FUTURE DEVELOPMENTS AND APPLICATIONS OF MARINE ROBOTICS

James G. Bellingham and Brett Hobson

*Monterey Bay Aquarium Research Institute,
Moss Landing, CA USA*

Abstract: In the coming decades, marine robotics will transform human activities in the ocean, providing an adaptable and pervasive presence in portions of the planet all but inaccessible today. Fleets of mobile robotic systems, capable of autonomous operation, will draw power and communicate through networks of subsea cables and arrays of deep-water moorings. Sophisticated teleoperated systems will be used to install, operate, and maintain seafloor equipment. Researchers and the general public will access these systems through internet portals which will make complexities of data search and synthesis transparent to the user.

Keywords: autonomous, mobile robots, robotics, marine systems, telecontrol.

1. INTRODUCTION

As our understanding of the comparative delicacy of Earth's ecosystem increases, so to does our appreciation for the ocean's central and complex role in climate change. Yet our ability to observe the ocean, especially its interior, is largely based on expensive and old technology relying heavily on human presence. Marine robotics impacts this in important ways, at one extreme enabling comparatively small and inexpensive autonomous platforms capable of being deployed in large numbers, and at the other extreme providing systems which support teleoperation of increasingly complex activities.

Continuing improvements in computing power, memory, and communication bandwidth underpin the increasing sophistication of autonomous and semi-autonomous systems, making more complex algorithms practical in real-time application on small power-limited systems. At the same time, advances in subsea telecommunication and mooring cable technology are converging to allow the extension of power and communication from land to the interior of the sea. When combined with the Internet, these capabilities cumulatively promise to open the ocean not just to scientists, but to everyone.

This paper provides a brief overview of some emerging classed of ocean observing systems, and highlights their capabilities. Underpinning technologies include Autonomous Underwater Vehicles (AUVs), seafloor cables, advanced deep-water moorings, satellite communications, acoustic communications, and assimilative ocean models. Often these developments are proceeding in separate communities. For example, development of mobile platforms have been largely driven by physical, chemical, and biological oceanography needs, while seafloor observatories have been motivated largely by marine geology and geophysics requirements. Yet the various activities are highly complementary, provided linking elements, for example AUV docks, can be brought to practical use.

2. EMERGING CLASSES OF OBSERVATORIES

A variety of observatory classes are emerging today, with different strengths and weaknesses. Some systems make extensive use of Autonomous Underwater Vehicles to provide a flexible and reactive presence in the ocean. The Autonomous Ocean Sampling Network (AOSN) paradigm is prototypical of mobile platform-centric approaches [Curtin et al, 1993]. Other systems focus on the extension of power and communication infrastructure into the ocean. While these systems are largely being developed by different communities, they are highly complementary in nature.

The crucial role of ocean observatories in 21st century ocean studies was recognized by the U.S. National Research Council in their report entitled Illuminating the Hidden Planet [NRC, 2000]. The NRC concluded that "Seafloor observatories present a promising, and in some cases essential, new

Fig. 1. Autonomous Ocean Sampling Network deployment in Monterey Bay.

approach for advancing basic research in the oceans." More broadly, the recommendations of the Ocean Sciences at the New Millennium report [NSF, 2001] state that "The profound impact of new technologies for executing novel experiments and for capturing new data from the oceans is a theme that runs throughout this report. Their success justifies a vigorous effort in technology development, implementation and support in all areas of ocean science. … New fixed (cabled and moored) and mobile (ROV, AUV, drifter) ocean observing systems are an essential complement to ships and satellites, and must be deployed if critical events are to be captured." Based on these and many other reports, the National Science Foundation has proceeded with the Ocean Observatories Initiative to support long-term research observations and interactive experiments from the sea surface to the seafloor and beneath. Observatories at coastal, regional, and global scales are included in this initiative.

2.1 Mobile Platform-Based Observatories.

The proposition that the ocean is under-observed is one with which most oceanographers would instantly agree. However, aside from simply spending more money and deploying more ships, how can we do better? The Autonomous Ocean Sampling Network, (AOSN) concept is an approach that seeks to bring a host of new technologies to bear on the observation problem, from AUVs, to gliders, to acoustic communications. By linking these systems to assimilation and modeling systems, AOSN provides a more effective tool for combining measurements into a single 'picture' of the ocean, or part of the ocean, and to develop some quantitative methods to plan more effective sampling strategies. Work towards this goal of integrating an adaptive, mobile observation system with assimilation-modeling tools has now been underway for over a decade.

