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Design and Control of Autonomous Underwater Robots: A Survey

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Abstract. During the 1990s, numerous worldwide research and development activities have occurred in underwater robotics, especially in the area of autonomous underwater vehicles (AUVs). As the ocean attracts great attention on environmental issues and resources as well as scientific and military tasks, the need for and use of underwater robotic systems has become more apparent. Great efforts have been made in developing AUVs to overcome challenging scientific and engineering problems caused by the unstructured and hazardous ocean environment. In the 1990s, about 30 new AUVs have been built worldwide. With the development of new materials, advanced computing and sensory technology, as well as theoretical advancements, R&D activities in the AUV community have increased. However, this is just the beginning for more advanced, yet practical and reliable AUVs. This paper surveys some key areas in current state-of-the-art underwater robotic technologies. It is by no means a complete survey but provides key references for future development. The new millennium will bring advancements in technology that will enable the development of more practical, reliable AUVs.

Keywords: underwater robots, autonomous underwater vehicles, underwater navigation and control

1. Introduction

The ocean covers about two-thirds of the earth and has a great effect on the future existence of all human beings. About 37% of the world's population lives within 100 km of the ocean (Cohen et al., 1997). The ocean is generally overlooked as we focus our attention on land and atmospheric issues; we have not been able to explore the full depths of the ocean and its abundant living and non-living resources. 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. Only recently we have discovered, by using manned submersibles, that a large amount of carbon dioxide comes from the seafloor and extraordinary groups of organisms live in hydrothermal vent areas. Underwater robots can help us better understand marine and other environmental issues, protect the ocean resources of the earth from pollution, and efficiently utilize them for human welfare. However, a number of complex issues due to the unstructured, hazardous undersea environment make it difficult to travel in the ocean even though today's technologies have allowed humans to land on the moon and robots to travel to Mars.

Most commercial unmanned underwater robots are tethered and remotely operated, referred to as remotely operated vehicles (ROVs). This paper focuses on autonomous underwater robots, often called autonomous underwater vehicles (AUVs). Extensive use of manned submersibles and ROVs are 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. In recent years, various research efforts have increased autonomy of the vehicle and minimized the need for the presence of human operators. A self-contained, intelligent, decision-making AUV is the goal of current research in underwater robotics.

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

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Table 1. Development of autonomous underwater vehicles (AUVs) in the 1990s.

Year	Vehicle	Purpose	Depth (m)	Developer
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 countermeasures	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 Voyager 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	Hugin	Survey	600	Norwegian Defense Establishment, Norway
1993	Marius	Survey	600	IST, Lisbon, Portugal (w/France and Denmark)
1994	Large-D UUV	Military/testbed	300	Naval Undersea Warfare Center, Newport, RI
1994	OTTER	Testbed	1000	MBARI, CA
1994	Explorer	Pipeline inspection	1000	Shenyang Institute of Automation, China
1995	ODIN II	Shallow water	30	ASL, University of Hawaii, Honolulu, HI
1995	R1	Bottom survey	400	Mitsui Engineering, IIS, U. of Tokyo, Japan
1995	Autosub-1	Environmental monitoring	750	Southampton Oceanography Centre, UK
1996	Theseus	Survey under Arctic sea-ice	1000	ISE, Canada
1997	REMUS	Survey	150	Woods Hole Oceanographic Institution, MA
1997	VORAM	Testbed	200	Korea Research Inst. of Ships & Ocean Engr., Korea
1998	Solar AUV	Testbed	N/A	Autonomous Undersea Systems Institute, NH
1998	AUV-HM1	Testbed	N/A	National Taiwan University, Taiwan
1998	AMPS	Military	200	Pacific Missile Range Facility, Kekaha, HI
1998	SIRENE	Undersea shuttle	4000	DESIBEL, European project led by IFREMER, France
1999	SAUVIM	Military/scientific intervention	6000	ASL, University of Hawaii, Honolulu, HI

water and under ice so the performance capabilities are still embryonic. Table 1 shows a list of AUVs developed in the 1990s. Configurations of some existing AUVs are summarized in Table 2 and potential applications of underwater robots are summarized in Table 3 (Smith et al., 1995; Adakawa, 1995; Yoerger et al., 1991; Blidberg, 1991; Bellingham and Chryssostomidis, 1993; Dane, 1993; Adam, 1985; Robinson, 1986; Tucker, 1986; Adam, 1991; Ashley, 1993; Judge, 1992; Kok et al., 1984; Bellingham and Willcox, 1996).

AUVs have various potential applications and great advantages over ROVs in terms of operational cost and safety. However, there are still many crucial research issues to make the vehicle fully autonomous and reliable, such as robust underwater communication technology, on-board sensors for x-y navigation, and high density power source. The objectives of this paper are to identify key subsystems of the autonomous underwater robots; to survey recent developments in each subsystem; and to summarize the current state-of-the art in

Table 2. Configurations of some existing autonomous underwater vehicles.

AUV	Year	Operating system	Main CPU	Other processors	Power	Thrusters	Sensory system	Remarks
AE 1000 KDD, Japan	1992	V × Works	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 knot 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 Voyager II FAU, USA	1993	V × Works	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.	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	V × Works	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	V × Works	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

Table 3. Potential applications of underwater robots.

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 tours • Fisheries-underwater ranger

underwater robotic technology for future advancement. Various subsystems are listed in Table 4. Sections of this paper are devoted to dynamics; control systems; navigation and sensors; communications; power systems; pressure hulls and fairing; mechanical manipulators; and summary and evaluation.

