

Challenges in developing deep-water human occupied vehicles

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Human occupied vehicles (HOV) offer enhanced manoeuvring over the remotely operated vehicles and autonomous underwater vehicles. The presence of human increases the dexterity of the HOV operations, but at the same time, the man-rated vehicle design and operation requires significant attention to vehicle reliability, and in turn human safety. This article details the challenges involved in the design and development of deep water HOV, with specific reference to the 6000 m depth-rated HOV designed by the MoES–National Institute of Ocean Technology for enhancing India’s engineering capability in the deep ocean scientific research.

Keywords: Ballast, batteries, deep ocean, human occupied vehicle, navigation.

Introduction

HUMAN occupied vehicles (HOVs) are essential for carrying out deep water activities such as high resolution bathymetry, biological studies, geological surveys, search activities, salvage operations and engineering support. Even though unmanned underwater vehicles have improved manoeuvring capabilities and excellent vision systems that resemble direct observation, HOV provides a feeling of direct physical presence for the researchers. The successful operation of the first-generation bathyscaphe Trieste at a water depth of 10,906 m in the Mariana Trench triggered initiatives for the development of efficient HOV with manoeuvring capabilities^{1,2}. Since 1964, in pace with the advancing subsea technologies, the second generation deep-water HOVs were developed. They include Alvin of the USA in 1964, Nautile 6000 of France in 1984, MIR 6000 submersibles of Russia in 1987, Shinkai 6500 of Japan in 1989, Jiaolong 7000 of China in 2010 and the Deep sea Challenger in 2012. These HOVs continue to contribute immensely to various deep sea scientific research activities^{3–10}. With the advancements in metallurgy, buoyancy materials, energy storage, underwater navigation and life support systems; supported by advanced modelling tools and precision

manufacturing capabilities, the upcoming third generation HOVs are aimed at a lighter personnel sphere, efficient propulsion and control, precise navigation systems with increased reliability, safety and higher vehicle operational endurance. In order to achieve these, the International Association of Classification Societies (IACS) including organizations such as the American Bureau of Shipping (ABS), Det Norske Verities-German Lloyds (DNV-GL), Bureau Verities (BV) and American Society of Mechanical Engineers standards for human occupancy (ASME-PVHO) have established comprehensive safety rules and guidelines for the design and construction of HOV^{6,10}.

MoES–National Institute of Ocean Technology (NIOT) is involved in the technology developments for deep-ocean exploration of the non-living resources such as polymetallic manganese nodules, gas hydrates, hydrothermal sulphides and cobalt crusts, which are located at a depth between 1000 and 5500 m in the Central Indian Ocean Basin (CIOB), Bay of Bengal and the Arabian Sea¹¹. A 6000 m depth-rated Remotely Operated Vehicle ROSUB6000 had been developed by MoES–NIOT and qualified at 5289 m to enable effective exploration of the resources. Exploration for gas hydrates was conducted at a depth of 1019 m in the Krishna–Godavari basin, polymetallic nodules site at a depth of 5289 m in the CIOB, and for hydrothermal sulphides at the Rodriguez Triple Junction in the Central Indian Ridge system at depths of 2800 m (ref. 12). Submersibles such as the 6000 m depth-rated *in-situ* soil tester, 3000 m depth-rated Autonomous Coring System, 500 m depth-rated integrated polymetallic mining system and 500 m depth-rated Polar Remotely Operated Vehicle (PROVe) for enabling polar research have also been successfully developed and demonstrated^{13–16}.

MoES–NIOT is developing a HOV with a depth capability of 6000 m for carrying out deep-ocean research based on the expertise gained over the past two decades. The HOV is designed to carry three persons with an operational endurance of 12 h and systems to support emergency endurance up to 72 h (ref. 17). This article presents the studies undertaken to understand the critical technologies involved in the deep-water HOV development such as the personnel sphere, ballast and trim systems, energy storage, vehicle control, navigation and communication.

