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Review

Advancements in the field of autonomous underwater vehicle

Avilash Sahoo[a,b,*], Santosha K. Dwivedy[a], P.S. Robi[a]

[a] Indian Institute of Technology Guwahati, Guwahati, 781039, India
[b] National Institute of Technology Meghalaya, Shillong, 793003, India

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) are robotic devices with a propulsion system for navigation and an onboard computer for decision making. AUV research is gaining popularity because of its extensive applications in fields from military to science. Robotic systems are need of the hour for exploration and environmental safety of the vast and deep oceans and water bodies. This paper presents current research trends in the field of AUVs and highlights future research directions. Here localization and navigation techniques such as inertial navigation to simultaneous localization and mapping being used in current AUVs are discussed in detail. Different optimal path planning and control methods are highlighted. Use of different sensor technology like sonar, laser, acoustic modems and stereo vision systems for localization, navigation and mapping is presented. Recent developments in underwater wireless communication along with the commercially available devices are discussed.

1. Introduction

Most of the earth's surface is covered with water in the form of oceans, rivers and lakes, many of which remain unexplored till date. These environments contain some of the most natural resource-rich habitats. These habitats directly or indirectly affect humans. Deployment of underwater robotic vehicles can help to study these environments to ensure their safety against environmental pollution and use the available natural resources for human development.

Manned underwater vehicles have humans on board which increase the risk as well as operational cost, so underwater unmanned systems are getting very popular. These systems can be used in greater depth and extremely harsh conditions. “Autonomous underwater vehicle (AUV)” and “Remotely operated underwater vehicle (ROV)” are two categories of unmanned underwater robotic systems. ROVs are controlled from the surface, generally by a wired connection. These can do a variety of tasks, but the wired connection limits its manoeuvrability as well as accessibility to remote locations. AUVs navigate autonomously relying on its navigation algorithm and surrounding information. Once deployed, they collect data and come back to the surface after completion of the predefined task. As AUVs are not connected to the ground they have high manoeuvrability, can travel to remote locations, narrow complex pathways, involve no human fatigue and operation cost is very less. Underwater wireless communication has its limitations so AUVs have seen an increase in interest from the underwater research community. It has always been a challenge to make a robotic device to explore these hostile territories. With advancements in AUV research, materials, manufacturing techniques, sensors, computational power and battery technology, autonomous decision making underwater robots have become more reliable and practical. A reliable, fully autonomous decision making robotic system is the objective of current AUV research.

The first AUV “SPURV (The Self Propelled Underwater Research Vehicle)” was developed by Stan Murphy and Bob Francois in 1957 in the Applied Physics Laboratory at the University of Washington (Remotely Operated Vehicle Committee of the Marine Technology Society). “SPURV” operated at 2–2.5 m/s up to a depth of 3600 m Widditsch (1973). In the 1970s few AUVs were developed in MIT and also in the Soviet Union (Remotely Operated Vehicle Committee of the Marine Technology Society). These early underwater robots were bulky, expensive and inefficient. AUVs have come a long way since then. The modern-day AUVs can have six degrees of freedom, can travel faster than 20 m/s, accurately detect obstacles and map ocean floors. These are getting compact, less expensive, yet sophisticated and accessible to the general population for exploration, fishing, and entertainment etc.. These systems have yet to go a long way in terms of autonomy till fully autonomous robotic systems help us explore and protect these deep and hazardous habitats.

AUVs have a large number of applications in hazardous underwater environments. Still, AUVs have to overcome some limitations to have large-scale adoption. Some of the key challenges are low price, underwater wireless communication, long lasting batteries, advanced

* Corresponding author. Indian Institute of Technology Guwahati, Guwahati, 781039, India.
E-mail addresses: avilash@iitg.ac.in (A. Sahoo), dwivedy@iitg.ac.in (S.K. Dwivedy), psr@iitg.ac.in (P.S. Robi).

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Table 1
Applications of AUVs.