2. Dynamics

Dynamics of underwater robotic vehicles, including hydrodynamic parameter uncertainties, are highly nonlinear, coupled, and time varying. Several modeling and system identification techniques for underwater robotic vehicles have been proposed by researchers (Fossen, 1995; Goheen, 1995). When one or more manipulators are attached to the vehicle, it becomes a multi-body 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 (Mahesh et al., 1991; McMillan et al., 1995). The effect of thruster dynamics on the vehicle also becomes significant, especially when the vehicle has slow and fine motion (Yoerger et al., 1990). Therefore, accurate modeling and verification by simulation are required steps in the design process (Lewis et al., 1984; Pappas et al., 1991). Integrated simulation (or HILS: hardware in the loop simulation) with actual parts of the vehicle and the environment is more desirable than completely numerical stand-alone simulation. Integrated simulation packages, including 3D graphics and virtual reality capabilities, are useful for developing advanced underwater robotic vehicles since actual field-testing is very expensive (Choi and Yuh, 1993; Brutzman et al., 1992; Kuroda et al., 1995).

The six degrees-of-freedom nonlinear equations of motion of the vehicle are defined with respect to two coordinate systems as shown in Fig. 1. The vehicle coordinate system has six velocity components of motion (surge, sway, heave, roll, pitch, and yaw). The velocity vector in the vehicle coordinate system is expressed as $\dot{\boldsymbol{q}} = [u\ v\ w\ p\ q\ r]^T$. The global coordinate system OXYZ is a fixed coordinate system. Translational and rotational movement in the global reference frame are represented by $\boldsymbol{x} = [x\ y\ z\ \phi\ \theta\ \psi]^T$ that includes earth-fixed positions and Euler angles. The equations of motion for underwater robots without manipulators can be written as follows:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{J}(\boldsymbol{x})\dot{\boldsymbol{q}} \\ \boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{C}(\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{D}(\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{x}) &= \tau + \boldsymbol{w} \\ \tau &= \boldsymbol{B}\boldsymbol{u} \end{aligned}$$

where $\boldsymbol{J}(\boldsymbol{x})$ is a 6×6 velocity transformation matrix that transforms velocities of the vehicle-fixed to the earth-fixed reference frame; $\boldsymbol{M}$ is a 6×6 inertia matrix as a sum of the rigid body inertia matrix $\boldsymbol{M}_{\mathbf{R}}$ and the hydrodynamic virtual inertia (added mass) $\boldsymbol{M}_{\mathbf{A}}$; $\boldsymbol{C}(\dot{\boldsymbol{q}})$ is a 6×6 Coriolis and centripetal matrix including rigid body terms $\boldsymbol{C}_{\mathbf{R}}(\dot{\boldsymbol{q}})$ and terms $\boldsymbol{C}_{\mathbf{A}}(\dot{\boldsymbol{q}})$ due to added mass; $\boldsymbol{D}(\dot{\boldsymbol{q}})$ is a 6×6 damping matrix including terms due to drag forces; $\boldsymbol{G}(\boldsymbol{x})$ is a 6×1 vector containing the restoring terms formed by the vehicle's buoyancy and gravitational terms; τ is a 6×1 vector including the control forces and moments; $\boldsymbol{w}$ is a 6×1 disturbance vector representing the environmental forces and moments (e.g. wave and current) acting on the vehicle; $\boldsymbol{B}$ is a control matrix of appropriate dimensions; and $\boldsymbol{u}$ is a vector whose components are thruster forces.

As the robot moves underwater, additional force and moment coefficients are added to account for the effective mass of the fluid that surrounds the robot and must be accelerated with the robot. These coefficients are referred to as added (virtual) mass and include added moments of inertia and cross coupling terms such as force coefficients due to linear and angular accelerations. The hydrodynamic added mass may be written

Table 4. Subsystems of autonomous underwater robots.

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 & subjective models
	Data fusion	Meaningful & correct information from massive data of multi-sensors	Analytic methods, AI
Computer	Software	Tools for developing computer codes for vehicle, support and simulation systems, fault-tolerance operation	System software, application software
	Hardware	Integration of electronic modules in a powerful, robust & flexible manner	System architecture, communication network, mass storage
	Fault-tolerance	Accommodation of hardware & software failures	Redundancy design
Platform	Hull	Platform for mission package; depth & 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, & payload	
	Workpackage	Tools for cutting, sampling, cleaning, marking, stabilization, docking, retrieval & 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
	Obstacle avoidance system (OAS)	Detecting & avoiding obstacles: order of 50 m & order of 10 degrees	Acoustic, laser
	Self-diagnostic	Monitoring and evaluating the vehicle operational parameters for subsystem status	Sensors for voltage, thruster rpm, speed sensor, leak, & temperature
	Communication	Transferring commands and data between a surface station and vehicles	Fiber-optics, acoustic, radio, laser
Development & support	Logistic support	Organization, equipment, spares, repair & 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, 3D graphics

with the SNAME (The Society of Naval Architects and Marine Engineers) convention such that for the hydrodynamic added mass force Y_{A} along the y-axis due to a linear acceleration $\dot{u}$ in the y-direction is shown $Y_{\mathrm{A}} = -Y_{\dot{u}} \cdot \dot{u}$ where $Y_{\dot{u}} = \partial Y/\partial \dot{u}$. Triantafyllou and Amzallag (1984) discussed how to calculate the various elements in $\boldsymbol{M}_{\mathbf{A}}$ for different geometrical bodies. In an ideal fluid, $\boldsymbol{M}_{\mathbf{A}}$ is strictly positive and symmetrical.