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The potential failures are identified through reliability analysis including Failure Mode Effect and Criticality Analysis (FMECA) and functional failure trees. The results are used to define the system redundancy requirements to achieve the required level of reliability and safety for the man-rated system.

Personnel sphere

The personnel sphere (PS) is one of the most critical sub-systems of the HOV designed to accommodate three persons, human life support and vehicle control systems. It is provided with an entry hatch, three view ports that enable external vision and electro-optic penetrators for electrical and optical interfaces from the vehicle exostructure located systems. The internal diameter of the PS is 2.1 m, based on the human occupancy requirements and ergonomic design. The material of construction for PS depends on the strength to weight ratio, corrosion resistance, creep properties under external hydrostatic pressure, cyclic pressurizing effects, collapse strength and elastic-plastic behaviour. All the deep-water submersibles use titanium alloy Ti-6Al-4V (refs 3–10), whereas Russia's Mir 1 and Mir 2 use martensitic nickel steel. In view of its high strength to weight ratio, excellent post-weld performance, negligible stress-induced corrosion and higher fatigue life, Ti6-Al-4V ELI (Grade 23) is identified as the material of construction for PS. With respect to the PS shell thickness, the deep water submersibles, currently in operation are built with a design safety factor in the range 1.2–1.55 (ref. 6).

The thickness required for the PS of the 6000 m depth-rated HOV was calculated using analytical and numerical methods. Analytical calculations were based on the data from the literature, design rules of DNV-GL, ASME-PVHO and other applicable standards (Figure 1) from which a hull thickness of 80 mm was identified, including the overall out-of-roundness (OOR) of <1% of the

nominal inside diameter, and local shell tolerance of <0.5% of the nominal outside radius. Numerical analysis incorporating the material properties and geometrical non-linearity was also carried out for both the perfect and imperfect spheres to identify the buckling behaviour. Studies on fatigue crack growth based on the damage tolerance design methodology were carried out to understand the influence of the cracks inevitably developed during the manufacturing processes^{18,19}.

The design and development of the hull viewports made of acrylic material were performed with the aid of the American Society of Mechanical Engineers standards for human occupancy (ASME-PVHO). The scaled-down models of viewports with the internal and external diameters of 200 mm and 500 mm and of 150 mm thickness are developed in-house and qualified for 600 bar external pressure conditions in the in-house hyperbaric chamber. Further optimization of the viewports was carried out using numerical models (Figure 2).

The stress distribution and displacement of the PS including the titanium sphere, view ports, entry hatch and the electric penetrators were identified through numerical analysis (Figure 3). The simulations are carried out as per DNV-GL 2017 code for an external pressure of 104 MPa and a collapse pressure of 1.73 times the working pressure. The localized stresses shall be reduced by various stress reduction techniques such as the biological growth method²⁰.

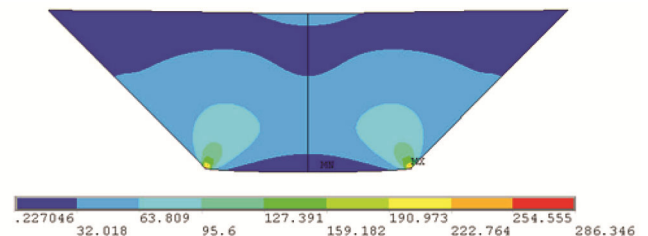


Figure 2. Stress plot of view port (units in MPa).

