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Review Article

An overview of the mechanical features of human occupied vehicles

Bhaskaran Pranesh*, **Shanmugam Karthikeyan, Dharmaraj Sathianarayanan, Manickavasagam Palaniappan and Gidugu Ananda Ramadass**

Deep Sea Technologies, National Institute of Ocean Technology, Chennai 600100, India

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Abstract

Scientists are using human occupied vehicles to explore underwater environments. There are several mechanical features used in the design of human occupied vehicles. These mechanical features are primarily based on environmental factors such as high external pressure, low temperature, and corrosion resistance. In this paper, human occupied vehicles rated for 6,000 m depth are studied, including Alvin, Jiaolong, MIR-1/MIR-2, Nautile, and Shinkai 6500, as well as vehicles rated at 11,000 m depth, like Deep Sea Challenger, Fendouzhe, and Triton. As a review, this paper examines various mechanical systems in human occupied vehicles, such as the pressure hull, hatch, ballast system, trim system, exo-structure, and syntactic foam.

1. Introduction

Ocean resources and environments provide humans with opportunities for ocean expedition. Moreover, the complexities of the ocean, and the new wealth available from it, led to the exploration of the ocean by vehicles at the beginning of the 19th century. The two types of underwater vehicles most commonly used for ocean exploration are crewed vehicles and uncrewed vehicles. Human occupied vehicles (HOVs) come under the category of crewed vehicles, whereas Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) come under uncrewed vehicles. ROVs are connected to ships through umbilical cables/tethers, whereas AUVs are not connected to ship through umbilical cables. Fully autonomous AUVs are pre-programmed or logic driven to complete a mission without human intervention (Agarwala, 2022, 2023). AUV operations are autonomous and can cover a larger area as compared to ROV ones.

Biological, chemical, geochemical, geological, and geophysical research can be performed by oceanographers using underwater vehicles. It is possible to observe and collect samples from underwater creatures in their natural habitats. In the case of special purpose ROVs, the samples collected can be analyzed with the help of *in situ* instruments. Due to the complexity of ocean

*Corresponding author: Deep Sea Technologies, National Institute of Ocean Technology, Chennai 600100, India
E-mail address: praneshsb@yahoo.com

surfaces and structures, human occupied vehicles are essential for collecting valuable data. There have been numerous developments in human occupied vehicles since the early decades of the 20th century.

The most familiar deep water HOVs that are currently in operation are selected for this review. They are Alvin, Jiaolong, MIR-1/MIR-2, Nautile, Shinkai 6500, Deep Sea Challenger, Fendouzhe, and Triton. A 1962-built American vehicle, Alvin has a reach of 6,000 m (Moorhouse, 2015). Scientists in China have developed Jiaolong, which can reach 7,000 m of water depth (Zhang et al., 2019). MIR-1/MIR-2 was developed by Russian scientists, Nautile by French scientists, and Shinkai 6500 by Japanese scientists. Each of the above-mentioned human occupied vehicles is capable of diving to 6,000 m of ocean depth (Drogou et al., 2013; Kohnen, 2013; Sagalevitch, 2012; Yang et al., 2021; Zhang et al., 2019). In addition to the above, the Deep Sea Challenger, Fendouzhe, and Triton vehicles were developed for deeper water operations. They can reach a depth of 10,000 m in the deep ocean (Deep Sea Challenger, 2012; Limiting Factor, 2018; Yang et al., 2021).

All of the above mentioned human occupied vehicles use unique mechanical features to perform their operations. There are several key features of human occupied vehicles discussed in this paper, including vehicles rated for 6,000 and 11,000 m of sea water. This article discusses the various mechanical systems used in human occupied vehicles, including pressure hulls, hatches, ballast systems, trim systems, exo-structures, syntactic foam, and pressure vessels/enclosures. The review also explains the working principles of various ballast and trim systems in human occupied vehicles. These concepts can be used by design engineers for the selection of suitable trim systems for future human occupied vehicles.

2. World-wide human occupied vehicles up to 6,000 m of sea water

There is scattered information regarding human occupied vehicles. The various vehicles considered under 6,000 m of seawater category are Alvin, Jiaolong, MIR-1/MIR-2, Nautile, and Shinkai (HOVs are arranged in alphabetical order). Detailed descriptions are provided for each human occupied vehicle. Table-1 shows the summary of different human occupied vehicles upto 6000 m of sea water. Researchers use human occupied vehicles for biological adaptations, colonization, chemical analysis, and hydrothermal venting (Drogou et al., 2013).

2.1 Alvin

Allyn Vine, a physicist, developed a human occupied vehicle based on Froehlich’s design in 1962. It is sponsored by Woods Hole Oceanographic Institutions (WHOI). In 1964, Alvin embarked on his first dive in the Bahamas at a depth of 1,829 m. During each dive, Alvin could carry one pilot and two scientists to a maximum depth of 4,500 m. Over 600 dives were conducted in the Alvin between 1965 and 1968, including the discovery of Spain's lost H-bomb. WHOI has begun converting Alvin into a vehicle capable of 6,500 m with funding from the National Science Foundation and the Office of Naval Research. As a result, it will be able to cover a larger area of the ocean. **Figure 1(a)** shows Alvin’s different stages of development (WHOI, 2019).

2.2 Jiaolong

Jiaolong was developed by China. Jiaolong has a petal type titanium spherical pressure hull from Russia and syntactic foam from the United States (Kohnen, 2013). Jiaolong and its subsystems are qualified in various stages, such as 1,000, 3,000, 5,000, and 7,000 m. In 2013, this human occupied vehicle was tested and proved to a maximum depth of 7,062 m. A total of 100 dives were completed by Jiaolong in three different coastal regions, including the Pacific and Indian oceans. The shape of the vehicle is shown in **Figure 1(b)** (Zhang et al., 2019).

2.3 MIR-1/MIR-2

MIR-1/MIR-2 were developed by the Soviet Academy of Sciences and Rauma Raepola Oy Company of Finland in 1987 and was operated by P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences; it is shown in **Figure 1(c)**. The hulls of the MIR-1/MIR-2 human occupied vehicles are made of martensitic steel with a 50 mm wall thickness. They have an operating capacity of 17 - 20 h and an exploring capacity of 98 % of the seabed. Russia has the capability to deploy two HOVs (MIR-1/MIR-2) from their mother ship. It is possible to deploy another human occupied vehicle if one of the human occupied vehicles becomes stuck on the seabed. Also, in some research activities, the two vehicles have been combined to perform operations effectively through synergistic functions (Zhang et al., 2019).

2.4 Nautile

This human occupied vehicle of 6,000 m depth, developed by the French Ocean Exploration Research Institute (IFREMER), is shown in **Figure 1(d)**. It began its sea trials in 1984 and reached a depth of about 6,000 m in 1985. From 1984 to 1999, Nautile dived around 100 times a year (Zhang et al., 2019). Two hemispheres made of Ti-6Al-4V are bolted together to form the spherical pressure hull, avoiding welded joints.

2.5 Shinkai 6500

Japan Agency for Marine Earth Science and Technology (JAMSTEC) developed the first flagship human occupied vehicle in 1989. The Shinkai 6500 held the record for the deepest human occupied vehicle until 2012, this record being overcome by Jiaolong. The shape of the vehicle is shown in **Figure 1(e)** (Kohnen, 2013). A total of 1,000 dives were completed by Shinkai 6500 on March 15, 2017, accompanied by more than 800 scientists (Sagalevitch, 2012; Seedhouse, 2011). An investigation rating of 98 % is given to Shinkai 6500, which has a capacity of 8 h.

