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An approach towards the design and development of a flexible 5dof AUV

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Present study consists the overall development aspects of an Autonomous Underwater Vehicle (AUV) such as mechanical design, modelling, software architecture, controllers and navigation in combination with the lake experiments conducted on the vehicle at a shallow depth. AUV prototype in discussion is designated, AUV-150 and is designed to operate at a depth of 150 meters. It is a cylindrical-shaped carrier with streamlined fairing to reduce hydrodynamic drag. It is embedded with active propulsion, navigation, and control systems. Propulsion system comprises thrusters for generating motion in different directions to control surge, sway, heave, pitch, and yaw. Two arrays of cross-fins have also been fixed at the two ends to provide additional stability to the AUV against roll. A lithium polymer battery powers the vehicle and a pressure hull contains its electronics and energy system. Equipped with a camera, CTD and side scan sonar as payload sensors the AUV-150 is perfectly designed for performing underwater terrain mapping as well as oceanographic survey activities. The experimental results obtained from the shallow depth operation are quite satisfactory from the operational point of view.

[Keywords: AUV, Navigation & control, Thrusters, Sensor, Modular. Ocean parameters, hydroplanes]

Introduction

Underwater robotic systems like Remotely Operated Vehicles (ROVs) & Autonomous Underwater Vehicles (AUVs) helps us in monitoring various ocean parameters and facilitates exploitation of unlimited resources from the ocean. ROVs being tethered vehicles, they have certain limitations from the operational point of view whereas AUVs can be deployed in a comparatively easier way since they are not tethered and carry their own power supply on board.

Mission requirement and payload generally dictates the size and configuration of an AUV. The vehicle is manoeuvred underwater with the help of actuators like thrusters and/or control surfaces/hydroplanes/ fins. Modelling and simulation studies are important for analyzing and predicting the system dynamic behaviour at the design stage itself for risk reduction before the AUV is finally deployed in a completely non-structured and unknown environment like seas or oceans[1,2,3,4]. For practical applications, navigation, guidance & control aspects of the vehicle in an unknown, hostile and hazardous environment become extremely critical for carrying out specific mission tasks, the primary requirement of such tasks demanding that the vehicle follows a specified trajectory faithfully and operates in a robust and reliable manner. Many navigation, guidance and control strategies have been proposed by various researchers, all aiming towards development of efficient algorithms for reliable operation of AUVs[5,6,7,8,9].

A modular approach in the design provides a greater flexibility of the overall AUV system, starting from the basic configuration to software code development. The flexibility afforded by the modularity enables the system to behave in a more generic way without reconfiguring the overall design along with changes in the mission. However, such modularity complicates the electrical harnessing design and communication between various modules. Present study discuss the developmental issues along with initial experimental results with a 5-d of modular AUV at shallow water in Idukki Lake which has been designed for application of sea-bed mapping and scientific data collection up to a depth of 150 m.

Materials and Methods

The Present system

The test prototype of the AUV is designed considering the following key parameters as:

- maximum working speed 4 knot
- depth of operation 150 m
- payload Side Scan Sonar, CTD & Camera
- mission time 4-6 hours

The various aspects considered during design are: a) Configuration, b) Modularity, c) Degrees of freedom, d) Stability, e) Near neutral buoyancy, f) Hydrodynamic modelling, g) Pressure Hull design, h) Onboard energy System, i) Navigational Sensors, j) Navigation, guidance and control, k) Communication and l) Payload Sensors

