UNDERWATER VEHICLES

The ocean covers about 70% of the earth. Ocean-related activities are extremely diverse—aquaculture, commercial fishing, ocean research, seafood marketing, ocean recreation, marine mining, marine biotechnology, and ocean energy. Living and nonliving resources of the ocean are abundant. For example, it is estimated that there are about 2,000 billion tons of manganese nodules on the floor of the Pacific Ocean near the Hawaiian Islands. The ocean also plays a critical role in global environmental issues such as pollution and carbon cycles, and the ocean retains more heat than the atmosphere. Therefore, it is not difficult to predict that the ocean will have a great effect on the future existence of all human beings. In spite of its importance, the ocean is generally overlooked as we focus more of our attention on land and atmospheric issues, and we have not been able to explore the full depths of the ocean and its resources. Only recently we discovered, by using manned submersibles, that a large amount of carbon dioxide comes from the seafloor and extraordinary groups of organisms living in hydro-thermal vent areas. Underwater vehicles can help us better understand marine and other environmental issues, protect our ocean resources from pollution, and efficiently utilize them for human welfare. However, ocean travel is difficult because of unpredictable and hazardous undersea environments, even though technology has allowed humans to land on the moon and allowed exploration of other planets.

TYPES OF UNDERWATER VEHICLES

Underwater vehicles can be manned or unmanned submersibles. Manned submersibles include military submarines and smaller manned submersibles while unmanned submersibles include remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV). Unmanned underwater vehicles (UUV) are often called underwater robots. This article emphasizes UUV technology. Since manned submersibles are used primarily for military purposes, the details of their engineering design are not available.

Manned submersibles are controlled by on-board human operators. One example of such a vehicle is the NAUTILE, developed by IFREMER, France. NAUTILE is a three-man submersible capable of descending to a depth of 600 m. This vehicle was used to conduct reentry operations into deep sea boreholes, about 800 of which have been drilled all over the ocean floor by the Ocean Drilling Program for scientific mis-

Table 1. Development of Remotely Operated Vehicles (ROVs)

Year	Vehicle	Purpose	Depth (m)	Developer
1974	RCV	Inspection	412	Honeywell, San Diego, CA
1977	Scorpio	Drilling, construction	1000	Ametek Offshore Ltd., Aberdeen, Scotland
1979	Filippo	Inspection	300	Gaymarine, Italy
1982	Pinguin	Mine countermeasures	100	MBB/VFW, West Germany
1984	Sea Hawk	Drilling, inspection	500	Scandinavian Underwater Technology, Sweden
1985	Dragonfly	Construction	2000	Offshore Systems Engineering Ltd., Norfolk, UK
1985	Triton	Drilling, construction	3050	Perry Offshore, Riviera Beach, FL
1985	Trojan	Drilling, survey	3000	Slingsby Engineering Ltd., York, England
1986	SeaRover	Mine countermeasure	259	Benthos, North Falmouth, MA
1986	Phantom	Inspection, survey	600	Deep Ocean Engineering, San Leandro, CA
1986	Delta	Observation	150	QI, Tokyo, Japan
1986	Trail Blazer	Military applications	915	International Submarine Engineering Ltd., Port Moody, B.C., Canada
1986	MUC	Trench digging, cable/flow line burial, seabottom work	200	Travocean, France
1987	RCVIWO	Investigation and inspection of cooling water outfalls from nuclear power plants	N/A	Hytec, Montpellier, France
1987	Buster	Inspection	500	ROVTECH, Laksevag, Norway
1987	Hysub	Drilling, construction	5000	International Submarine Engineering, Port Moody, B.C., Canada
1987	Achilles	Inspection and observation	400	Comex Pro, France
1988	ARMS	Mine countermeasures	305	AMETEK, El Cajon, CA
1988	RTV-KAM	Inspection of long power plant conduits	30	Mitsui Engineering & Shipbuilding Co., Ltd., Tokyo, Japan
1988	Dolphin 3K	Construction, survey	3300	Mitsui Engineering & Shipbuilding Co., Ltd., Tokyo, Japan
1991	no name	Nuclear power plants	N/A	Deep Ocean Engineering, San Leandro, CA
1992	no name	Nuclear power plants	N/A	RSI Research Ltd., Canada