	Surveillance	REMUS-6000, 2012 Kongsberg Maritime. 2018; AUV-150 (Shome and Das, 2012)
Military	Anti-submarine warfare	Bluefin21, Echo Ranger, Gavia Defence, SOG Seagliders, Eagle Ray (AUVAC)
	Mine countermeasures	Bluefin21, 2016 General Dynamics Mission Systems. 2012; Panish and Taylor (2011)
	Inspection of wreckage	U-CAT Allotta et al. (2018)
	Payload delivery to ocean floor	GIRONA 500 I-AUV (Simetti et al., 2017)
	Search and rescue	Bluefin21, 2016 General Dynamics Mission Systems. 2012
	Air crash investigation	GIRONA 500 I-AUV Prats et al. (2012); Sanz et al. (2012)
	Ocean exploration and bathymetric study	Theseus AUV (Ferguson, 2009; Kaminski et al., 2010); REMUS-6000, 2012 Kongsberg Maritime. 2018; AUV-150 (Shome and Das, 2012); AE 2000A (Kim et al., 2013)
	Mapping of ocean floor	Autosub 6000 (Morice et al., 2009); AUV-150 (Shome and Das, 2012); D. Allan B (Thompson et al., 2012a); Bluefin21, 2016 General Dynamics Mission Systems. 2012
Scientific	Marine biology studies	Maya AUV (Desa et al., 2007); SoFi Katzschmann et al. (2018)
	Geological Survey	Tri-TON 2 (Tri-ton, 2013)
	Archaeological survey	MARTA, A-Size Allotta et al. (2018)
	Environmental monitoring	Maya AUV (Desa et al., 2007); REMUS-6000, 2012 Kongsberg Maritime. 2018, Folaga Alvarez et al. (2005)
	Track oil-spill and gas leakage	SOTAB (Kimura et al., 2013)
Industry	Repair and maintenance	SAUVIM Marani et al. (2009), Folaga Alvarez et al. (2005), SeaCat (Jacobi, 2015)
	Track and repair underwater cables	AE1000 (Kato et al., 1994)
	Underwater structure inspection	SeaCat (Jacobi, 2015)
Other	Underwater video footage collection	Maya AUV (Desa et al., 2007)
	Fishing	
	Entertainment and Tourism	

manufacturing techniques, smart materials, compact on-board computers with high computational power for better decision making, on-board energy generation and its efficient use. In this paper, the major subsystems of AUVs are presented in different sections. The different sections are applications, AUV structure, propulsion techniques, kinematics and dynamics, planning and control, navigation and localization and underwater communication. The objective of this paper is to present recent developments and challenges in the field of AUV. The next section discusses different useful applications of the AUVs.

1.1. Application

AUVs are becoming very popular for underwater exploration in commercial, military and industrial applications. Over the years a large number of AUVs have been developed for various application. Table 1 lists the potential applications along with AUVs used for these purposes.