After several iterations, the hull geometry was chosen to be cylindrical with streamlined fairing to reduce hydrodynamic drag. AUV has its own power, propulsion system, intelligent navigation and guidance control modules. Propulsion system consists of five thrusters mounted at suitable locations. A pressure hull is used to accommodate the control electronics and power systems. Vehicle is programmed with a set of instructions that enables it to carry out underwater missions without assistance from an operator on the surface. AUV has six modules from nose to tail, as shown in Fig. 1. Various components like thrusters, battery packs, sensors, computational platforms and associated electronics have been judiciously placed inside alternate dry and wet chambers. Detailed design is described in[10]. All the sensors and other devices are mounted judiciously on-board the AUV so that the system behaves metacentrically, i.e. the AUV remains hydrostatically stable through CG & CB adjustments. Two arrays of fixed cross-fins at the two ends provide additional roll damping moment. After several iterations, the length and diameter of the AUV were fixed at 4.6 m & 0.5 m respectively. Weight of the final AUV prototype made of special grade Al alloy (Al-6061), as shown in Fig. 2, including all its onboard subsystems, is 490 kgf. AUV has slight positive buoyancy (around 5 kgf) including its payload to facilitate its retrieval in case of a power failure.

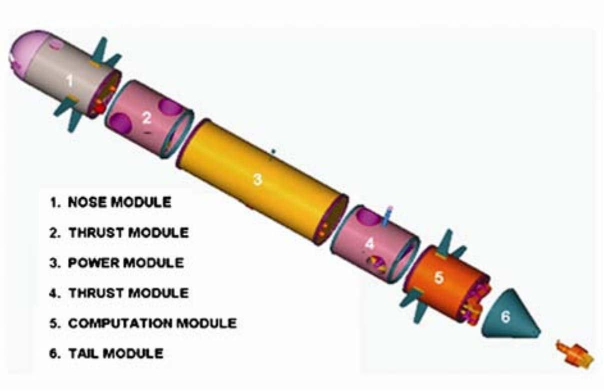

Fig. 1—Modular design of AUV

Actuators, Sensors and other devices

The nose module houses the forward-looking sonar (Super SeaKing of Tritech, UK) and camera (OE14-110/111 of Kongsberg Simrad) with lights HID Underwater Lamp OE11-139 of Schilling Robotics) at the front to detect obstacles in front of the body and for obtaining environmental pictures. Side scan sonar (Seaking SCU, of Tritech) is fitted at the bottom for mapping of the sea-bed. CTD (NXIC of Falmouth) is mounted in this section for recording the temperature, depth and conductivity at various operating locations. Acoustic modem with Ultra hort Base Line (USBL, TracLink 5000 of Link Quest) positioning system is fitted at the top of this section for communicating with the surface station and obtaining the position of the system with respect to the surface control station. The nose module also contains a pressure hull for housing a Single Board Computer (SBC) and Digital Video Server (DVS-350 m of Advantech).

There are two identical wet thrust modules each of which houses 2 tunnel thrusters (model SI-MCT01 of Seaeye), one in the horizontal direction and other in the vertical direction. Four tunnel thrusters are used for control in vertical and horizontal planes, enabling the vehicle to manoeuvre in the four modes: sway, heave, pitch and yaw. Propulsion thruster (model 1020 of Techadyne) is mounted at the end of the

Fig. 2—AUV Prototype

tail module to provide the forward motion of the vehicle, resulting in surge of the vehicle. Tail module also houses altimeter (model 1007 of Konsberg) and depth sensor (model EOPM of Falmouth). A Xenon flasher (RF-700C1 Combo of NOVATECH) mounted at the top of the tail side thrust module makes AUV visible at night.

The power module is specifically designed to keep energy system and inertial navigation system (PHINS of IXSEA) in dry condition within the pressure hull and Doppler Velocity Log (model WHN300 of RD Instruments) sensor outside the pressure hull i.e., in wet condition. This is the heaviest section which is placed centrally. Considering the safety and light weight, standard Li-polymer batteries with high specific energy, higher life and low self-discharge are used. Total energy system is divided into a number of battery packs due to functional requirement and ease of operation and these are monitored in real time to estimate the State of Charge (SOC).

Computational module is the brain of the AUV. All the computational devices are housed in dry condition inside the pressure hull of the computation module. All the devices of the other modules are connected to this module through interconnecting cables with proper harnessing. GPS and RF (ProPak V3 V3 L1 L2 GPS Receiver & 702GG Antenna of NovAtel) antennae are fitted on the top of this module. Onboard software residing on the computation module helps the AUV to take decision autonomously through the coordinated execution of in-built control modules functioning on the basis of navigational data obtained from different sensors.

