

Potential of autonomous underwater vehicles as new generation ocean data platforms

Elgar Desa*, R. Madhan and P. Maurya

National Institute of Oceanography, Dona Paula, Goa 403 004, India

This article introduces the reader to a new generation of ocean data platforms known as Autonomous Underwater Vehicles (or AUVs) brought about by promising technology developments in new sensors, memories, embedded controllers and materials. There has been a growing interest by oil and gas exploration industry in using deep water AUVs to map bathymetry around an oil well head, by the navy in mine surveillance or intelligence gathering, and abundant activity by the scientific and engineering communities scattered in several dozen universities and research establishments around the globe in building their own versions of AUVs for scientific data collection. In order to demystify the notion that AUVs are complex, high technology devices, we include a description of the main building blocks that go into the design of an AUV. This is followed by a brief look at the current scenario in AUV developments, but narrowing our attention to three noteworthy operational AUVs, and to our on-going development of a small AUV at the National Institute of Oceanography, Goa. The ultimate aim in AUV research and development is to reach the stage of unescorted missions that will see AUVs leaving and entering the world's harbours autonomously or doing the same from the shore. We shall see that this implies the implementation of safety standards of a high degree in a stable, well-tested and reliable vehicle architecture.

Keywords: Autonomous underwater vehicles, navigation, ocean data platform, safety, sensors.

AUTONOMOUS Underwater Vehicles (AUVs) are free-swimming marine robots that require little or no human intervention. In contrast, Remotely Operated Vehicles (ROVs) depend on a flexible tether to feed power and control signals from a support ship to underwater systems in an open cage. AUVs are compact, self-contained, low-drag profile crafts powered (in most cases, but not all) by a single underwater DC thruster. The vehicle uses on-board computers, power packs and vehicle payloads for automatic control, navigation and guidance. They can be equipped with state-of-the-art scientific sensors to measure oceanic properties, or specialized biological and chemical payloads to detect marine life when in motion. As is common in most developments today, AUVs have been operated in a semi-autonomous mode under human supervision, which

requires them to be tracked, monitored, or even halted during a mission so as to change the mission plan. However, there have been successful attempts at true autonomy, and that operational mode will soon be routine.

Building an AUV

AUVs are built from well-proven technology products that are commercially available. In the control of these vehicles, the designer uses rate gyros and magnetic compasses from the aircraft industry, high-speed radio modems and small-form GPS (Global Positioning System) receivers from the satellite communications industry, embedded controllers and high capacity memory storage used in general data-logging applications, and standard fin and rudder sections as described in textbooks on aerodynamics. What is needed then is to integrate these technologies into building the machine using a set of skills encompassing software engineering, hydrodynamics of rigid bodies, hydrostatics, navigation, electronics and control systems engineering. What ultimately binds all these systems together is the amount of intelligence incorporated in the software created for the AUV.

The main building blocks of an AUV¹⁷ are shown in Figure 1. The blocks are labelled as vehicle guidance and control, guidance, navigation, mission control, data-logging of sensors, communications, and vehicle safety, (the electronics block is not shown explicitly).

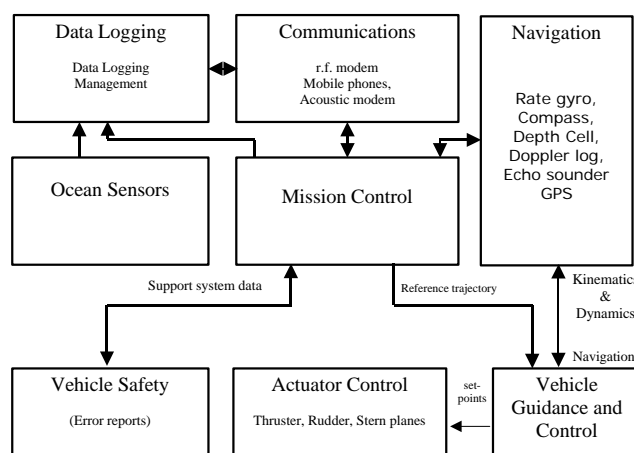


Figure 1. Main building blocks of an AUV (adapted from Oliveira *et al.*¹⁷).