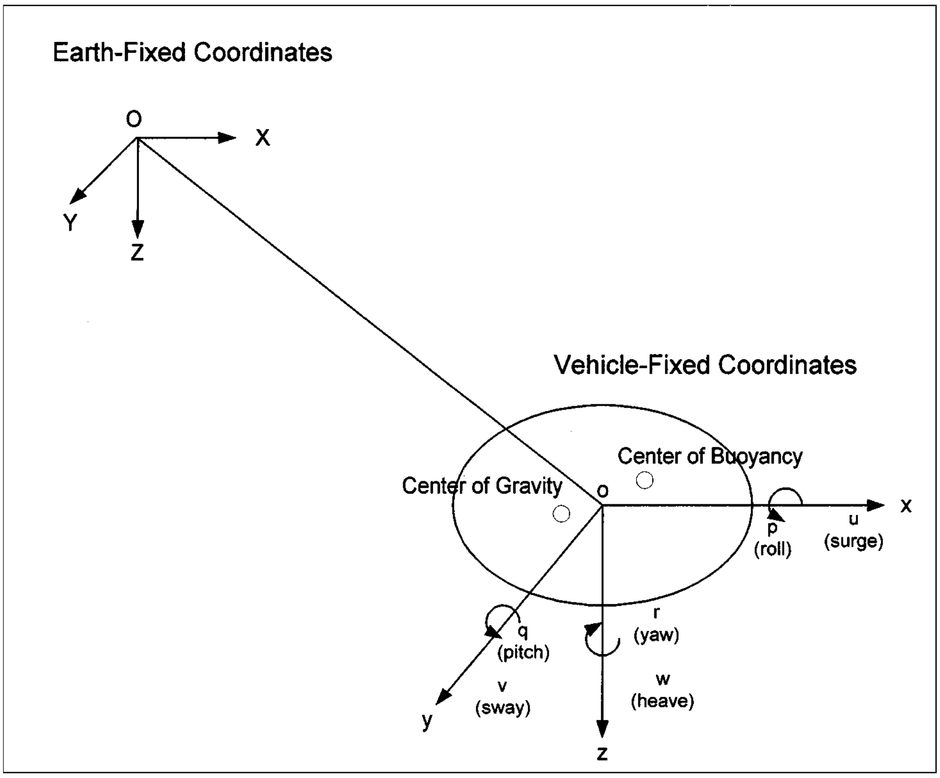

Figure 1. The coordinate systems for underwater robots.

Based on the kinetic energy of the fluid, $\boldsymbol{E} = \dot{\boldsymbol{q}}^T \boldsymbol{M}_{\mathbf{A}} \dot{\boldsymbol{q}}/2$, the added mass forces and moments can be derived by Kirchhoff's equations (Kirchhoff, 1869; Sagatun, 1992). Then, the added mass forces and moments can be seen as a sum of hydrodynamic inertia forces and moments $\boldsymbol{M}_{\mathbf{A}}\ddot{\boldsymbol{q}}$ and hydrodynamic Coriolis and centripetal forces and moments $\boldsymbol{C}_{\mathbf{A}}(\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$. In an ideal fluid, the hydrodynamic damping matrix, $\boldsymbol{D}(\dot{\boldsymbol{q}})$, is real, non-symmetrical and strictly positive. With rough assumptions such as a symmetric robot and non-coupled motion, it can be simplified to a diagonal matrix $\boldsymbol{D}(\dot{\boldsymbol{q}}) = \boldsymbol{diag}(\boldsymbol{d}_1 + \boldsymbol{d}_2|\dot{\boldsymbol{q}}|)_i \; i = 1, \ldots, 6$ where $\boldsymbol{d}_1$ is a linear damping coefficient and $\boldsymbol{d}_2$ is a quadratic (drag) damping coefficient. In the hydrodynamic terminology, the gravitational and buoyant forces are called restoring forces, $\boldsymbol{G}(\boldsymbol{x})$. The gravitational forces will act through the center of gravity while the buoyant forces act through the center of buoyancy. Environmental disturbances, $\boldsymbol{w}$, due to waves, wind, and ocean currents and their mathematical expressions are discussed in detail in Fossen (1994). Components of the control matrix, $\boldsymbol{B}$, are dependent on each robot's configuration, control surfaces, number of thrusters, and thruster locations. Therefore, $\boldsymbol{B}$ may not be a square matrix. The thruster force, $\boldsymbol{u}$, will be the output of each thruster whose dynamics are nonlinear and quite complex. For bladed-propeller type underwater thrusters driven by brushless DC motors, an experimental study to compare four thruster models including those by Yoerger et al. (1990) and Healey et al. (1994) was conducted by Whitcomb and Yoerger (1995). Under the assumption that the thruster dynamics have much smaller time constants than the vehicle dynamics, a simple static thruster model is often used as each thruster force $\boldsymbol{u}$ is proportional to $|\Omega|\Omega$, where Ω is the thruster propeller angular velocity and proportional to the motor drive voltage.