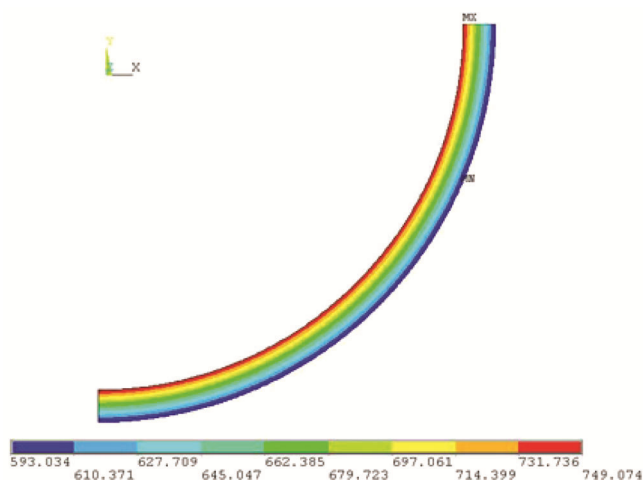


Figure 1. Stress plot of the personnel sphere.

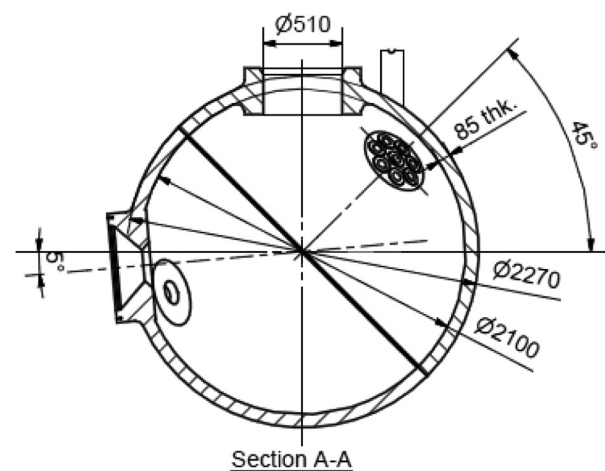


Figure 3. Personnel sphere design dimensions.

Human thermal comfort studies are undertaken based on numerical and experimental methods suggested by the guidelines of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHARE). The parameters assessed are predicted mean vote (PMV) and percentage people dissatisfied (PPD). The PMV is an average response of the large number of people to an environment and PPD is the estimate of the percentage of the people who will be dissatisfied in that environment. A computational fluid dynamic (CFD) analysis with heat generation and natural convective heat transfer using analytical thermal manikin was carried out. The thermal manikin analytical models are coupled with the CFD (Figure 4) to find the equivalent temperature and the PMV.

Hydrodynamic studies

Drag force analysis

Performing numerical hydrodynamic analysis is essential for estimating the drag force acting on the HOV, when moving at different velocities, multiple degrees of freedom

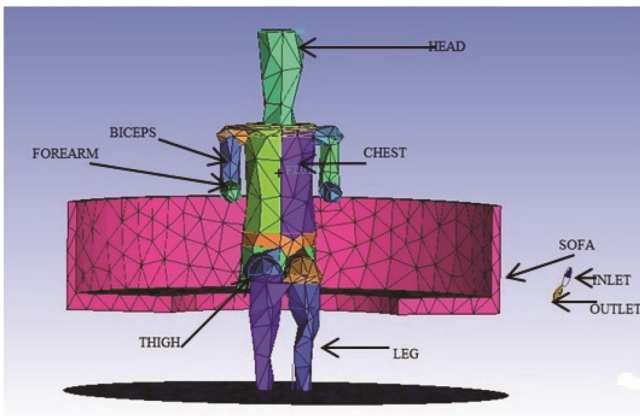


Figure 4. CFD analysis for thermal comfort.



Figure 5. Preliminary model of the HOV.

and varying pitch angles. These parameters were used for determining propulsion thrust, power and identifying the energy efficient descent–ascent scheme²¹. Numerical hydrodynamic drag analysis was carried out on the HOV model (Figure 5) for different vehicle velocities, external fluid flow fields and various angles of attack. The drag force acting on the vehicle for velocities up to 3 m/s and for various angles of attack (ranging for 0–90°) was calculated and plotted (Figure 6).