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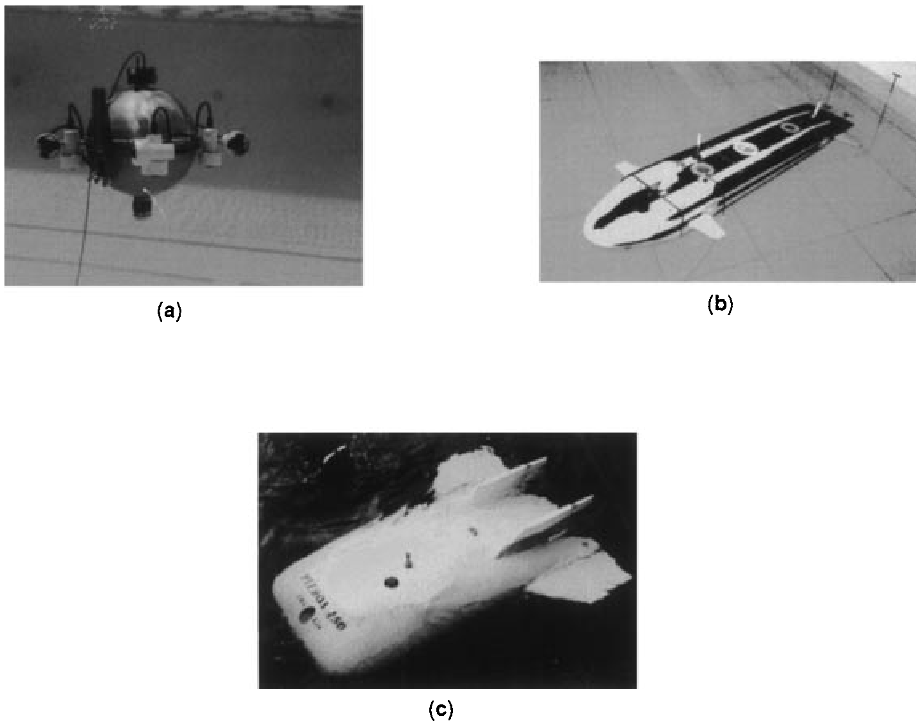
Table 2. Development of Autonomous Underwater Vehicles (AUVs)

Year	Vehicle	Purpose	Depth (m)	Developer
1963	SPURV 1	Water measurement	3658	APL, University of Washington, Seattle, WA
1972	UARS	Under-ice mapping	457	APL, University of Washington, Seattle, WA
1973	SPURV 2	Water measurement	1524	APL, University of Washington, Seattle, WA
1975	SKAT	Ocean research	NA	Institute of Oceanology, Moscow, USSR
1975	OSR-V	Ocean research	250	JSPMI, Tokyo, Japan
1977	No Name	Testbed	100	JAMSTEC, Yokosuka, Japan
1979	EAVE II	Testbed	914	MSEL, Univ. of New Hampshire, Durham, NH
1979	EAVE EAST	Testbed	150	MSEL, Univ. of New Hampshire, Durham, NH
1979	EAVE WEST	Testbed	610	Navel Ocean Systems Center, San Diego, CA
1979	RUMIC	Mine counter-measurements	NA	Naval Coastal Systems Center, Panama City, FL
1979	UFSS	Search	357	Naval Research Laboratory, Washington, DC
1980	SPAT	Acoustic training	240	Westinghouse Oceanics
1980	PINGUIN A1	Search	200	MBB GmbH, Bremen, West Germany
1980	CSTV	Submarine control tests	NA	Naval Coastal Systems Center, Panama City, FL
1982	Rover	Structure inspection	100	Heriot-Watt University, Edinburgh, Scotland
1982	Robot II	Bottom survey	91	MIT, Cambridge, MA
1982	B-1	Drag characteristics	90	NUSSC, Newport, RI
1983	AUSS	Search/identification	6000	Naval Ocean Systems Center, San Diego, CA
1983	Telemine	Vessel destruction	150	Teksea, Lugano, Switzerland
1983	TM 308	Structure inspection	400	Technomare, S.p.A, Venice, Italy
1983	EPAULARD	Bottom photography/topography	6000	IFREMER, Paris, France
1983	AUV	Hydrodynamic	NA	DARPA, Washington, DC
1984	AUV	Hydrodynamic drag studies	NA	Rockwell International, Anaheim, CA
1984	ARCS	Under-ice mapping	400	ISE, Ltd., Pt., Moody, BC, Canada
1985	Submarine Robot	Testbed-hydrodynamic flow	500	JAMSTEC, Yokosuka, Japan
1985	PLA 2	Nodule collection	5000	C.E.A. and IFREMER, France
1986	ELIT	Structure inspection	1000	IFREMER/COMEX, France
1986	No Name	Feasibility	NA	Simrad Subsea A/S, Horten, Norway
1987	EAVE III	Testbed	200	MSEL, Univ. of New Hampshire, Durham, NH
1987	LSV	Submarine testing	NA	Naval Coastal Systems Center, Panama City, FL
1988	Sea Squirt	Testbed	61	MIT, Cambridge, MA
1988	XP-21	Testbed	610	Applied Remote Tech., San Diego, CA
1988	MUST	Testbed	610	Martin Marietta, Baltimore, MD
1988	ACTV	Water measurements	250	APL, University of Washington, Seattle, WA
1989	UUV (1)	Testbed	NA	Draper Laboratory, Cambridge, MA
1989	FSMNV	Mine neutralization	NA	Naval Ocean Systems Center, San Diego, CA
1989	MT-88	Bottom/water	6000	IMSTP, Vladivostok, USSR
1989	AUV	Testbed	500	BC Marine Robot Project, Canada
1989	Pteroa150	Survey	2000	IIS, University of Tokyo, Tokyo, Japan
1989	Waterbird	Survey	100	Sasebo High Tech. Company, Sasebo, Japan
1990	UROV-2000	Bottom survey	2000	JAMSTEC, Yokosuka, Japan
1990	No Name	Testbed precise control vehicle	10	JAMSTEC, Yokosuka, Japan
1990	Musaku	Testbed Precise Control Vehicle	10	JAMSTEC, Yokosuka, Japan
1990	UUV (II)	Testbed	NA	Draper Laboratory, Cambridge, MA
1991	AROV	Search and mapping	NA	SUTEC, Linkoping, Sweden
1992	AE1000	Cable inspection	1000	KDD, Japan
1992	Twin Burger	Testbed	50	IIS, University of Tokyo, Tokyo, Japan
1992	ALBAC	Water Column	300	IIS, University of Tokyo, Tokyo, Japan
1992	MAV	Mine counter-measurements	NA	DARPA, Washington, DC
1992	Doggie	Bottom/sub-bottom survey	6000	Yard Ltd., Glasgow, Scotland
1992	Dolphin	Water characteristics monitoring	6000	Yard Ltd., Glasgow, Scotland
1992	ABE	Bottom survey	6000	WHOI, Woods Hole, MA
1992	Phoenix	Testbed	10	Naval Postgraduate School, Monterey, CA
1992	ODIN	Testbed	30	ASL, University of Hawaii, Honolulu, HI
1993	Ocean Voyage II	Science mission	6000	Florida Atlantic University, Boca Raton, FL
1993	Odyssey II	Science mission	6000	MIT Sea Grant, Cambridge, MA
1993	ARUS	Bottom survey	NA	EUREKA (European Consortium)
1993	ODAS	Survey	900	Marconi Underwater Systems, UK
1993	Marius	Survey	600	IST, Lisbon, Portugal (w/France and Denmark)
1994	Large-D UUV	Military/testbed	300	Naval Undersea Warfare Center, Newport
1994	OTTER	Testbed	1000	MBARI, CA
1995	ODIN II	Testbed	30	ASL, University of Hawaii, Honolulu, HI
1995	R1	Bottom Survey	400	Mitsui Engineering, IIS, U. of Tokyo, Japan



