Pelagic Open ocean environment. A marine sediment with that fraction derived from the continents indicating deposition from a dilute suspension distributed throughout deep-sea water.

Phyllosilicate Layered or sheet silicate mineral, formed by sharing three of the four oxygens in neighboring silicon tetrahedra.

Plankton Aquatic organisms that drift, or swim weakly. Can be either plants (phytoplankton) or animals (zooplankton).

Redox Abbreviation for reduction–oxidation, usually expressed as a potential.

Seamount Underwater mountain, 1000 m or higher elevation from seafloor base. Morphology may be peaked or flat-topped, with the latter called guyot.

Suboxic Condition lacking free oxygen, but not extremely reducing.

Zeolite Any of the minerals of the zeolite group. Aluminosilicate minerals with an open framework structure that allows for easily reversible hydration, gas adsorption, and either cation or anion exchange.

See also

Aeolian Inputs. Clay Mineralogy. Hydrothermal Vent Deposits. Manganese Nodules. Mineral Extraction, Authigenic Minerals. Platinum Group Elements and their Isotopes in the Ocean. Pore Water Chemistry. Rare Earth Elements and their Isotopes in the Ocean. River Inputs. Sediment Chronologies. Sedimentary Record, Reconstruction of Productivity from the. Tracers of Ocean Productivity. Transition Metals and Heavy Metal Speciation. Uranium–Thorium Decay Series in the Oceans Overview.

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AUTONOMOUS UNDERWATER VEHICLES (AUVs)

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An autonomous underwater vehicle (AUV) is an uncrewed, untethered, underwater vehicle capable of self-propulsion. Such vehicles are mobile instrumentation platforms that have actuators, sensors, and on-board intelligence to successfully complete survey and sampling type tasks with little or no human supervision. A large number of AUVs have been developed, ranging in dry weights from less than 50 kg to nearly 9000 kg, with the majority of vehicles at the small end of the scale. In the last several years, acceptance of AUVs for oceanographic, commercial, and military missions has risen dramatically, leading to a sharp rise in AUV operations.

By far the most common AUV configuration is as a torpedo-like vehicle, consisting of a streamlined body with propeller and control surfaces at the stern (**Figure 1**). Operational speeds for such vehicles range from 0.5 to 5 m s^{-1}, with most vehicles operating at a cruising speed of about 1.5 m s^{-1}. In order to remain controllable, torpedo-like AUVs must move forward at some minimum speed in order to maintain flow over control surfaces, and therefore are not capable of station keeping. When a higher

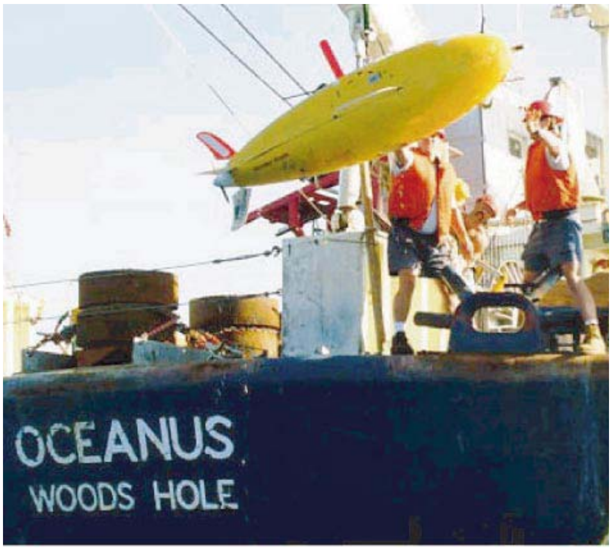

Figure 1 An Odyssey class AUV being deployed from the stern of the R/V *Oceanus*.

degree of control over vehicle attitude and trajectory is required, vehicles are constructed with multiple thrusters. AUVs with multiple thrusters obtain greater maneuverability, but at a cost of reduced range.

Depth ratings of most existing AUVs fall into two categories: vehicles designed for depths on the order of 200 m, and vehicles designed with maximum ratings of 3000–6000 m. The non-oceanographic applications for AUVs are important factors in determining depth rating. Shallow-water mine hunting has motivated the development of a number of vehicles in the 200 m category. Deep-water applications are heavily influenced by the emergency of a deep-survey requirement in the oil and gas industry, which have encouraged the development of 3000 m rated systems.