Ballast system design

The ballast system enables the HOV to change its depth by varying its buoyancy either by using a drop weight system or by displacing the water in and out of the ballast tanks. The ballast systems of the HOV include the fixed buoyancy offered by the PS, syntactic foam, variable ballast and main ballast tanks. In the variable ballast system, hard tanks provide precise changes in buoyancy required to maintain neutral buoyancy. In the main ballast system, the soft tanks are used for making freeboard adjustments during surfacing. An ascent–descent scheme is identified based on a trade-off among the system reliability, ascent/descent duration, energy usage and human comfort, using detailed studies.

Numerical analysis is done for the variable ballast system involving hard ballast tanks with internal diameters ranging from 0.5 to 1.25 m and with water pumping rates ranging from 6 to 20 litres per minute. A ballast weight of 150 kg could result in 4 h descent duration and increase in the ballast >400 kg shall not have significant reduction in the descent time.

Power budget and battery sizing

Based on the hydrodynamic analysis, a 6 thruster configuration was envisaged with 2 thrusters in surge, 2 for heading and 2 for vertical degrees of freedom. The energy

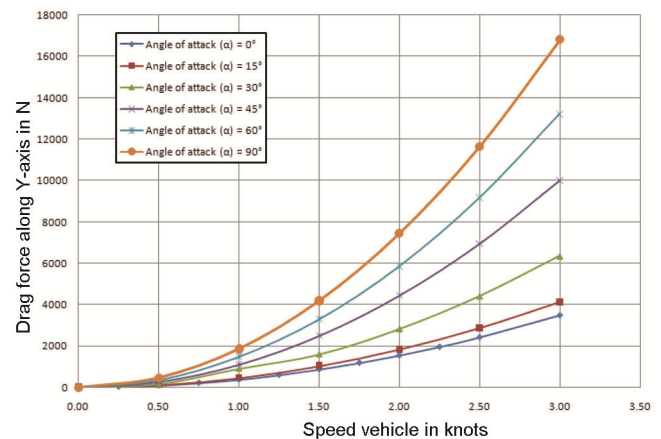


Figure 6. Drag force for various DOF for different pitch angles.

requirement for the different phases of mission involving 6000 m depth of operation and 150 kg ballast weight is plotted in Figure 7. The total energy requirement for a 12 h mission involving an operating period of 4 h at 6000 m water depth and with an emergency endurance of 72 h is about 100 kWh. Considering the uncompromising safety requirements, energy and power budget needs, operational reliability, stable electrical performance, superior weight and volume density, and market availability, pressure-balanced oil-filled (PBOF) lithium-polymer (Li-Po) batteries were selected for the manned submersible²².

Control, navigation and communication

The architectures for the vehicle control, navigation and communication systems are designed based on the IACS and IEC 61508 HSE standards for electrical, electronics and programmable applicable for the time-critical systems involving human risk. The architectures aim to avoid single point failures and with mutually independent instrumentation for essential functions and emergency operations. The HOV component and subsystem failure rates are computed based on the guidelines provided by the Failure-In-Time Determination for Electronics Systems (FIDES) guide, MIL HDBK 217 handbook, IEEE 493 recommended practice for the design of reliable electrical systems, DNV Offshore Reliability data (OREDA) handbook, and the handbook for reliability prediction procedures for mechanical equipment.

The failure mode effective criticality analysis (FMECA) studies are carried out for HOV critical operations including descent/ascent function, navigation, ship-HOV communication and unsafe scenarios such as vehicle hard

landing on the sea bed, collision with forward objects, manipulator entanglement and vehicle entanglement^{23,24}. Failure trees (FT) are modelled using TOTAL-GRIF reliability estimation software based on the system functional diagrams. The FT is simulated with the identified failure-in-time (FIT) values and respective degradation pattern to identify the probability of failure (PoF) of the system in one year. The methodology adopted for the studies is shown in Figure 8. The numerical reliability approach is a yardstick to quantify the improvements required, selection of alternate technologies, redundancy and maintenance planning.