*For correspondence. (e-mail: elgar@darya.nio.org)

The vehicle-control block represents the actual dynamics and kinematics of the vehicle, together with the vehicle actuator dynamics (thruster and control surfaces). The vehicle dynamics is driven by the forces and torques generated by the control planes and also by external forces and torques due to the medium where the vehicle moves. The outputs of this block are the position and attitude of the vehicle, together with the respective velocities. The navigation block provides estimates of the vehicle position and attitude, and respective rates. Part of the data is used by the guidance block, which compares the desired path from mission control with the actual path of the vehicle (as estimated from the navigation data) and generates corrective commands for velocity and attitude, so as to force the vehicle to reduce the path following error to zero. These commands are in turn read by the control (autopilot) block that implements control algorithms aimed at reducing velocity and attitude tracking errors to zero. The mission control block within the AUV interacts with a user through the communications block to receive a mission file having selected waypoints specified in latitude and longitude coordinates for actual execution by the guidance and navigation blocks.

The AUV hull

The large AUVs (e.g. Hugin, Norway or Autosub, UK) tend to have free-flooding hulls with separate interconnected pressure vessels that contain batteries, payloads, and electronics mounted on an internal metal framework or chassis, and enclosed by removable metal/fibreglass sheet panels.

Small AUVs (in most cases) consist of a removable torpedo-shaped nose section, a straight cylindrical section and a removable tail (or aft) section. The removable sections are mechanically secured to the cylindrical section by threaded bolts mounted on locking collars. A simple sectional view of this configuration is shown in Figure 2. The thruster motor that propels the AUV, is mounted at the extreme end of the tail cone so that no obstructions are present in the vicinity of the propeller blades. A pair of stern planes in the XY plane when rotated about a shaft along a diameter of the cylindrical section, is used to pitch the AUV upwards or downwards during diving manoeuvres. A single rudder plane (or pair of rudders) is mounted in the XZ plane of the AUV, and is used in heading (or yaw) control of the vehicle. The set of two stern and two rudder planes is positioned in a cross-arrangement (north–south–east–west) and is located as far aft as is possible, namely close to the tail cone so as to increase the distance of the lift forces on the control planes to the centre of gravity (CG). This produces higher pitching and turning moments that lead to diving and heading changes.

The overall shape of the body is important as this decides the propulsive energy needed to overcome the drag resistance to motion. The total energy density of the bat-

teries on-board determines the range and endurance of the vehicle, and must provide power for propulsion, sensors and actuators for the control foils.

Vehicle model of the AUV

A complete set of hydrodynamic derivatives for a given AUV body shape can be measured with a Planar Motion Mechanism (PMM) in a tow tank facility¹. If this is not possible, then one needs to use analytical and semi-empirical methods that borrow design methodologies used in aerodynamics². A complete six degrees of freedom mathematical model relates real forces (X, Y, Z) and moments (K, M, N) on the AUV to a nonlinear combination of the hydrodynamic derivatives. Constructing the model is an important exercise in AUV development, as it enables one to simulate its dynamic behaviour, and improve the performance of the control systems for manoeuvring well before field tests of the vehicle at sea. System identification tests using open loop manoeuvres in the sea are often used to determine the dynamic response of the vehicle and fine tune the autopilots and iteratively improve the hydrodynamic model².

Distributed architecture using networks

Electronic systems on board most AUVs are built around a distributed network consisting of intelligent nodes that control fin and rudder movement, thruster rpm, depth, speed, avoid collisions using a scanning sonar, or monitor and manage power usage, and trigger safety devices. Higher performance nodes are reserved for mission control, navigation and communications. Networked systems in AUVs encourage sharing of tasks by modular software development thus removing the dependence on a single control computer, and allow for intelligent decisions on safety to be made if anything should fail. Apart from this, distributed systems reduce wiring, minimize the number of expensive wet connectors, and permit easy expansion of additional nodes without any major restructuring of software programs. It is surprising that electronics hardware in AUVs occupies the minimum of space when compared to other subsystems, e.g. batteries, sensor and vehicle payloads. The

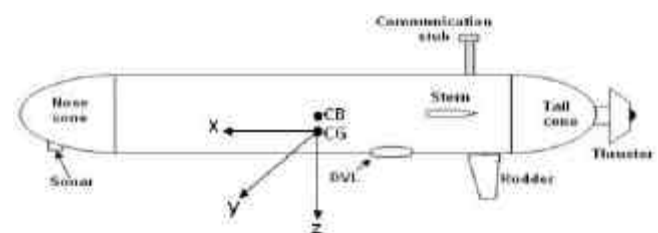


Figure 2. Side view of the small AUV, MAYA showing modular nature of its components.

future will see further drastic reductions in cost and volume of high performance scrap computer nodes that will effectively control the complex motion of versatile marine robots³.