With the help of different sensors, these vehicles can collect a variety of useful scientific information like temperature, depth, pH level, chemical composition, turbidity etc. This information can help in environmental monitoring and scientific study. Cameras can be used to take pictures of the environment to study underwater ecosystems, different aquatic animals and underwater ground structure (Desa et al. (2007); Ferguson (2009); Kaminski et al. (2010); Shome and Das (2012) Kongsberg Maritime. 2018). With multiple cameras and sonars, 3D mapping and reconstruction of the sea floor can be done which can be used in site selection for constructions like tidal energy plant, ports; claim the maritime borders with continental shelf data (Shome and Das (2012); Thompson et al. (2012a); Morice et al. (2009); Kim et al. (2013)). Allotta et al. (2018) presented AUVs "MARTA" and "A-Size" used for 3D mapping of underwater archaeological sites and a turtle-inspired bio-mimetic AUV "U-CAT" used for ship wreckage penetration and survey. AUVs are being used for inspection of cracks and damages in underwater structure Jacobi (2015), track and discover ore Tri-ton (2013), oil, natural gas reserves. Underwater vehicles can be used to track oil leakages from oil mines, gas leakage from under-sea gas pipelines to protect the underwater ecosystem and avoid pollution Kimura et al. (2013). Intervention-AUVs with autonomous manipulator systems are being used for various intervention tasks such as self-docking, search and retrieve objects (Sanz et al. (2012)), payload delivery to the ocean floor, pipeline and cable deployment etc. Such I-AUVs can be used for black-box search and retrieval during air crash investigations. Various co-operative tasks such as pipeline (Simetti et al., 2017) and cable deployment, transportation of long and heavy payload to the ocean floor can be carried out by a fleet of AUVs and I-AUVs. Some bio-mimetic underwater robot like a snake and fish robots and other AUVs are being used for inspection and surveillance Shome and Das (2012). Bio-mimetic robots (SoFi Katzschmann et al. (2018)) are being developed with soft flexible materials to create lifelike motion. Such AUVs can be used for close-up observation of aquatic life without disturbance. Apart from these scientific and commercial applications, AUVs are being extensively used for military purpose. Bio-mimetic, as well as other AUVs, can be used for surveillance and reconnaissance. Using sonar AUVs can be used for mine countermeasures without engendering human life. Other applications may include anti-submarine warfare, search and rescue and site inspection etc. Generally, these robotic vehicles are used in oceanographic applications. Underwater robots are also being used to study underwater environments in rivers and lakes and carry out surveys. In recent years AUVs have gained much more popularity because of its potential applications in the fields of scientific research, military and industries. AUVs have been initially developed by military and research establishments for specific applications. Later multi-purpose as well as application specific industrial AUVs have been developed. "REMUS-6000" (Fig. 1 (a)) developed by Kongsberg Maritime. 2018 is such a multi-purpose industrial AUV. REMUS-6000 weighs 862 kg with a maximum depth range of 6 km and travel velocity up to 2.3 m/s. The AUV houses acoustic modem for communication, side-scan sonar for bathymetric data collection and acoustic underwater positioning and navigation system with IMU(Inertial Measurement Unit) and DVL (Doppler Velocity Log) sonar for navigation. This AUV can be used for fisheries research, habitat mapping, under ice exploration, marine archaeology, deep-sea ecology, seabed investigation, deep-sea mining, mine countermeasures, surveillance and reconnaissance etc. "Bluefin-21" (Fig. 1(b)) developed by General Dynamics Mission Systems. 2012 is another multi-purpose industrial AUV rated for 4.5 km depth. This AUV can be used for the oceanographic study, mine countermeasures, anti-submarine warfare and underwater exploration etc. Maintenance and repair of underwater gas and oil pipelines is a major potential industrial application for AUVs. An AUV (Fig. 1(d)) with a robotic arm for pipeline inspection is under development by Kawasaki Subsea (UK) Limited, to be launched in the year 2020. Table 2 presents some examples of AUVs being used in the field for various applications encountered during this literature survey. More examples of such AUVs used for different applications can be found in the AUV database AUVAC. The following section talks about the structural design of the AUVs.