Table 1 Specification of 6,000 m human occupied vehicles (Hu & Cao, 2020; Moorhouse, 2015; WHOI, 2019; Zhang et al., 2019).

Human occupied vehicle	Alvin	Jiaolong	MIR-1/MIR-2	Nautile	Shinkai 6500
Country	USA	China	Russia	France	Japan
Depth rating (m)	6,500	7,000	6,000	6,000	6,500
Number of viewports	Five	Three	Three	Three	Three
L×B×H (m^3)	7×2.6×3.68	8.3×3.8×3.0	7.8×3.8×3.0	8×2.7×3.8	9.5×2.7×3.2
Operational time (hrs)	6 - 10	10	17 - 20	5	8
Pay loads (kg)	181	220	290	200	200
Speed (knots)	2.5	2.5	5	2.5	2.5

3. World-wide human occupied vehicles up to 11,000 m of sea water

The various vehicles considered under 11,000 m of seawater category are Deep Sea Challenger, Fendouzhe, and Triton (HOVs are arranged in alphabetical order). Detailed descriptions are provided for each human occupied vehicle. Table-2 shows the summary of different human occupied vehicles upto 11,000 m of sea water. Researchers use human occupied vehicles for biological adaptations, colonization, chemical analysis, and hydrothermal venting.

3.1 Deep Sea Challenger

Acheron Project Private Limited, Australia, has developed Deep Sea Challenger, a one-person human occupied vehicle. Deep Sea Challenger can dive to a depth of 11,000 Meters of Sea Water (MSW). Approximately 70 % of this vehicle is covered by syntactic foam, which is a combination of epoxy resins and glass spheres. Deep Sea Challenger is a vertical moving human occupied vehicle that paved the way for easy ascents and descents and is shown in **Figure 1(f)**. It is capable of withstanding high ocean depth pressures of approximately 1,100 bars (Deep Sea Challenger, 2012).

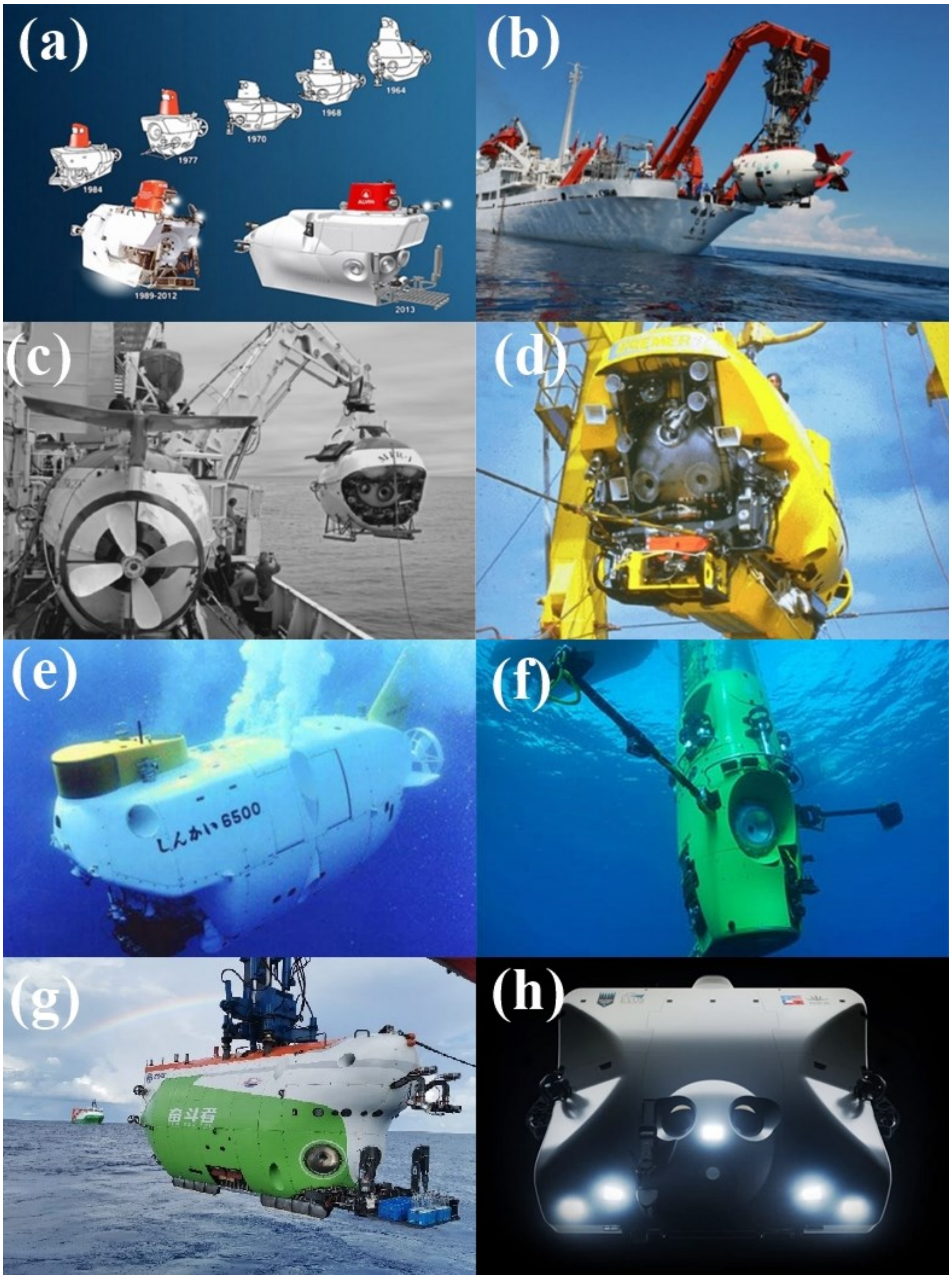


Figure 1 (a) Stages of Alvin development (Zhang et al., 2019), (b) Jiaolong (Zhang et al., 2019), (c) MIR-1/MIR-2 (Sagalevitch, 2012), (d) Nautile (Zhang et al., 2019), (e) Shinkai 6500 (Zhang et al., 2019) (f) Deep sea challenger (Deep Sea Challenger, 2012) (g) Fendouzhe (Yang et al., 2021), and (h) Triton (Limiting Factor, 2018).

3.2 Fendouzhe

The vehicle Fendouzhe dived to a depth of 10,909 m in the Mariana trench with a titanium alloy spherical pressure hull that can accommodate three persons; it is shown in **Figure 1(g)**. Fendouzhe is also known as Striver. More than 1,000 scientists from universities, companies, and institutes have contributed towards the design and development of Fendouzhe (Yang et al., 2021).

3.3 Triton

At the Mariana trench in 2019, Triton dived to a depth of 10,928 m and spent 248 min on exploration and research. The shape of the triton is shown in **Figure 1(h)**. Triton is also known as Limiting Factor. A prominent feature of the Triton pressure hull is that it is machined with 99.9 % true spherical form and clamped. Triton's 65 kW batteries allow diving time of more than 16 h. Triton has been designed for simplicity and minimal complexity. Det Norske Veritas-Germanischer Lloyd (DNV-GL) has rated Triton as a human occupied vehicle for full ocean depths (Limiting Factor Data, 2018).