AUV navigation and communications

Acoustic transponder methods

The acoustic approach to navigation uses an array of transponders that are deployed around the working site. The AUV operates within this area, and by triangulation determines its position in deep water. This method has been used widely by the Acoustic Benthic Explore (ABE) of the Woods Hole Oceanographic Institution (WHOI, USA). The approach is expensive and needs a support ship to deploy and recover transponders, but gives navigational accuracies as good⁴ as 2 m. A variant to the use of transponders on the seabed, has been the use of three free-floating GPS intelligent buoys (from ORCA, France) equipped with differential GPS receivers, and in VHF communication with a support ship. The AUV emits an accurately timed acoustic ping that is received by the GPS buoys. The position of the AUV underwater can be computed knowing the ping arrival times and buoy positions.

GPS and dead reckoning of the AUV

Navigation using GPS receivers offers position accuracies of ~25 m at low cost, or with more expensive differential GPS, accuracies of less than a metre. However, since GPS receivers have no use beneath the sea surface, it is necessary that the AUV breaks surface so that navigational algorithms can be updated with a satellite fix at the surface. When it dives, the Doppler Velocity Log (DVL), and pressure sensor are used to compute positional coordinates (x, y, z) of the AUV, until navigational errors mount to unacceptable levels. This method has been widely used by the Autosub AUV of the Southampton Oceanographic Center, UK, and has worked well in over 240 missions. In one spectacular example, Autosub travelled a distance of 600 km completely unattended by a support ship⁴.

Finally, acoustic modems can be used to communicate and track AUV movement below the sea surface from a support ship as is done with the HUGIN AUV of Norway, which in a strict sense belongs to the UUV (Unmanned Underwater Vehicle) class. In shallow coastal waters of 30 m or less, acoustic modems may encounter multi-path effects caused by acoustic signals bouncing off the sea surface or from stratification of the upper water layers.

Mission control

Mission control is defined as a means by which a non-technical user can design a mission script for the AUV to

execute. The script consists of a series of waypoints identified by latitude, longitude and depth coordinates of the AUV in the 3D space of the ocean. When these waypoints are geometrically connected, the mission paths for the AUV to follow are known. In most scenarios, the user will enter the mission script on a GUI (Graphical User Interface) program that runs on a laptop. The script is downloaded over an RF modem link to the AUV server, which then executes the mission. The end waypoint can be arranged to end near the user so that the AUV can be retrieved for another mission, if required.

AUV energy sources

The energy available on board and the rate of usage by the AUV subsystems remain one of the severest limitations on the sustainable operation of AUVs. The issue of cost-effectiveness of power sources must be factored into the power problem. Table 1 lists an increasing trend in the use of lithium ion, lithium polymer, alkaline with specific energy >150 Wh/kg. Lead acid is a poor candidate as it offers a low power-to-weight ratio. Many other types of batteries have been used, e.g. silver zinc, nickel metal hydride and more recently, fuel cells in the larger AUVs (HUGIN, ALTEX). In all cases, the cost of current energy sources is high until a cheaper, more effective source is available. The most promising approach in the future will be towards hybrid power systems coupled to intelligent utilization of energy rather than to maximum power available⁵. Solar-powered AUVs like the SAUV (described below) have moved ahead in this direction.

Safety aspects of an AUV – emergency abort

A common safety mechanism on AUVs is by dropping a ballast weight from the hull in the case of an emergency abort situation. AUVs are carefully trimmed to have a small positive buoyancy, but remain 99% submerged at the start of a mission. A small positive buoyancy within permitted limits is the norm⁵. The dropping of a ballast weight increases the range of positive buoyancy causing the vehicle to float up to the sea surface on detecting a mission failure. Emergency aborts can happen for several different reasons, e.g. maximum depth of operation has been crossed, the network nodes in the AUV have become silent, or non-completion of a segment of a mission track due to drift from strong currents, a jammed control foil or low battery levels. In the case of network silence, each node should initiate actions that contribute to the emergency abort, in case the mission control node has failed.