In the early 90s, AUVs and emerging communications capabilities were recognized as providing the building blocks for creating networks of autonomous vehicles. In the AOSN vision, the operation of observation elements within a communication infrastructure allows one to couple real-time ocean models to the observation system. Models provide a sophisticated tool for synthesis of observations, a predictive capability, and a tool for planning observation strategies. The mobility of observation elements provides wide latitude in the modification of observation plans, for example to better satisfy the needs of the predictive models. Thus adaptive sampling is a central element of AOSN.

At the heart of AOSN are mobile platforms. Two classes of mobile platforms are used: faster propeller driven AUVs, and longer endurance buoyancy driven gliders. The propeller-driven vehicles typically operate at speeds of 1.5 m/s and carry payloads consuming tens or even hundreds of watts. The gliders operate closer to 0.35 m/s, and carry payloads consuming on the order of one watt. While the propeller-driven vehicles typically carry much more comprehensive instrument suites, the gliders have much greater endurance. Gliders are able to operate for months at a time, while propeller-driven AUVs will typical run for a day.

For vehicle developers, the goal has been the creation of small, high-performance systems to support multiple vehicle operations. Small systems can be operated with less support equipment, by fewer people and from smaller ships. Increased robustness to mishandling makes small vehicles more amenable to deployment and recovery in rough weather. Finally, manufacturing costs are lower, especially since small vehicles can make use of materials and manufacturing techniques, such as plastics and vacuum forming, not practical for larger platforms.
Cumulatively, these factors strongly enable multi-vehicle operations by reducing operational and hardware costs.

A large number of AOSN field programs have been carried out; the 2003 field program in Monterey Bay provides a useful example. Over 21 autonomous robotic systems, three ships, an aircraft, CODAR, drifters, floats, and numerous fixed (moored) observation assets were used in the field program to produce an unprecedented data set of upwelling and relaxation processes in the vicinity of Monterey Bay. A combination of gliders and AUVs were employed, respectively, to obtain sustainable presence as well more heavily instrumented observations.

How is AOSN configured and operated? Figure 2 shows the various phases of design and operation roughly followed in AOSN experiments. On the left, the planning process outlines the progression from the definition of the goals of the experiment, through the identification of tasks, to the selection and allocation of specific assets to tasks. An example of a goal might be to predict oceanographic temperature and salinity fields in a particular volume. Typically a given experiment will have a large number of goals reflecting the varied research interests of the investigators involved. Documentation of this process for the 2003 field program can be found at http://www.mbari.org/aosn/Documents.htm.

During the experiment design process a key step is identifying the observation tasks and allocating assets to those tasks. The designers must understand the capabilities of the possible elements as they relate to achievement of the goals. For example, monitoring the interaction of the California current with the coastal waters requires a platform that can dive to about a thousand meters. Observing the biological response to upwelling requires a platform carrying biological sensors. To allocate assets to these tasks, one must understand how well they will perform. How many gliders will it take to maintain a synoptic characterization of the California current? The measurement is complicated by the fact that gliders move slowly, and the processes being characterized will change significantly before an observation is complete. This is the essence of the experiment design problem. The importance of platform technology should be clear. For example, the observation quality is improved if platforms can complete measurement rapidly (e.g. if they have a higher coverage rate).

