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A Review on Recent Advancements in Unmanned Underwater Vehicle Design

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ABSTRACT

Recent advancements in miniature hardware technologies pushed the development of unmanned underwater vehicles (UUVs) towards more innovative designs to cater for unique mission definitions. Considering the recent 10 years of work done by various researchers in the literatures, presented in this paper is an overview of several state of the art technologies involved in the development of UUVs. Design studies are presented, whereby divided into various aspects including structure/hull shapes, propulsion, and motion/hydrodynamics. Emphases are given to the selection of shapes/geometry and the materials used. The advantages and the disadvantages of the components were discussed with respect to hydrodynamic forces acting on the UUVs such as resistance, stability, and motion. In terms of propulsion aspects of the UUVs, the discussions are focused on the related components used and the energy supply on-board of the UUVs.

KEYWORDS: *Unmanned Underwater Vehicles; Recent Trends; Underwater Robotics*

1.0 INTRODUCTION

Unmanned underwater vehicles (UUVs) have received worldwide attention and becoming increasingly popular for underwater exploration in ship maintenance, military applications, hydrographical surveys, mineral field surveys, environment monitoring and oceanographic studies [1] [2]. Modern UUVs can be classified into two groups; Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) [3]. ROVs are hard-tethered to a surface support vessel by means of an umbilical cable, which permits for limited movements. Such ROVs are able to move within small range of area, depending on the cable length and flexibility [4]. On the other hand, AUVs are more flexible in terms of movements, which are suitable for long–range survey missions, while at the same time able to cater for complicated maneuver that are assisted with expensive and elaborate navigations systems [3].

In the development of underwater vehicles, the design activities started with the theoretical design studies, which involve several important analyses that focus on resistance, propulsions, maneuverability and energy requirements [5]. Such design studies usually started with shape/form design, which aimed to transport certain payloads in a UUV that possess low resistance hull form [6]. Such activities are followed by the determination of the UUVs' propulsion systems, which considered the UUV's capability to travel with low drag [7] while maintaining its maneuvering performance [8]. Later, the endurance of the UUV that dictate its size is considered in order to determine its suitable power sources for the UUV [9] [10].

The following subsections shall discuss on the recent works reported in the literatures. Consistent with the design flow used in designing UUVs as presented above, the discussion in this paper shall be focusing on the geometry aspects, followed by the components with respect to hydrodynamics and motion, materials selection and finally the energy supply and power systems.

2.0 GEOMETRIC ASPECTS OF UUV

Unmanned underwater vehicle is an important instrument designed to facilitate researchers to explore and solve problems related with underwater mission, e.g. pipeline inspection, underwater mapping, coral monitoring and underwater agriculture [11]. Therefore, for each mission, it is possible for an UUV to possess unique designs and sizes. Typical UUVs used in industry are of small sizes to achieve ease of handling and launching [2], however larger UUVs are more suitable for heavier payload (e.g. sensors and additional modules) and increased mission depth [12]. In this section, two common shapes are discussed, namely conventional box- or cylinder-type UUV, and the unconventional-shape UUV.

2.1 Box- and Cylinder-like UUV Design

Generally, a UUV may possess the form of a box- or cylinder-like object. Each shape has their advantages depending on the mission definition of the UUV. Box shape is one of the simplest forms of a UUV (Figure 1), which consist of a set of rectangular frames with payloads (thrusters, battery pack and controller board) [13]. One of the prominent advantages of a box-like UUV is the maneuvering capability [14], which allows for zero steady turning radius. Other than that, such shapes are capable to carry more thrusters that results for increased degree of freedom [15]. Due to the lack of curves and its dependence towards the use of bare-frames, one of the major drawbacks of a box-like UUV is the drag force [16]. High drag force that hinders the efficiency is more prominent during high speed cruising, however the need to move from one place to another in high-speed motion is not necessary for such design [17].

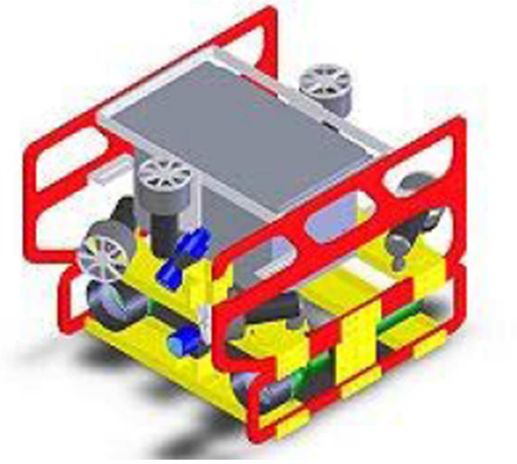

Figure 1: A box-like shape UUV [13]

Another simple form of a UUV commonly found in the literatures is cylindrical shape. A typical cylindrical-like UUV is shown in Figure 2. Such UUV normally consist of several modules (thrusters, battery pack and controller board) as shown in Figure 3 that are properly arranged inside the enclosure and possess bigger/longer cylinder as its final form [2].The advantages of a cylindrical UUV shape lies on its low resistance and its modular design [2]. Such UUVs are capable to move from one location to the other with lower energy consumption thus able to cover larger research area [18]. In terms of construction, cylindrical-shaped UUVs are easier to transport and able to be assembled in-situ due to its modular design.