3. Control Systems

Major facts that make it difficult to control underwater robots include: the highly nonlinear, time-varying dynamic behavior of the robot; uncertainties in hydrodynamic coefficients; the higher order and redundant structure when the manipulator is attached; disturbances by ocean currents; and changes in the centers of the gravity and buoyancy due to the manipulator motion which also disturbs the robot's main body. It is difficult to fine-tune the control gains in air or during operation in water. Therefore, it is highly desirable to have a robot control system that has a self-tuning ability when the control performance degrades during operation due to changes in the dynamics of the robot and its environment.

Various advanced underwater robot control systems have been proposed in the literature, such as sliding control (Yoerger and Slotine, 1985; Healey and Lienard, 1993), nonlinear control (Nakamura and Savant, 1992), adaptive control (Goheen et al., 1990; Yuh, 1990a, 1996; Cristi et al., 1991; Tabaii et al., 1994, Choi and Yuh, 1996; Nie et al., 1998), neural network control (Yuh, 1990b, 1994; Lorenz and Yuh, 1996; Ishii et al., 1998), and fuzzy control (DeBitetto, 1994; Kato, 1995). Various control architectures for autonomous underwater vehicles were also discussed in the literature (Valavanis et al., 1997; Girard et al., 1998). This section focuses on low-level control systems rather than control architectures.

Yoerger and Slotine (1985) have proposed a sliding mode controller for an underwater vehicle to control trajectory. They have investigated the effects of uncertainty of the hydrodynamic coefficients and negligence of cross-coupling terms. Healey and Lienard (1993) have used the sliding mode methods for the control of underwater vehicles and separated the system into non-interacting (or lightly interacting) subsystems, grouping certain key motion equations together for the separate functions of steering, diving, and speed control. Nakamura and Savant (1992) have proposed a nonlinear tracking control of a 4 dof (surge, roll, pitch and yaw) AUV considering kinematic motion. They have made use of the nonholonomic nature of the system without considering the dynamics of the system. Goheen et al. (1990) have proposed multivariable self-tuning controllers as an autopilot for underwater vehicles to overcome model uncertainties while performing autopositioning and station-keeping. Yuh (1996) and Choi and Yuh (1996) have developed and implemented a new Multiple Input Multiple Output (MIMO) adaptive controller using bound estimation for underwater robotic systems and experimented with the control system on an AUV, Omni Directional Intelligent Navigator (ODIN). A hybrid adaptive control (suggesting that the procedure is a mixture of continuous and discrete operations) of an AUV was investigated by Tabaii et al. (1994). The system was simulated in the continuous domain while the control and identification sections were discrete.

Yuh (1990b, 1994) has proposed a neural network control system using a recursive adaptation algorithm with a critic function (reinforced learning approach). The special feature of this controller is that the system adjusts itself directly and on-line without an explicit model of vehicle dynamics. Lorenz and Yuh (1996) present experimental results on ODIN using the method proposed by Yuh (1994). Ishii et al. (1998) have proposed a neural network based control system called "Self-Organizing Neural-Net-Controller System" (SONCS) for AUVs and examined its effectiveness through application to the heading keeping control of an AUV called "Twin-Burger." In their study, a quick adaptation method of the controller called "Imaginary Training" is used to improve the time-consuming adaptation process of SONCS. DeBitetto (1994) has investigated a 14-rule fuzzy logic controller for the depth control of a UUV. Tsukamoto et al. (1999) experimentally implemented four model-free control systems for the position and velocity control of a single thruster system: on-line neural net controller, off-line neural net controller, fuzzy control, and non-regressor based adaptive control. The off-line neural controller used the Intel i80170 Electrically Trainable Artificial Neural Network (ETANN) chips (Intel, 1992).

While many underwater remotely operated vehicles (ROVs) have mechanical manipulators, most AUVs do not have manipulators. For a large robot, effects of the arm motion on the main body may be negligible, and the main body and arm can be considered as two separate systems in different bandwidths. For a small robot, coupled effects of the main body and arm are significant and must be considered in the overall control system design. With the arm attached to the vehicle, the overall system becomes a multi-rigid body system. The vehicle main body continuously moves in water and high performance of arm control, in terms of speed and accuracy, requires highly accurate information about the vehicle position and velocity. Most commercial sensors for vehicle position and velocity do not meet the accuracy requirements of the arm control. Therefore, there are many challenging engineering problems for vehicles with manipulators.

There are very few papers about the coordinated motion of the vehicle and manipulator (Mahesh et al., 1991; McLain et al., 1996; Shoults, 1996; Antonelli and Chiaverini, 1998; and Canudas-de-Wit et al., 1998). Mahesh et al. (1991) have developed a coordinated control scheme, using a discrete-time approximation of the dynamic model of underwater robotic systems, which controls the vehicle and manipulator simultaneously and compensates for end-effector errors resulting from motion of the vehicle. McLain et al. (1996) have conducted experiments at the Monterey Bay Aquarium Research Institute (MBARI) using the OTTER vehicle and have shown that dynamic interaction between robot arm and vehicle can be very significant. They pointed out that coordinated motion control strategy along with an accurate model of the arm/vehicle hydrodynamic interaction forces enhance the station-keeping capability and end-effector accuracy. Shoults (1996) has investigated a nonlinear model based control scheme that simultaneously controls the position and orientation of the vehicle and manipulator. Canudas-de-Wit et al. (1998) have designed a robust nonlinear control for a vehicle/arm system to compensate for the coupling effects due to an onboard robot arm. They have used different bandwidth characteristics of the composite vehicle-manipulator dynamics as a basis for the controller design via singular perturbation theory. They have pointed out that both the robust controller and partial linearized controller achieve similar performance even in the presence of saturation. Antonelli and Chiaverini (1998) proposed a task-priority based redundancy resolution scheme for kinematic control of an underwater vehicle-manipulator system by suitably using the null space vector.