Modelling, Control and Navigation

Modelling is carried out through IDEAS software code and structural analysis by ANSYS finite element software code. A number of design iterations and analyses were carried out along with control simulation for better performance, which has been published in [10].

The following 6 DOF nonlinear dynamic equations [11] of AUV in body-fixed coordinate frame are used:

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau \qquad \ldots (1)$$

where,

$$M = M_{RB} + M_A \qquad \ldots (2)$$

$$C(\nu) = C_{RB}(\nu) + C_A(\nu) \qquad \ldots (3)$$

$$D(\nu) = D_L + D_Q|\nu| \qquad \ldots (4)$$

Here M_{RB} and M_A respectively represents the rigid body and added mass/inertia matrices.

C_{RB} (ν) and C_A (ν)are respectively the rigid body and added Coriolis and centripetal matrices. and D_L and $D_Q|v|$ are linear and quadratic drag matrices.

Resultant vector of gravity and buoyancy forces is denoted by g(η) and τ is the resultant vector of thruster forces and moments. Vector of linear and angular positions in the global/earth coordinate frame is denoted by η. Vector of linear and angular velocities in the vehicle body coordinate frame is denoted by ν.The detailed components of τ, η and ν are represented as:

$$\tau = [\tau_1^T, \tau_2^T]^T; \quad \tau_1 = [X, Y, Z]^T; \quad \tau_2 = [K, M, N]^T;$$
$$\eta = [\eta_1^T, \eta_2^T]^T; \quad \eta_1 = [x, y, z]^T; \quad \eta_2 = [\phi, \theta, \Psi]^T;$$
$$\nu = [\nu_1^T, \nu_2^T]^T; \quad \nu_1 = [u, v, w]^T; \quad \nu_2 = [p, q, r]^T;$$

where X,Y and Z are forces and *K*, *M* and N are moments acting on the vehicle; x, y and z are absolute positions; φ, θ and Ψ are Euler angles in Z–Y–X convention; *u*,*v* and *w* are linear velocities and *p*, *q* and *r* are angular velocities of the vehicle with respect to the body coordinate frame. Linear and angular velocities in the absolute coordinate frame and the body coordinate frame are related through the Jacobian matrix and the relation expressed as:

$$\dot{\eta} = J(\eta)\nu \qquad \ldots (5)$$

where, $J(\eta) = \textit{diag}\{J_1(\eta_2), J_2(\eta_2)\}$

$$J_1(\eta_2) = \begin{bmatrix} c\Psi c\theta & -s\Psi c\phi + c\Psi s\theta s\phi & s\Psi s\phi + c\Psi c\phi s\theta \\ s\Psi c\theta & c\Psi c\phi + s\phi s\theta s\Psi & -c\Psi s\phi + s\theta s\Psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix},$$

$$J_2(\eta_2) = \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi / c\theta & c\phi / c\theta \end{bmatrix}$$

where $s\cdot = \sin(\cdot), c\cdot = \cos(\cdot)$ and $t\cdot = \tan(\cdot)$.

However, by ensuring roll stability through mechanical design, the total number of controlled degrees of freedom was reduced to 5. Total drag on the vehicle is summation of the drag due to viscous pressure resistance and the drag due to skin friction. Viscous Pressure Resistance (Drag) was estimated by using:

$$R_{Di} = \frac{1}{2} \quad A_{Fi} C_{Di} \left| v_i \right| v_i \qquad \ldots (6)$$

While, the drag due to skin friction was estimated by the following relationship:

$$R_F = \frac{1}{2} \quad S C_F \left| v_i \right| v_i ; \qquad C_F = 0.075 / (\log_{10} R_n - 2)^2 \qquad \ldots (7)$$

Here, ρ is seawater density, v_i is the velocity component in i^{th} direction of the AUV (either *u*,*v* or *w*), A_{Fi} is the frontal area (depends on the direction of movement), S is the wetted surface area, C_{Di} is the viscous pressure drag coefficient, C_F is the skin friction drag coefiicient, and R_n is Reynolds number. Viscous pressure drag coefficient C_{Di} also depends on R_n .