Based on the identified PoF, the safety integrity level (SIL) requirements for the control network were identified based on IEC 61508 standards. SIL defines the degree of safety protection required by the safety function which has four levels, 1 to 4. The higher the level is, the safer the system will be. The SIL levels required for the control functions identified based on the consequence are shown in Table 1.

Control system

The HOV control architecture designed based on the described methodology is shown in Figure 9. The control system includes a real-time controller located inside the exostructure-located pressure-rated enclosure, which communicate with the computers inside the PS through electro-optic penetrators. The communication is based on ethernet protocol in electrical and optical formats. Based on the component failure rates, the PoF of the control network with optical ethernet (primary link) is computed to be in SIL2; and the control network with electrical ethernet (secondary) is also computed as SIL2. As the network needs to be SIL3 compliant, the configuration

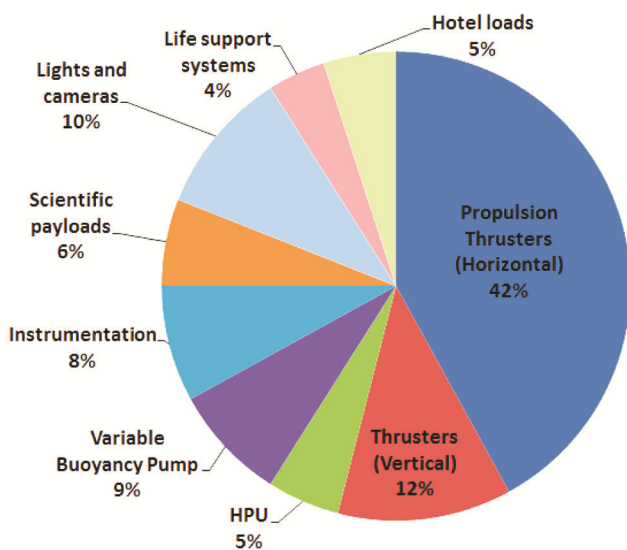


Figure 7. Energy requirements for the HOV subsystems.

Table 1. Consequence and IEC 61508 SIL requirements

Consequence	SIL	PoF
Minor injury	1	10 ⁻² to 10 ⁻¹
1 life at risk or sever injury possible	2	10 ⁻³ to 10 ⁻²
>1 life at risk	3	10 ⁻⁴ to 10 ⁻³
Many lives at risk	4	10 ⁻⁵ to 10 ⁻⁴

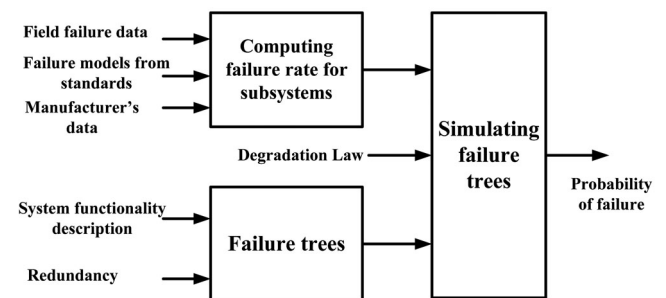


Figure 8. Methodology adopted for identifying PoF.