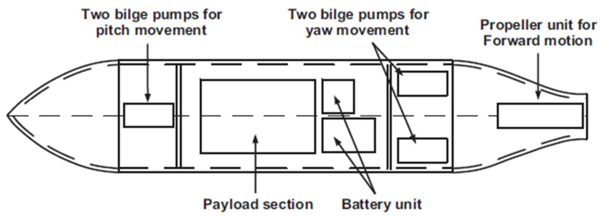

Figure 2: Modular-based cylindrical UUV [2]

2.2 Unconventional Shapes UUV

Generic fish shape: While simple cylindrical and box shapes are popular among the design of UUVs, there exists a more refined form of UUV *i.e.* bio-inspired shapes [19]. Bio-inspired UUV derived its forms based on the nature-inspired shapes *e.g.* fishes [20]. In 2008 a blue fin tuna fish (Figure 3) was built by [21] leveraging the capability of the fish to swim faster and perform quick maneuvering.

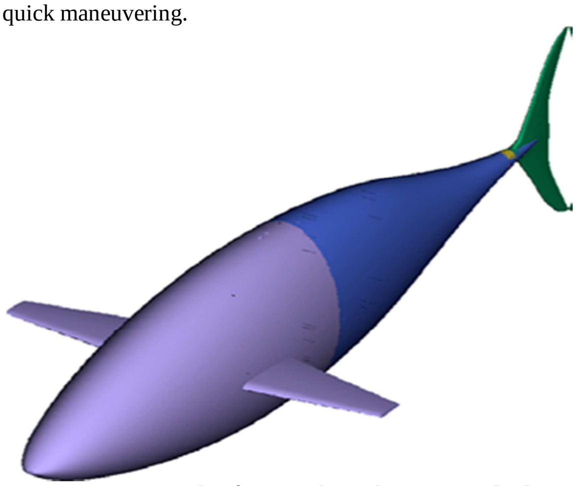

Figure 3: Blue fin tuna shape design UUV [21]

Flat-fish shape: The flat–fish shape is also famous for UUV form design for easy arrangements of components within the UUV structure [22]. *Wayamba*, as shown in Figure 4 is one of the UUVs that was inspired from the flat-fish form, which designed to possess excellent maneuvering characteristics as reported by [23], which consequently adapted for large class UUV.

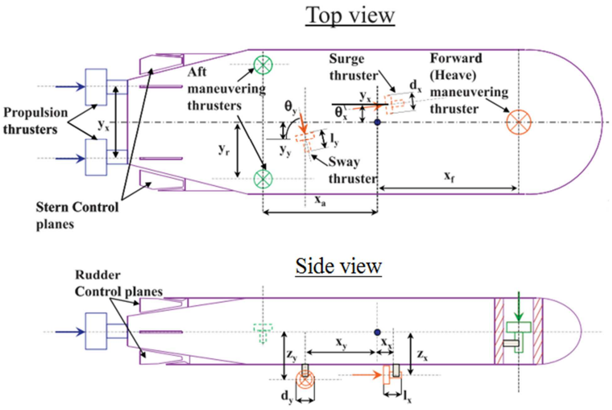

Figure 4: Flat fish shape design UUV [22]

Boxfish Shapes: Nature has shown that the capability to manoeuver in confined space is possible through the example of small fishes, *e.g.* boxfish (*Ostracion melagris*), as discussed in [24]. [19] demonstrated that a micro-class UUV design inspired by boxfish (Figure 5) is capable to manoeuver in confined space with a near zero turning radius and possess a self-correcting mechanism that makes its trajectories immune to water disturbances.

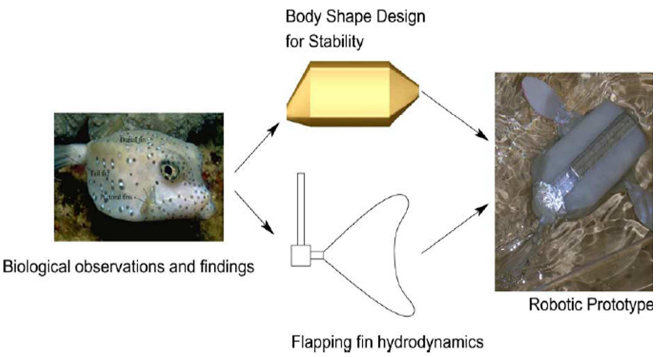

Figure 5: A spotted boxfish [19]

Soft robots: Cephalopods-inspired robot (Figure 6) is one of the classes of soft robots that possess unique movement and grasping capability due to its redundant degrees of freedom [25]. [8] replicated the ability of cephalopods and built a soft underwater vehicle where the structure and functional characteristic which inspired by *Octopus vulgaris.* Furthermore, the special morphology of the body (no rigid structure) and high maneuverability contributed towards the capabilities to interact with various environments [25].