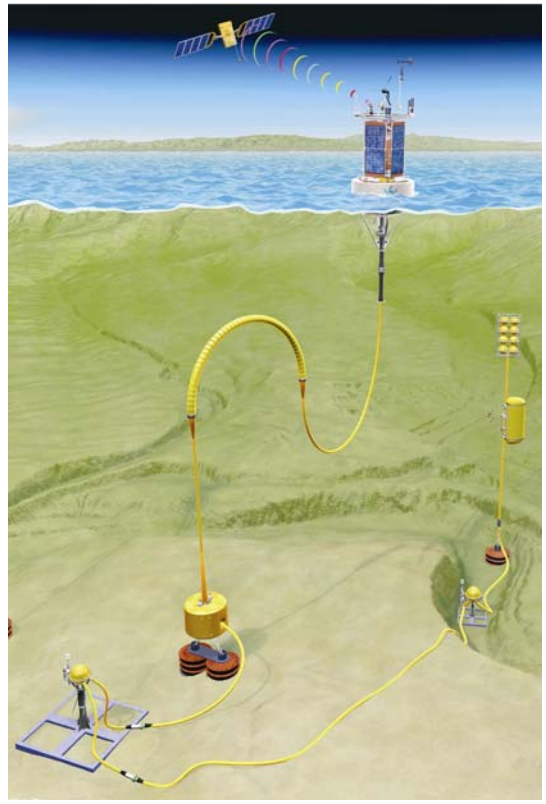

Fig. 3. MOOS Mooring. The MOOS mooring electro-optical-mechanical cable allows power and communications to be provided from the surface to networks of instruments on the seafloor.

AOSN is a distributed observatory concept. Its goal is characterizing and predicting ocean properties. Its performance is determined by the size of the volume it can successful characterize, and the fidelity of its observations and predictions. However, many key measurements for such a system must be made from a propeller-driven AUV, and such vehicles are still heavily dependent on ships. Consequently, an important goal for creating sustainable, economic Autonomous Ocean Sampling Networks, is extending the operational capabilities of its mobile

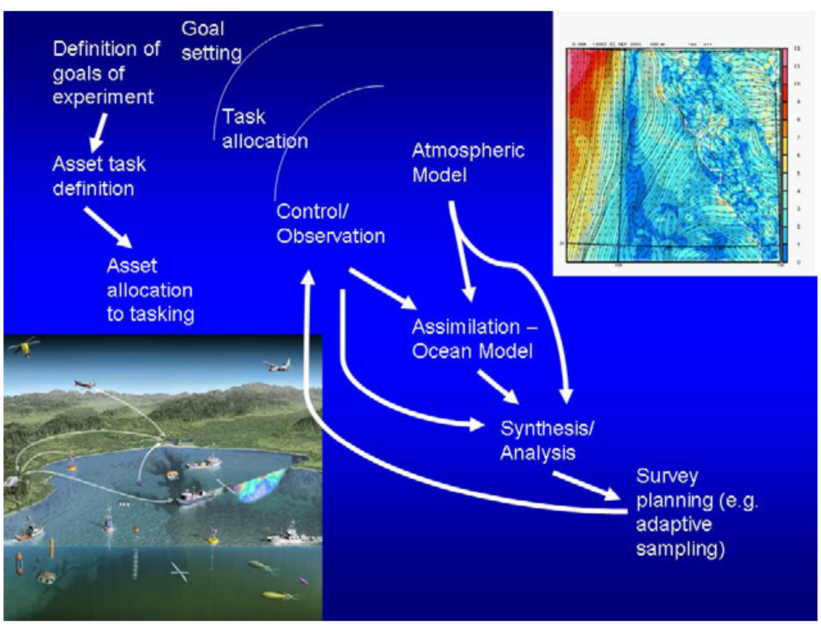

Fig. 2. Stages of design process and experiment management for AOSN field program.

robotic assets.

2.2 Mooring-based Observatories

Moorings can provide power and communication gateways to the seafloor, thus enabling a class of observatories supporting networked seafloor instrumentation in remote regions of the world. The surface expression of the mooring can be equipped with satellite communications and various power generation systems. For example, solar power, wind power, and even diesel power have all been used to improve on batteries as an energy source. At the seafloor, ROV-laid cables can extend power and communication from the mooring base to networks of instruments on the seafloor.

A major development emphasis at MBARI has been a new generation of mooring system, the MOOS mooring, capable of providing observations of water-column and benthic processes in near real-time [Chaffey and Mellinger, 2001]. The cable provides a fibre-optic and copper connection from the seafloor to the surface float. Radio and satellite based communications between shore and the mooring enable instrument query, control, event detection, and response. The mooring is designed to be deployed from regional class vessels in waters up to 4000 m. A number of test deployments of the system have been carried out, and the first major science deployment is now underway off the California coast.

2.3 Cabled Observatories

Cabled ocean observatories promise to provide a powerful infrastructure supporting scientist's observations and experiments in the ocean. Enabled by a range of technological developments in the telecommunications and computer industries, small-scale cabled observatories have demonstrated the scientific utility of delivering power and high-bandwidth communications to the seafloor. LEO-15 is an early cabled observatory which is deployed in 15m water depths [Grassle et al.,1998]. MARS is a more advanced system being deployed off Monterey, California at a depth of 900m (see figure 4). A large system, with thousands of kilometres of cable, is being planned for deployment on the Juan de Fuca Ridge under the ORION program.

