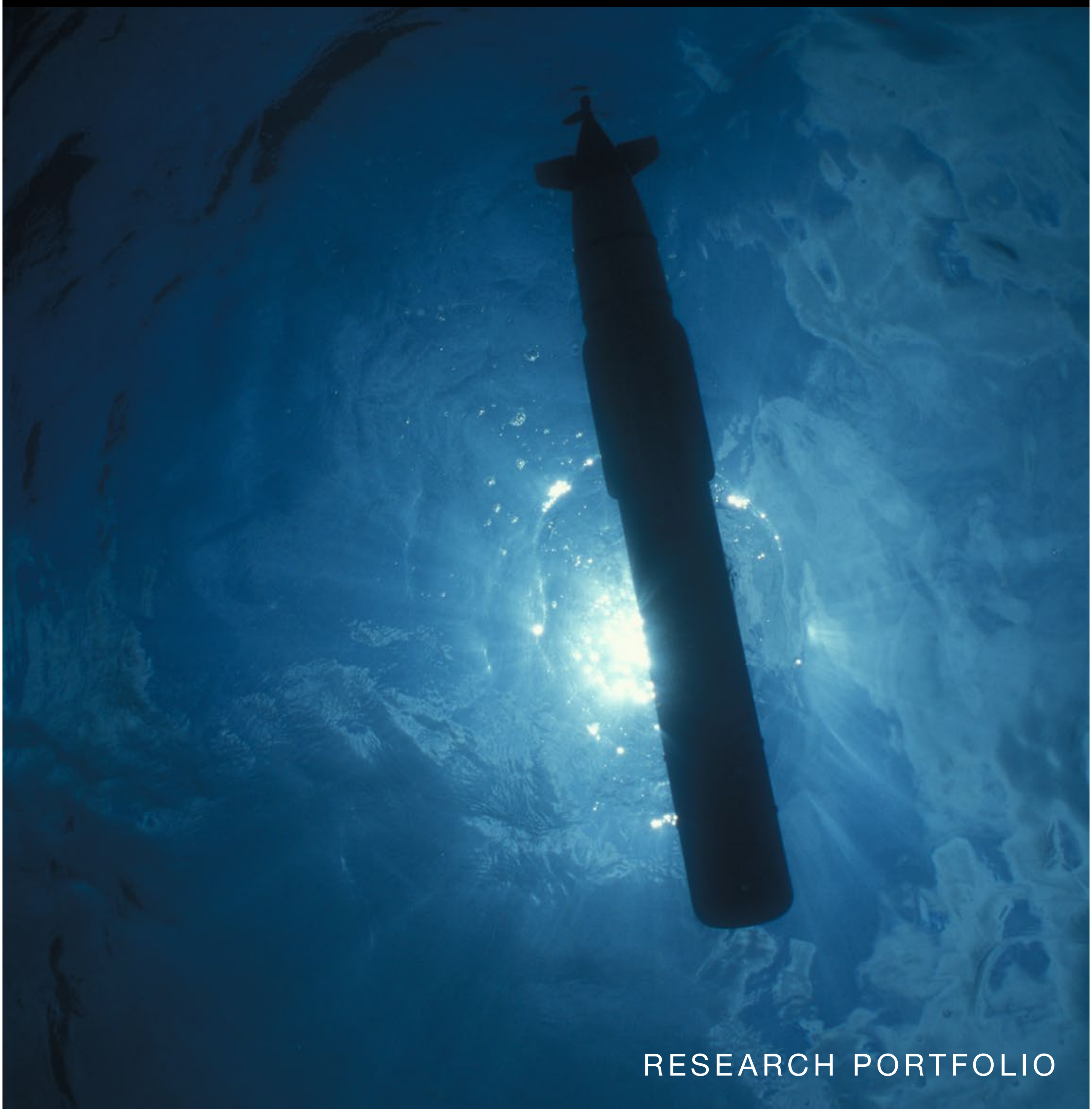
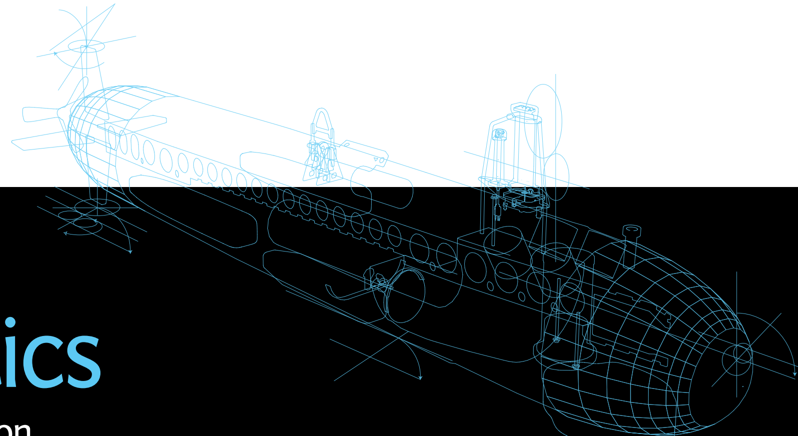
Center for Marine Robotics

Woods Hole Oceanographic Institution



RESEARCH PORTFOLIO



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Revolutionizing how humans and machines work in the ocean

Robotic systems promise to open the ocean to humans in new ways. Recent advances in robotics are improving efficiency, lowering costs, and reducing the risks of marine operations. Robots also allow science, industry, and the military to address problems in new ways, often producing solutions that cannot be achieved through conventional methods.