AUV developments

An internet search on the number of AUV development projects around the world reveals that there are nearly 58

Table 1. Comparison of different AUVs

Specs	AUTOSUB	REMUS	SAUV	MAYA
Size	7 m long, 0.9 m dia	1.6 m long, 0.19 m dia	2.3 m by 1.1 m by 0.31 m	1.8 m long, 0.234 m dia
Weight (kg)	1500	37	200	55
Depth (m)	1600	100	500	200
Speed	2 m/s	1.5 m/s	2 km/h	1.5 m/s
Endurance	500 km or 6 days	22 h at 1.5 m/s	Days (on usage)	20 km
Energy (Wh/kg)	Alkaline (191)	Lithium-ion (145)	Li-ion, solar panel	Li-polymer (182)
Vehicle payload	Attitude sensor, pressure sensor, echo sounder, CTD, ADCP	DVL/ADCP	Sonar altimeter, GPS	Doppler velocity log, micro sonar, GPS, RF, rate gyro
Science payload/options	Fluorometer, transmissometer, oxygen sensor, <i>in situ</i> manganese sensor, flow cytometer, water sampler, turbulence probe, additional ADCPs, upward-looking sonars, sidescan sonars, swath bathymetry and digital cameras	Sidescan sonar, CTD profiler, light scattering and turbidity sensor, fluorometer, INS, video camera, GPS, video plankton recorder	CTD	CTD, oxygen sensor, chlorophyll sensor
Navigation	Navigation is by frequent surfacing that uses GPS and DGPS to update its position	Navigation inside the ocean is by LBL and USBL acoustic sensors, and by Doppler-assisted dead reckoning	GPS	GPS on surface, dead reckoning underwater using the DVL
Launch and recovery	Needs specialized support on ship	From an inflatable boat	From a ship	From a small boat

of these in different stages of use and development (see www.ausi.org/auvs/auvs.html). We shall briefly examine/describe developments in two major application categories (leaving aside military reconnaissance and mine detection), namely AUVs for survey and search missions, and AUVs for use in science missions.

AUVs for search and survey

There has been a gradual implementation of AUVs in this class primarily for deepwater tasks involving pipeline, bathymetric and drill site surveys at typical depths of 3000 m. The HUGIN family of AUVs from Norway has been used extensively in bathymetric surveys, the MIT Odyssey vehicle in surveys of coastal fronts in the Hero Strait, British Columbia in 1996, and the laying of the 175 km long fibre optic cable under sea ice by the ISE Theseus AUV in the Canadian Arctic; these are examples of real missions at sea. These large machines are extremely well-engineered and have proven track records of collecting reliable high resolution data in difficult oceanic conditions. Another vehicle in the survey class of AUVs and close to operational status is the Infante AUV by the Institute of Systems and Robotics of IST, Lisbon.

The multinational 'Shell' has estimated that AUVs for oil field development could bring in significant savings for itself reckoned at about US \$100 million, and for the oil industry as a whole, nearly US \$772 million over the next five years⁶. Despite these promising projections,

AUVs are taking a slow route to the market. The constraints to their widespread use have been discussed widely, and possible reasons for this have been the small number of survey companies worldwide that have become dependent on ROVs, and lastly, the well-known conservatism of oil companies to the use of AUVs.

AUVs for science missions

The oceanographic community working in tandem with small, high technology companies, and engineering departments at universities, has been quick to use nearly all the recent developments of the underwater vehicle community. Ocean science has used every type of vehicle from manned submersibles, ROVs; ships with towed arrays of sensors; sea-gliders, notably the SPRAY glider and AUVs. The AUV in this context, is seen by most field oceanographers as an 'extension arm' of the research vessel – a low-cost, mobile data platform. Innovative sensors (mass spectrometer, bubble resonator, flow cytometer, nutrient sensors) have been interfaced as AUV systems for the collection of valuable data at sea⁵.

It would be beyond the scope of this article to describe all the developments that are taking place in this category. Hence, we shall single out three examples of AUV development that merit attention by having made substantial progress towards acquiring real data at sea. In doing so, we shall be looking out for those attributes that will be useful in monitoring and detecting marine life in the oceans,

particularly in near shore areas where the number of applications is numerous.

Our examples dwell upon:

1. AUTOSUB – designed and operated by the Southampton Oceanography Centre, UK.
2. REMUS (Remote Environmental Monitoring Unit) developed by Oceanographic Systems Laboratory of WHOI, USA and now being commercialized by Hydroid Inc, USA.
3. The SAUV – the solar powered AUV jointly developed by the Autonomous Undersea Systems Institute, USA and the Institute for Marine Technology Problems (IMTP), Vladivostok.