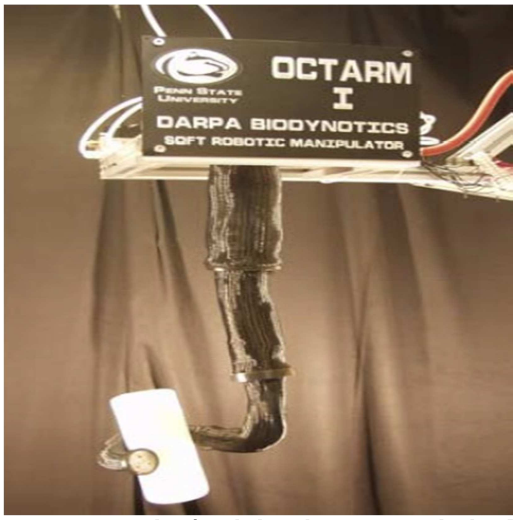

Figure 6: An example of cephalopods arm-inspired robot [25]

Hexapod-type UUV: The TURTLE (Tele-operated Unmanned Robot For Telemetry and Legged Exploration) is one of the UUV hexapod variant that has the ability to swim, and walk in three environments; above ground, under water and above water [26]. Such work is a shift from traditional research on hexapod robots that are more focused in the walking style, climbing over a rough road and walking in the rough ground and steep train [27]. Multiple degrees-of-freedom articulated leg that controls the position and the orientation of the hexapod body (Figure 7) demonstrated its capability to serve as general-purpose underwater robotics platform [26].

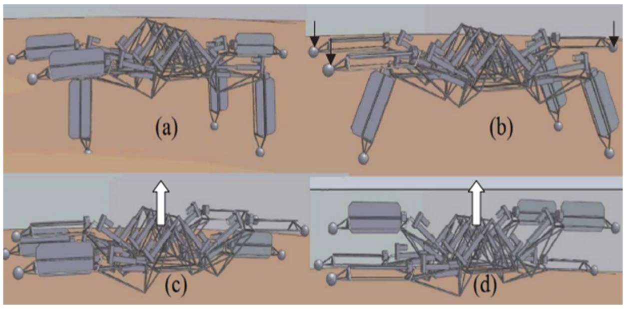

Figure 7: Standing to swimming transition: (a) 3-leg lift; (b) 3 feet perform flapping to lift body; (c) supporting feet lift off ground; (d) balanced flapping [26].

3.0 COMPONENTS OF UUV WITH RESPECT TO HYDRODYNAMICS & MOTION

Typical components of UUVs with respect to its hydrodynamics with some examples from the literatures are introduced in this section. The discussions on the hydrodynamics are within the scope of resistance, stability and motion of the UUV.

3.1 Resistance: Velocity and Drag

Box-shaped UUV: The box-shape like UUV named MACO as shown in Figure 8 uses four thrusters to ensure adequate amount of directional control [16]. Two vertical thrusters are located at the aft and stern of the slender hull, which minimize the energy usage to move vertically. The horizontal thrusters are located close to the sides of the hull to minimize parasitic drag while providing MACO with adequate turning capability [3].

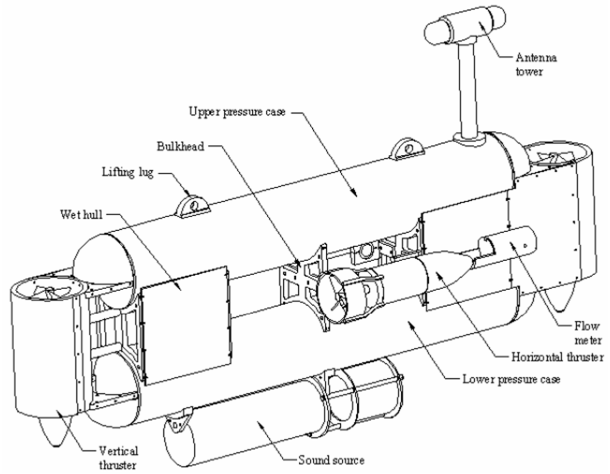

Figure 8: The position thrusters of UUV (MACO) [3]

Spherical UUV: The spherical-shaped UUV as shown in Figure 9 requires more thrusters than that of a box-shaped UUV. This is due to the lack water flow separation and symmetrical straight streamline to assist directional movement such that of a box- and cylindrical-shaped UUV. Therefore, consideration on the number and the position of the thrusters is important for spherical-shaped UUV. Usually eight thrusters are attached around the body of such UUV; four in vertical and the other four in horizontal position to provide stable movement of the UUV [28].