Cabled observatories offer the prospect of providing nearly unlimited power and connectivity to the deep ocean – at least by normal oceanographic standards. For example, MARS will be cable of providing up to 10 kW to connected devices. The combination of high-bandwidth and power will support a new generation of sophisticated instrumentation for oceanography. The promise of this can be understood by extrapolating from the evolution of Remotely Operated Vehicles (ROVs). The early ROVs were effectively eyeballs in the ocean. Very quickly, manipulators were added, and ROVs began to be used for tasks like recovery of objects. As more specialized work packages were developed,

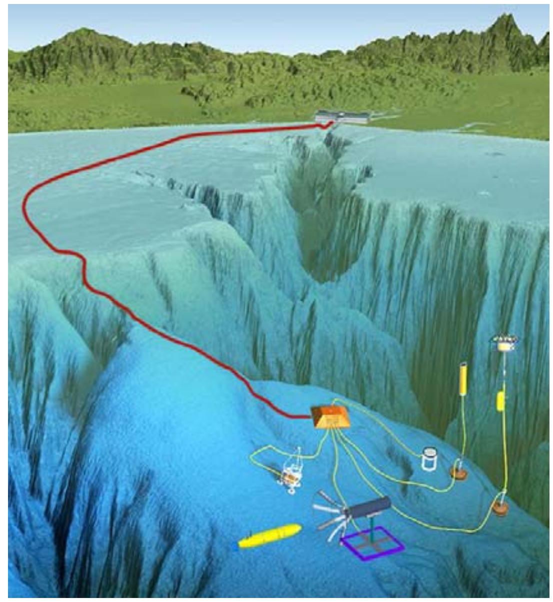

Fig. 4. MARS cabled observatory. The MARS cabled observatory will provide 10 kW of power and Internet connectivity to instruments at 900m water depth off the coast of Monterey.

ROVs could carry out more complex activities such as assisting in assembly of underwater structures. Recently, ROVs have been used as laboratories in the oceans. Devices like laser Raman and nuclear magnetic resonance spectrometers were carried to the seafloor on an ROV, allowing process experiments to be carried out in situ [Kleinberg et al., 2002; Brewer et al., 2003]. Cabled observatories offer the same potential for in situ experiments with complex instrumentation. The difference will be that the scientists will be able to conduct their experiments from anywhere they have access to the Internet, and will not be limited by the need to recover the ROV to the ship and return to shore.

3. USING OBSERVATORIES

Maturing hardware capabilities have provided the opportunity to learn how ocean observing systems can be used most effectively. For example, AOSN efforts in the mid 90s primarily focused on hardware and software debugging. In the late 90s, attention shifted to putting observation system elements together, and the complex trade space for observation system design began to come into focus. The AOSN II experiment in 2003 demonstrated that individual elements, including models, were mature enough to be integrated into a collective system, but at the same time, highlighted sensitivity of system performance to the effectiveness of the data system. Analysis of the 2003 experiment provided spatial and temporal statistics on variability which allowed synoptic performance of different survey system configurations to be quantified [Bellingham and Zhang, 2005].

The nature of interactions of investigators has changed greatly over a decade of AOSN research. Perhaps the greatest change came in 2003 during the

AOSN II experiment. AOSN investigators decided to let an operational team control the disposition of all the observational assets. They also agreed to share data among team members, and publish graphical data and model products to an open site web immediately. These decisions were made with no small degree of trepidation. Customarily, investigators maintain the authority to direct their own observational assets during field programs, and data is held private for one or two years. However, the coordinated operation of the observation elements lead to an extremely powerful data set, and the open nature of the experiment created a high visibility for the field program. In an experiment recently completed in Monterey Bay – the Monterey Bay 2006 experiment - these same arrangements were adopted as a matter of course.

4. FUTURE

What does the brief history of ocean observing systems let us say about the future? What are the emerging trends, and how might these be extrapolated? New technological capabilities have profound impacts on the way oceanographers run their experiments, work with their data, and interact with their colleagues. Evolution in scientific practices has, in turn, profound implications for the demands scientists will make for new technical capabilities.