(a)

(b)

(c)

Figure 1. (a) Omni-Directional Intelligent Navigator (ODIN) AUV. Courtesy of the Autonomous Systems Laboratory (University of Hawaii). (b) Phoenix AUV. Courtesy of the Center for Autonomous Underwater Vehicle Research (Naval Postgraduate School). (c) PTEROA150 AUV. Courtesy of Ura Laboratory (University of Tokyo, Japan).

sions. An existing borehole is located by NAUTILE and then NADIA, a nonpropelled, free falling device, is dropped into the water from the mother ship. NAUTILE then moves NADIA from the landing point and places it into the borehole.

ROVs draw power from and are controlled through an umbilical line from a mother vessel. A human operator on the mother vessel generates desired vehicle motion signals that are fed into a ship's computer to calculate the ROV's thruster control input signals. These input signals are sent to the vehicle thruster systems via a tether. About 70% of the ROVs are equipped with one or two manipulator arms, ranging from simple grabbers to highly sophisticated robot arms. Scorpio, an ROV developed by Ametek Straza in 1977, is used for offshore oil-drilling support. Operating to a depth of 1,000 m, the Scorpio has two manipulators controlled by a master-slave system. The slave arm is mounted on the ROV and a smaller replica—the master—is located in the support ship's control room. The human operator moves the master arm to generate desired arm motions; a computer measures the new coordinates, computes control signals for each joint actuator and sends these control signals to the slave arm via a tether. More than 100 different types of commercial ROV models exist worldwide, some of which are listed in Table 1.

AUVs, in contrast with ROVs, carry their own power supplies and have some degree of intelligence. There are more than 46 AUV models. Most of the current AUVs are survey research vehicles without manipulators. Only a few of them have performed in deep water and under ice so the performance capabilities are still embryonic. Development of AUVs is listed in Table 2. One AUV is the AE 1000, developed by a Japanese telecommunication company, KDD, in 1992. The vehicle was designed to inspect undersea telecommunication cables and is controlled by an on-board central processing unit (CPU) (MC68040) and equipped with various sensors such as a gyroscope, obstacle avoidance sonar, and AC magnetometer. The vehicle's sensor detects the undersea cable enabling this AUV to automatically navigate along the cable and inspect its condition. Pictures of three AUVs—ODIN, Phoenix, and Pteroa150—are shown in Fig. 1.

Extensive use of manned submersibles and remotely operated vehicles is currently limited to a few applications because of very high operational costs, operator fatigue, and safety issues. The demand for advanced underwater robot technologies is growing and will eventually lead to fully autonomous, specialized, reliable underwater robotic vehicles. During recent years, various research efforts have been made to increase autonomy of the vehicle and minimize the need for the presence of human operators. A self-contained, intelligent, decision-making AUV is the goal of current research in underwater robotics. Achieving this goal requires advances in various areas, including high resolution, 3-D imaging systems; artificial intelligence and knowledge-based computer systems, adaptive and learning control systems, acoustic-laser telemetry systems, highly dexterous manipulator systems, and lightweight structures able to withstand high pressure and high density power sources.

VEHICLE SUBSYSTEMS

Various subsystems such as navigation sensors, mission sensors, computers, mechanical systems, and manipulators are needed for unmanned underwater vehicles (Table 3).