To speed development of robotic technologies, the Woods Hole Oceanographic Institution has created the Center for Marine Robotics. The goal of the Center is to collaborate with industry, academia, and key government agencies to change the way people and machines work together in the marine environment.

Become a sponsor of the Center for Marine Robotics and join scientific, commercial and military users and developers in creating the next generation of autonomous and remotely operated ocean systems.

A legacy of innovation

The scientists and engineers at the Woods Hole Oceanographic Institution have helped shape knowledge about the ocean for more than 80 years. Today, the Institution is a recognized leader in the research, development, and deployment of robotic and related systems whose methods and technologies have proven their value in a range of applications:

» Long-duration, deep-ocean survey and sampling of marine chemistry, geology, and biology
» Deep- and shallow-water forensic investigations
» Harbor and coastal infrastructure security
» Environmental incident response and monitoring
» Routine access to deep-water, under-ice, and complex environments

Academic Partners

» Johns Hopkins University, Laboratory for Computational Sensing and Robotics
» Georgia Tech Research Institute
» MIT Computer Science and Artificial Intelligence Laboratory (CSAIL)
» Carnegie Mellon University Robotics Institute
» University of Rhode Island Ocean Exploration Trust

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Sponsor Benefits

Corporate sponsorship of the Center for Marine Robotics (CMR) provides privileged and sustained access to research and development in marine robotics conducted at the Woods Hole Oceanographic Institution and at the Center's academic partner institutions.

Sponsorship benefits

» Establish a portfolio of sponsored research projects or define an engineering research program tailored to your company's needs, with negotiated intellectual property rights.

» Support graduate students or postdoctoral investigators who will participate in your company's sponsored research projects.

» Place a company researcher in a CMR lab, with the prior approval of the participating CMR principal investigator.

» Participate on a committee that selects and reviews the progress of innovative research projects proposed by CMR investigators and funded through a CMR members' pool of funds.

» Receive research progress reports and pre-prints.

» Attend robotics seminars, courses, and in-water demonstrations, as well as an annual research conference on the future of marine robotics.

» Participate in industry advisory committee meetings to help guide CMR direction and strategy.

» Recruit robotic engineers and ocean scientists from the MIT/WHOI Joint Program in Oceanography and Applied Ocean Science and Engineering.

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Untethered ROVs for intervention and surveys

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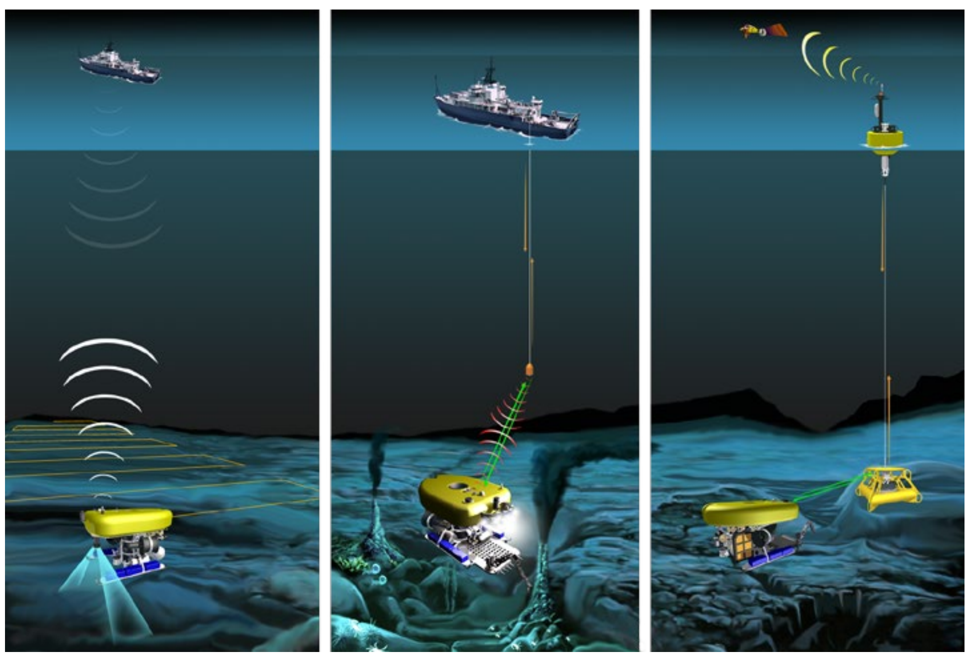
Remotely operated vehicle (ROV) systems have traditionally used tethers to relay power and control signals down to the vehicles while at the same time transmitting sensor data and high-quality video up to the surface. But tethers also place significant constraints on vehicle operations. Winches and cables required to support the vehicles, for example, are quite large and can limit deep-water operations to large vessels with dynamic positioning capabilities.