Thrusters were selected on the basis of estimated drags using relevant drag coefficient from standard handbook data for similar cylindrical geometries. An efficient controller was then designed & applied for the intended purpose of seabed mapping and data collection based on the customized dynamic formulation.

The AUV needs to track through a predefined trajectory or follow a prescribed path based on mission requirement. The AUV has to follow a course while underwater, which is pre-programmed prior to launching as mission requirement. During surface operation, the required trajectory is traced by regulating and controlling the surge and yaw motion of the AUV through control of appropriate thrusters.

Advanced controller based on PID & Feedback Linearization technique was developed and simulated as shown in [10]. For efficient navigation highly specialized Inertial Navigation system (INS) was used. For better position estimation Doppler Velocity Log (DVL) & GPS data were linked with INS data through sensor fusion methodology. Vehicle was programmed with a set of instructions that enables autonomous underwater missions.

Different activities or phases of the AUV mission are as follows:

i) Launching
ii) Trajectory follow
iii) Surge and heading control
iv) Diving
v) Collision avoidance
vi) Depth and pitch control, and
vii) Retrieval

Yaw or heading error is corrected by obtaining the current orientation data for the vehicle from sensors and feeding subsequent processing of the data by controllers, which issues the required control command for the actuators. During the diving phase, the AUV performs a series of operations consisting of pitching and heaving using the vertical tunnel thrusters while maintaining the attitude of the vehicle at a particular depth. For obstacle avoidance, the AUV first obtains the positional information of the obstacle through a Forward Looking Sonar. This data i.e. the range and bearing of the obstacle with respect to the vehicle is fed to a fuzzy logic controller as input, which finally provides an output the deviation required for avoiding the obstacle. Vehicle returns to its original trajectory after avoiding the obstacles. Obstacle avoidance part of the activity follows a deliberative control strategy i.e. sense-plan-act. Heading and surge corrections are performed through a low-level reactive control strategy.

The entire mission of the AUV is pictorially depicted in Fig. 3. Only when the desired depth is reached, the vehicle starts its cruising operation in the specified directions (heading). Once the entire trajectory has been traversed, the mission terminates and the AUV surfaces using the vertical thrusters. In the lake tests, the trajectory that is used is a set of consecutive straight line runs in different directions. All the motions are coordinated properly in order to enable the system operate successfully. The entire pre-programmed mission plan is stored inside an onboard database for immediate access during mission.

On board Software Architecture

The autonomous operation of the vehicle is achieved through a collection of routines organized in the form of on-board distributed software architecture based on the PC-104 standard and residing on a networked multi-processor environment.

Major tasks of the software are organized as follows:

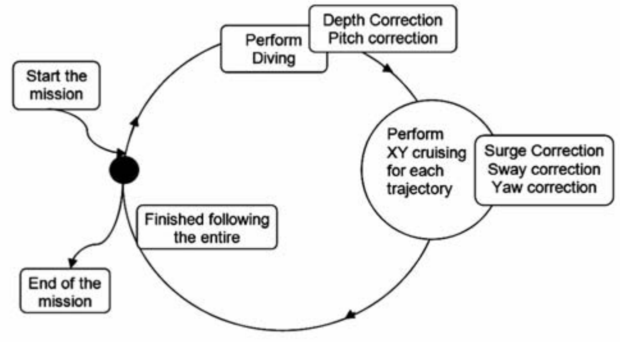

Fig. 3—Representative AUV mission

- Mission Management
- Navigation, guidance and control
- Payload data collection
- Surface communication

Hybrid reactive-deliberative software architecture was adopted for efficient organization and coordinated functioning of various control and decision making modules. Reactive layer consists of low-level control modules involving thruster control and feedback-based motion control. On the contrary, the deliberative layer is responsible for sequencing tasks and overall planning.