Dynamics

Dynamics of underwater vehicles, including hydrodynamic parameter uncertainties, are highly nonlinear, coupled, and time-varying. Several modeling and system identification techniques for underwater vehicles have been proposed by researchers (1,2). When one or more manipulators are attached

Table 3. Subsystems of Unmanned Underwater Vehicles

Systems	Subsystems	Needs/Requirements	Methods/Models
Mission	Sensors	Long range information for detecting and inspecting a target of interest	Sonar
	Planner	Plans for the mission goals, unexpected events or system failures	Traditional planner
	World modeling	Set of models for the AUV system and its mission environment	Objective and subjective models
	Data fusion	Meaningful and correct information from massive data of multi-sensors	Analytic methods, AI
Computer	Software	Tools for developing computer codes for the vehicle, support and simulation systems, fault-tolerance operation	System software, application software
	Hardware	Integration of electronic modules in a powerful, robust and flexible manner	System architecture, communication network, mass storage
	Fault-tolerance	Accommodation of hardware and software failures	Redundancy design
Platform	Hull	Platform for mission package; depth and power requirements; stability; modularity for different mission parameters; materials; drag reduction	Steel, aluminum, titanium, composite, ceramic
	Propulsion	Navigation/stationkeeping	
	Power	Power for propulsion, mission systems, and payload	
	Workpackage	Tools for cutting, sampling, cleaning, marking, stabilization, docking, retrieval and launch	Manipulators
	Emergency	Initiating appropriate action in response to the abnormal vehicle condition and providing means for locating a disabled AUV	Emergency buoy, drop weight, flame smoke, beacon, water dye
Vehicle Sensor	Navigation	AUV position relative to a fixed coordinate system	Acoustic, Doppler, fiber-optic gyro, GPS, inertia system
	OAS	Detecting and avoiding obstacles; order of 50m and order of 10 degrees	
	Self-diagnostic	Monitoring and evaluating the vehicle operational parameters for subsystem status	Sensors for voltage, thruster rpm, speed sensor, leak, and temperature
	Communication	Transferring commands and data between a surface station and vehicles	Fiber-optics, acoustic, radio, laser
Development and Support	Logistic support	Organization, equipment, spares, repair and maintenance, documentation, etc.	
	Simulation	Tools for testing the vehicle design and interface mechanism for the analysis of the vehicle operations	Stand-alone simulation Integrated simulation Hybrid simulation in the virtual environment
	User interface	Tools for displaying data, inputting command data	Virtual reality device, joystick, 3-D graphics

to the vehicle, it becomes a multibody system and modeling becomes more complicated. The effect of the hydrodynamics of each link of the manipulator on vehicle motion has to be considered in modeling the vehicle and manipulator (3,4). The effect of thruster dynamics on the vehicle also becomes significant, especially when the vehicle has slow and fine motion (5). Therefore, accurate modeling and verification by simulation are required steps in the design process (6,7). Integrated simulation with actual parts of the vehicle and the environment is more desirable than completely numerical stand-alone simulation. Integrated simulation packages, including 3-D graphics and virtual reality capabilities, will be useful for developing advanced underwater vehicles since actual field-testing is very expensive (8–10).

Intelligent Systems

Unlike ROVs or manned submersibles, AUVs operating without human intervention and supervision require sufficient onboard intelligence and must reliably perform the required tasks. The intelligent system is a high-level control system for the vehicle. Valuable information has to be extracted and identified from a massive amount of signals obtained by various sensors. With information about control state, system status, environment conditions, and mission plans and goals, an intelligent system should be able to cope with unanticipated situations, support automated reasoning in real-time, and guide and control the vehicle. Therefore, an intelligent system

Table 4. Acoustic Long Baseline Navigation System Error Sources

Random errors	Transponder detection delay	~0.3 ms
	Transponder turnaround time variation	~0.1 ms
	AUV receiver detection delay	0.3 ms
	Compass error	~1 deg.
	Depth sensor error	~0.25%
Bias errors	Sound velocity	0.2 m/s
	Transponder calibration	~1 m