AUTOSUB – a large AUV

AUTOSUB belongs to the class of large AUVs conceived as a tool for scientific research in the oceans, and with a long-term objective of unescorted missions without a support ship (Figure 3). It has a total weight of 1500 kg, length of 7 m, a cruising speed of 2 m/s, a range of 200 km and a maximum operating depth of 500 m (see Table 1 for more details). Navigation is by frequent re-surfacing that uses GPS and DGPS to update its position. The first autonomous mission was in 1996. To date, it has carried out a total of 121 operational missions, of which eight missions in 1999 were unescorted. An upgrade in 2001–02, enabled AUTOSUB to undertake three science missions underneath the ice shelves in Antarctica and Greenland⁴. An excellent account of the range of multidisciplinary scientific studies made by AUTOSUB has been documented⁵. There are interesting conclusions that point to the potential of AUVs in making measurements that would be difficult to do otherwise using traditional methods of towed undulators and ships:

- Accurate acoustic estimates of the abundance and distribution of fish biomass over the entire water column is possible using echo sounders on AUVs to look up and down; a distinct advantage over ship-based surveys.
- In a study of fish schools in the western North Sea with AUTOSUB, it was shown from echosounder records that noise radiated from DC motors on AUVs do not affect fish schools⁷. Schools of fish separate, but do not scatter as was thought previously.
- The ability of AUVs to dive below the sea surface and to maintain depth control provides the flexibility to observe biota more closely overcoming sound attenuation and noise from the sea surface.
- AUVs can be programmed to follow seabed terrain, and algorithms for this are under development.
- Using a combination of multiple sensors and understanding how they behave in an AUV can lead to new

insights on biological and physical processes in the ocean.

REMUS (Remote Environmental Monitoring Unit) – a small AUV

REMUS⁸ belongs to the small AUV class. It weighs 32 kg with a length of 1.6 m, diameter 19 cm, cruising speed of 1.5 m/s that provides for an endurance of 22 h, and a maximum operating depth of 100 m (Table 1). Navigation inside the ocean is by long base line (LBL) and ultra-short base line (USBL) acoustic sensors, and by Doppler-assisted dead reckoning. The standard configuration of sensor payloads consists of:

- Dual up/down looking Acoustic Doppler Current Profilers (ADCP)
- Sidescan sonar
- CTD profiler
- Optical back-scattering sensor.

Several other sensor payloads have been integrated with the REMUS hull, including:

- Video plankton recorder
- A bioluminescence sensor (– or bathy-photometer)
- Chlorophyll fluorometer
- Radiometers.

REMUS has executed thousands of missions in shallow waters, and has a range of 100 km when driven at low speeds of 1.5 m/s. It can be launched and retrieved from an inflatable boat. The portability and smallness of REMUS with an operational depth of 100 m, endows it as the vehicle of choice for studies in the coastal zone. Compared to AUTOSUB, REMUS can execute many more short missions over limited track lengths at lower cost without the need of an expensive support ship and cranes. However, it has limitations: (1) Low volume space requires small-sized sensors, and this is of overriding concern until small AUV-compatible sensors are manufactured; (2) REMUS depends heavily on LBL acoustic positioning, which implies the use of transponders on the sea bed for computing the position of the AUV below the surface – this is a more severe limitation than the first one, with the attendant problems of calibrating transponder arrays and moving them to new survey areas.

SOLAR AUV (SAUV) – a medium size AUV

Our third example on the SAUV highlights the true potential of small AUVs. The use of solar arrays mounted on the top of the AUV extends the endurance time of an AUV mission to days and weeks, thereby sampling the ocean over long time and space scales. A long-term objective of this development is to develop SAUVs that operate in ex-