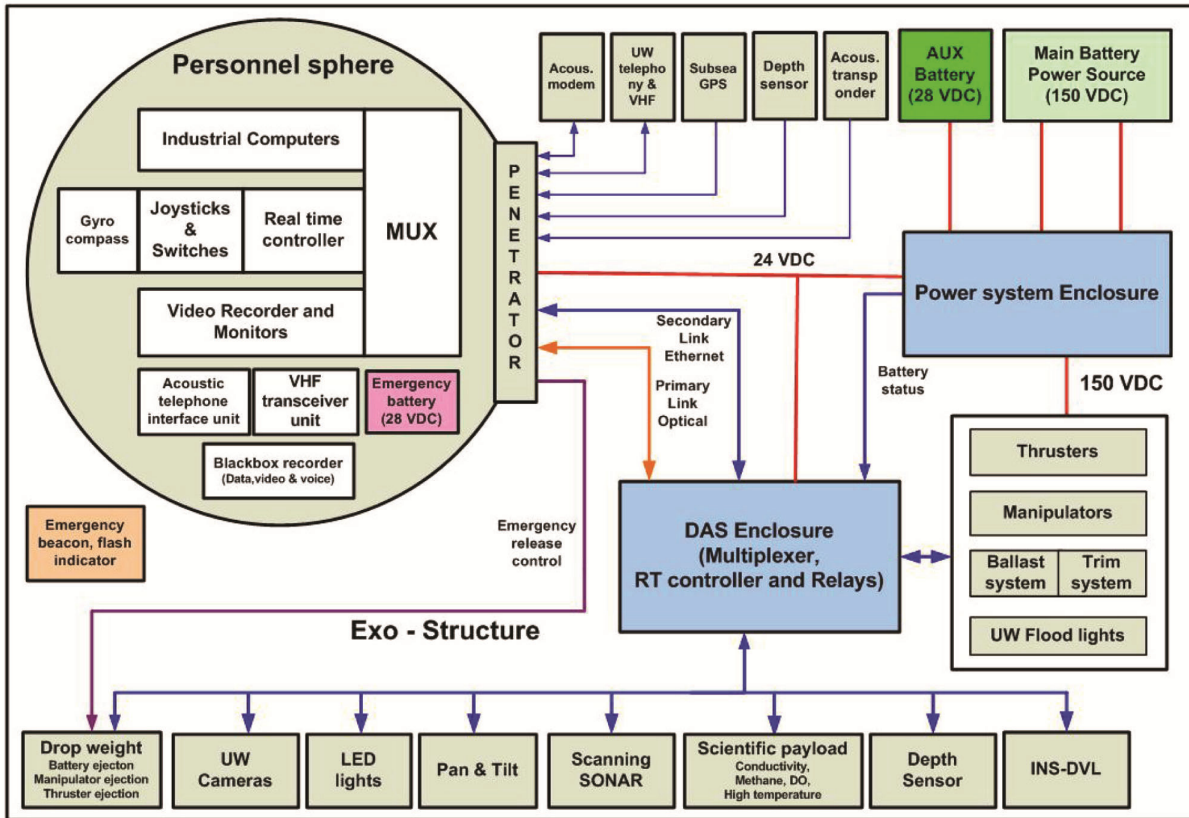


Figure 9. Vehicle control architecture.

Table 2. PoF and SIL levels for control architecture

Architecture	PoF	SIL
Optical network only	3.4×10^{-3}	2
Ethernet network only	1.03×10^{-2}	2
Optical and ethernet in redundancy	5×10^{-4}	3

with primary and secondary networks operated in redundancy was identified and the PoF is shown in Table 2.

However, in case of critical scenarios such as water flooding the pressure-rated enclosure, jettison requirements during manipulator and vehicle entanglements, the drop weight and the jettisoning functions shall be done directly using the PS power and control systems through the penetrators.

Navigation system

When the HOV is at the surface, the initial position will be obtained from the GPS. When the HOV is underwater, the position is computed using the onboard navigation sensor suite comprising of high-precision Internal Navigation System (INS) aided by the Doppler Velocity Log (DVL), depth sensor and acoustic base line systems²⁵.

Based on the reliability analysis, the HOV navigation system needs to be operated as redundant for SIL2 compliance²⁴. As a redundancy to the on-board navigation system, the position of the HOV determined by the deployment ship USBL system will also be provided as redundant input to the HOV through acoustic telemetry.