Physically the modules reside on different processors interconnected through Ethernet. Tasks are implemented through processes and threads for concurrent execution of the modules. Software modules are carefully located on respective hosts, intercommunicating according to a pre-defined communication protocol.

Integration and Trial

All equipments were tested and calibrated individually before integration. Thorough experimentation has been carried out with sensors like DVL, FLS and PHINS for their necessary calibration. Thrusters have been characterised for control purposes as in[10]. Systematic wiring and electrical harnessing was implemented for efficient communication. Actual prototype was balanced so as to bring the system to near-neutral buoyancy. Further incorporated high-speed WLAN antennae to provide improved communication link with the AUV while on surface. Acoustic communication was used during underwater operation. This is achieved with an Ultra Short Base Line (USBL) system associated with a low bandwidth acoustic link. It is found that a more precise and accurate positional information was obtained through the integration of DVL and GPS with Photonic-INS.

To enable retrieval of the vehicle in case of dwindling power, we incorporated a battery management system for monitoring the residual charge left with the cells, which, in case of an emergency would report to the emergency monitoring and controlling unit. This, in its turn, would issue instructions for the AUV to surface. It is further included a leak detection module for detecting the leakage of water inside the vehicle dry modules. On sensing a leakage, this module would transmit a signal to trigger a relay for snapping the power supply to the entire system, thereby avoiding damage.

We rigourously tested the final AUV prototype of AUV and evaluated its performance at the Idukki Lake, Cochin, India. Launching point was considered to be the start position for most of the trials. External underwater cameras were used for taking snapshots and capturing video.

The testing conformed to a carefully designed test plan with necessary checks and balances. Trials were conducted for two categories of mission, viz. straight course keeping and closed loop mission, during diving and on-the-surface operations. AUV was to maintain its own heading and perform corrections during the forward direction to reach the desired position. Closed loop missions consisted of straight-line paths in the form of a square or a trapezoidal profile. During all such trials, mission was carried out with the help of a pre-compiled mission file, which was stored in the memory of the onboard computational unit.

Results and Discussion

The field trials yielded results that were extremely encouraging in terms of AUV operation. Trials began with extensive surface operations. After this, depth operations with various mission specifications were conducted. We provide a representative straight course mission where the depth was 5 meters as per the mission specifications given in Table 1:

According to the mission specifications, the AUV was supposed to achieve a depth of 5.0 meters as the first phase of the overall mission, irrespective of heading and surge corrections. Thereafter, heading would have to be aligned to 0°, i.e. in the north direction with no surge. After attaining the desired heading, the AUV was required to settle for better steady state behaviour for duration of 6 seconds (0.1 minute). Subsequently, it was required to move for 20 meters twice consecutively along the same direction and settle for the specified durations,

Table 1—Mission specifications containing depth, heading and surge references together with settling time

BEGIN			
Depth: 5.0	Heading: X	Surge: X	Settle-Time: X
Depth: 5.0	Heading: 0.0	Surge: 0.0	Settle-Time: 0.1
Depth: 5.0	Heading: 0.0	Surge: 20.0	Settle-Time: 0.2
Depth: 5.0	Heading: 0.0	Surge: 20.0	Settle-Time: 0.2
Depth: 5.0	Heading: 180.0	Surge: 0.0	Settle-Time: 0.3
Depth: 5.0	Heading: 180.0	Surge: 20.0	Settle-Time: 0.2
Depth: 5.0	Heading: X	Surge: X	Settle-Time: X
END			

thereby resulting in a total surge for 40 meters along the north (0^o) direction. After moving 40 meters in the north direction, the AUV turns back in the south direction making heading as 180°. With subsequent stalling at the present configuration for duration specified in the mission file as described above, the AUV was supposed to go for a surge of 20 meters along the new direction.

Figure 4 depicts the response of the system during diving operation with no cruising. It is evident that the AUV could attain the requisite depth after 7 sec. In this regard, we should mention that the reference depth was changed dynamically on the basis of instantaneous altimeter readings on the sub-sea path. We undertook this exercise to delineate a feasible diving zone for the AUV where it would not encounter small mounds, high rising boulders (as shown in Fig. 8) and landmasses. The broken lines in Fig. 4 represent the continuously reference depth.