WHOI engineers have developed a multi-mode, opto-acoustic communications system that eliminates many of these requirements while still providing high-definition, low-latency video that pilots need for manipulator operations. The system's optical modem provides links up to 15 Mbit/s through up to 100 meters of water. With suitable video compression, the optical modem can support real-time video. The system that was recently deployed on WHOI's battery-powered *Nereus* vehicle demonstrated the capability to operate the vehicle, to take samples, and perform work with no tether.



A hybrid, untethered system equipped with sophisticated communications and control systems is capable of performing a range of missions using low-bandwidth acoustic communications (left), as well as optical communications via a ship-mounted relay (center) or seafloor relay (right) associated with subsea infrastructure.

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Long-range, unattended AUV surveys

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Most AUVs are currently launched from surface vessels, monitored from the vessel during dives, and then recovered. The convergence of improvements in battery technologies, on-board power management, efficient propulsion, low-drag hull designs, navigation systems, and overall system reliability will soon allow vehicles to run for long periods without supervision—and will radically alter operational paradigms.

For many missions, vehicles could be launched from shore, transit in a low-power mode to a remote work site, perform a survey, and then return to shore completely on their own. With no vessel requirements and operational personnel needed only to monitor periodic updates obtained periodically via satellite when the vehicle surfaces, the costs for AUV operations will greatly diminish, thereby enhancing the usefulness of AUVs to science and industry.

A long-range AUV based on the REMUS 600 would incorporate improved hydrodynamics, energy efficiency, and power management to permit missions of up to 10 days total length.

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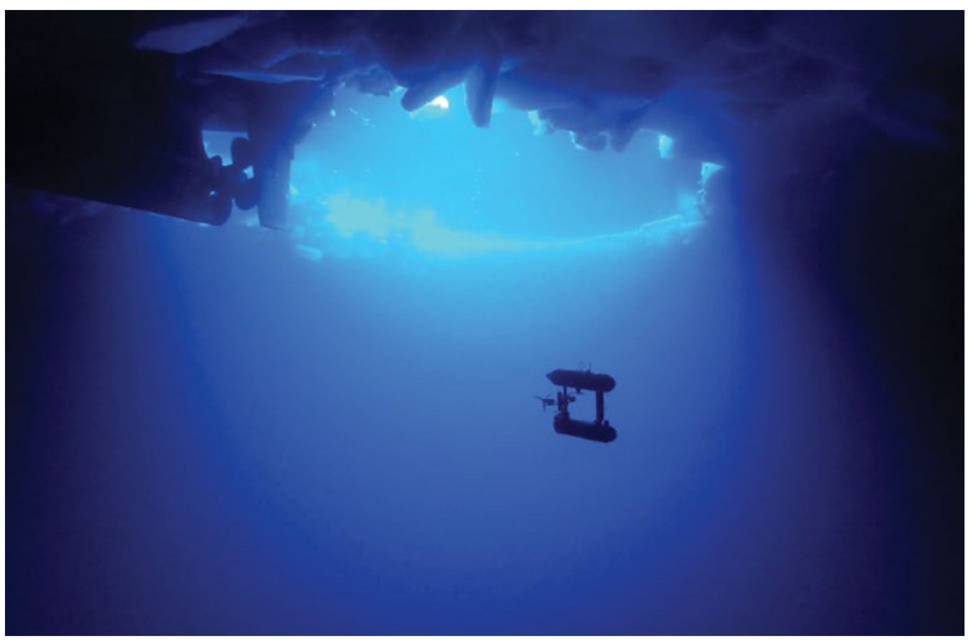
AUV and ROV operations under ice

Autonomous and remotely operated vehicles deployed under glacial and sea ice are able to investigate a number of questions related to ice dynamics, ice formation and melting, and under-ice ecosystems that are particularly compelling given recent and continuing changes to Earth's climate and increased interest in hydrocarbon and mineral extraction in the Arctic. Operating under ice requires solving a number of specialized technical problems, including vehicle reliability, navigation at high latitudes, and communications over long horizontal ranges in highly reverberant acoustic environments.

WHOI currently operates two classes of AUVs under ice—SeaBED and REMUS—to gather data on ice thickness and the physical processes under the ice. These observations complement WHOI's accomplishments in tethered and moored profiling instruments also routinely deployed on and under the ice. WHOI is also developing a new polar ROV (PROV), designed to transit up to 20 kilometers under sea ice while transmitting high-definition video images over a fiber-optic link that is similar to the one WHOI scientists built to remotely control WHOI's *Nereus* vehicle in the Challenger Deep.