Table 2 Specification of 11,000 m human occupied vehicles (Deep Sea Challenger, 2012; Limiting Factor, 2018; Yang et al., 2021).

Human occupied vehicle	Deep Sea Challenger	Fendouzhe	Triton
Country	Australia	China	USA
Depth rating (m)	11,000	11,000	11,000
Number of viewports	1	3	3
Number of persons	1	3	2
L×B×H (m)	2.3×1.7×8.1	7×3.68×2.6	4.6×1.9×3.7
Operational time (h)	16	10 - 13	16
Pay loads (kg)	---	200	220
Speed (knots)	3	2.5	3 (Lateral)

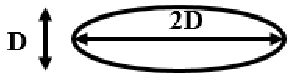
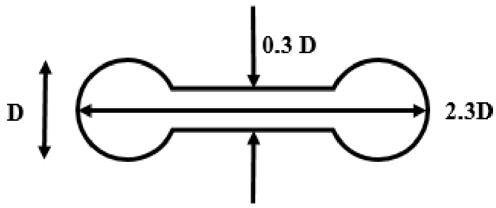
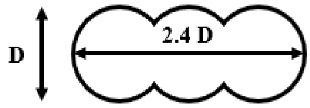
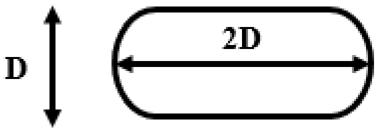
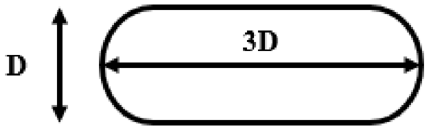
“---“ represents data that is not known

4. Mechanical systems in a human occupied vehicle

4.1 Pressure hull

In human occupied vehicles, the design of the pressure hull is critical for ensuring a safe environment for humans and for controlling the efficacy of research. The material for pressure hulls must have sufficient strength and corrosion resistance and a minimum weight. The shape of the pressure hull is largely influenced by the weight-to-displacement ratio (W/D). A well-designed and equipped shape will have a lower W/D ratio. In **Table 3**, various W/D ratios are shown for different shapes.

Table 3 W/D ratio of different shapes (Busby, 1976).

Shape	Figure	W/D ratio
Sphere		0.39
Ellipse		0.40
Sphere cylinder		0.41
Tri-sphere		0.42+
Cylinder with elliptical ends		0.43
Cylinder with hemisphere ends		0.42

A pressure hull is typically a sphere, an ellipse, or a cylindrical shape. There are advantages and disadvantages to each of these three shapes. Among the pressure hull shapes, the spherical pressure hull gives the best W/D ratio and the most complex stress analysis. Spherical-shaped pressure hulls have the disadvantage of being difficult to arrange the components inside. The ellipse-shaped hull has a high W/D ratio combined with an efficient interior arrangement. However, the ellipse pressure hull has several drawbacks, including a high cost of fabrication and difficulties in analyzing the stresses. A cylindrical pressure hull is more efficient than the other two due to its ease of fabrication, reduced hydrodynamic drag, and well-integrated interior. The requirement for stiffeners for depths greater than 305 m and having a higher W/D ratio are the most inherent challenges for the cylindrical shaped pressure hull (Busby, 1976).

Most of the human occupied vehicle hulls have a spherical pressure hull (Binbin & Weicheng, 2011). Titanium alloys are the most commonly used hull materials, but martensite nickel steel is used in the MIR-1/MIR-2 human occupied vehicle. Pressure is the function of ocean depth. The pressure on the external boundaries of the hull increases as the human occupied vehicle descends deeper. As the operational depth increases, the hull thickness increases (ASME PVHO-1, 2007). **Table 4** shows that all human occupied vehicles included in this review for study have internal diameters in the range of 2 m, except for Deep Sea Challenger with 1.09 m.

Table 4 Pressure hull materials and thicknesses (Binbin & Weicheng, 2011).

Human occupied vehicle	Material	Shape	Thickness (mm)	Internal diameter (m)
Alvin	Titanium	Sphere	72	2.0
Jiaolong	Titanium	Sphere	76 ~ 78	2.1
MIR-1/MIR-2	Martensite nickel steel	Sphere	75	2.1
Nautile	Titanium	Sphere	62 ~ 73	2.1
Shinkai 6500	Titanium	Sphere	73.5	2.0
Deep Sea Challenger	EN26 steel	Sphere	64	1.09
Fendouzhe	Titanium alloy	Sphere	---	1.8
Triton	Titanium alloy	Sphere	90	---

“---“represents data that is not known.

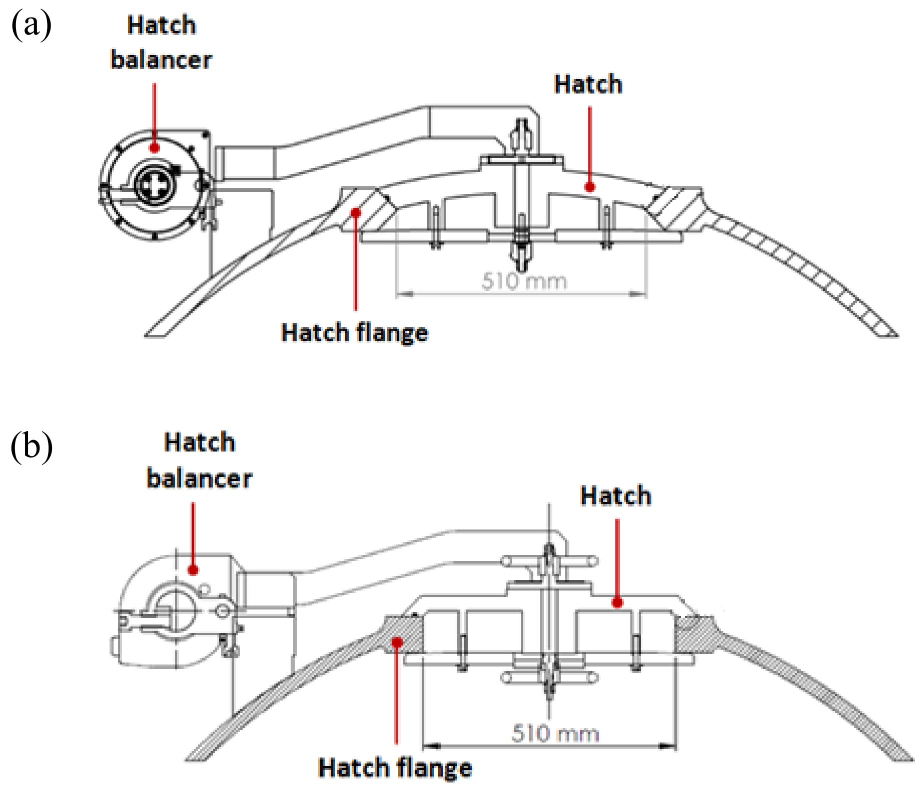


Figure 2 (a) Plug type hatch (b) Seat type hatch (Allmendinger, 1990).