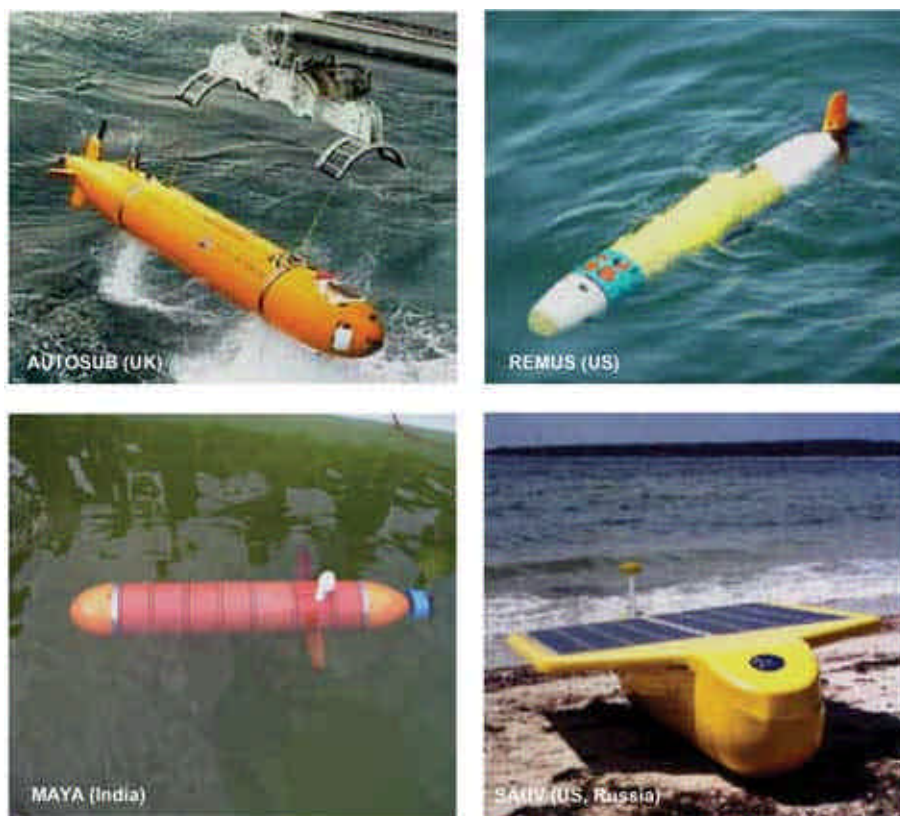


Figure 3. Different AUVs under development and in use.

cess of one year. At present, the SAUV has to surface on a daily basis for recharging its batteries during the day, with depth missions during the night. The specifications of SAUV are shown in Table 1.

Sensor payloads that are being used on the SAUV include

- Seabird CTD
- Oxygen sensor
- Fluorometer
- Light scattering sensor
- Spectral radiometers.

The SAUV⁹ has broken new ground in the endurance time of AUVs. The principal issue is one of energy utilization of stored energy from the sun for payloads and propulsion. The concern is that on-board systems must not use more energy than can be stored on-board between recharge periods. The second limitation is the energy conversion efficiency of solar arrays, which averages to ~20%. When this technology improves, the range of SAUV will be increased proportionally. The third limitation is that of bio-fouling of solar panels and sensors on the SAUV, which can drop its power output to 50% by 30 days, and reduce the reliability of its sensors unpredictably. In summary, the extended endurance of SAUV implies that larger volume of data can be gathered over longer spatial and temporal

scales, and this is where it scores over the AUTOSUB and REMUS. With advances in solar panel and anti-biofouling technology, the SAUV will evolve into a potentially useful autonomous platform of the future.

Small AUV (MAYA) development at NIO, Goa

Specifications of the Maya AUV are listed in Table 1, and a cross-sectional view of it is shown in Figure 2. The nose cone is a low-drag slender ellipsoid, unlike the torpedo-shaped nose of most small AUVs (e.g. REMUS, GAVIA). The main hull is bored from a solid bar of aluminum that has been pressure-tested to depths of 200 m, and a rear cone that follows a classical Myring profile¹⁰. The measured drag coefficient is ~0.310 at 1.5 m/s. Other features on the MAYA AUV include a communications stub containing the GPS and RF antenna mounted near the stern plane region, and a Doppler Velocity Log (DVL) that is used to estimate the speed and position of the AUV below the sea surface. The payloads that will be integrated in the hull include a miniature Conductivity Temperature Depth (CTD) sensor, Dissolved Oxygen (DO) sensor, and a single wavelength fluorometer to measure chlorophyll and turbidity. A miniature scanning sonar will be mounted on the nose cone with the purpose of avoiding obstacles during the flight of the AUV. When the development of MAYA is complete, the first mission will be on monitor-

ing of coastal hypoxia that is observed towards the end of the SW monsoon, off the coast of Goa¹¹. This would require a GPS-based YoYo (descent and ascent manoeuvre that resembles a sine wave motion in water) that will enable it to measure DO, CTD and chlorophyll as a function of water column depth, while moving along a transect perpendicular to the coastline, thus providing spatial and depth data of this effect.