In October 2012, engineers from WHOI's Deep Submergence Laboratory deployed the SeaBED-class vehicle Jaguar *into the East Antarctic Sea to create three-dimensional maps of the underside of sea ice. The risks presented by deploying a vehicle under sea ice (and recovering in the event of a failure) makes under-ice exploration a compelling application of robots that safely and effectively extends the reach of humans in the ocean.*

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Underwater acoustic/optical communications and data connectivity

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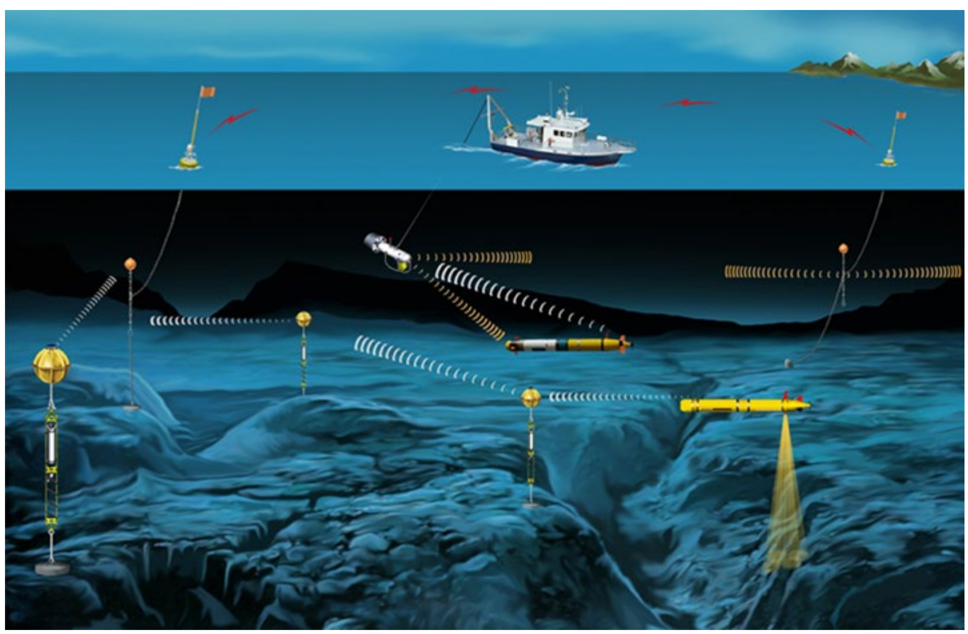
Improved underwater communications is enabling humans and robots to work together more effectively to solve difficult problems that have not traditionally been amenable to fully automated solutions. Underwater robots differ from their terrestrial, aerial, and space counterparts in that once they are submerged, they cannot employ radio frequencies for telemetry because seawater attenuates electromagnetic radiation over very short ranges.

WHOI engineers recently developed and patented a free-space, underwater optical communications system using light to transmit data through water. This system provides unprecedented bandwidth (1 to 10 Mbit/s) at ranges up to 200 meters. Combined with additional underwater acoustic communication technology pioneered at WHOI, the system can also provide more modest bandwidths over much longer ranges.

In a recent experiment, WHOI scientists employed a combination of optical and acoustic modems to conduct sampling and manipulation operations using an untethered ROV. These technologies are enabling a new generation of AUVs and untethered ROVs that can communicate with each other and with controllers on the surface without a physical connection and can offload large data files from autonomous instruments.



Moored, AUV-mounted, and towed communications systems employing broadband acoustic and optical components would greatly enhance data transmission and autonomous data harvesting in the subsea.

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Navigation, localization, and state estimation in complex environments

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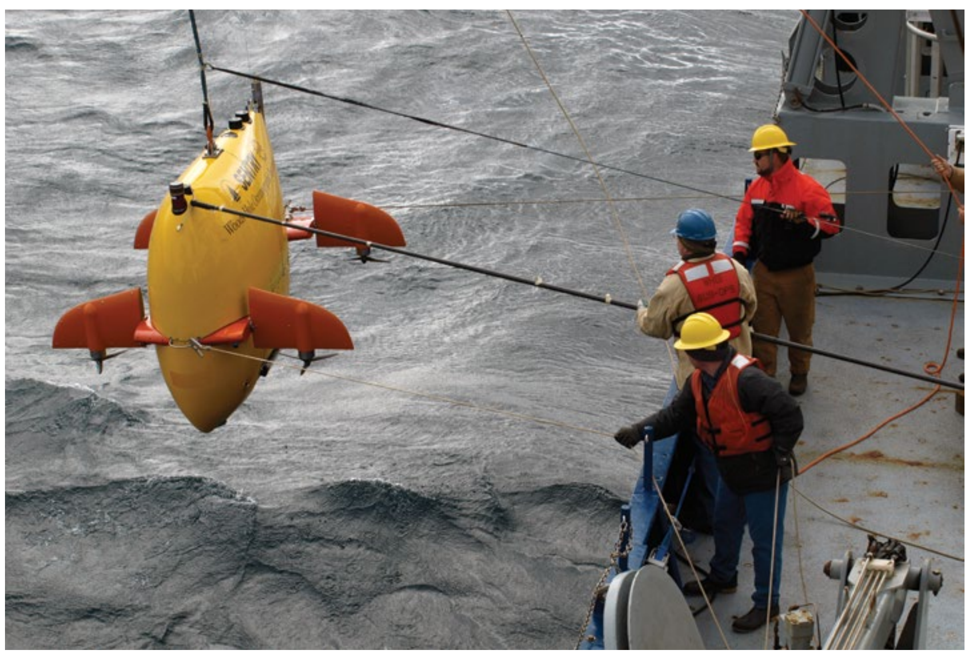
Autonomous and semi-autonomous robotic vehicles operating with minimal human supervision are presently used in commercial offshore operations that, for safety reasons, typically conduct surveys far from valuable and sensitive infrastructure. ROV operations, on the other hand, routinely occur near complex infrastructure, but only under careful supervision by skilled human pilots.