The unstructured and hazardous ocean environment also presents many challenging problems in the event of system failures for autonomous underwater robots. For any major failure of the robot's subsystems, the robot should rise to the surface and signal for retrieval; however, for any tolerable failures, the robot should be able to adjust for the failure and complete the assigned task. Therefore, an efficient and effective fault tolerant system becomes imperative for AUVs. A fault tolerant system consists of three areas: fault detection, fault isolation, and fault accommodation. The fault detection process is a high-level function that monitors the robot's overall systems—both hardware and software—for any signals that exceed any preset tolerance or measured sensor values. Once a fault is detected, the fault isolation process determines the exact cause and location of the fault and its severity (i.e. whether it is tolerable or not). If the fault is evaluated to be tolerable, the fault accommodation process either accommodates or reconfigures the robot's control architecture to successfully carry out the assigned task. Several methods for fault-tolerant control of autonomous underwater robots have been discussed in the literature (Babcock, 1990; Healy, 1992; Dunn, 1992; Orrick, 1994; Takai, 1994; Yang et al., 1999).

4. Navigation and Sensors

The sensory system is one of the major limitations in developing vehicle autonomy. The vehicle's sensors can be divided into three groups: (1) navigation sensors, for sensing the motion of the vehicle (Cox and Wei, 1994); (2) mission sensors, for sensing the operating environment; and (3) system sensors, for vehicle diagnostics. 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 (1995) 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, back-scattering, 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 fish 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 approaches that current vehicles use are acoustic long baseline (LBL), short baseline (SBL), or ultra short baseline (USBL)

Table 5. Doppler sonar sensors.

	Litton (phone 804 974-2227 fax 804 974-2259)	RD Instruments (phone 619 693-1178 fax 619 695-1459)	EDO Corporation (phone 801 486-7481 fax 801 484-3301)
Price (US $)	45490 (with valve)	24900	48000
Model	SRD 500	Doppler velocity log; workhorse navigator	Model 3050 DSVS
Components (parts)	Transducer, electronics, master display	Transducer, pressure case, electronics, power supply, input/output cables, manuals/software, spares/tool kit	Transducer, electronics
Outputs	Speed	Speed, flux-date compass, pitch, roll, temperature	Speed
Bottom lock (m)	1.2 to 200	1 to 200	2 to 250
Speed range (m/s)	Fore/Aft: $-10/+25$; Port/Stbd: $+/-5$	$+/-10$	Fore/Aft: $+/-20$; Port/Stbd: $+/-10$; vertical: $+/-5$
Operating temperature range (°C)	-15 to 55	-5 to 45	0 to 35
Max Depth	600 KPA	2000 m	Standard pressure: 1500 psi
Acoustic data	Frequency: 307 kHz; four beams	Frequency: 307 kHz; four beams	Frequency: 287.5 kHz; four beams
Accuracy (bottom)	Precision: <1 m/s $+/-0.005$ m/s; >1 m/s $+/-0.025$ m/s	Precision: 1 m/s $+/-0.003$ m/s; 5 m/s $+/-0.008$ m/s; accuracy: $+/-0.4$%	Precision: 0.01 m/s; resolution: 0.004 m/s; accuracy: $+/-0.1$%
Power requirements	100/115/230VAC ($+/-10$%); 50/60 Hz, 100 vA	20 to 60 VDC, 0.4 A; average power: 17 w	20 to 32 VDC; power at max range: 42 w
Interfaces (output)	Digital: RS232, RS422, NMEA0183; analog: 1 mA full scale or 0.1 volt/knot	RS232, RS485, RS422	RS232, RS422
Operating life (years)	10	10	N/A
Warranty (years)	2	1	1
Off shelf	Yes	Yes	Yes
Delivery time (months)	0.5 (2 weeks)	3	4 to 6
Dimension (inches)	Master display $14.4 \times 10.7 \times 8.5$; electronics $16.7 \times 14.0 \times 5.98$; transducer: 8 diameter	Transducer 8.9 diameter ($8.2 \times 8.9 \times 8.9$)	$10.75 \times 6 \times 4.85$ (without connector)
Weight (lbs)	Master display: 15; electronics: 15; transducer: 60	Weight in air: 21; weight in water: 11	Weight in air: 14.6; weight in water: 8.5

methods requiring external transponders (Black and Butler, 1994; Austin, 1994). However, signal attenuation varies with distance, frequency, and temperature, and positioning systems with acoustic beacons are expensive and often impractical (Vaganay et al., 1996).

Sonar based navigation and localization have been studied in the literature (Auran and Silvan, 1995; Cristi et al., 1995, Marco, 1996; Vaganay et al., 1996; Nie et al., 1998).

Some samples of commercial sensing systems for underwater navigation were surveyed in 1998. Tables 5–8 show Doppler sonars, ultra-short baseline sonars, inertia navigation systems, and pressure sensors, respectively. The purpose of this survey is not to provide a complete list of commercial products with a best choice but to provide general information about what is available commercially. This survey may be outdated within five years (if not sooner) since various efforts to improve efficiency of such products are being made in research sectors.