4.2 Hatch

The hatch acts as the entry and exit for humans in the pressure hull. An effective hatch design must consider both the external pressure from the sea water and the relative movement between the hatch flange and the hatch. Hatches can be either circular or oval. When the vehicle surfaces, the pressure inside the hull will vary significantly from the external pressure. For humans, the 95th percentile shoulder breadth is about 508 mm. Hence, the minimum required diameter for the circular hatches is 510 mm (MIL-STD-1472g, 2012). The diameter of the hatches used in the human occupied vehicles is 483 mm (Alvin), 558.8 mm (Nautile) and 600 mm (Shinkai 6500) (Busby, 1976). The opening and closing of hatches should always be carried out by a single person, with arrangements made on both sides of the hatches (ASME PVHO-1, 2007). The two types of hatches commonly used are seat and plug type hatches, shown in **Figure 2**. Seat type hatches are heavier than plug type hatches, but are less expensive to manufacture and can only be used in shallow water applications. However, plug type hatches are typically in the form of a shell with a lower weight that is directly bolstered by pressure hull. Hatches are designed with counterbalance weights or spring-assisted mechanisms to render the operation easier for a single person (Allmendinger, 1990). The schematic diagrams of seat and plug type hatches are shown in **Figure 2**.

4.3 Ballast system

The relative position of the human occupied vehicle at the working depth is of utmost importance for carrying out research activities without any disturbance. It is difficult for human occupied vehicles to maintain a constant position (keel) along with ascent due to the addition or removal of payloads. It is important to note that the weight of a pressure hull and vehicle depth play a significant role in determining the buoyancy of human occupied vehicles, which is entirely dependent upon ballast systems. A vehicle's buoyancy can be positive, negative, or neutral. Through ballast systems, human occupied vehicles can be brought to neutral by adjusting the buoyancy force acting on them (Defa et al., 2011; Liu et al., 2006). The different types of ballast systems used in various human occupied vehicles are given in table-5. The human occupied vehicle employs two ballast systems, reversible and irreversible. The working principle of the system can be clearly identified from its name, with reversible systems capable of providing both positive and negative buoyancy. An irreversible system, on the other hand, provides either positive buoyancy or negative buoyancy during the dive (Busby, 1976). **Figure 3** illustrates the classification of ballast systems.

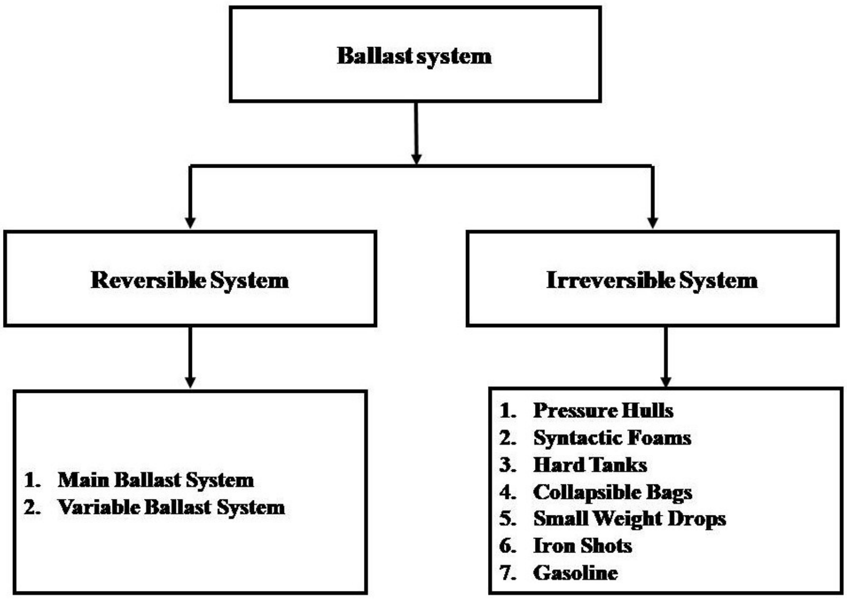


Figure 3 Classifications of ballast systems (Busby, 1976).

The most commonly used ballast systems in reversible systems are the main ballast system (MBS) and the variable ballast system (VBS). The most frequently used MBS is the water hydraulic system. A vent valve floods seawater into the main ballast tank to achieve neutral buoyancy, followed by negative buoyancy in the water hydraulic system. As soon as the tank reaches maximum capacity, the human occupied vehicle will begin to descend. The addition of extra water to a VBS can sometimes result in negative buoyancy. The working principle of the water hydraulic MBS is shown in **Figure 4(a)**.

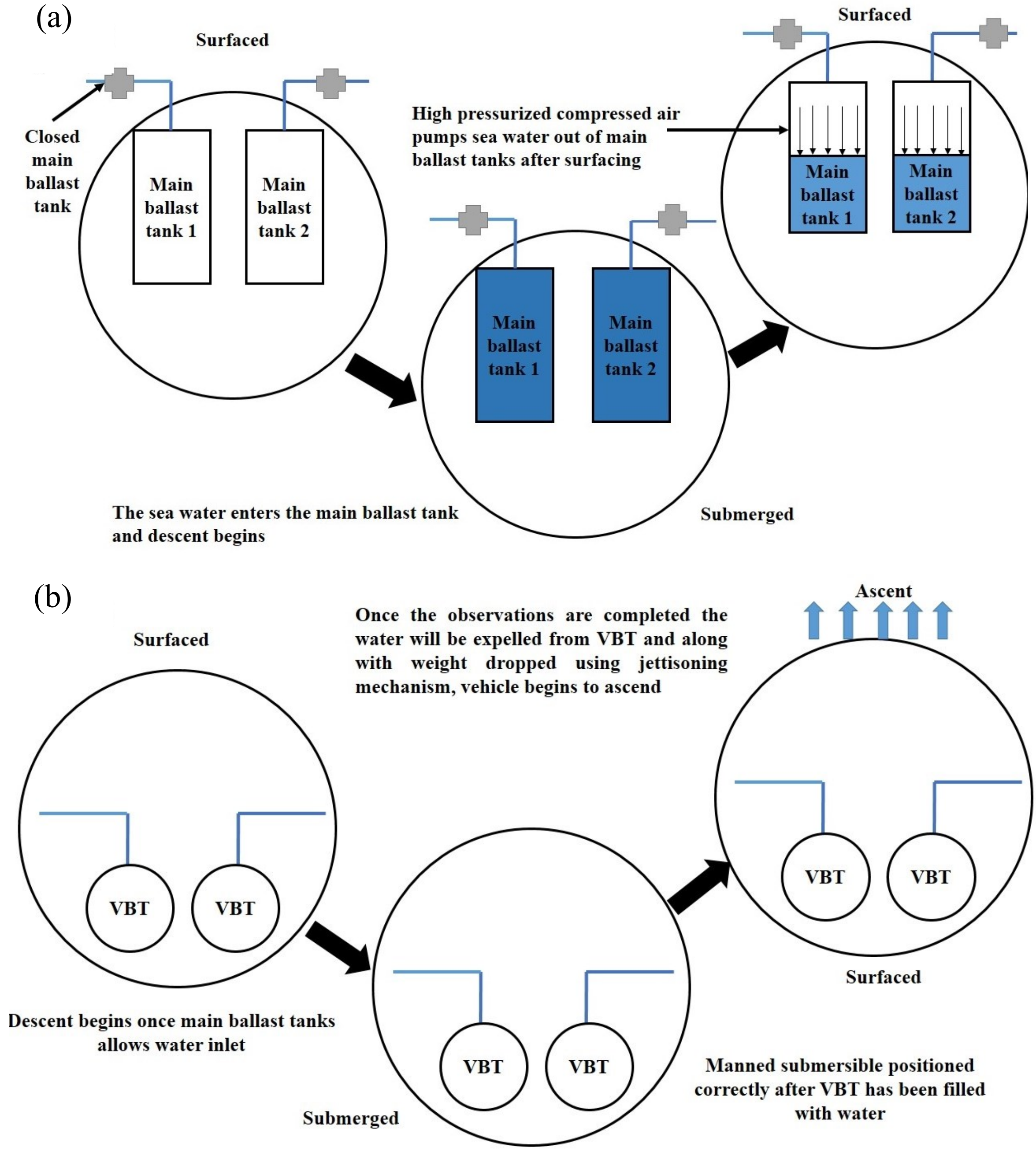


Figure 4 Working principle of water hydraulic (a) Main ballast tank and (b) Variable ballast tank.