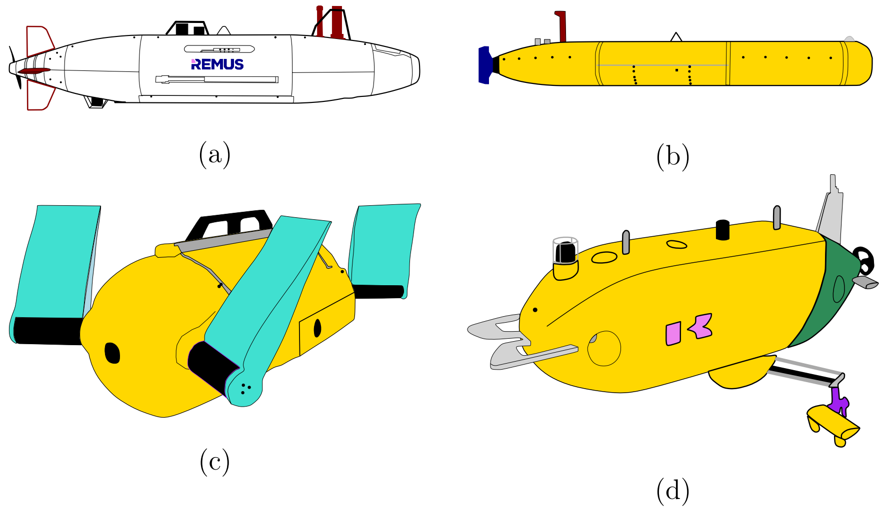

Fig. 1. (a)"REMUS-6000" (Kongsberg Maritime. 2018) (b)"Bluefin-21" (General Dynamics Mission Systems. 2012) (c)"U-CAT" (Allotta et al. (2018)) (d) Kawasaki AUV (Kawasaki Subsea (UK) Limited. 2019).

2. AUV structure

The body structure of AUV is an important element as it safely houses all the mechanical and the electronic components in a water-tight enclosure. The shape of the AUV also affects the dynamics of motion because of the fluid-structure interaction with the surrounding water. Inspired from submarines, AUVs are generally torpedo shaped. The first AUV "SPURV" Widditsch (1973) was torpedo shaped. AUV presented by Jun et al. (2009), Shome and Das (2012), Ferguson (2009), Hiller et al. (2012), Hyakudome (2011), 'STARFISH' by Hong et al. (2010), 'Maya' by Desa et al. (2007), 'SPARUS II' by Carreras et al. (2018), 'FOLAGA' by Alvarez et al. (2005) and 'MARTA' by Allotta et al. (2015a) are some examples of torpedo-shaped AUVs. Depending on different requirement AUVs have adopted various shapes. Fittery et al. (2012) developed an egg-shaped AUV called 'Omni-Egg' at MIT. He et al. (2015), Yue et al. (2013), Ma et al. (2014), Li et al. (2017) and Wan et al. (2014) presented spherical AUVs. These AUVs are highly manoeuvrable and can easily travel in complex pathways and access remote locations which are otherwise difficult to access. Apart from these simple structures, nowadays AUVs are being developed in complex shapes with hydrofoil profiles to increase efficiency and reduce drag. P-SURO AUV Li et al. (2010), AUV presented by Alam et al. (2014) are some such AUVs. All these AUVs with different body shapes use a watertight close-frame structure. AUVs operating at low speed often use open frame structures as the drag force at low speed is less. Girona 500 AUV Wirth et al. (2013) and AUV presented in Hung et al. (2008) are some open-frame AUVs.

Apart from these artificial structures, AUVs have taken inspiration from nature and mimicked aquatic animals. In addition to exploration and other underwater applications, these bio-mimetic AUVs can seamlessly integrate to the marine environment to study and understand the aquatic life without disturbing them. Fish robots are most popular among the bio-mimetic AUVs. Yang et al. (2011), Parameswaran and Selvin (2011), Ashar et al. (2013), Vo et al. (2010), Choi and Lee (2012), Listak et al. (2008), Yu et al. (2016) and Jung et al. (2013) developed fish robots. Fig. 2 presents the robotic fish developed by Yang et al. (2011).

AUVs have also been developed which mimic other aquatic animals such as snake, turtle, beetle and crab etc. Zhao et al. (2008) presented turtle-like robots with four mechanical flippers inspired by softshell turtles. Allotta et al. (2018) presented a turtle-like robot 'U-CAT', developed for shipwreck penetration. Kim et al. (1997) presented a six-legged underwater robot CALEB 10 (D.BeeBot) inspired by beetles which can walk as well as swim. Jun et al. (2012, 2013) also presented a six-legged seabed walking robot 'CR200' inspired by crabs. Kang et al. (2018); Nguyen et al. (2018) presented underwater glider inspired by the manta ray. Recently soft Bio-mimetic AUVs have been used for closeup exploration of aquatic-life without disturbing the natural

Table 2
AUVS Used in different field applications.