Table 5. Attitude Angle and Motion Sensing Systems

	AHRS-C303, Watson Industries	IMU600AD, Watson Industries	AX100, Precision Navigation	TCM2, Precision Navigation, Inc.	DGS3, KVH Industries	MotionPak, Systron Donner
Power Consumption	12 vDC/350 mA	3–4 W	3 W	+5 vDC regulated, 6 to 25 vDC unregulated 6 to 12 mA	12 vDC/300 mA	±15 vDC, 7 W
Weight	907.2 g	907.2 g	1,135 g	45.36 g	1,740 g	907.2 g
Dimensions (W × T × H) mm	146.8 × 79.5 × 117.6	146.8 × 82.3 × 118.9	100 × 100 × 108	63.5 × 50.8 × 28	193.5 × 103 × 84.3	77.5 × 77.5 × 91.5
Outputs	3 axis & Heading rate, Roll, Pitch, South and North Heading	AHRS-C303+3 Axis Linear Acceleration	Azimuth, Pitch, Roll and Rates	Heading, Roll, Pitch 3 axis Magnetic field	Heading, Roll, Pitch	3 axis rate 3 axis linear acceleration
Rate Accuracy	Static ±0.2 deg/sec Dynamic ±2%	1% F.S. Range = ±100 deg/sec	0.05% Input ±0.05%	—	—	Resolution < .004 deg/sec
Attitude Accuracy	Static ±1 deg Dynamic ±2%	0.2 deg to 30 deg	0.2 deg	±4 deg Resolution .2 deg	±3 deg Peak ±1 deg typical	—
Heading Accuracy	Static ±2 deg Dynamic ±2%	±3 deg to 15 deg tilt	0.2 deg	0–55 deg ± 1.25 deg 56–80 ±3 deg Resolution .2 deg	±3 deg Peak ±1 deg typical	—
Acceleration Accuracy	—	<0.5% F.S. Range = ±3g′s	—	—	—	Resolution < 10 mg
Inputs	Forward velocity	—	—	—	—	—
Interfaces	RS232 or Analog	RS232	RS232	RS232 or Analog	RS422	Analog
Roll, Pitch Limit	No limit			80 deg	45 deg	—
Data Output Rate	12–70 Hz	50 Hz	50 Hz	—	20 Hz	60 Hz
PRICE	$8,518	$11,343	$10,000	$1,199	$1,995	$13,000

should be designed with flexible communication, efficient solution to temporal planning and resource allocation, information integration and recognition in the process of multisensor operation, planning ability for a given task, and capability to adapt to the changes in the system and environment. D. R. Blidberg and R. Turner (11) reviewed some artificial intelligence (AI) techniques for underwater vehicle mission planners.

Control Systems

Control systems in current unmanned underwater vehicles are quite immature compared to on-land systems. The vehicles have preprogrammed controllers for repetitive, routine work or are controlled by human operators. Therefore, these control systems have to be reprogrammed for different tasks or a well-trained operator has to be hired. Operating periods and performance of ROVs for a given task are limited due to operator fatigue. Major factors that make it difficult to control underwater vehicles include the highly nonlinear dynamic behavior of the vehicle and manipulator, difficulty in determining hydrodynamic coefficients, and disturbances of the ocean currents and manipulator motion to the vehicle main body. It is difficult to obtain high performance using conventional control strategies. The control system should be able to learn and adapt to the changes in the dynamics of the vehicle and its environment. Various studies have been done on advanced underwater vehicle control systems such as sliding control, adaptive control, neural network control, and fuzzy control (12–18).

Sensors

The sensory system is one of the major limitations in developing vehicle autonomy. The vehicle's sensors can be divided

Table 6. Communication Methods

	Advantages	Disadvantages
Acoustic	Useful in water	Moderate data rate High error rate
Radio	Well developed technology High data rate Low error rate	Surface only
Laser	High data rate Reduced noise	Under development Short range

Table 7. Specific Energy Comparison of Batteries and Fuel Cells

System	Energy/Weight (Watt-hr/lb.)
Lead–Acid	10–18
Ni–Cd	12–20
Ni–Fe	20–25
Ag–Cd	18–45
Ag–Zn	40–48
Hi–H_2	80–90
Acid fuel cells	70–460
Alkaline fuel cells	110–430

Table 8. Comparison of Pressure Hull Materials

	Steel Alloy	Aluminum Alloy	Titanium Alloy	Graphite Composite	Ceramic
Ultimate stress (Kpsi)	60	73	125	100	100
Density (lb/in^3)	0.283	0.1	0.16	0.057	0.13
Fabrication	excellent	very good	good	fair	fair
Corrision resistance	poor	fair	very good	excellent	excellent
Magnetic susceptibility	very high	medium	high	very low	very low
Relative cost	very low	very low	moderate	moderate	moderate

into two groups: (1) system sensors, for sensing the motion of the vehicle and (2) mission sensors, for sensing the operating environment. Different tasks require different sensors: optical, x-ray, acoustic imaging, and laser scanners for inspection; Doppler, sonar inertial system, and gyroscope for navigation; sonar, magnetometer, laser scanner, magnetic scanner, and chemical scanner for recovery; and force, tactile, and proximity sensors for construction. Blidberg and Jalbert (19) described mission and system sensors, and reviewed current navigation sensors and sonar imaging sensors. Multiple sensors are often needed for the same task. For instance, information concerning the objects and local terrain surrounding the vehicle can be gathered via a combination of sonar imaging, laser triangulation, and optical imaging. Sonar can provide most of the obstacle avoidance information. Video images plus specialized machine vision algorithms can provide high resolution information concerning the shape and range of near objects and terrain. Laser triangulation can provide the same type of data at a slower rate but with the additional capability of operating in turbid water. Geometric information concerning the vehicle's surroundings from multiple sensing systems may be redundant and conflicting. This resulting sensor fusion problem must be handled by the intelligent system. An absorbing, backscattering, and color-distorting medium such as the ocean environment causes difficult problems in using video images since the illumination is highly nonuniform and multidirectional. Additional complexities arise because the artificial light sources mounted on the vehicle move with the vehicle. The movement of both plants and fishes also creates confusion in perceived bottom topography. Another difficulty is in *x*-*y* position sensing because there are no internal system sensors for the *x*-*y* vehicle position. The most common approach that current vehicles use is acoustic long baseline or short baseline method requiring external transponders. However, signal attenuation varies with distance, frequency, and temperature. Error sources of the acoustic long baseline navigation system are listed in Table 4. Commercial sensing systems for attitude angle and motion are summarized in Table 5.