Cruising on the horizontal plane starts after the desired depth and heading were achieved. Underwater heading correction was performed for 0° (from t=5 sec to t=15 sec as shown in Fig. 5). Underwater surge operation started after desired heading is corrected at t=15 sec and continues up to t=27 sec. We found that during heading correction underwater surge correction is limited by the magnitude of the heading error, which helps considerably in avoiding undesirable drift. Similar motions were repeated for the rest of the mission.

The blue band shown in Fig 5 represents the period during which only diving is performed. The alternate yellow and pink bands represent the heading and surge corrections for each particular segment as read from the mission file.

It is evident from Fig. 5 that a surge of 20 m was achieved in 12 sec, which defines the average vehicle speed as 1.67 m/sec which is consistent with the design speed of the vehicle.

Plot of altimetry logged during diving operation and underwater cruising is shown in Fig. 6. The outermost profile represents the depth of lake-floor from the surface, whereas the innermost profile represents altimetry as logged by the altimeter. The difference between the two represents operational depth of AUV, which is given as part of the pre-defined path profile to be tracked by the vehicle. It is found that this difference remains almost constant during the total mission period after attaining the desired depth. This representation also suggests that the AUV control was performing perfectly since at no instant it hits the bottom.

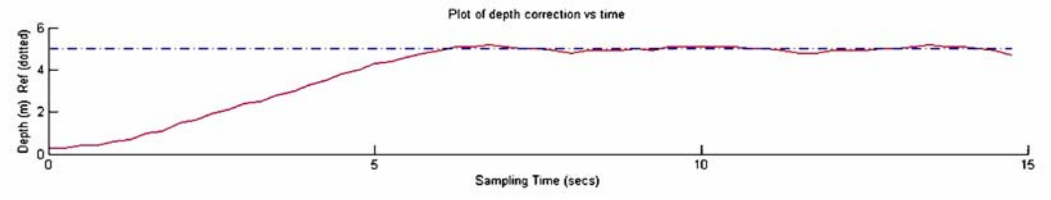

Fig. 4—Diving Response of the AUV over time operation

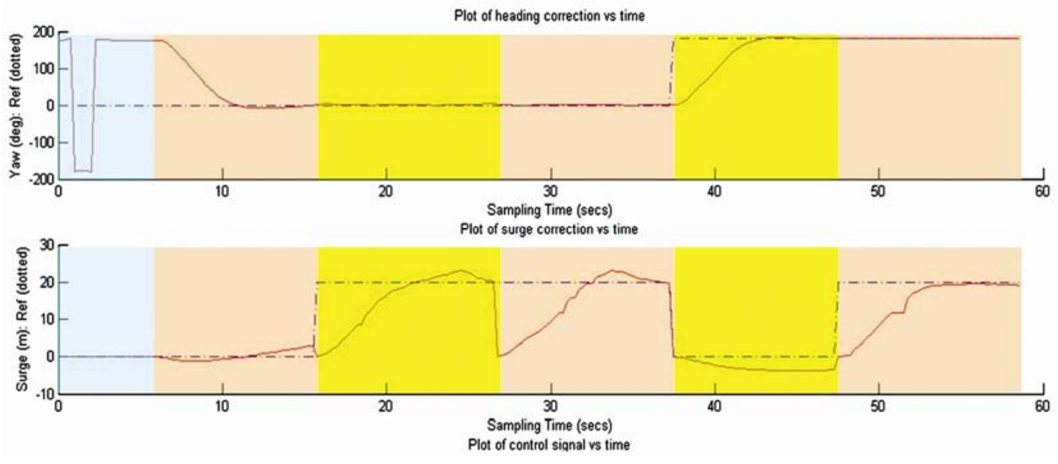

Fig. 6—Altimetry and depth of lake floor

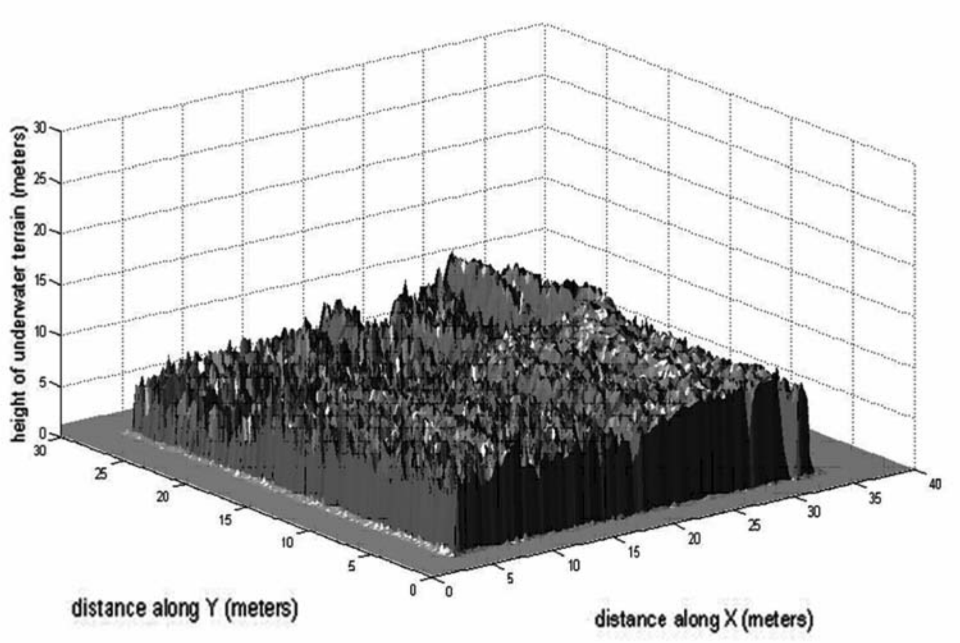