Communication system

When the HOV is underwater, the data and voice communication between the deployment vessel and the HOV is essential for monitoring the health of the HOV systems. The hydro-acoustic communication poses several challenges because of signal fading due to attenuation, multipath reflections, shadow zones, time and depth-dependent refractive properties of the ocean sound channel and water temperature. The quality of the communication defined in terms of the bit error rate (BER) depends upon the channel properties, operating frequency, distance between the acoustic transmitter and the receiver, transmitter power and the modulation techniques used in the communication protocols. Commercial hydro-acoustic full duplex telemetry systems offer reliable communication with data rates of 62 kbps at 150 kHz for

10 W in shallow waters, 14 kbps at 20 kHz for 55 W in 3500 m and 9 kbps in 6000 m range²⁶. Thus the deployment vessel has to follow the HOV so as to be within the reception range. Furthermore, the design of the system has to ensure that the communication systems are not affected by the electromagnetic noise interference generated by the other HOV systems such as thrusters. Based on the IACS, two independent acoustic telephones are required and the ship-HOV voice communication navigation system needs to be SIL2 compliant²⁴ which requires redundancy based on reliability analysis. The usage of underwater telephones operating at 27 and 10 kHz at a range of 6 and 10 km respectively, has been planned to comply with the requirements.

Other critical systems

Life support systems

The life support systems (LSS) are required for the crew housed inside the PS. Studies on the LSS design are done based on the guidelines provided by the IACS, standards and the available literature. The LSS are designed to maintain the internal environment with 20% of oxygen supplied from oxygen cylinders housed inside the PS, <1.0% of CO₂ managed using scrubbers, suitable dehumidifiers and emergency packaged re-breather oxygen systems, appropriate monitoring equipment for these critical parameters including the oxygen, CO₂, temperature, pressure and relative humidity. A mockup acclimatization sphere of 2.1 m diameter, with internal arrangements and ergonomics simulating the actual depth-rated personnel sphere was used to aid the design of the LSS and to acclimatize the crew. The oxygen supply system design considering that the leakage from a single cylinder does not increase the pressure and oxygen concentration inside the PS greater than 1.2 bar and 23% respectively.

Launching and recovery systems

Safe launching and recovery of the HOV in the offshore environment is a major challenge, which has to be carried out in a rapid manner. Once the HOV is launched on the sea surface, the diving team off-hooks the handling slings, and when the HOV surfaces, the team slings the ship crane's slings with the HOV. Based on the experiences gained in handling such systems, it is planned to launch and recover the HOV using the aft-located A-frame of the MoES–NIOT Technology Demonstration Vessel *Sagar Nidhi*. Design for the modification of the A-frame, deck strengthening, augmenting the vessel handling systems, communication and acoustic positioning systems have been undertaken to suit the HOV operations.

Emergency support systems

The emergency systems of the HOV include subsystem jettisoning mechanisms and rescue support systems suitable for locating the HOV in distress. When the HOV gets entangled with sea floor objects, IACS recommends prioritized jettison of the subsystems such as manipulators, science basket, batteries using frangi-bolted arrangements. In case the HOV is entangled, the pilot actuates the buoy-pinger mechanism, which pops up the buoy with a Kevlar cable connected to the HOV along with an acoustic pinger. The system helps the vessel to identify the location of the stranded HOV.

Conclusion

The efforts undertaken by MoES–NIOT in the design and development of the deep-water human occupied vehicle are presented in this article. The studies undertaken to understand the critical HOV technologies include the pressure-rated personnel sphere, energy storage, ballast systems, vehicle control, navigation and communication are presented. Realization of the 2.1 m diameter made of titanium alloy PS with the described specifications and qualifying for its pressure-rated integrity is a big challenge as only a few manufacturing and testing facilities are available globally. The manufacturing of the PS involves critical processes retaining the material properties, maintaining the manufacturing tolerances and ensuring the operating depth capability over the envisaged life time. The detailed engineering design of the batteries, control, communication, navigation, life support systems, submersible exo-structure, fairings, syntactic foam for buoyancy, scientific payloads and the emergency recovery systems are underway. Studies are also undertaken for analysing the submersible hydrostatic stability and trim control for effective manoeuvrability over the deep ocean floor and when it is on the sea surface. The failure modes of subsystems and the needs for redundancies also analysed so that they can be incorporated in the system design stage.

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