AUVs are used primarily for bottom mapping and water column observations. Bottom mapping sensors deployed on AUVs include side-scan sonar, mechanically scanned sonar, multibeam bathymetric sonar, laser-linescan imaging systems, still and video imaging, and subbottom profilers. Measurements made in the water column include temperature, salinity, chlorophyll fluorescence, optical backscatter, pH, oxygen, bioluminescence, and a wide range of inherent optical properties. Specialized uses of AUVs include use as mobile acoustic arrays, and mobile sources for acoustic tomography. Given the rapid increase in organizations operating and employing AUVs, the number of applications and suite of available sensors is also likely to increase.

There are a number of acronyms used to describe underwater vehicles, and brief description may prevent some confusion. An ROV is a remotely operated vehicle, and is controlled and powered via a tether. The term UUV is employed by the US Navy to refer to unmanned underwater vehicles. This usage encompasses both ROVs and AUVs, but is most frequently used to refer to an AUV. Occasionally the acronym UUV is used for untethered underwater vehicle, to describe systems that, while untethered, still require a human operator to complete missions. When this usage of UUV is used, the meaning of AUV is narrowed to mean a vehicle capable of completing missions independently. For the following discussion, the more common usage of AUV outlined initially is used.

Example Application Deep-water Survey Operations

Deep-water surveys are one important application for which AUVs are gaining attention, primarily for economic reasons. In operations below 1000 m, the tether dominates the dynamics of a towed system, greatly reducing speed and maneuverability. AUV survey rates at 3000 m can be two to four times greater than deep-towed systems. Not only are AUV cruising speeds two to three times faster than typical deep-tow speeds, but the lengthy process of turning a deep-tow system for multiple passes across a survey site are completely eliminated. Turning a ship with a towed system at the end of several kilometers of cable can take many hours, during which time the system is completely unproductive.

AUVs can also provide much higher data quality. For many sonar systems, mapping quality is a function of stability and the ability of the platform to maintain constant altitude over the bottom with high fidelity. The tether in a deep-towed system not only makes flying precise trajectories highly demanding, it also can couple in motion from the surface vessel to the towed body, especially in rough weather. AUVs are attractive in that they can provide a stable survey platform, and at the same time offer increased maneuverability for bottom following and avoidance.

Under some circumstances, AUV operations can lead to a reduction in the number of ships required for a survey. For many commercial deep-tow operations, two ships are employed, one for towing, and one for determining the position of the tow-body. The second ship is required because the drag of the cable can result in the tow-body lagging many kilometers behind the towing ship, especially as towing speeds increase. Acoustic tracking systems used to determine the position of the tow-body relative to the ship cannot be used effectively by the towing ship. Thus a second ship is required to maintain station above the tow body for optimal tracking. For AUV operations there is no tether constraining the location of the AUV support vessel and thus the same ship can provide tracking.

A final attractive feature of AUVs is the potential for multiple vehicle surveys. Although multiple vehicle operations have been limited to shallow water thus far, the potential for increasing survey rates by employing two or more AUVs simultaneously is especially attractive for abyssal operations. This is not an option for deep-tow systems operated from a single surface vessel.

Control

Control of AUVs can be roughly divided into three levels: dynamic control, task control, and mission control. These refer respectively to the processes of controlling vehicle attitude and position, of achieving specific tasks, and of achieving a series of tasks as part of a more complex mission. For fully autonomous systems, the onboard computer must achieve all of these. When acoustic communications are available, hybrid control techniques can also be used in which a human operator provides some mission or task-level control, referred to as supervisory control. Although control remains an active area of research, the present state-of-the art provides the ability to perform a wide variety of survey missions.

At present, AUVs are generally capable of conducting missions involving flying specified trajectories through space. The trajectories might be very simple – a straight line, for instance – or might involve a length sequence of tracklines, waypoints, and depth excursions. For flight profiles that approach the bottom, most AUVs are capable of using sonar to follow terrain at constant altitude and avoid bottom collisions. The ability of a specific vehicle to operate near the bottom depends on the bottom relief, the maneuverability of the vehicle, and the bottom sensing capabilities of the vehicle. In general, operation near-bottom in regions with cliffs or escarpments is very difficult with the current state of the art. More sophisticated operations involve having the AUV adapt its survey on the basis of data acquired during operations. For example, a vehicle profiling a section of the water column might be programmed to follow a thermocline. Although such capabilities are used by experienced operators, they are not routinely available.