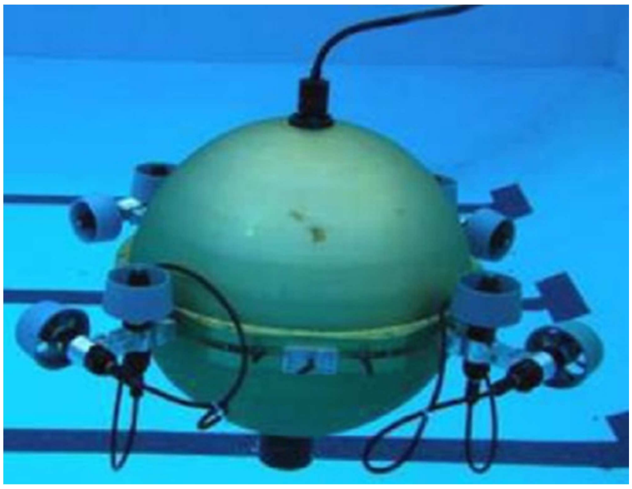

Figure 9: The position thrusters of spherical UUV (ODIN) [28]

Cylindrical UUV: According to [1], the cylindrical shape of UVV that inspired by the torpedoes is mostly used due to the unique characteristic in which such shape has favorable geometry in terms of even pressure distribution. Such characteristic results no obvious stress concentrations and provide for the slenderness that contributes to minimum drag. Although cylindrical-shaped UUV is easy to be controlled along straight lines, it performs poorly to follow a fast moving, agile target [28].

3.2 Stability

Metacentric Height Stability: According to the works of [29], in order to design a UUV that is able to operate in a dynamic environment, a good buoyancy characteristic is achieved when the center of buoyancy (CB) is close enough to the center of gravity (CG). Robotic Research Centre (RRC) [30] has developed a special ROV for the pipeline inspection with open frame structure of 1 m long, 0.9 m wide and 0.9 m high. It is capable of performing passive roll and pitch motion due to its metacentric height that provided adequate static stability. Other components include four thrusters to generate 70 N of thrust, four balancing steel weight with two cylindrical float, sensors with navigation pod (Main pod 1 and 2), and altimeter with two halogen lamps.

Ballast tank stability: Three main factors must be considered for the glider in to function, which are; buoyancy, operational depth of glider and pitching angle. Ballast tank is incorporated as the subsystem for this process because it contributes in the motion control where the gliding motion is depend on the water volume intake by the ballast tank [29]. Piston ballast tank is one of the most common static diving method that consist of cylinder and piston that acts like a big syringe where the piston draw water inside and pushes it out, when necessary [31] to perform ascending and descending motion.

Fin stability: According to [21], some of the UUVs that are based on bio-inspired design usually used fin for stabilization. Such stabilization strategy also act as efficient propulsion mechanism, which allows the UUV to perform quick maneuvering. The pectoral fin of UUV which was inspired from bluegill sunfish [32] possess such unique characteristic, which is not limited for propulsion but also maneuvering using almost exclusively via the use of pectoral fins.

3.3 Motion of UUV

Propeller-based Thruster: The use of propeller-based thrusters in UUV is not limited as a mean of propel its body vertically and horizontally, but also to perform roll, pitch and yaw movements [33]. Although propeller-based thrusters are capable of dynamic maneuver, one of the weaknesses of thrusters is its inclination towards positive buoyancy that requires additional payload to be incorporated to the UUV to achieve neutral buoyancy [13]. This method used a lot of power to keep UUV underwater because the thrusters must remain active at all time to prevent positive buoyancy [1].

Water jet Propulsion: Although propeller and rudder are used widely for propulsion and steering [21], water jet-based steering system demonstrated as an option for better performance owing to its mechanical simplicity (less rotating parts and simpler transmission mechanisms), low control complexity, low-cost, high robustness with respect to transportation and safe for underwater swimmers in the proximity of the vehicle [2].

An example to support the above discussions is demonstrated in the work of [7], which incorporates vectored water jet propulsion technique. Such mechanism incorporates the combination of several parallel manipulator joints; revolute joint, prismatic joint and spherical joint as shown in Figure 10. The system is capable to control 6 degree-of-freedom movements, in which the hydraulic pump produces thrust force via water jets. Some notable advantages of such proposal are less cavitation, low noise and high degree of directional flexibility.