AUV Name	Developed In	Applications	Dimensions	Working Depth
AE1000 (Kato et al., 1994)	Japan	Inspection of underwater telecommunication cables	2.3m × 2.8m x 0.7m	1000m
Maya AUV (Desa et al., 2007)	NIO, Goa, India	Oceanography study	1.742m, dia 0.234m	200m
Theseus AUV (Ferguson, 2009; Kaminski et al., 2010)	Canada	Under-ice bathymetric surveys	10.7m, dia 127 cm	2000m
Autosub 6000 (Morice et al., 2009)	AUVAC, USA	Scientific survey and mapping	5.50m × 0.90m x 0.90m	6000m
REMUS-6000, 2012 Kongsberg Maritime. 2018	Kongsberg Maritime. 2018, Norway	oceanography study, Monitoring, surveillance and reconnaissance etc.	3.96m, dia 71 cm	6000m
AUV-150 (Shome and Das, 2012)	CMERI, India	oceanography study, mapping, surveillance and reconnaissance etc.	4.85m, dia 0.5m	150m
D. Allan B (Thompson et al., 2012a)	MBARI, USA	Seafloor mapping	5.18m, dia 54 cm	6000m
SOTAB (Kimura et al., 2013)	Osaka University, Japan	Track oil leakage from oil mines	3m, dia 27 cm	200m
AE 2000A (Kim et al., 2013)	Japan	Under-ice survey	3m × 0.7m x 0.7m	2000m
Tri-TON 2 (Tri-ton, 2013)	University of Tokyo, Japan	Estimate ore reserves in underwater hydrothermal deposits	1.4m × 0.7m x 1.4m	2000m
SeaCat (Jacobi, 2015)	Germany	Autonomous inspection of underwater structures	2.5m × 0.58m x 0.67m	600m
Bluefin21, 2016 General Dynamics Mission Systems. 2012	General Dynamics, USA	Search and explore, Oceanography, Mine countermeasures	5m, dia 53 cm	4500m

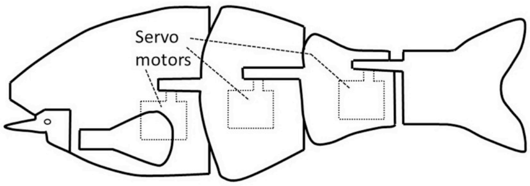

Fig. 2. Robotic fish "ichthus" Yang et al. (2011).

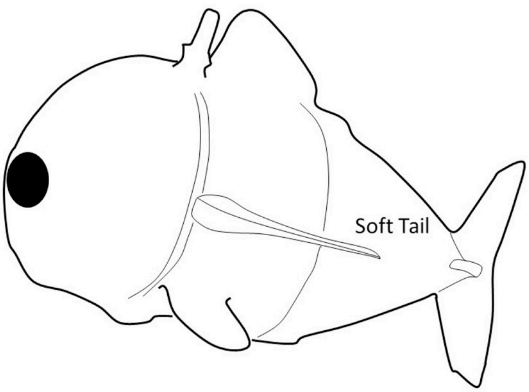

Fig. 3. Soft robotic fish "Sofi" Katzschmann et al. (2018).

habitats. For example, Ming et al. (2014) developed a soft snake robot and recently a soft robotic fish (SoFi) was designed and developed by) (Fig. 3).

AUVs nowadays are adapting modular design in the body structure. The whole AUV is a combination of different modules such as propulsion, sensor modules which can be easily and quickly replaced in case of a failure as well as can be interchanged with different modules according to the mission requirements. Such modular AUVs are highly versatile and incur less maintenance cost. 'AUV-150' Shome and Das (2012), 'MAYA' (National Institute Of Oceanography (NIO). 2012), 'STARFISH' Hong et al. (2010), 'Bluefin21' (General Dynamics Mission Systems. 2012), 'SPARUS II' Carreras et al. (2018), 'FOLAGA' Alvarez et al. (2005), 'MARTA' Allotta et al. (2015a) and AUVs presented in Alam et al. (2014) and Hiller et al. (2012) are examples of some modular AUVs.