5. Communications

The most common approach for ROV communications uses an umbilical line with coaxial cables or fiber optics. This tether supplies duplex communications.

Table 6. Ultra short baseline sonar sensors.

	SonaTech (CA) (phone 805 683-1431 fax 805 683-4862)	Desert Star (CA) (phone 408 384-8000 fax 408 384-8062)
Price (US $)	350000	9985
Model	NS-031	Pilot PT 3
Components	SSBL processor unit; primary projector unit; auxiliary projector unit; interconnect cable	STM-1 surface station w/ 'over the side' transducers; VLT-1 tracking transponder; DiveBase-L2 multi-target tracking software for window 95/NT includes GPS integration and chart overlay capability
Housing material	7075-TG aluminum or 6AL4V titanium	VLT-1 transponder: Al 6061T6, hard anodized
Max slant range	9000 m	1000 m (may vary between 800 m and 10000 m)
Accuracy	Azimuthal bearing accuracy: <0.5 degree relative to processor unit housing for CW pulse signals; <0.1 degree achievable with wide band signals	Range accuracy: $+/-0.15$ m (typical)
Operating temperature range (°C)	-4 to 40	-4 to 50
Max depth (pressure) rating	6000 m aluminum; 9000 m titanium	1000 m
Transmitter characteristics, interrogate signals	Source level: >186 dB re 1 uPa @ 1 m @ 7 kHz; frequencies: four unique frequencies selectable; pulse width: 0–100 ms programmable; max. interrogation rate: 1 per 10 seconds	Source level: $>=186$ dB; multi-channel digital synthesized transmitter, 5 kHz–95 kHz (4 channels in normal operation.)
Receiver characteristics	Frequencies: up to 15 receive frequencies from 7 to 17 kHz; sensitivity, MDS (minimal detectable signal), 50% probability of detection: $<=80$ dB re 1 uPa	Digital synthesized superheterodyne receiver, operating freq. 5 kHz–95 kHz; sensitivity $<=80$ dB
Power requirements	18–36 VDC (28 VDC nominal), 3.5 A max.	9–16 VDC@0.18 amp average during navigation operation (1 amp peak during transmit)
Interfaces (output)	ASCII RS-422	RS232C
Operating life (years)	>7	Unlimited with every 3 yrs regular service
Warranty (years)	1	1
Off shelf	Yes	Yes
Delivery time (months)	6 months ARO	2 months
Dimension (inches)	Processor unit length: 39.1 aluminum, 37.2 titanium, OD both 8.75	VLT-1: 3 D × 16.5 L
Weight (lbs.)	In air: 120 aluminum, 123 titanium; in salt water: 44 aluminum, 60 titanium	VLT-1: 3.9 lb in air, 0.5 lb in water

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, thinner cables. 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 and 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. 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

Table 7. Inertia navigation systems.

	Precision Navigation Inc.	Systron Donner (BEI)	Watson Industries
Price (US $)	699	13,489	12,636
Model	TCM2-20	MotionPak	IMU-BA604
Measurements (outputs)	Heading, roll, pitch, magnetic field data, temperature	3 outputs for linear acceleration, 3 outputs for angular velocity, temperature	Heading, roll, pitch, and their rates, acceleration in 3 axis
Max roll and pitch (degree)	$+/-20$	N/A	$+/-180$ roll; $+/-90$ pitch
Power consumption (mA)	15–20 (depends)	<270	<600
Operating temperature range (°C)	−20 to 70	−40 to 80	−30 to 60
Sampling rate (Hz)	1–30	>60 for rate; >300 for acceleration	71 (depends)
Operating life (years)	8.2 (72000 hours)	10	5.7 (50000 hours)
Accuracy (degree if not specified)	Heading: when level: $+/-0.5$ RMS; when tilted: $+/-1$ RMS; resolution: 0.1; repeatability: $+/-0.1$ (RMS: Root mean square)	Threshold/resolution: <= 0.004/sec for rate; <= 10 ug for acceleration	Rate resolution: <0.025/SEC; rate bias: <0.5% of F.S.; acceleration resolution: better than 2 mG's; acceleration bias: <10 mG's
Accuracy (degree if not specified)	Tilt: accuracy: $+/-0.2$; resolution: 0.1; repeatability: $+/-0.2$; range: $+/-20$		Bank and elevation accuracy: 0.2 to 20, static, 2% dynamic, 1% F.S. static to 60
Input voltage (VDC)	+5 regulated (or 6 to 18 unregulated)	+ and −15 $+/-10\%$	+12
Interfaces (output)	Digital: RS232, NMEA0183, analog: 0–5 V linear; 0–5 V quadrature	Analog: $+/-2.5$ VDC for rate; $+/-7.5$ VDC for acceleration	Digital: RS232; analog $+/-10$ VDC
Warranty (years)	1	1	1
Off shelf	Yes	Yes	Yes
Delivery time (weeks)	4 to 6	6 to 8	4 to 6
Dimension (inches)	2.50 × 2.00 × 1.25	3.6 × 3.05 × 3.05	6.5 × 6.5 × 3
Weight (lbs.)	1.6/16 (1.6 ounces)	1.98 (900 g)	<4

have estimated the characteristics of the water channel through which a signal will travel and adjusted the signal accordingly (Fricke, 1994). Acoustic modems, at a 1,200-baud rate were developed, are sufficient for sending oceanographic data and transmitting video images. Herold and Johnson (1994) describe a compact underwater acoustic modem for the shallow water environment. Chappell et al. (1994) describe acoustic communication between two AUVs. Table 9 shows some of the recent acoustic modem systems.