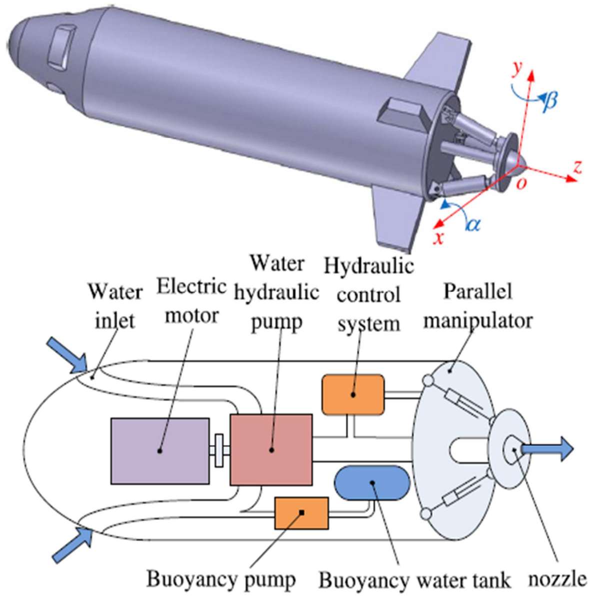

Figure 10: Water jet propulsion system [7]

Depth Estimation: In order to achieve robustness in mission execution, sensors are used to acquire data of the ocean response towards vehicle movements [12]. Good characteristics of sensors are smart, low-powered, highly reliable, and small in size [34]. Discussed in [13] is one of the best pressure-based transducer that acts as the depth sensor for a miniature-class UUV that is able to measure pressure value up to 700 bars.

4.0 MATERIALS SELECTION

The materials typically incorporated in UUVs are reviewed in this section. The discussions shall revolve around the use of alloys, composites and plastic materials.

4.1 Alloy Materials

According to [5], the choice of material is important where it should possess good corrosion resistance, have high strength-to-weight ratio and must be affordable. Putting cost aside, Nickel-Titanium is one of the potential alloy in which it is able contract in cold condition and return to its original state if placed in hot condition [21]. Alternatively, aluminium alloy is preferred due to its light in weight, high strength, inexpensive, better workability and does not prone to magnetization [4].

4.2 Composite Materials

Composite material, in comparison to metals, can be used for the UUV structure due to its unique characteristic such as for weight reductions and the ability to expand the operational depth [4]. Fiber-reinforced composite materials are one of the composite materials that can be tailored to match the requirement of certain applications such as to withstand high external pressure, good sound absorption quality and so on as compared to the conventional materials [35]. According [5], glass-fiber reinforced plastic (GFRP) is an inexpensive composites with high strength-to-weight ratio. On the other hand, carbon fiber reinforced composite (CFRP) is three times more expensive compared to GFRP while having high tensile modulus (better rigidity) [4].

4.3 Plastic Materials

Plastic materials are normally used as building material for UUVs that are operated for shallow water (10 meter depth or less) [5]. The material of the plastic components consists of high-strength Acrylonitrile butadiene styrene (ABS), Polyvinyl chloride (PVC) and Acrylic fiber. While ABS-based components are normally used for small connections, some UUV incorporated PVC for minor body parts, while Acrylic for the major body parts of the UUV.

PVC is one of the prominently used materials due to several superior characteristics, such as; non-corrosive, lightweight and low cost [15]. However, PVC is only incorporated to support minor parts of UUV because of two main reasons; (i) PVC does not provide adequate sealing surface as smooth as other type of material, (ii) PVC possess high material variability (poor clearance, prone to leakage and rapidly decrease in reliability) [1].

Acrylic fiber is of the widely used material as a component in the UUV structure, mainly for the pressure-resistant viewports. Acrylic fiber does not corrode and have good strength-to-weight ratio. [36] demonstrated the use of a transparent acrylic submersible for the full whole ROV that is able to operate up to 1000 meter (10 Mpa) below the surface.

5.0 ENERGY AND POWER SYSTEMS

Discussed in this section are the alternatives for the supply of energy of UUVs *e.g.* battery, fuel cell, solar panel and hybrid power system. Succinct descriptions are presented together with its respective reviews in the following sections.

5.1 Battery

Battery is one of the effective power sources for UUV due to its lightweight and compact characteristics [4]. Small-sized battery is favored, otherwise the energy efficiency and maneuverability performance of the UUVs will diminished. At the same time, the use of battery results low vibration and noise footprint hence protect from interference to sensitive equipment such as sensors and communication devices.

Strategically, batteries used in UUV consist of primary and secondary supply, in which the secondary supply typically of the rechargeable type [9]. Typical UUVs reported in the literatures mostly consume energy from the secondary batteries (rechargeable batteries) although it possess smaller endurance. Comparatively, primary batteries have better endurance than the secondary but it is expensive to use, and rather act for redundancy [37].

The latest development of UUVs are incorporating several types of battery with respect to the efficiency, capability, endurance, safety and cost of the individual primary and secondary system [9], as summarized in Table 1.