Communications

The most common approach for ROV communications uses an umbilical line with coaxial cables or fiber optics. This tether supplies duplex communications. While coaxial cables would be effective for simple operations with limited data transmission, fiber optic cables can transmit more data with less electromagnetic interference and are lighter and thinner. This is important since cables cause substantial drag and often become snagged. About ten percent of ROVs are lost because of broken tethers. A tethered vehicle also requires an operating base, the surface mother ship, whose operating cost may be more than $20,000 per day. Research and development of untethered autonomous vehicles is needed but communicating with AUVs presents formidable challenges. Different approaches of untethered communication are compared in Table 6. The main approach today for through-water transmission involves acoustics in which transducers convert electrical energy into sound waves. Since the ocean rapidly weakens the acoustic energy as the frequency is increased, relatively low frequencies are desirable for longer-range communications. But at very low frequencies, the required transducer size is impractically large and the data rates are lower. The speed and direction of sound signals vary depending on surface waves, temperature, tides, and currents. Josko Catipovic and his research staff at Woods Hole Oceanographic Institution have studied the characteristics of the water channel through which a signal will travel and to adjust the signal accordingly (20). Acoustic modems at a 1,200 baud rate were developed, which is good enough for sending oceanographic data and transmitting video images.

Table 9. Comparison of Various Pressure Hull Shapes

	Advantages	Disadvantages
Single Sphere	Low weight/vol. ratio Excellent for deep diving vehicles	Low optimum vehicle *L*/*D* ratio
Cylinder	Ease of fabrication High optimum vehicle *L*/*D* ratio	High *W*/*V* ratio End closures
Saucer	Improved hydrodynamics in horizontal plane Ease of hovering in currents	Inefficient structure Low controllability Limited to shallow depths
Egg	Good hydrodynamics Good *W*/*V* ratio	Difficult to design & fabricate

Table 10. Potential Applications of Underwater Vehicles

Science	• Seafloor mapping • Rapid response to oceanographic and geothermal events • Geological sampling
Environment	• Long term monitoring (e.g., hydrocarbon spills, radiation leakage, pollution) • Environmental remediation • Inspection of underwater structures, including pipelines, dams, etc.
Military	• Shallow water mine search and disposal • Submarine off-board sensors
Ocean Mining and Oil Industry	• Ocean survey and resource assessment • Construction and maintenance of undersea structures
Other Applications	• Ship hull inspection and ship tank internal inspection • Nuclear power plant inspection • Underwater Communication & Power Cables installation and inspection • Entertainment—underwater tour • Fisheries—underwater ranger

Power Systems

While tethered ROVs can be powered by the mother ship, operating hours of untethered vehicles are limited by the onboard power system. Most power systems for current AUVs rely on batteries that supply limited energy. A typical battery type is lead-acid. Silver–zinc offers roughly double the energy density of lead-acid batteries. However, silver–zinc batteries are expensive. A 325-kWh silver–zinc battery is about $400,000. Low-cost, high-density batteries which provide the vehicle with more than 24-hours endurance are desired. Fuel cells or fuel-cell-like devices which are more energetic than silver–zinc batteries are being considered. Specific energy comparisons of batteries and fuel cells are listed in Table 7.

Pressure Hulls

Water pressure on the vehicles can be enormous. The deep oceans range from 6,000 to 11,000 m in depth. At a mere 10 m depth, the pressure will be twice the normal one atmosphere pressure, or 203 kPa. The chemical environment of the sea is highly corrosive, thus requiring the use of special materials which have rigidity, strength, and environmental resistance. Many ROVs use open-frame structures with a few pressure hulls while many AUVs have torpedo-shape fairings that include a few pressure hulls for on-board electronics and batteries. The most common materials are aluminum or titanium. Recently, composite materials have been considered. The potential advantages of composite materials for undersea pressure hulls are well-known and numerous research and development are underway (21–24). Pressure hull materials and shapes are summarized in Tables 8 and 9.

Mechanical Manipulators

Mechanical manipulators are needed for underwater intervention missions. While many ROVs are equipped with one or two arms, most AUVs do not have arms and are limited to survey type applications. Unlike stationary industrial manipulators in factories, underwater manipulators are attached to vehicles that are constantly moving. Therefore, it is quite difficult and tedious to operate these manipulators with accuracy. Teleoperation using a master/slave system is a common approach. In the offshore oil industry, teleoperated manipulators are used on the tethered ROVs. These vehicles often use two arms—one to latch onto the structure for stability and the other to perform tests and maintenance. For multitask operations, more than one type of manipulator end-effector may be needed. To change the end-effector with the current vehicle system, the vehicle must be brought to the surface and the end-effector changed for each task. This procedure is time-consuming and expensive. A flexible and dexterous design of the end-effector and workpackage is necessary to carry out multitask and sophisticated operations.