6. Power Systems

While tethered ROVs can be powered by the mother ship, operating hours of untethered robots are limited by the on-board 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. For example, a 325-kWh silver-zinc battery is about US $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. Active research and development in the area of batteries has been in progress, especially with recent attention on electric vehicles that has accelerated the development of more efficient and safer batteries. In the near future, the underwater robotics community is expected to receive a great benefit from this development. Specific energy comparisons of current batteries and fuel cells are listed in Table 10.

Table 8. Pressure sensors.

	Data Instruments, Inc. (tel: 800 333-3282 fax: 508 263-0630)	BEI Electronics, Inc. (tel: 818 362-0300 fax: 818 362-2487)	Tavis Corp. (tel: 800 842-6102 fax: 209 966-4930)	Parascientific, Inc. (tel: 425 883-8700 fax: 425 867-5407)
Price (US $)	1108	2720	2099	5900
Model	DS (option 2)	6-142-1325-01	P110C	8B7000-L
Submersible in seawater, max one month	Yes	Yes	Not completely	Yes
Temperature compensated	Yes	Yes	Yes	Yes
Operating temperature range (°C)	−18 to 93	−4 to 85	−18 to 85	−25 to 65
Compensated temperature range (°C)	−1 to 54	−1 to 71	−1 to 54	−2 to 40
Pressure (psi)	Yes	Over range 15,000	Yes	Yes
Accuracy	Overall: 0.5%; linearity: 0.34%; hysteresis: 0.15%	Overall: +/−0.5%	Overall: +/−0.5%	Each: +/−0.01%
Material	Housing: 316 stainless steel (ss); diaphragm: 15-5 PH stainless steel; connector: elastomer	316 ss	External: 17-4 PH and 300 ss	Varies (titanium possible)
Excitation voltage (VDC)	14–50	6–26	17–50	6–25
Output	16+/−0.16 mA into 0 to 2000 ohm loop resistance (4–20 mA)	4–20 mA	4–20 mA	RS-232
Warranty (years)	1	1	1	5
Off shelf	Yes	Yes	Yes	Yes
Delivery (weeks)	6	8	16	8
Dimension (inch. (mm))	7.25 × 1.375 (184 × 36)	4.11 × 1.75 (104 × 44)	3.65 × 2.2 (93 × 56)	10.48 × 2.2 (56 × 27)
Weight (lbs.)	2.5	2 (max)	3 (max)	6

Table 9. Acoustic modem systems.

Developer	Data rate (kbps)	Range (km)	Modulation
Datasonics (Fang et al., 1987)	5	1	Incoherent
WHOI (Eastwood et al., 1996)	5	5	Incoherent
WHOI (Johnson et al., 1994)	5	Shallow, under ice	Coherent
JAMSTEC (Sasaki and Suzuki, 1992)	16	6.5 vertical	Coherent
IFREMER/ORCA (Ayela and Coudeville, 1991)	19.2	2 vertical	Coherent
Oki Elec. (Kaya and Yauchi, 1989)	500	0.06	Coherent

7. Pressure Hulls and Fairings

Water pressure on the vehicles can be enormous. The deep oceans range from 6,000 to 11,000 m. At a mere 10 m depth, the pressure will be twice the normal atmosphere pressure of 203 kPa. The chemical environment of the sea is highly corrosive, thus requiring the use of special materials that have rigidity, strength, and environmental resistance. Many ROVs use open-frame structures with a few pressure hulls while many AUVs have torpedo-shaped fairings that include a few pressure hulls for on-board electronics and batteries. Table 11 shows the pros and cons of different shapes of fairings. The most common materials for pressure hulls

Table 10. 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-H2	80–90
Acid fuel cells	70–460
Alkaline fuel cells	110–430

are aluminum or titanium. Recently, composite materials are being considered. The potential advantages of composite materials for undersea pressure hulls are well known and numerous research and development projects are underway (Walton, 1991; Du Pont, 1991; Anderson et al., 1992; Davies et al., 1993). Pressure hull materials are summarized in Table 12.

8. 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 for ROVs. 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 multi-task 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 multi-task and sophisticated operations. Lane (1995) and Davies et al. (1998) presented a new design of the underwater end-effector that has flexible fingers for dexterous operation.

As mentioned above, most underwater arms were designed for ROVs and they are actuated by hydraulic drivers. They are also designed for teleoperation rather than robotic operation. Hydraulic drivers are disadvantageous for AUVs or underwater robots because of high power requirements and noise generation. Electrical drivers are preferred for AUVs that have limited

Table 11. Comparison of various vehicle (fairing) shapes.

	Advantages	Disadvantages
Single sphere	Low weight/vol. (W/V) ratio, excellent for deep diving vehicles	Low optimum vehicle length/diameter (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 12. Comparison of pressure hull materials.

	Steel alloy	Aluminum alloy	Titanium alloy	C/peek composite	Ceramic
Ultimate stress (Kpsi)	60	73	125	300	100
Density (lb/in^3)	0.283	0.1	0.16	0.056	0.13
Fabrication	Excellent	Very good	Good	Fair	Fair
Corrosion 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

Table 13. Commercial underwater manipulators.