WHOI scientists are pursuing a collaborative research program with colleagues at the Massachusetts Institute of Technology (MIT) to demonstrate the ability of AUVs to localize and navigate in an environment that includes complex manmade structures. The program will combine WHOI's experience in navigation and control of AUVs in rugged natural terrain with MIT's experience in computational methods for mobile robot localization and navigation in manmade environments. Research will begin with basic work in a test tank fitted with appropriate structures and obstacles, then progress to testing around the WHOI dock and finally to an actual offshore structure.



Advances in navigation, localization, and state estimation could permit high-mobility AUVs such as Sentry *to routinely operate in close proximity to complex, human-made infrastructure and environments.*

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In situ identification of marine environmental chemical pollution

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Making measurements in situ rather than collecting samples for later analysis in a shipboard or shore-based laboratory fundamentally transforms oceanographic observation. WHOI's long history of situ instrumentation development dates back at least 80 years to Athelstan Spilhaus' invention of the bathythermograph for submarine detection. More recently, oceanographic sensing technologies have transitioned to autonomous operation, enabling observation and interpretation without human operators. These autonomous sensing technologies to a diversity of applications such as marine hydrocarbon detection.

Over the past decade WHOI researchers have begun fusing in-situ sensing with machine learning to create intelligent payload sensors that can be used to autonomously detect, classify, and map trace chemicals dissolved in the water column. This embedded intelligence is particularly effective when coupled with robotic vehicle guidance systems. In 2004 researchers in WHOI's Deep Submergence Laboratory demonstrated the ability to use real-time data from a hydrocarbon sensor to dynamically re-task an AUV for hydrocarbon detection. In 2006 a WHOI scientist led spill response operations after hurricane Katrina using a newly developed mass spectrometer to locate petroleum leaks among damaged offshore oil infrastructure. Over the ensuing years these techniques have been successfully demonstrated with the U.S. Coast Guard for detecting heavy oil on the seafloor, identifying groundwater discharge and point-source pollution in coastal marine environments, tracking natural hydrocarbon seeps plumes at distances of several miles, and identifying unconventional military munitions.

In 2009, through a NASA ASTEP research grant, WHOI researchers built and demonstrated an embedded expert system that enabled a payload mass spectrometer operating on the *Sentry* AUV to autonomously discover and classify environmental states suitable for extreme life forms in the deep sea off the coast of California. Although this research program focused on extending autonomous robotics detecting life on other planets, the technologies developed were adapted to positively identify and track a subsea hydrocarbon plume emanating from the Macondo well in 2010.

These real-time chemical detection and mapping capabilities are limited to local spatial scales on the order of tens of kilometers. However, research is currently underway to develop a new generation of AUV-based chemical sensing systems that will enable persistent, low-cost monitoring of chemical pollution on basin-to-global scales. When coupled with real-time analysis and decision-making, this technology will provide a level of situational awareness that enables immediate response to episodic or abrupt oceanographic events.

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Co-robotics, scalable autonomy, and adaptive sampling