During motion, AUV experiences drag and lift forces because of the friction between the body and surrounding water, which affect the dynamics of AUV. Body structure greatly affects these forces. Fluid-structure interaction study of the AUV with the surrounding water is essential to predict the drag and lift. Minimising these forces using different numerical and optimization technique, increases the efficiency of the AUVs. Drag and lift estimation also help in developing an accurate dynamic model for navigation and control. Alam et al. (2014) used a non-dominated sorting genetic algorithm (NAGA), population-based optimization algorithm and in-feasibility driven evolutionary algorithm (IDEA) to optimize the hull structure of a torpedo-shaped AUV for minimum drag and clash-free component placement. Sun et al. (2017) presented an underwater glider with a blended wing-body structure. The glider structure is shape-optimized for maximum gliding range considering the internal space as a proportional function to energy reserve. Elsayed et al. (2015) presented an elliptical submersible pressure hull designed with multi-objective optimization to minimise buoyancy and maximize buckling load capacity to reach a depth of 6000m. ANSYS FEM analysis is carried out to verify the design. Nguyen et al. (2018) presented a shape optimized underwater glider inspired by manta ray using CFD analysis to have the least fluid resistance. Mitra et al. (2019) presented an experimental and numerical study on the effect of free stream turbulence on hydrodynamic parameters of AUV hull structure. Experiments were carried out at three different depths and the results are used to validate the estimations predicted by a Reynolds stress model. It was observed the presence of free stream turbulence to decrease skin friction, drag and lift coefficients. Such studies can help in the development of more efficient AUV structures. A popular Computational Fluid Dynamics (CFD) software 'ANSYS (FLUENT)' is being used for the hydrodynamic study of the AUVs. Allotta et al. (2015b) presented the design and development of a low-cost 5-DOF AUV "Tifone". The shape of the AUV is optimized for maximum efficiency with ANSYS CFX finite element modelling. Alam et al. (2014), He et al. (2015), Yue et al. (2013) and Ma et al. (2014) used ANSYS (FLUENT) to study the hydrodynamic behaviour of their AUVs. Liou (2011), Listak et al. (2008) and Wu (2010) adapted theoretical and experimental method for hydrodynamic study.

AUVs experience hydrostatic pressure due to water head and hydrodynamic pressure due to their movement. AUV body can deform or get damaged due to excess pressure, which increases with depth. Researchers are using 'Finite Element Method' (FEM) for stress and buckling analysis of the hull structure which helps in selection of proper material, the thickness of the wall as well as set the operational depth limit of the AUVs. Stevenson et al. (1998) presented mechanical design and development of a deepwater AUV "AUTOSUB-1" considering the buckling failure. Shome and Das (2012) and Jun et al. (2013) used FEM for stress estimation of the AUV bodies. Błachut et al. (2008) presented a numerical and experimental study of buckling of a multi-segment pressure hull subjected to uniform hydrostatic pressure. Rahim et al. (2009) presented the design of a pressure hull for an underwater pole inspection robot. Finite element stress and buckling analysis were carried out to determine the wall thickness of the structure. Allotta et al. (2015b) used FEM for buckling verification of the central cylindrical structure at 700m water depth and experimentally verified up to 300m depth. Li et al. (2017) presented a stress analysis of the frame holding the servo motor and water-jet propellers. Complex hydrofoil structures are difficult to manufacture and costly with traditional materials and techniques. Composite materials can be used in such cases for ease of manufacturing and strength and other properties comparable and sometimes better than traditional materials. Kang et al. (2018) presented an underwater glider made of carbon fibre composite with similar strength but 40% less weight compared to high tensile aluminium. Here stress and buckling analysis is used to show that the glider can withstand the underwater pressure at 200m depth with 1.8 factor of safety. Next section presents different propulsion methods used by AUVs for navigation.