Potential of AUVs with sensor payloads

The technology of the AUV described above assumes great value when specialized sensors are interfaced to on-board computers on the AUV. New techniques in innovative data sampling and data processing will be needed to take full advantage of the ability of an AUV to move with fair accuracy between different coordinates in the 3D volume of the ocean. We then have a potentially useful data platform with numerous applications in search, survey, and in science. Examples where AUVs are being used are listed below.

Biogeochemical mapping of coastal waters

A good example of this has been the use of REMUS fitted out with a passive spectral radiometer, fluorometer, and a CTD sensor to obtain high spatial and depth dependence of the inherent and apparent properties of sea-water constituents. This has spin-off applications in the calibration and validation and of Ocean Colour Satellites¹².

Coral reef monitoring

By incorporating a digital or video camera in the nose cone of a small AUV, we have a near-perfect tool for monitoring of coral reefs in Indian waters using a digital video camera. This technique would require the AUV to maintain safe depth and to follow the coral reef terrain using a scanning sonar. Other sensors to measure UV wavelengths and water temperature would be of use to ecologists. Similar approaches could be used in photographing ancient marine archaeological sites in India.

Coastal bathymetry of shallow waters

Coastal hazards created by storm surges, tsunamis and sea-level rise can be addressed by the use of AUVs equipped with bathymetric scanning sonars to generate accurate bathymetric maps from the high tide-line to the shelf edge. Knowledge of coastal bathymetry will help determine the direction and height of surges as waves encounter shallow sea bottoms in their coastal zones. Identification of inundation zones and safe human habitats in coastal areas will then be possible.

Other applications

- Small AUVs could be used to sniff polluted hotspots using special ammonia/urea sensors. This would require techniques in adaptive mission planning which are being implemented on the REMUS¹³.
- Rapid monitoring of marine biodiversity with shore-based AUVs.
- AUVs can be used as a test platform for the development of new sensors or propulsion systems – examples of bioluminescence, flow cytometers, and mass spectrometers have been interfaced to AUV systems by researchers elsewhere (see website www.mbari.org/education).

Safety – legal issues

There are legal issues that need to be addressed in case an AUV is involved in a collision with another moving or stationary platform. Griffiths *et al.*¹⁴ and Brown¹⁵ have touched upon these issues and these are best summarized as follows.

1. Status of shore-based AUV missions in national and international law is unclear.
2. AUVs have not been registered or classified as is done for other vessels.
3. International Maritime Organization (IMO) assessment procedures are not formulated with AUVs in mind.
4. Shore-launched AUVs have increased risks relative to ship-borne AUVs, particularly in operational integrity, collisions with ships, loss of life and injury, and loss when transiting to the site of operation, and in transiting across maritime zones.

Conclusion

This article leads us to the following conclusions:

1. The technology for control, navigation and guidance of AUVs is available. Current developments in this area are on sea-bed terrain following vehicles, improved navigation algorithms and the coordination control of multiple AUVs in flight formation¹⁶.
2. Reliability of an AUV is a key issue in new developments of AUVs, as it implies the use of high standards of safety through software and hardware in these systems. Each new AUV has to undergo numerous engineering trials to achieve reliability before utilization as a data platform.
3. There exists the need to develop appropriate, critical, AUV-compatible sensors for detection of marine life in the ocean. In this respect, small, compact sensor modules combining concurrent acoustic and optical detection techniques are waiting to be developed if

species identification is the key to a viable census of marine life.

4. AUVs, when equipped with the right sensor sets, have a vast potential for discovery in the oceans. Synergy between sensors must be exploited for new insights.
5. In studies of marine biodiversity up to the shelf edge, the small AUV, if appropriately equipped, affords the best means by which to carry out low-cost, rapid biodiversity surveys in coastal waters.
6. Legal issues relating to shore- and ship-based AUVs need to be addressed nationally within countries before going international. Unescorted missions of AUVs, and the technical capability to do this type of mission exist today. In harbour areas, the AUV will have to be armed with more precise navigational sensors to navigate correctly. AUTOSUB and REMUS AUVs have to a large extent demonstrated the feasibility of this approach.

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