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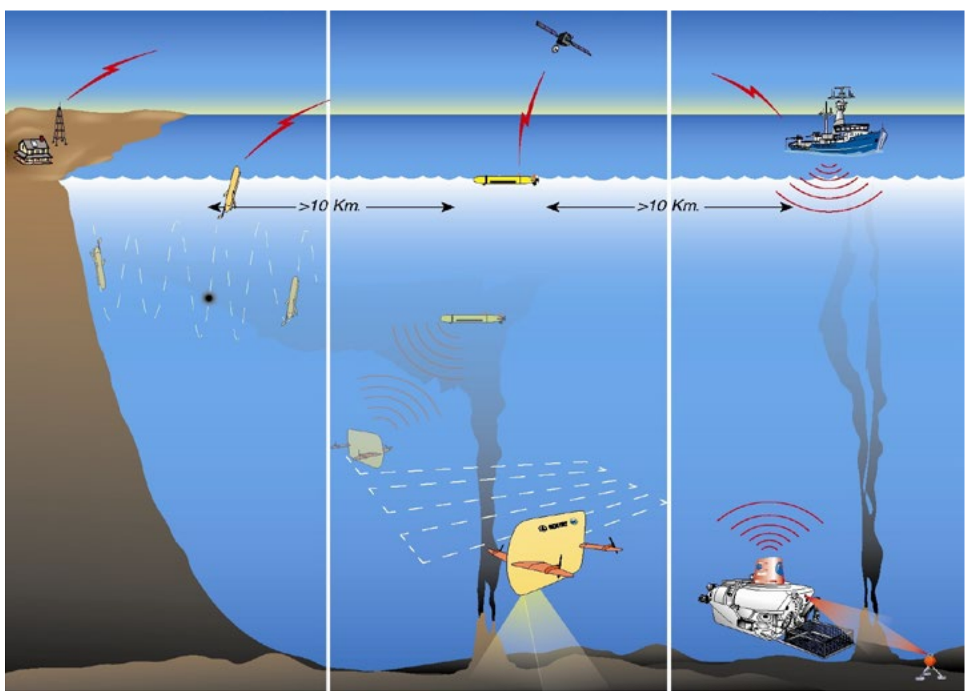
The dichotomy between fully autonomous underwater robots and robots controlled directly by humans is rapidly disappearing. Remotely operated vehicles, which are traditionally controlled manually by a pilot, are becoming more automated. Untethered autonomous vehicles now include increasingly reliable and capable acoustic communications links that enable experts on the surface to use data from the vehicle to reprogram missions on-the-fly. Following a recent demonstration of high-rate, short-range, through-water optical communications to control an untethered ROV in real time, WHOI scientists are currently engaged in research to determine how best to combine automation with human knowledge and skill to improve vehicle capabilities.

The concept of co-robotics recently emerged to describe robots that work side-by-side with people. WHOI scientists are extending this to include robots working with teams of humans on nearby support vessels and linked via the Internet. This effort will combine concepts from systems engineering, human factors, and social science methodologies to explore the best ways to implement co-robotic control systems. Such systems will feature scalable autonomy, in which appropriate combinations of human and machine intelligence are engaged to enable dynamic, adaptive surveys.



Parallel missions combining fully autonomous, tele-operated, and human-occupied underwater vehicles at a variety of scales and depths will enable new missions that are presently considered impractical or infeasible.

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Advanced materials for deep submergence operations

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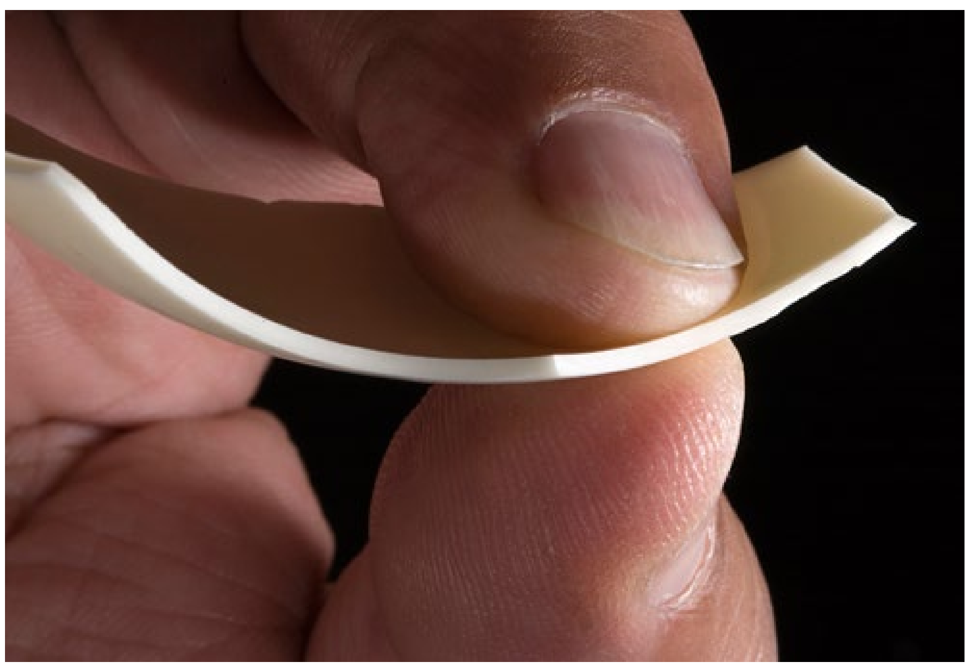
WHOI is a leader in design, construction, and operation of deep submergence vehicles such as *Alvin, Jason,* and REMUS 6000. These vehicles use traditional engineering materials, in particular titanium for strength and syntactic foam for buoyancy. To build the hybrid AUV/ROV *Nereus,* WHOI engineers determined that more advanced structural materials would be needed to reach the full depth of the ocean (11 kilometers or 7 miles), while at the same time meeting practical constraints on size and weight.