	Tecnomare, Italy	Western Space and Marine, Inc.	Kraft TeleRobotics, Inc.	Schiling Robotics Systems, Inc.	International Submarine Engr. Ltd., Canada
Model	Telemanipulator	The Arm-66	Predator	Titan III S	ISE 7F
D.O.F.	6 plus gripper	6 plus gripper	6 plus gripper	6 plus gripper	6 plus gripper
Master/slave	Master/slave	Master/slave	Master/slave	Master/slave	Master/slave
Power source	220 V-50 Hz/110 V-60 Hz, optional	110–240 VAC, 50/60 Hz, hydraulic power-2 GPM @ 3000 Psi, 5–25 Micron absolute	47–63 Hz, 105–250 VAC and hydraulic power @ 2000 Psi, 5 GPM, 25 micron absolute	50/60 Hz, 90–260 VAC and hydraulic power @ 3,000 Psi, 1.5–5.0 GPM, 10–200 cSt.	Hydraulic power @ 1250 Psi, 10 LPM, 25 micron filter
Material	Aluminum alloy type 6000	Aluminum, stainless steel composites, corrosion isolation system	Aluminum with teflon coating	6–4 titanium & 316 stainless	6061-T6 Aluminum
Joint sensors	Resolver at each joint and torque sensor at the output shaft	Position, velocity, and torque	Position and force feedback	Resolver	Potentiometers
Force/torque	Jaw closure force: 700 N	Jaw force controls and sets grip 0–350 lbs. (120 lb/ft)	Jaw closure force: 300 lbs., wrist torque: 100 ft.lbs	Gripping force: 1,000 lbf., wrist torque: 125 ft.lbs	Gripping force: 330 lbs., wrist torque: 140 ft/lb.
Actuator	DC motor - brushless	Hydraulic cylinders	Hydraulic cylinders	Hydraulic cylinders	Hydraulic cylinders
Price	$350,000–410,000	$280,000+	$119,000	$149,500	$70,000–250,000
Max reach	2.07 m	66 inches	80 inches	75.4 inches	59 inches
Payload	40 kg	145 lbs.	200 lbs.	250 lbs.	650 lbs. @ 1.4 m

power and use noise-sensitive sensors for the robotic operation. The University of Hawaii, the University of Genoa, and Ansaldo (Italy) jointly developed an electro-mechanical underwater manipulator. Table 13 lists samples of underwater manipulators currently available.

9. Summary and Evaluation

Underwater robotics represents a fast growing research area and promising industry as advanced technologies in various subsystems develop and potential application areas are explored. As shown in Table 2, common operating systems include V $\times$ Works and OS9. As PC technologies quickly become outdated, more low-cost solutions such as Linux are emerging in AUV research. New vehicles may take an advantage of this new development while many existing vehicles continue their development using current operating systems. However, different operating systems would not affect much on the direction of the basic research in other subsystems such as vehicle servo-level control. Research activities will increase in multi-vehicle operation area, including communication between vehicles, intelligent control architecture, and intelligent motion planning. Virtual reality is also a very attractive field for underwater robotics. Most of the time, visual images of the vehicle operation may not be available due to a lack of light in the deep ocean. It is often preferred to have a synthetic environment with actual images (if available), graphic images created by sensor feedback signals, and a world model from stored data. Introducing virtual reality technology will enhance interaction between the vehicle and operator.

Advanced development in navigation sensors is necessary for more reliable and accurate performance required by many potential applications. Current navigation sensors, as discussed in Section 4, still have a low performance-to-cost ratio. Because of the hazardous and noisy environment, it is difficulty to get robust outputs from sensors. It would be desirable to have on-board navigation sensors, avoiding physical constraints of some current sensors such as LBL. Advancement in underwater communication, high-density battery, and new materials for pressure vessels will also enhance the development in underwater robotics.

As the ROV industry continues to grow, development of hydraulic-driven arms with high telepresence will continue. Table 13 shows only a subset of what each company produces and all of their products are hydraulically driven teleoperating arms. As mentioned earlier, AUVs need robotic manipulators with low power consumption and low noise operation rather than teleoperation since AUVs have limited on-board power resources and various noise-sensitive sensors.

This paper surveyed the current state-of-the-art in key areas of the underwater robotics for underwater robots or AUVs. While not providing a complete survey, it is hoped that this survey can help provide a direction for future advancements in the subject area and attract more researchers and potential users of such robots. One of the key areas that this paper did not cover is *motion planning*. There have been many methods proposed for land mobile robots but only a few proposed for underwater robots (Vasudevan and Ganesan, 1996; Heart et al., 1996; Sugihara and Yuh, 1997). The new millennium will bring advancements in technology that will enable the development of more practical, reliable AUVs.

More information about recent development in autonomous underwater vehicles (robots) can be obtained from various resources. 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). It lists 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. Photos of various underwater robots can be found throughout this web site. Related technical societies include the Marine Technology Society (MTS), IEEE Oceanic Engineering Society, IEEE Robotics and Automation Society, and IFAC Technical Committee on Marine Systems. Technical meetings sponsored by these societies include the IEEE Symposium on Autonomous Underwater Vehicle Technologies; International Symposium on Unmanned Unthethered Submersible Technology; International Conference on Robotics and Automation, Underwater Technology, Underwater Intervention; ROVs; Control Applications in Marine Systems (CAM); 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) and Underwater Robots, Kluwer Publisher (1996).

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