A variable ballast system has been used to fine-tune the level of buoyancy in human occupied vehicles. Air, water, and oil are displaced from the tank to the balloon, which will then return to the fixed tank in order to achieve positive buoyancy. **Figure 3** illustrates the various ballast systems used in human occupied vehicles. A schematic diagram of the water hydraulic VBS, most commonly used in human occupied vehicles, is shown in **Figure 4(b)**. Water hydraulic ballast systems use a combination of compressed air and water pumps. Hydraulics and pneumatics work well together to eliminate the problem of venting in oil hydraulic variable ballast systems. They are also easy to use, simple to construct, and seal effectively (Woods et al., 2012; Liu et al., 2010). Water from the tank is pumped using a high-pressure pump. The commonly used positive displacement pumps are gear, vane, and piston pumps.

There are several methods that can be used in irreversible systems to obtain positive buoyancy, as shown in **Figure 4(b)**. A pressure hull can provide positive buoyancy, which is largely influenced by its W/D ratio. When ocean depth increases, syntactic foam becomes an increasingly important factor for positive buoyancy. For collapsible bags, the bags are drained in order to achieve the necessary buoyancy. Droppable weights form another type of irreversible buoyancy system. In order to achieve positive buoyancy, lead weights are dropped by enabling hydraulic or electrical systems. The electromagnetic system has been used in iron shots to drop the weights using magnetism. It is possible to retain buoyancy even at higher depths by using petroleum hydrocarbons such as gasoline, as their density (666 kg/m^3) is lower than that of seawater at deeper depths (1,055 kg/m^3 (Allmendinger, 1990)). A major drawback of petroleum products is their flammability (Busby, 1976).

Table 5 Ballast system (Cui et al., 2014; Defa et al., 2011; Komuku et al., 2007; Liu et al., 2010; Sagalevich, 2018; Walden & Brown, 2004; Yun et al., 2015).

Human occupied vehicle	Main ballast system	Variable ballast system	Pump used for VBS
Alvin	Water hydraulic system	Steel weights	Axial check valve type swash plate plunger pump
Jiaolong	Water ballast system	Water hydraulic system	High pressure sea water pump
MIR-1/MIR-2	Water hydraulic system	Water hydraulic system	High pressure pump
Nautile	Water ballast system	Water hydraulic system	High pressure pump
Shinkai 6500	Steel plates	Water hydraulic system	Axial seated valve type swash plate plunger pump
Deep Sea Challenger	Water hydraulic system and iron ballast weight using electromagnetic system	---	---
Fendouzhe	---	---	---
Triton	---	---	---

“---“represents data that is not known.

4.4 Trim system

A human occupied vehicle bow angle can be adjusted up and down using two operational modes: (1) Weight or displacement can be added or subtracted by adding or subtracting equipment or instruments on the opposite end. (2) Changes in bow angle are caused by an upward or downward sloping bottom (Busby, 1976). A trim system can be classified into two types, namely, external and internal. **Figure 5** shows the detail classification of trim systems. External trim systems adjust the bow angle by adjusting the weight outside the pressure hull, whereas internal trim systems adjust the bow angle by shifting the weight inside the pressure hull.

The water transfer internal trim system uses two tanks to produce the required bow angle of ±10° up or down. Two tanks are connected by polyethylene pipe and separate motors that pump water in only one direction to achieve the required bow angle, as shown in **Figure 6(a)**. Mechanical weight shift is an external trim system involves moving the weight inside the pressure hull from front to aft. As part of the mechanical weight shift internal trim system, movable weights are shifted/moved using a hydraulic system controlled by a solenoid valve. As a result, a trim angle of ±10° is achieved. The weight may be either cast iron or lead weight, as illustrated in **Figure 6(b)**.

The mercury-filled tank can be filled with oil through a solenoid-operated pump to obtain a larger trim angle of 25° with mercury transfer external trim systems. The movement of the oil causes mercury to move to the three small sphere tanks (two forward and one aft) and generate the necessary trim angles, as shown in **Figure 7(a)**. The sea water can also be used to move aft and fore to produce the required trim angles in VBS differential fill, shown in **Figure 7(b)**. Positive displacement piston pumps are used to generate a high pressure of water. Dust particles must be prevented from entering the pump by a strainer before the pump. The MBS differential works in the same way as the VBS differential, but it requires pressure compensation that can be provided by high pressure air. A drop shot is used in shot hopper differential fill to achieve up or down bow angles by dropping weights, as illustrated in **Figure 7(c)**. The weights are released using the shot valve. The battery shift mechanism produces a ±20° longitudinal trim angle, similar to the weight transfer mechanism. Adding 25 pounds of steel plates to the keel produces the required up/down bow angle by individually lowering the weights, as shown in **Figure 7(d)**. There are three tanks in the system, one portside tank, one starboard tank, and one aft mounted tank, that make up the water transfer system, shown in **Figure 7(e)**. The transfer of water using a hydraulically driven pump results in a bow angle of ±27° and a roll angle of ±12°. In the oil transfer trim system, the oil is supplied to the bladders by using a hydraulic trim pump to produce the required increase/decrease in aft/fore movement, shown in **Figure 7(f)**. The oil transfer system can be used to achieve a bow angle of 2.5°. **Table 6** shows the trim systems used in different human occupied vehicles.