Working with colleagues from the U.S. Navy and industry, the team pioneered a new generation of one-atmosphere pressure housings to hold *Nereus'* instruments, cameras, and batteries. Highly optimized ceramic spheres were chosen to provide main vehicle buoyancy. Ceramics materials have much higher strength-to-weight ratios compared to traditional deep submergence structural materials and enable *Nereus* to operate at the most extreme depths. For the next generation of ocean exploration systems, ceramics promise to reduce the weight required for main vehicle structure and buoyancy, leading to a significant increase vehicle payload, endurance, and capability.



The ceramics used to construct the pressure housings on HROV Nereus *can resist as much as 18,000 pounds per square inch and also provide flotation, where titanium used against full-ocean depth would add negative buoyancy to the vehicle.*

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Networked systems of multiple heterogeneous vehicles and distributed sensors

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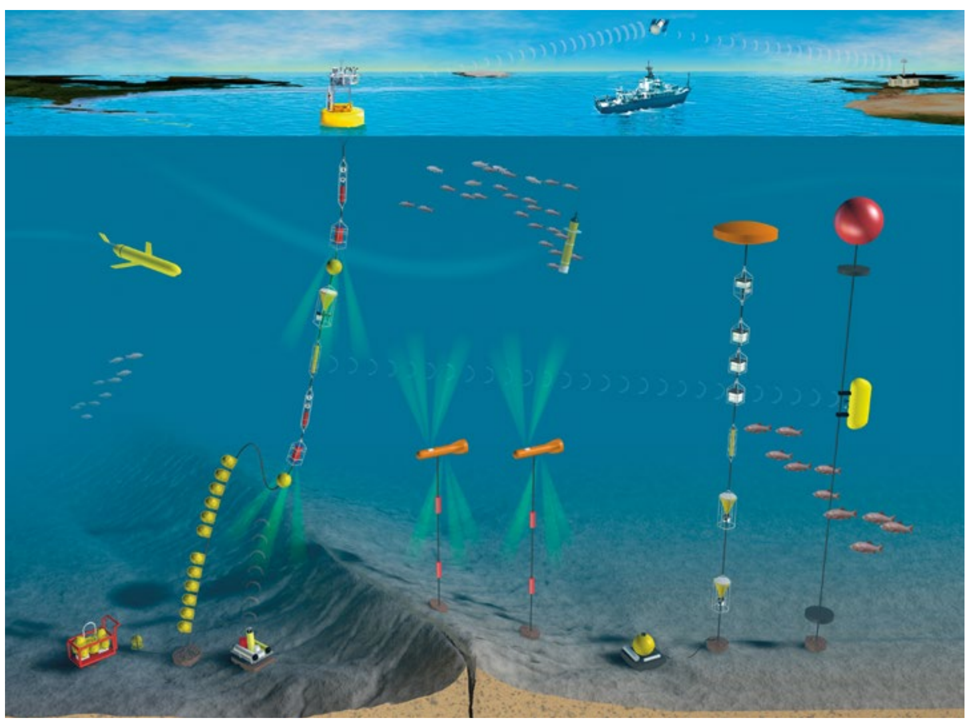
New underwater vehicles, in-situ sensors, and through-water communications capabilities will enable new approaches to oceanographic survey, observation, and monitoring. Teams of fixed and mobile platforms, including autonomous underwater vehicles, autonomous surface vehicles, bottom-mounted and moored instruments, and gliders will not only provide persistent spatial coverage, but will also give each other critical communication and navigation capabilities. Satellite connectivity to shore for surface vehicles will also give human operators the ability to analyze data and reprogram the vehicles as needed.

These elements can be combined in many different ways to address oceanographic problems in a variety of settings. Such an approach could, for example, play a critical role in long-term environmental monitoring of deep-water and Arctic oil and gas fields, particularly where conventional power and communications infrastructure is not available, such as during the exploration phase or after a field has been shut down. The strength of these approaches will be based on recognizing the complementary nature of different communications modalities and platforms and on combining them in new ways to address important problems.



Networks of fixed and mobile platforms, some associated with existing subsea infrastructure, can provide continuous, long-term monitoring of marine environmental conditions.