Ocean observing systems are in their infancy. The first large scale systems have yet to be deployed. Perhaps most notable, development of instrumentation that takes advantage of power and communications capabilities of mooring and subsea cable observatories has hardly yet begun. Consequently, a wide range of exiting opportunities awaits the marine robotics community. Possibilities include the development of sophisticated seafloor instrumentation to conduct in situ experiments, the development of ROVs designed to operate as part of a cabled observatory infrastructure, and the creation of practical AUV docks that could be attached to seafloor cabled and mooring-based observatories.

The ability to dock AUVs is an important need of next-generation seafloor observatories. Most seafloor observatory studies, starting with the 'Illuminating the Hidden Planets' report, identify docking capabilities and autonomous underwater vehicles as essential to enabling a wide range of observatory science. From a scientific perspective, docking systems open a new window into the ocean. The AUV provides a capability for establishing the spatial context of measurements made by fixed instruments. By supporting extended deployments, the dock enables multiple surveys. Thus sequential spatial snapshots of a given environment can be obtained to trace the evolution of small-scale oceanographic features. Perhaps most important, docking creates a powerful new capability for studying episodic ocean processes such as weather driven events, biological blooms, or volcanic eruptions.

Fig. 5. MBARI docking station being deployed prior to docking operations with a Dorado class AUV.

In a larger sense, docking merges mobile observatory approaches, such as AOSN, with the fixed seafloor observatories. For this reason, docking has been an important objective of MBARI's observatory program [Bellingham et al., 2006]. Figure 5 shows the deployment of a docking station in Monterey Bay prior to demonstration of docking, including homing, AUV battery charging, communications, vehicle reprogramming, and data extraction. This work was carried out using the Monterey Inner Shelf Observatory (MISO) cabled observatory built and maintained by the Naval Postgraduate School. A successful AUV docking capability creates the potential for large numbers of AUVs operating from moorings and seafloor cables distributed through the world's oceans.

While technological advances make new ocean observing systems possible, it is the pressing need to understand the ocean that drives their construction. Thus the great opportunities being created for the marine robotics community come with a responsibility to better understand the needs of the oceanographic science. Just as scientists are beginning to adapt to the opportunities and demands of observatory technology, marine technologists must learn to work more effectively with the diverse disciplines within oceanography. Together we can open new windows on the underwater world.

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REFERENCES

Bellingham, J. G., McEwen, R. S., and Hobson, B. W., (2006). The Development of a Docking Station for a Regional Cabled Observatory, *Proceedings of Scientific Submarine Cable 2006*, Dublin Ireland.

Bellingham J. G., and Zhang, Y. (2005). Observing Processes that Vary in Time and Space with Heterogeneous Mobile Networks, *Proc.*

International Workshop on Underwater Robotics for Sustainable Management of Marine Ecosystems and Environmental Monitoring, Genoa, Italy, pp 9-16.

Brewer, P.G., Malby, G., Pasteris, J.D., White, S.N., Peltzer, E.T., Wopenka, B., Freeman, J., Brown, M.O. (2004) Development of a laser Raman spectrometer for deep-ocean science. *Deep-Sea Res. I*, **v. 51**, 739-753.

Chaffey, M., Mellinger, E., and Paul, W. (2001). “Communications and Power to the Searfloor: MBARI’s Ocean Observing System Mooring Concept,” OCEANS 2001, **4**, 2473-2481.

Curtin T., Bellingham, J. G., Catipovic, J., and Webb, D., (1993). “Autonomous Ocean Sampling Networks,” *Oceanography*, **6**(3), pp 86-94.

Grassle, J. F., Glenn, S. M. and von Alt, C. (1998). Ocean observing systems for marine habitats, *OCC ’98 Proceedings*, Mar. Technol. Soc., Baltimore, Md.

Kleinberg, R.L., Flaum, C., Griffin, D.D., Brewer, P.G., Malby, G., Peltzer, E.T., Yesinowski, J.P., (2003) "Deep Sea NMR: Methane Hydrate Growth Habit in Porous Media and its Relationship to Hydraulic Permeability, Deposit Accumulation, and Submarine Slope Stability", *Journal of Geophysical Research B*, **108**, B 10, doi:10.1029/2003JB002389.

National Research Council (2000). *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*, National Academy Press, Washington D.C.