Fig. 7—3D Profile generated for the Lake Floor with data obtained from Side Scan Sonar

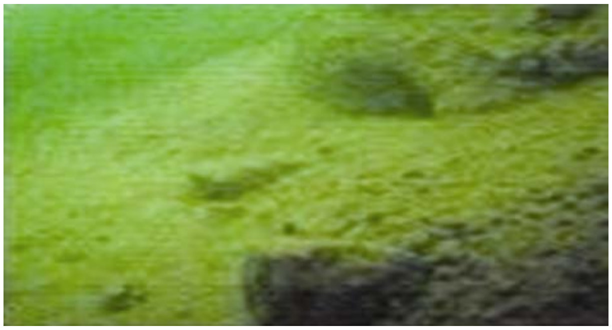

Fig. 8—Underwater images captured by the vehicle while undergoing a mission

As part of bathymetric survey, topological information of the underwater terrain was obtained from Side Scan SONAR (SSS) data during a closed loop mission. Surface profile modelling from the same was carried out as part of the post-operative data analysis, which we illustrate in Fig. 7. Underwater features were captured through camera mounted on the AUV. Fig. 8 illustrates in-situ snapshots captured by the camera.

Conclusion

The design of AUV with a set of assumed parameters were initiated and froze the final design through successive iterations, on the basis of which we fabricated the AUV prototype. Modular design adds on flexibility even in the hardware level. Addition or removal of any subsystem has been found to be very easy with adjustment of buoyancy. The necessery navigation and control algorathams for successful autonomous operation of the AUV with obstacle avoidance have also been developed. In the process calibration and characterisation for individual sensors, thruster and other devices prior to integration have been carried out. It is further devised a test protocol for the AUV taking into account the desired performance features. AUV prototype was found capable of efficient navigation while on a mission for the intended applications of seabed mapping, oceanographic data collection and underwater image capturing. On actual testing, it is found that the performance of the AUV falls well within the acceptable limits of error in the shallow water range. The algorithms and other subsystems would, however, require further fine tuning before the AUV is put to sea trials.

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