High-resolution marine gravity measurements with AUVs

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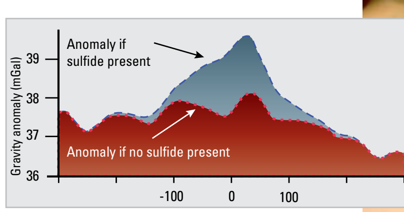
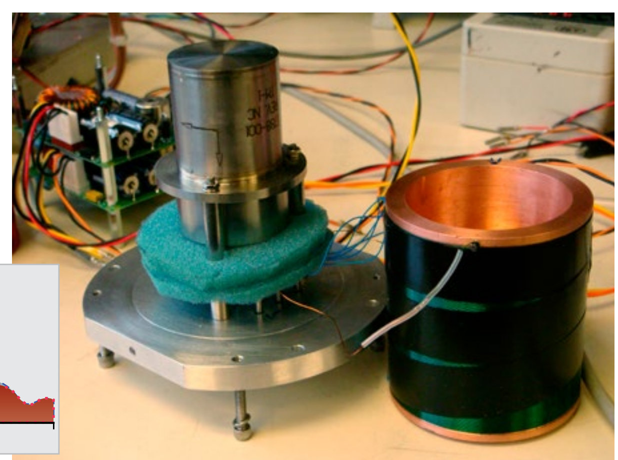
Measurements of variations or anomalies in Earth's gravitational field provide valuable information about the structure of the sub-seafloor that can help identify economically valuable mineral deposits and petroleum reserves. These measurements are routinely obtained using satellites or gravimeters aboard surface vessels, but these methods cannot detect small-scale gravity features because the magnitude of the anomaly decreases as the distance the seafloor and the sensor increases. Characterizing these anomalies requires gravity measurements from submerged platforms capable of operating near the seafloor. Piloted and remotely operated vehicles are too costly for such measurements; autonomous underwater vehicles (AUVs) provide a cost-effective alternative.

Engineers at WHOI and a commercial vendor are developing a new class of gravimeters that is compact and low-power—necessary attributes for AUV instrumentation—and tightly coupled to the navigation sensors on the vehicle. Concurrent to this effort, is research into improved navigation and control methods that will improve the accuracy and spatial resolution of AUV gravity measurements. Control work focuses on combining existing bathymetric maps and realtime sensor data to minimize both the distance from the seafloor (to increase the gravity signal) and the vehicle acceleration (to reduce noise resulting from vehicle motion). Navigation improvements focus on new methods for estimating vehicle acceleration to increase the ability to correct vehicle motion and thereby improve the quality of underway gravimeter measurements.





Measurements of seafloor gravity anomalies can reveal the presence of economically valuable mineral deposits or petroleum-bearing subsurface features. An AUV-mounted gravimeter (right) will permit higher resolution and finer detection of anomalies than satellite or surface measurements.

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Hybrid AUV inspection, monitoring, and intervention of seafloor and sub-seafloor pipelines

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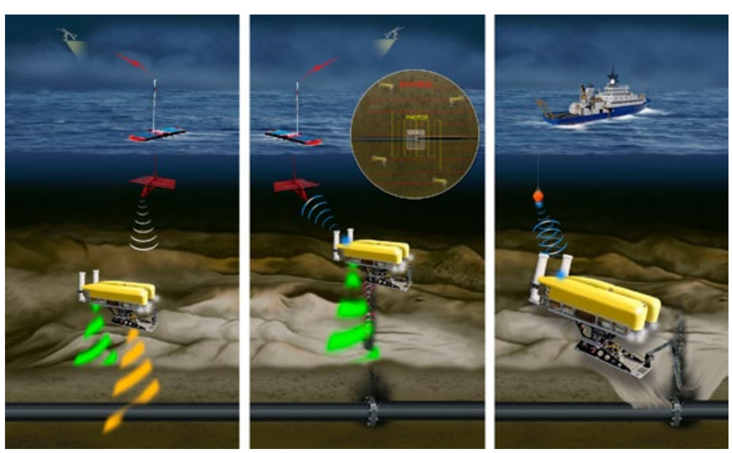
Minimizing the need for a surface vessel when working on seafloor and sub-seafloor pipelines presents opportunities to greatly reduce costs and improve response, a goal that is enabled by a range of technologies and methods pioneered by WHOI personnel over the years. These include developing and deploying high-mobility AUVs to conduct surveys and studies in close proximity to natural and manmade environmental hazards; experience detecting and quantifying physical and chemical changes in the marine environment; tetherless manipulation; extreme AUV mobility; autonomous surface vehicle (ASV) tracking; scalable communication; and AUV-based magnetic surveys.

A mature vision would include a highly maneuverable, hovering AUV equipped with low-powered mangnetometers and an ASV providing tracking and communications relay. The AUV would perform tasks including pipeline localization; detection and quantification of slumps, scours, and leaks; photo and video reconnaissance; and even contact-based measurements such as wall thickness. The AUV would collect data for later analysis and use onboard expert systems programmed with knowledge accumulated by WHOI personnel to make autonomous identification of seafloor and water column anomalies.

The AUV would be able to telemeter select data and status reports to and receive instructions from anywhere in the world through acoustic and satellite links on the ASV. In the event that the AUV identifies an anomaly (on its own or in collaboration with remote personnel) it could be commanded or pre-programmed to conduct a more detailed survey while it awaits the arrival of a surface support vessel. Upon arrival, a WHOI high-bandwidth optical communications package could be lowered to download the full survey data and turn the AUV into a light ROV that could provide real time video, direct remote control, and even light intervention capability while heavier assets are brought to the scene.



AUVs paired with an ASV or manned surface vessel offers a flexible, economical alternative to pipeline survey (left), leak detection (center), and intervention (right).