APPLICATIONS

As shown in Tables 1 and 2, underwater vehicles have performed various underwater tasks such as seafloor mapping, environmental monitoring, submarine surveillance, underwater pipe and cable inspection, and entertainment (25–35). The Titanic was explored by an ROV, the Argo/Jason. ROVs helped retrieve black boxes and other wreckage from airplane crashes like the TWA flight that went down offshore of Long Island, New York. For military applications, unmanned underwater vehicles are efficient tools to help salvage downed aircraft, test torpedoes, and conduct mine detection and hunting. The offshore oil industry has been a major customer of unmanned underwater vehicle manufacturers. One of the newer application areas is nuclear power plants (36–38). Current use of ROVs by GE Nuclear Energy Co. includes visual inspections in reactor vessels, equipment pools, and fuel storage pools. Potential applications of underwater vehicles are summarized in Table 10 and configurations of some existing AUVs are summarized in Table 11.

INFORMATION RESOURCES

More information about recent development in unmanned underwater vehicles can be obtained from various resources.

Table 11. Configurations of Some Existing Autonomous Underwater Vehicles

AUV		Operating System	Main CPU	Other Processors	Power	Thrusters	Sensory System	Remarks
AE 1000 KDD, Japan	1992	VxWorks	VME MC68040/4M	3 DSP ± Image processor	Lead–Acid	3	AC Magnetometers Camera VCR Recorder Laser Obstacle avoidance sonar Altimeter Depthometer Accelerometers Rate gyroscope Acoustic transponder Radio beacon, etc.	Max 2 knots 1,000 m depth
Phoenix NPS, USA	1992	OS-9	GESPAC MC68030/2M		Lead–Acid gel	6 with 8 control fins	Datasonic PSA900 altitude sonar ST1000, ST725 collision avoidance sonar Gyros	Max 1 knots 10 m depth
ABE WHOI, USA	1992	OS-9	68CH11	T800 SAIL Network	Lead–Acid gel Alkaline Lithium	6	Fluxgate compass Magnetic heading Angular rate sensor	2 knots 6,000 m depth
Ocean Voyage II FAU, USA	1993	VxWorks	VME MC68030/8M	Neuron chips LONTalk Network	Lead–Acid Silver–Zinc	1 with servo controlled rudder and stern plane	Watson 3 axis angle/rate Whisker sonar Sonic speedometer Pressure sensor Mosotech altitude sonar RF modem, etc. 9	Max 5 knots 600 m depth
Odyssey II MIT, USA	1993	OS-9	MC68030/8M	MC68HC11 SAIL Network	Silver–Zinc	1 with servo controlled rudder and elevator	Altimeter Temp. sensor Acoustic modem Obstacle avoidance sonar Pinger, etc.	6,000 m depth
OTTER MBARI, USA	1994	VxWorks	MVME167 (68040)	MVME167 NDDS Protocol	Nickel–Cadmium	8	Stereo CCD Fluxgate compass 2-axis inclinometer MotionPak 3-axis angle/rate Pressure sensor Sharp sonic ranging and positioning system	Max 4 knots 1,000 m depth 1 mechanical arm
ODIN II UH, USA	1995	VxWorks	VME MC68040		Lead–Acid	8	Pressure sensor Watson 3-axis angle/rate sensor Kaiyo sonic ranging and positioning system	Max 2 knots 30 m depth 1 mechanical arm

The technical committee on Underwater Robotics of the IEEE Society of Robotics and Automation continually updates its World Wide Web homepage (http://www.eng.hawaii.edu/ME/Research/URTC/URTC.html) with recent research and development activities such as conferences and workshops, and the page provides links to research institutions worldwide that are involved in underwater robotics. Related technical societies include Marine Technology Society (MTS), IEEE Oceanic Engineering Society, IEEE Robotics and Automation Society. Technical meetings sponsored by these societies include the IEEE Symposium on Autonomous Underwater Vehicle Technologies, International Symposium on Unmanned Untethered Submersible Technology, Underwater Intervention, ROVs, and Oceans. Regular journals and magazines include the IEEE Journal of Oceanic Engineering and Sea Technology. Two books in underwater robotics were recently published: *Underwater Robotic Vehicles—Design and Control,* TSI Press (1995) (39) and *Underwater Robots,* Kluwer Publisher (1996) (40).

BIBLIOGRAPHY

1. T. I. Fossen, Underwater vehicle dynamics. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
2. K. Goheen, Techniques for URV modeling. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.