Table 1: Performance comparison of typical battery power sources in UUVs

Technology	Type	Energy Density (Wh/dm^3)	Endurance (hour)	Cost	Maintenance
Lead acid	Secondary	10-20	4-8	Low	Low
NiCd/NiMH	Secondary	10-30	4-12	Low	Low
Alkaline batteries (heated to+45 deg C)	Primary	10-30	4-12	Low/ High	Low
Silver-Zinc	Secondary	30-50	12-20	High	Med.
Lithium Ion (D-cells)	Secondary	40-70	16-28	Med.	Low
Lithium polymer (poach)	Secondary	50-75	23-30	Med.	Low
Aluminium -Oxygen	Semi- fuel cell	80-90	32-36	Med.	High
Hydrogen-Oxygen	Fuel Cell	100+	40+	Med.	High
Lithium Batteries	Primary	100-150	40-60	High	Low

5.2 Fuel Cell System

In order to operate efficiently, the weight of a UUV must be equal to the buoyancy force acting on it [38]. As the depth increased, the internal pressure of the empty hull increased accordingly. This results the decreased ability of the UUV to carry useful weight. In such situation, fuel cell is a more effective power source due to several characteristics; lightweight due to compressed gas, rapid to refill and able to maintain constant load. In result, it contribute towards the increase of the efficiency of the system that allows for long endurance operation [18].

5.3 Solar-Powered UUVs

Solar-powered energy supply system is the one of the solution to support long distance operation using limited energy storage system [10]. Solar-powered UUVs (Figure 11) leveraged the inexhaustible source of energy from the sun, however required to ascend to the surface of water to recharge [34]. Since there exists vast area of the sea that are exposed to the sun, the strategy to efficiently incorporate solar energy for underwater vehicles can be applied with novel methods; maximum power control algorithm and equalization charging control method [10]. In the proposed strategy, the solar energy charging system consists of three operational modes, which are; operation mode, continuous recharge mode and deep recharge mode. In operation mode, all batteries are recharged only by the solar energy. In continuous recharge mode, solar panel or fuel cells are used to recharge the batteries while conducting missions. In deep recharge mode, non-critical modules *i.e* perception system is disconnected and all batteries are recharged directly by the solar panel and fuel cell [39] during operation. Such novel strategies allows for maximum recharge of the storage while maintaining the endurance requirement of the vehicle.

5.4 Hybrid Energy Generation Systems

Fuel-based propulsion system and electrical power propulsion system are common in UUVs, however the limitations for certain distance impeded its uses [10]. In a demanding situation *e.g.* long-range operation, Hybrid energy generation system is able overcome this problem [40]. Such system consist of the use of natural resource which is more environmentally friendly from the sun or waves while being assisted by battery bank, fuel cell or diesel generator to be used during demanding situation [41]. Such systems allow for high efficiency power delivery with resulting low emission footprint [42].

Figure 11: Example of a solar powered UUV [34]

CONCLUSION

Several state of the art technologies incorporated in the development of UUVs were reviewed in this paper. The discussions were focused on the recent 10 years of work reported in the literature which focused on the geometry, components that relates to hydrodynamics and motion, material selections and energy supply. In terms of geometry & propulsion, different level of accuracy and endurance are required for various missions, hence drive for unique designs. In such context, the shape of UUVs are not limited to only the box-, cylindrical-, and spherical-based geometry. Several UUVs incorporated bio-inspired strategies such as fish-, multilegged-, soft- and fin-based design to cater for different environment. In order to operate in dynamic environment, several strategies were reviewed in terms of stability strategies (metacentric-, ballast- and fin-based strategies), thruster strategies (propeller- and water jet-based strategies). Several considerations that involve material selections were reviewed; i.e. alloy, composite and plastic materials. Both advantages and disadvantages were highlighted to serve as a guideline for UUV designers in view of strength, operational depth and durability. Three energy supply systems were discussed which are; battery, fuel cell and solar-powered systems. The discussions on energy were concluded with the review on hybrid energy generation system that offers high efficiency power delivery with low emission footprint.

REFERENCE

[1] W. Wang, X. Chen, A. Marburg, J. Chase and C. Hann, "A low-cost unmanned underwater vehicle prototype for shallow water tasks," in *IEEE/ASME International Conference* , New Zealand, 2008.

[2] K. Alam, T. Ray and S. G. Anavatti, "Design and Construction of an Autonomous Underwater Vehicle," *Neuro Computing,* no. 142, pp. 16-19, 2014.

[3] J. Kennedy, A. A. Proctor, E. Gamroth and C. Bradley, "Development of a Highly Autonomous Underwater Vehicle For Scientific Data Collection," *Oceanic Engineering,* pp. 437-446, 2007.

[4] T. Hyakudome, "Design of Autonomous Underwater Vehicle," *International Journal Of Advance Robotic Systems,* vol. 8, pp. 122-130, 2011.