3. Propulsion techniques

AUVs depend on its propulsion system to travel in the underwater environment. Bio-mimetic AUVs mimic propulsion technique as well as body structure of aquatic animals. These AUVs travel in water using undulatory propulsion. In this technique, a pressure difference is created in water by moving some part of their body in a wave-like pattern. Most of these AUVs use electric motors for this purpose. Yang et al. (2011), Parameswaran and Selvin (2011), Ashar et al. (2013), Vo et al. (2010), Choi and Lee (2012), Yu et al. (2016), Zhao et al. (2008) and Jung et al. (2013) used servo and DC motors for moving their body parts for propulsion. Instead of rigid body parts, soft flexible parts are being used to have more life-like motion in case of these bio-mimetic AUVs. Katzschmann et al. (2018) presented a Soft Robotic Fish (SoFi) with a hydraulically driven flexible soft elastomer tail and servo driven hard fins. Smart materials have also been used to create such wave-like motions for propulsion. Ming et al. (2014) have presented a soft snake underwater robot made of piezoelectric fibre composite, which mimics undulatory propulsion of a sea snake. These vehicles are energy efficient, quiet and flexible in operation. Such systems are suitable for surveillance and ecological study as they produce no noise and don't disturb the aquatic animals nearby.

Bio-mimetic AUVs are incapable of carrying heavy payloads and achieving high speed. AUVs used for these applications generally use multiple propellers or thrusters for propulsion along with rudders and fins for directional control. AUVs presented in Isa and Rizal A. (2011); Alam et al. (2014); Jun et al. (2009); Shome and Das (2012); Hiller et al. (2012); Ferguson (2009); Hyakudome (2011), STARFISH Hong et al. (2010), Maya (National Institute Of Oceanography (NIO). 2012 and AQUA EXPLORER 1000 Kato et al. (1994) use wings and rudder along with propeller for motion. AUVs presented in He et al. (2015), Li et al. (2017) and Yue et al. (2013) use servo controlled water jet propellers whereas AUVs in Ma et al. (2014), Fittery et al. (2012) and Wan et al. (2014) use servo controlled hydraulic pump for propulsion. Bluefin21 AUV (General Dynamics Mission Systems. 2012) uses a gimbaled, ducted thruster. AUV can follow complex trajectories with fixed thrusters using different control algorithms. Typhoon AUV Allotta et al. (2016a), SPARUS II AUV Font et al. (2016), Girona 500 AUV Wirth et al. (2013), P-SURO AUV Li et al. (2010), Hovering AUV (General Dynamics Mission Systems. 2012) and AUV presented in Hung et al. (2008) are some examples of such AUVs with fixed thrusters. Kinematics and dynamics relations of different AUVs are discussed in the next section.

4. Kinematics and dynamics

Kinematic model of a robot is the mathematical correlation between the inertial, non-inertial frame and links of a robot which defines the position, velocity and acceleration of different parts of the robot with respect to some frame of reference. Dynamic model correlates forces and moments with the position and velocity of the robot. A rigid body AUV is considered as a single link manipulator and its kinematic model correlates the body-fixed frame and the earth-fixed frame as shown in (Fig. 4). The Body-fixed frame is attached to the geometrical centre of the vehicle with axes in the directions of surge, sway and heave respectively. Earth-fixed or inertial (X, Y, Z) frame coincides with the North-East-Down directions and fixed to a point on the water surface.

As presented in Table 3 coordinates along X, Y, Z axis (x, y, z) and rotational angle about these axis (ϕ, θ, ψ) constitute the position and orientation vectors of AUV Centre of Gravity (C.G) in the inertial frame presented as $\eta = [\eta_1^T, \eta_2^T]^T$; where $\eta_1 = [x, y, z]^T$, $\eta_2 = [\phi, \theta, \psi]^T$.Linear and angular velocity of the AUV C.G in the body fixed frame is denoted as$\nu = [\nu_1^T, \nu_2^T]^T$; where $\nu_1 = [u, v, w]^T$ and $\nu_2 = [p, q, r]^T$.Parameters in both the frames can be correlated using Euler transformation presented as:

$$\dot{\eta} = J(\eta_2)\nu \tag{1}$$

where $J(\eta_2)$ is the Jacobian matrix. Detailed derivation of the kinematic and dynamic model is presented in Fossen (1994, 2011); Antonelli (2014).