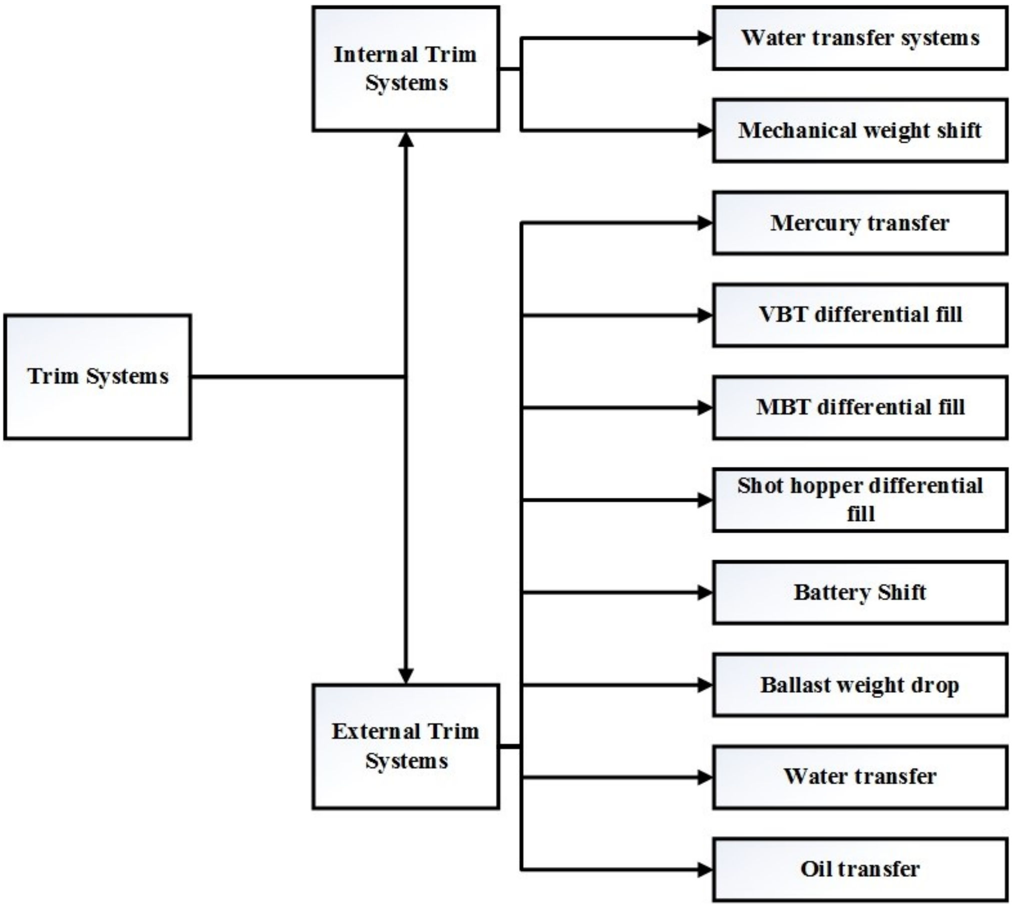


Figure 5 Various trim systems used in manned sumersibles.

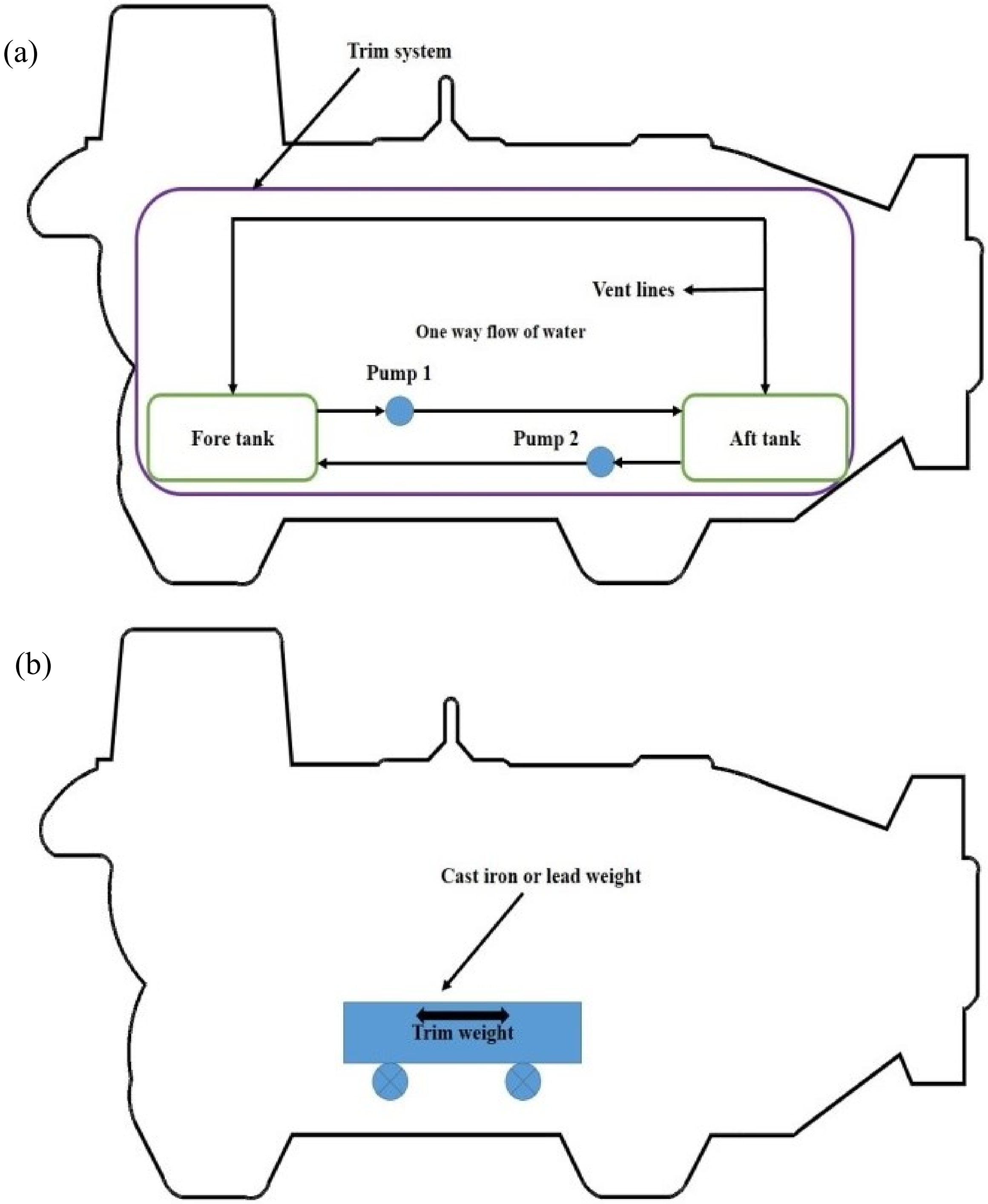


Figure 6 Internal trim systems- (a) Water transfer system, and (b) Mechanical weight shift.

4.5 Exo-structure

An exo-structure is a frame that forms the backbone of a human occupied vehicle. An exo-structure is usually required to assemble or host the equipment on most human occupied vehicles. The exo-structure is bolted as well as welded. To avoid residual stress in the heat-affected zone, attachment points are welded before final stress reliving (Busby, 1976). Exo-structures should be strong enough to support all the equipment mounted on them. Fatigue caused cracks in the joints of Nautile's exo-structure after 1,850 dives. Therefore, to prevent crack formation, periodic maintenance of the exo-structure is necessary (Drogou et al., 2013). **Table 7** shows the various exo-structure materials used in human occupied vehicles.