[5] W. Wang, R. Engelaar, X. Chen and J. Chase, The State-Of -Art Of Underwater Vehicles-Theories and Applications, Austria: Mobile Robots-State Of The Art In Land,Sea, and Colloborative Missions, 2009.

[6] S. Fangxi, Z. Lianhong, W. Ziliang and W. Leping, "On resistance calculation for autonomous underwater vechicles," *Adv,Mater,Res,* pp. 189-193, 2011.

[7] B. Xin, L. Xiaohui, S. Zhaocun and Z. Yuquan, "A Vectored Water Propulsion Method For Autonomous Underwater Vehicle," *Ocean Engineering,* no. 74, p. 133–140, 2013.

[8] F. G. Serchi, A. Arienti and C. Laschi, "Biomimetic Vortex Propulsion: Toward the New Paradigm Of Soft Unmanned Underwater Vehicle," *Transactions On Mechatronics1,* pp. 484-493, 2012.

[9] N. Storkersen and Q. Hasvold, "Power Sources for AUVs," *Science and Defence Conference,* pp. 1-5, 2004.

[10] H. Yuli and W. Jiajun, "Study On Power Generation And Energy Storage System Of A Solar Powered Autonomous Underwater Vehicle (SAUV)," *EnergyProcedia,* no. 16, pp. 2049-2053, 2011.

[11] D. J.F.Toal, C. Flanagan, W. B.Lyons, S. Nolan and E. Lewis, "Proximal Object and Hazard Detection For Autonomous Underwater Vehicle With Optical Fibre Sensors," *Robotics and Autonomous Systems,* no. 53, p. 214–229, 2005.

[12] Q. Hasvold, K. H. Johansen, O. Mollestad, S. Forseth and N. Storkensen, "The Alkaline Aluminium Hydrogen Peroxide Power Source In The Hugin II Unmanned Underwater Vehicle," *Journal of Power Sources,* no. 80, p. 254–260, 1999.

[13] M. A. Mohd Yusoff and M. R. Arshad, USM Mini Remotely Operated Vehicle: Vehicle Development& Integration, Nibong Tebal Seberang Perai Selatan,Pulau Pinang: USM Robotic Research Group, School Of Electrical and Electronic Engineering Universiti Sains Malaysia, 2008.

[14] E. Allmendinger, M. Delavergne and H. Jackson, "Hydrodynamical Principle In Allimendinger Submersible Vehicle System," *Society of Naval Architects And Marine Engineers,* pp. 191-261, 1990.

[15] J. P. Avila, D. C. Donha and J. C. Adamowski, "Experimental Model Identification Of Open-Frame Underwater Vehicles," *Ocean Engineering,* no. 60, pp. 81-94, 2013.

[16] B. Morrison, A. Mailet, M. Brown, L. Holloway, D. Howse, M. White, J. Young, M. Chaffey, S. Collins, M. Coles, B. Penney and G. Diamond, "ROV," *Marine Technology Society Journal,* pp. 98-109, 2009.

[17] A. Frost, A. McMaster, K. Saunders and S. Lee, "The Development Of A Remotely Operated Vehicle (ROV) For Aquaculture," *Aquacultural Engineering,* vol. 15, no. 6, pp. 461-483, 1996.

[18] T. F.Miller, F. S.Gandhi and R. J.Rufino, "Morphing Hull Concept For Underwater Vechicles," *Ocean Engineering,* no. 92, p. 92–102, 2014.

[19] P. Kodati, J. Hinkle, A. Winn and X. Deng, "Micro Autonomous Robotic Ostraciiform (MARCO): Hydrodynamics, Design and Fabrication," *IEEE Transactions on Robotics,* vol. 1, no. 24, pp. 105-117, 2008.

[20] N. Kato, H. Liu and H. Morikawa, "Biology-Inspired Precision Maneuvering of Underwater Vehicles," *Bio-Mechanisms Of Swimming And Flying,* pp. 111-125, 2004.

[21] A. Suleman and C. Crawford, "Design and Testing of a Biomettic Tuna Using Shape Memory Alloy Induced Propulsion," *Computers and Structure,* vol. 86, pp. 491-499, 2008.

[22] M. Santhakumar and T. Asokan, "Power Efficient Dynamic Station Keeping Control Of a Flat-Fish Type Autonomous Underwater Vehicle Through Design Modification Of Thruster Configuration," *Ocean Engineering,* pp. 11-21, 2013.

[23] D. Sgarioto and C. Madden, "Full-scale manoeuvring trials for the Wayamba Unmanned Underwater Vehicle," *Underwater Technology,* vol. 32, no. 2, pp. 67-79, 2014.

[24] I. K. Bartol, M. Gharib, P. Webb, D. Weihs and M. S. Gordon, "Body-induced vertical flow: a common mechanism for self-corrective trimming control in boxfishes," *The Journal of Experimental Biology,* vol. 1, no. 208, p. 327–344, 2005.