Some challenges associated with fully autonomous operations can be avoided by using acoustic communications to link a human operator with the AUV. However, the relatively low bandwidth, short ranges, and time lag prevent excessive reliance on acoustic communications. Performance is highly dependent on the environmental characteristics of the operating environment. One might expect to obtain 0.1–20 kbit s^{-1} communications over a distance of 4 km depending on the acoustic properties of the water medium between the vehicle and the support vessel. The lower bandwidths, or even no communications at all, would be expected when operating in water much shallower than the separation between the ship and the AUV. Higher communication rates can be obtained when operating in deep water, with the ship directly over the AUV. Even when high-bandwidth communications are available, limitations imposed by the speed of sound in water mean that AUVs must be capable of handling any event requiring a rapid response. For example, a separation of 5 km requires about 6.7 s for round-trip acoustic communication. This introduces a communications latency requiring the vehicle software be sufficiently intelligent to handle dynamic control and tasks such as bottom avoidance.

Navigation

No single navigation system solves all, or even the majority, of navigation demands for AUV operations. Consequently, a variety of navigation methods have been developed each satisfying certain classes of missions. These techniques can be grouped into three general categories: inertial, long-baseline, and ship-tracked navigation. Other methods are under development or used under special conditions, such as feature-relative navigation, but the bulk of AUV operations employ some combination of the following three.

Inertial navigation is used primarily on larger, more expensive AUVs, although continued development promises to make this capability economical for smaller vehicles. Usually the navigation suite consists of an Inertial Navigation System (INS), a velocity sensor, and a Global Positioning System (GPS) receiver. The GPS is required to initialize the navigation system, and for position determination when the AUV is on the surface. Although very high performance INSs exist, those appropriate for AUVs are limited in performance to position drift rates on the order of several kilometers per hour in the absence of other navigation aids. Substantial improvement in performance can be achieved by providing an earth-relative velocity estimate to the INS. A Doppler Velocity Log (DVL) measures velocity relative to an acoustic scatterer, typically the seafloor. A well-integrated INS–DVL system can provide navigation accuracy better than 0.1% of distance traveled. Thus a vehicle traveling 100 km will know its position with an accuracy better than 100 m at the end of the run. However a DVL operates best at high acoustic frequencies, which are heavily attenuated by sea water. Therefore, present DVL assisted navigation is usually limited to altitudes no more than 20–200 m off the bottom, depending on the precise frequency system employed. For applications that impose the requirement of operating further from the seafloor, correlation velocity logs can be used in place of a DVL. Correlation logs operate at low frequencies compared to Doppler navigation systems, and can be operated at greater altitudes over the seafloor, although such systems are much less readily available.

Long-baseline (LBL) tracking systems use a widely separated array of acoustic transponders or synchronized pingers that are interrogated or detected by the vehicle. Depending on the frequencies employed, array sizes can range from a hundred meters to significant fractions of an ocean basin. The most commonly used LBL systems employ 7.5–15 kHz frequency transponders, and are used to cover regions up to a few hundred square kilometers in size with accuracies as good as several meters. The equipment and logistical costs of LBL navigation can be substantial, since the number of acoustic beacons which must be deployed and whose position must be determined can be large. Water depth typically determines the number of beacons required, with a commonly employed rule of thumb stating that transponders should be separated by no more than twice the total water depth. Accuracy of LBL navigation is usually environmentally limited. Variations in the speed of sound can significantly effect the time for an acoustic pulse to travel between two points, and can even lead to shadowing effects effectively precluding sound transmission, for example across a thermocline. Multipath, which is the phenomenon whereby a transmitted pulse reverberates in the underwater environment, leads to ambiguity in arrival detection and greatly complicates the process of relating time-of-flight to range. Consequently, LBL navigation, although providing the best navigation accuracy of any underwater navigation system, requires expert operators and can incur substantial costs.

Ship-tracked methods use a surface vessel to monitor the position of an AUV. Although this requires dedicating a ship to AUV operations, it eliminates the need for deploying an extensive array of transponders as would be required for LBL navigation. Such systems are attractive in that they are not limited by the geographic coverage of an array of acoustic beacons, and do not have a navigation accuracy which deteriorates with time as do inertial-base systems. Tracking an AUV from a surface vessel is accomplished acoustically, with both USBL (ultrashort-baseline) and SBL (short-baseline) systems being employed to provide direction and range to a transponder-equipped submerged vehicle. This ship-relative location is turned into a geographic position by measuring the ship's position and attitude. The accuracy of USBL- and SBL-based tracking deteriorates as the separation of the ship and the AUV increases, with significant consequences for deep-water operations. Consequently, some deep-water survey strategies with AUVs employ a hybrid of ship-based tracking and inertial navigation.