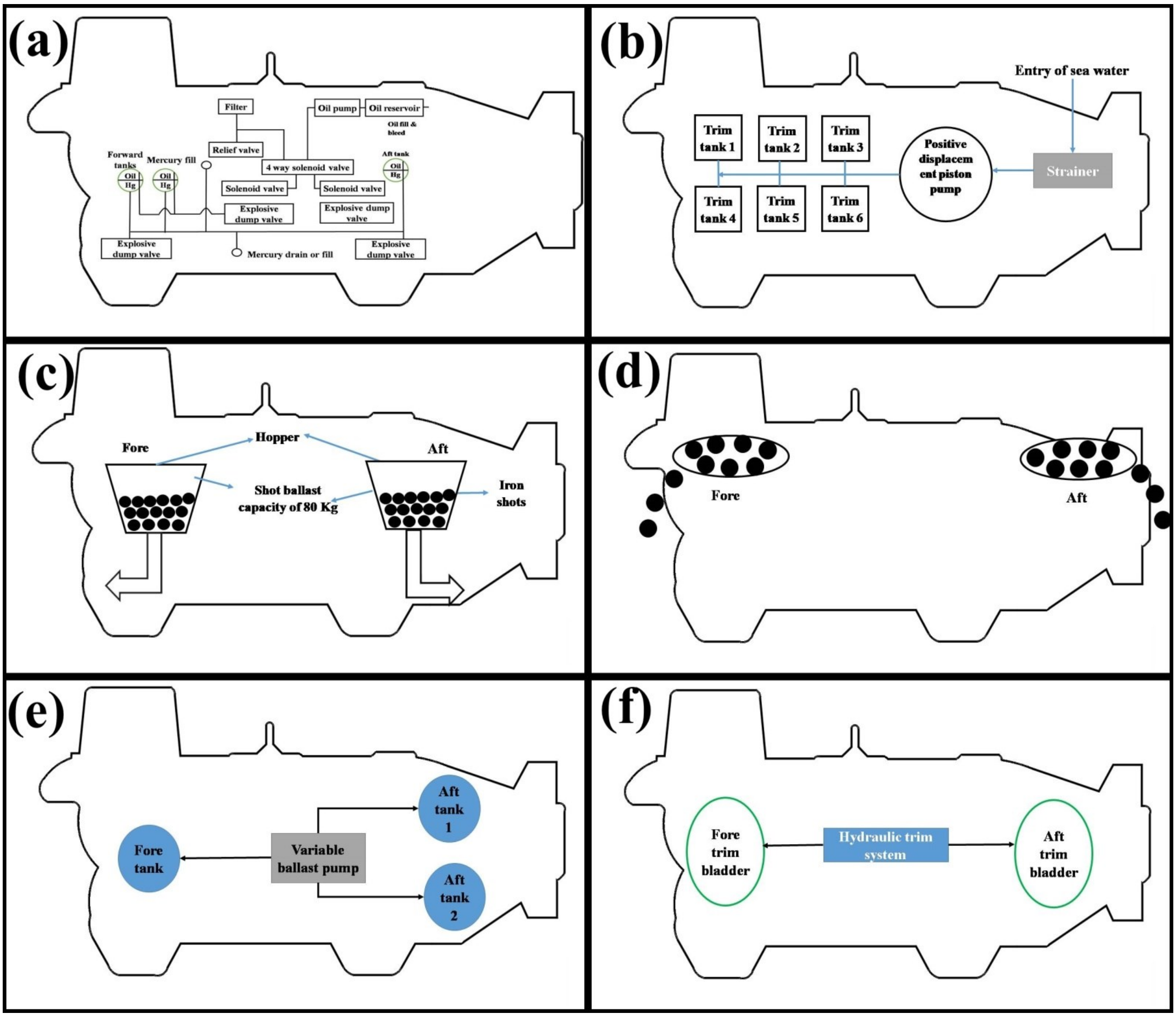


Figure 7 External trim systems- (a) Mercury transfer (Refer **Appendix** for clear texts), (b) VBS differential fill (Refer **Appendix** for clear texts), (c) Shot hopper differential fill, (d) Ballast weight drop, (e) Water transfer, and (f) Oil transfer.

Table 6 Trim systems in human occupied vehicles (Busby, 1976; Cui, 2013; Deep Sea Challenger, 2014; Grandvaux, 1986; Jamieson et al., 2019; Komuku, 2007; Sagalevich, 2016).

Human occupied vehicle	Trim system
Alvin	Mercury transfer system
Jiaolong	Oil transfer systems
MIR-1/MIR-2	Water transfer system
Nautile	Mercury transfer system
Shinkai 6500	Mercury transfer system
Deep Sea Challenger	Steel shots
Fendouzhe	---
Triton	Ballast weight drop

“---“ represents data that is not known.

4.6 Syntactic foam

One of the important components of the human occupied vehicle is syntactic foam. Low density and high strength should be the characteristics of syntactic foam. Typically, syntactic foam materials are polymer matrices with micro-balloons, or metal or ceramic materials. Micro-balloons are made of cenospheres, glass, carbon, or polymers, and have low coefficients of thermal expansion. **Table 8** shows the density of syntactic foam used in human occupied vehicles.

Table 7 Types of exo-structure materials used in human occupied vehicles (Drogou et al. 2013; Nakanishi, 1986; Shengjie, 2019; Walden & Sharp, 1984).

Human occupied vehicle	Exo-structure material
Alvin	Titanium alloy
Jiaolong	Titanium alloy
MIR-1/MIR-2	Titanium alloy
Nautile	Titanium alloy
Shinkai 6500	Titanium alloy
Deep Sea Challenger	---
Fendouzhe	---
Triton	---

"---" represents data that is not known.

Table 8 Density of syntactic foam used in different HOVs (Bernstein, 1967; Hardy et al., 2014; Jamieson et al., 2019; Momma, 1999; Pan et al., 2012).

Human occupied vehicle	Density (kg/m^3)
Alvin	500
Jiaolong	526
MIR-1/MIR-2	---
Nautile	---
Shinkai 6500	536
Deep Sea Challenger	700
Fendouzhe	---
Triton	625

"---"represents data that is not known.

4.7 Pressure vessel / Enclosure

A pressure vessel is a device designed to withstand external pressure and which has to accommodate electronic devices, wires, and joints in an electrical system. Structures for ocean vehicles requiring mass reduction and high containment ratios require thin-walled pressure vessels (ASME PVHO-1, 2007). The shape of the pressure vessels can be designed based on the requirements. **Figure 8** illustrates the most common pressure vessel shapes, which are cylindrical and cylinder bolted with two hemispheres. AA7075-T6 and Titanium alloy (Gr.5) are the materials used in the manufacturing of pressure cases.

Figure 8 Pressure vessels.

4.8 Drop weights

The ascent of a human occupied vehicle can be obtained by dropping weights attached to it. Each human occupied vehicle uses a different weight-dropping mechanism, which may be mechanical, electrical, or hydraulic. Power will be supplied by the emergency battery inside the pressure hull to disconnect the cable holding the weight for the electrical system (Busby, 1976). The drop weights are used to create positive buoyancy in the vehicle. **Table 9** shows the materials and mechanisms used in the drop weights of different human occupied vehicles.

Table 9 Drop weight materials and mechanisms (Cui, 2013; Hardy, 2013; Jamieson et al., 2019).

Human occupied vehicle	Materials	Mechanism
Alvin	Solid weights	Electric system
Jiaolong	Solid weights	Electromagnetic & hydraulic system
MIR-1 / MIR-2	Magnetic shots	Electromagnetic system
Nautile	Steel shots	Electromagnetic system
Shinkai 6500	Steel plates	Hydraulic system
Deep Sea Challenger	Cast iron barbell weights	Mechanical release system
Fendouzhe	---	---
Triton	Steel plates	Electromagnetic system

“---” represents data that is not known.