[25] I. D. Walker, D. M. Dawson, T. Flash, F. W. Grasso, R. T. Hanlon, B. Hochner, W. M. Kier, C. C. Pagon, C. D. Rahn and Q. M. Zhang, "Continuum Robot Arm Inspired By Cephalopods," *Unmanned Ground Vehicle Technology VII,* pp. 1-12, 2005.

[26] S. N. Cubero, "Design Concept For A Hybrid Swimming And Vechicle," *Procedia Engineering,* no. 41, pp. 1211-1220, 2012.

[27] A. Irawan, K. Nonami and M. R. Daud, "Optimal Impendance Control with TSK-Type FLC for Hark Shaking Reduction On Hydraulic Driven Hexapod Robot," in *Intelligent Systems, Control and Automation: Science and Engineering Autonomous Control Systems and Vehicle* , Japan, Springer Japan 2013, 2013 , pp. 223-236.

[28] M. Chybaa, T. Haberkorna, R. Smith and S. Choic, "Design And Implementation Of Time Efficient Trajectories For Autonmous Underwater Vehicles," *Ocean Engineering,* no. 35, p. 63–76, 2008.

[29] N. A. Ali Hussain, M. R. Arshad and R. Mohd Mokhtar, "Underwater Glider modelling And Analysis For Net Buoyancy, Depth And Pitch Angle Control," *Ocean Engineering,* no. 38, pp. 1782-1791, 2011.

[30] Y. Hong Eng, C.-S. Chin and W. W.-S. Lau, "Added Mass Computation For Control Of An Open-Frame Remotely Operated Vechicle : Application Using WAMIT And MATLAB," *Journal of Marine Science and Technology,* vol. 22, no. 405, pp. 405-416, 2014.

[31] H. Kondo and T. Ura, "Navigation of an AUV for investigation of underwater structure," *Control Engineering Practice,* pp. 1551-1559, 2004.

[32] G. Lauder and B. Jayne, "Pectoral Fin locomotion in fish: Testing drag based model using three dimensional kinematics," *Amer.Zoologist,* pp. 567-581, 1996.

[33] J. Akhtman, "The design and development of a small manoeuvrable Autonomous Underwater Vehicle," *Society for Underwater Technology,* vol. 28, no. 1, pp. 31-34, 2008.

[34] D. Blidberg, "The Development Of Autonomous Underwater Vehicles (AUV) ; A Brief Summary," in *International Conference on Robotics and Automation,* Lee New Hampshire, USA, 2010.

[35] M. Chuljin, K. In- Hoon, C. Bae- Hyeon, K. Jin- Hwe and C. Jin-Ho, "Buckling Of Filement-Wound Composite Cylinders Subjected to Hydroustatic Pressure For Underwater Vechicle Applications," *Composite Structure,* vol. 92, pp. 2241-2251, 2010.

[36] J. Stachiw, "Acrylic plastic as structural material for underwater vehicles," *International Symposium on Underwater Technology,* pp. 289-296, 2004.

[37] A. Bradley, M. Feezor, H. Singh and F. Sorrell, "Power Systems for Autonomous Underwater Vehicles," *Oceanic Engineering,* vol. 26, no. 4, pp. 526-538, 2001.

[38] Q. Hasvold and N. Storkersen, "Electrochemical Power Source for Unmanned Underwater Vehicle Used in Deep Sea Survey Operations," *Journal of Power Sources,* no. 96, pp. 252-258, 2001.

[39] F. Garcia-Cordova and A. Guerrero-Gonzalez, "Intelligent Navigation for a Solar Powered Unmanned Underwater Vehicle," *Advance Robotic Systems,* vol. 10, no. 185, pp. 1-13, 2013.

[40] C.-H. Lee and J.-T. Yang, "Modeling Of The Ballard-Mark-V Proton Exchange Membrane Fuel Cell With Power Converters For Applications In Autonomous Underwater Vehicles," *Journal Of Power Source,* no. 196, pp. 3810-3823, 2011.

[41] N. Khare and P. Singh, "Modeling And Optimization Of A Hybrid Power System For An Unmanned Surface," *Journal of Power Sources,* no. 198, pp. 368-377, 2012.

[42] Q. Cai, D. Brett, D. Browning and N. Brandon, "A Sizing-Design Methodology For Hybrid Fuel Cell Power Systems And Its Application To An Unmaaned Underwater Vehicle," *Journal Of Power Sources,* no. 195, pp. 6559-6569, 2010.

[43] M. Caccial, G. Casalino, R. Cristi and G. Veruggio, "Acoustic Motion Estimation And Control For Unmanned Underwater Vechicle In a Structured Environment," *Control Engineering Practice,* pp. 661-670, 1998.