3. M. Mahesh, J. Yuh, and R. Lakshmi, A coordinated control of an underwater vehicle and robotic manipulator, *J. Robotic Systems on Underwater Robotics,* **8**: 339–370, 1991.
4. S. McMillan, D. E. Orin, and R. B. McGhee, DynaMechs: An object oriented software package for efficient dynamic simulation of URVs. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
5. D. N. Yoerger, J. G. Cooke, and J. E. Slotine, The influence of thruster dynamics on underwater vehicle behavior and their incorporation into control system design, *IEEE J. Ocean Eng.,* **OE-15**: 167–178, 1990.
6. D. J. Lewis, J. M. Lipscomb, and P. G. Thompson, The simulation of remotely operated underwater vehicles, ROV'84, 1984.
7. G. Pappas et al., The DARPA/NAVY unmanned undersea vehicle program, *Unmanned Systems,* **9**: 24–30, Spring, 1991.
8. S. K. Choi and J. Yuh, Design of advanced underwater robotic vehicle and graphic workstation, *Proc. IEEE Int'l Conf. on Robotics and Automation,* vol. 2, 1993, pp. 99–105.
9. D. P. Brutzman, Y. Kanayama, and M. J. Zyda, Integrated simulation for rapid development of autonomous underwater vehicles, *IEEE AUV 92,* Washington, D.C., 1992.
10. Y. Kuroda et al., A Hybrid environment for the development of underwater mechatronic systems, IECON, 1995.
11. D. R. Blidberg and R. Turner, Mission planner, in J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
12. D. N. Yoerger and J. E. Slotine, Robust Trajectory Control of Underwater Vehicles, *IEEE J. Oceanic Eng.,* **OE-10**: 462–470, 1985.
13. J. Yuh, Modeling and control of underwater robotic vehicles, *IEEE Trans. Syst., Man Cybern.,* **20**: 1475–1483, 1990.
14. J. Yuh, A neural net controller for underwater robotic vehicles, *IEEE J. Oceanic Engineering,* **15**: 161–166, 1990.
15. J. Yuh, Learning control for underwater robotic vehicles, *IEEE Control System Magazine,* **14**: 39–46, 1994.
16. R. Cristi, F. A. Papoulias, and A. J. Healey, Adaptive sliding mode control of autonomous underwater vehicles in the dive plane, *IEEE J. Oceanic Eng.,* **15**: 462–470, 1991.
17. N. Kato, Applications of fuzzy algorithm to guidance and control of underwater vehicles. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
18. A. J. Healey and D. B. Marco, Slow speed flight control of autonomous underwater vehicles: experimental results with NPS AUV II, Proc. ISOPE, 523–532, 1992.
19. D. R. Blidberg and J. Jalbert, AUV mission & system sensors. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
20. J. R. Fricke, Down to the sea in robots, *Technology Review,* **10**: 46, 1994.
21. J. M. Walton, Advanced unmanned search systems, *Oceans '91,* 1392–1399, 1991.
22. Du Pont Co., *Advanced Submarine Technology—Thermoplastic Materials Program,* Phase IIA Final Report, DARPA Contract # MDA972-89-0043, 1991.
23. S. M. Anderson et al., Design, analysis and hydrotesting of a composite-aluminum cylinder joint for pressure hull applications, ASTM/STP on Compression Response of Composite Structures, 1992.
24. P. Davies et al., Durability of composite materials in a marine environment—a fracture mechanics approach, *Proc. of ICCM-9,* **II**: Madrid, Spain, 308–315, 1993.
25. S. Smith et al., Design of AUVs for coastal oceanography. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
26. K. Adakawa, Development of AUV: Aqua Explorer 1000. In J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque: TSI, 1995.
27. D. R. Yoerger, A. M. Bradley, and B. B. Walden, The autonomous benthic explorer, *Unmanned Systems,* **9**: 17–23, Spring, 1991.
28. D. R. Blidberg, Autonomous underwater vehicles: a tool for the ocean, *Unmanned Systems,* **9**: 10–15, Spring, 1991.
29. J. G. Bellingham and C. Chryssostomidis, Economic ocean survey capability with AUVs, *Sea Technology,* 12–18, April 1993.
30. A. Dane, Robots of the deep, *Popular Mechanics,* 104–105, June 1993.
31. J. A. Adam, Probing beneath the sea, *IEEE Spectrum,* 55–64, April, 1985.
32. R. C. Robinson, National defense applications of autonomous underwater vehicles, *IEEE J. Oceanic Eng.,* **OE-11**: 1986.
33. J. B. Tucker, Submersibles reach new depths, *High Technology,* 17–24, February, 1986.
34. J. D. Adam, Using a micro-sub for in-vessel visual inspection, *Nuclear Europe Worldscan,* 5–6, 10, 1991.
35. S. Ashley, Voyage to the bottom of the sea, *Mech. Eng.,* **115**: December 1993.
36. H. T. Roman, Robot applications in nuclear power plants, *Newsletter of the IEEE Robotics and Automation Society,* 8–9.
37. J. Judge, Jr., Remote operated vehicles—a driving force for improved outages, *Nucl. Eng. Int.,* **37**: 34–36, July 1992.
38. Kok et al., Application of robotic systems to nuclear power plant maintenance tasks, *Proc. of the 1984 National Topical Meeting on Robotics and Remote Handling in Hostile Environments,* 161–168, 1984.
39. J. Yuh (ed.), *Underwater Robotic Vehicles: Design and Control,* Albuquerque, NM: TSI, 1995.
40. J. Yuh, T. Ura, and G. A. Bekey (eds.), *Underwater Robots,* Boston, MA: Kluwer, 1996.

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UNINTERRUPTIBLE POWER SUPPLIES. See BATTERY STORAGE PLANTS.

UNION PROBLEM. See BACKTRACKING.

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