Energy and Vehicle Performance

Energy is a limiting factor for many AUV applications, restricting range, and inhibiting the use of certain power consumptive technologies. Although runs of several hundred kilometers have been achieved by some of the larger AUVs, smaller vehicles typically are used for runs of less than a hundred kilometers.

Propulsion typically consumes a large fraction of the power required to operate an AUV. The amount of energy required to move a vehicle through the water is a function of both the drag of the vehicle, and of the efficiency of the propulsion system. The drag characteristics of a vehicle are dependent on such factors as the vehicle size, shape, surface finish, appendages, and orifices. Propulsion systems lose efficiency to such mechanisms as electrical motor losses, gearbox inefficiency, shaft seal friction, viscous losses, and hydrodynamic inefficiency of the propeller. Considerations such as the interaction of the wake of the hull and the inflow of a propulsion system are also important to achieving optimal efficiency. Consequently, vehicles designed for range and speed tend to have streamlined hulls with a minimum of appendages or orifices, and a single efficient propeller at the stern.

Hotel load is used to describe power consumed by the vehicles for functions other than propulsion. Computers, altimeter sonar, payload sensors, depth sensor, attitude sensors, and navigation are all systems that contribute to hotel load. Reduction in hotel load is clearly attractive, and is assisted by continuing advances in computers and low-power electronics. However it is not unusual for some systems, for example sonars or optical imaging systems requiring lighting, to be governed by physical considerations driving power consumption. This in turn

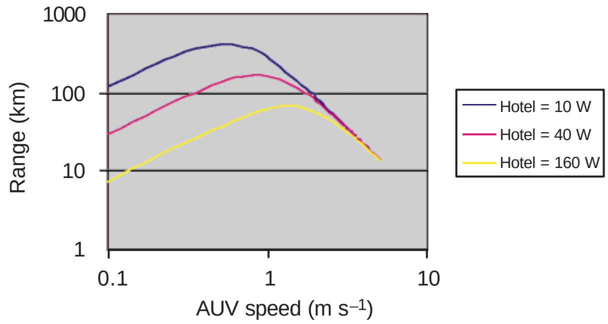

Figure 2 Range as a function of hotel load and speed. These calculations were made for a low drag 2.2 m long, 0.6 m diameter vehicle with high efficiency propulsion and batteries providing 3.3 kW·h of energy

has a substantial impact on one of the fundamental trade-offs in vehicle design, which is the trade-off between speed and range. In simplest terms, as hotel power consumption increases, the vehicle speed for best range also increases. This is illustrated for an existing AUV in **Figure 2**.

A growing number of battery technologies are available, with specific energies (energy per battery weight) ranging over more than an order of magnitude. Lead–acid cells are the lowest energy specific energy, roughly $30\,W \cdot h\,kg^{-1}$, but are inexpensive, easy to use, and can be recharged many times. Other commercially available batteries include those based on silver–zinc, lithium-ion, and lithium polymer chemistries. The first has been extensively used for underwater vehicles, providing energy densities more than three times lead–acid batteries, whereas the latter two are battery chemistries that are only recently available and are just beginning to be employed for AUVs. Primary cells are occasionally used, for example alkaline manganese-dioxide D-cells are used to power at least one vehicle, and certain lithium primary batteries offer the highest specific energy of the readily available energy sources with specific energies roughly ten times those of lead–acid. Fuel cells and semifuel cells are also being developed for and used on AUVs, and offer the potential for both high energy capacity and power delivery.

Future Prospects

The overview of AUVs and AUV technology provided here has been necessarily brief. Among the topics neglected are a variety of exciting technological developments that are experimental at the time of this writing, but likely to be of interest to the reader. These include advances in navigation, mapping sonar, energy storage, and propulsion systems to name a few. The recent emergence of significant markets in both commercial and military arenas has led to increased activity in areas spanning research to manufacture and operation of AUVs. This in turn is fostering a significant development effort on the part of component suppliers to customize their product line to better support AUVs. The result is a rapid expansion in AUV capabilities, which will likely continue for some time.

See also

Deep Submergence, Science of. Manned Submersibles, Deep Water. Manned Submersibles, Shallow Water. Remotely Operated Vehicles (ROVs). Sonar Systems. Towed Vehicles.

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