5. Summary and conclusions

Mechanical systems are the heart of the human occupied vehicle; without them, the HOV cannot operate. A review of the mechanical systems in selected human occupied vehicles such as

Alvin, Jiaolong, MIR-1/MIR-2, Nautile, Shinkai 6500, Deep Sea Challenger, Fendouzhe, and Triton are presented. Mechanical features are reviewed, including the pressure hull, hatch, ballast system, trim system, exo-structure, syntactic foam, and drop weights. The following key points are identified based on this study.

1. Pressure hulls are most commonly shaped as spheres with internal diameters of 2.1 m, but in the case of Deep Sea Challenger, the diameter is 1.09 m. For a three-person occupant vehicle, the minimum required internal diameter is 2.1 m while, for a single occupant vehicle, the minimum requirement is 1.09 m.
2. The pressure hull thickness is determined by the diving depth of the HOV. It is observed that the titanium alloy spherical pressure hull thickness of human occupied vehicles varies from 64 to 90 mm. It is always advised to use standard rules like American Society of Mechanical Engineers Pressure Vessel Human Occupancy (ASME PVHO)-1or DNV or LR, etc., for the estimation of minimum pressure hull thickness, in order to have a safe and reliable system.
3. The most widely used hatches on human occupied vehicles are double-acting hatches that are capable of withstanding external pressure. It is up to the vehicle designer to define the hatch diameter, but a minimum diameter of 508 mm must be maintained.
4. The water hydraulic system is the most commonly used system in both main ballast systems and variable ballast systems. A high-pressure pump, such as an axial check valve type or a plunger pump, is used to pump sea water inside the ballast tanks.
5. Various trim systems are used in each human occupied vehicle because the required trim angle is different for each vehicle.
6. The exo-structure material is surrounded by sea water. As a result, the selection of material should require higher corrosive resistance. Hence, titanium alloy is commonly used as exo-structure material.
7. Syntactic foam not only covers the parts, but also controls the buoyancy of the human occupied vehicle. The material chosen for syntactic foam should be of high strength and low density. The density of syntactic foam ranges from 500 to 700 kg/m^3. The selection of density depends on the diving depth of the vehicle. It is necessary to use 500 kg/m^3 for deep water applications and 700 kg/m^3 for ultra-deep water depth applications.
8. Dropping weights from human occupied vehicles will initiate their ascent. Electromagnetic systems and hydraulic systems are commonly used for dropping weights.

Resources become scarcer as the population grows. It is necessary to develop new scientific tools to explore the ocean's seabed and its underlying layers. The key points identified based on the above study will help in the design and development of deep water human occupied vehicles.

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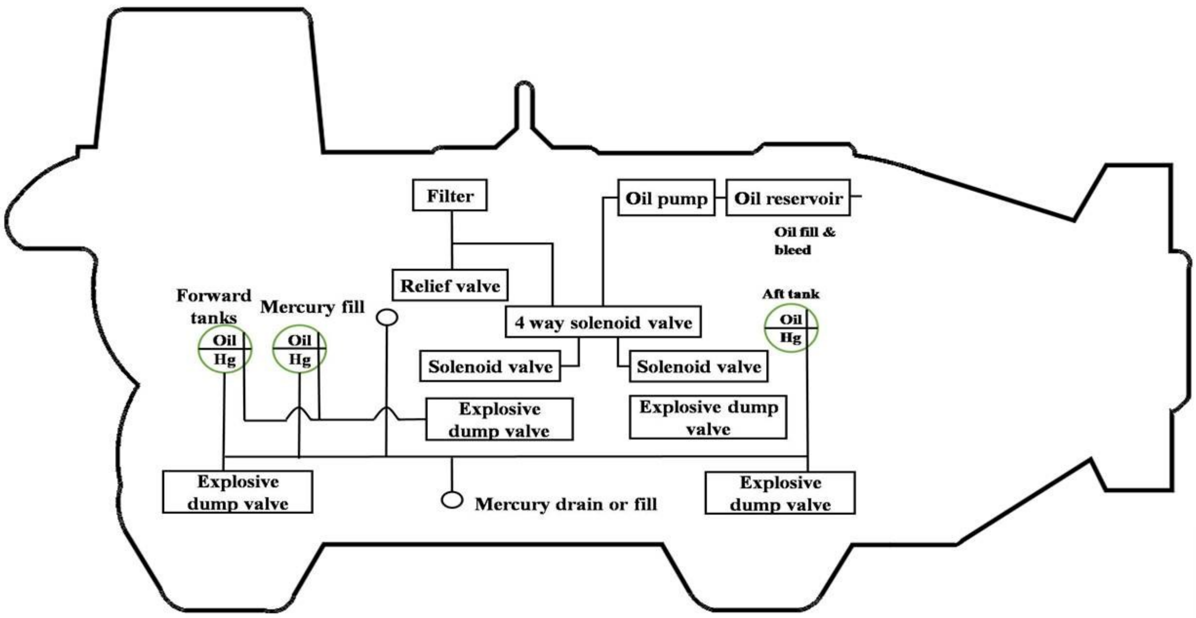
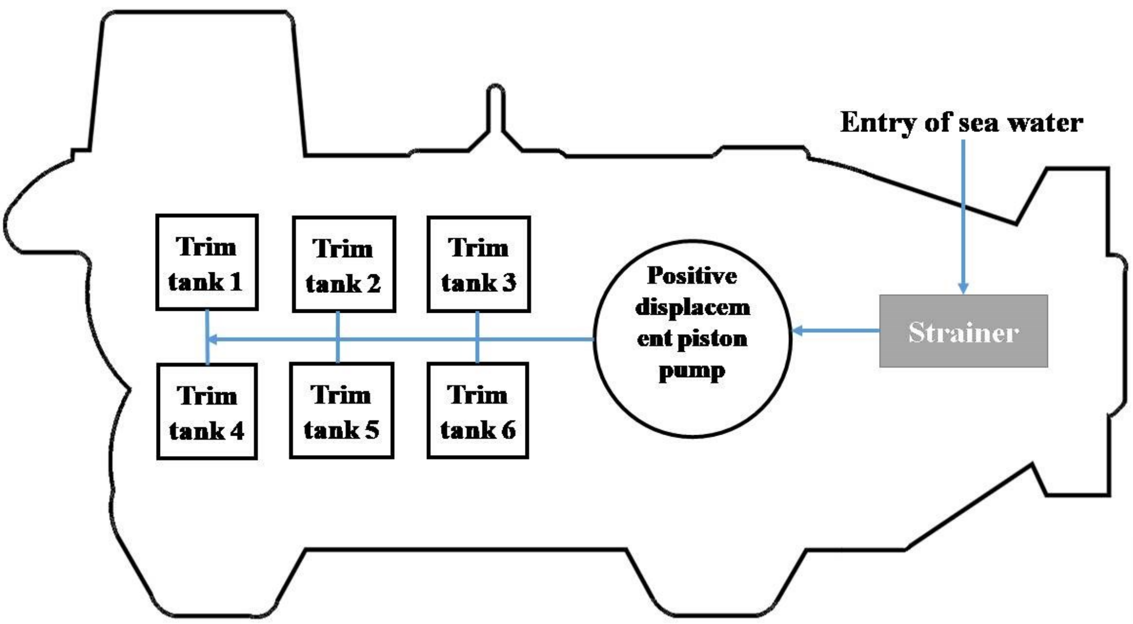
Appendix: External Trim System



(a) Mercury Transfer



(b) VBS differential fill