work if needed.

REFERENCES

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