An accurate dynamic model is essential for an AUV for its control and navigation. Fossen et al. (1995) have presented non-linear modelling of a 6 degree of freedom marine vehicles which can be extended for a rigid body AUV. The interaction between the motion of an AUV and different related forces and torques can be expressed as:

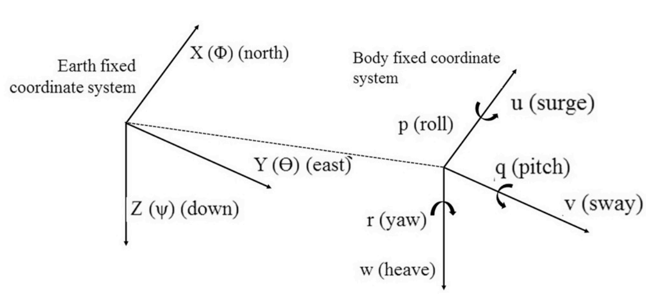

Fig. 4. Definition of reference frame and relative motion.

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau \tag{2}$$

where $M = M_{RB} + M_A$; M_{RB} and M_A are the constant inertia and added mass matrix of the AUV respectively, $C(\nu) = C_{RB}(\nu) + C_A(\nu)$; $C_{RB}(\nu)$ and $C_A(\nu)$ are the Coriolis and Centripetal matrix of the rigid body, and the added mass respectively, $D(\nu)$ is the Damping matrix containing drag and lift terms, $g(\eta)$ is the vector of restoring forces and moments which includes gravitational and buoyancy forces, and τ is the vector of body-fixed forces from the actuators. Hydrodynamic added mass can be interpreted as virtual mass added to a system because when the body accelerates or decelerates it must move some volume of the surrounding fluid as it moves through it. Added mass matrix M_A depends on the shape of the AUV. M_A is positive and symmetrical for submerged bodies.

Different modern tools such as CAD modelling and CFD analysis techniques can be used to find close estimates of these above-mentioned parameters. Different system identification techniques have to be employed to accurately measure these system parameters by comparing the simulated results with the experiments. Weiss et al. (2013) presented a method to develop the dynamic model for underwater vehicles in real-time by system identification, which can be used for position and velocity estimation. This method uses Recursive Least Squares estimator to minimise the square of the error between the modelled and measured response to find out the unknown parameters. Yue et al. (2013) presented a dynamic model for the spherical robot 'SUR-II' along with parameter estimation to determine the hydrodynamic added mass matrix to the damping matrix. Here CFD analysis using ANSYS Fluent is used for parameter estimation. Shen et al. (2016), Chin et al. (2006), Allotta et al. (2016a), Ngatini et al. (2017), Isa and Rizal A. (2011), Hyakudome (2011), Shome and Das (2012), Wang et al. (2014) and Sarhadi et al. (2016) presented dynamic model of the AUVs similar to the model discussed above. Silva et al. (2008) discussed different dynamic models for simulation and control of underwater vehicles. A simplified approach towards the solution of a dynamic model is discussed.

For various practical applications such as retrieval of objects and repair work etc., underwater manipulators are essential. Work-class ROVs with remotely operated underwater manipulators are being used for underwater intervention and manipulation works. These systems are very expensive because of the requirement of skilled operators, high-bandwidth communication link and they have to be deployed form the ships with sophisticated control stations. Apart from these, operator fatigue is also a major issue. Cheaper autonomous intervention systems can effectively replace these expensive manipulator systems. Such Intervention AUVs (I-AUVs) can be easily deployed from less sophisticated surface vehicles and require less human intervention. 'ODIN' Choi et al. (1994) and 'OTTER' Wang et al. (1995) are some of the first AUVs to be equipped with a simple 1-DOF robotic arm. Lane et al. (1997) presented the 'AMADEUS' project for cooperative manipulation using a 7-DOF electromechanical arm with-in a water tank. "UNION" project Rigaud et al. (1998) demonstrated a coupled AUV-manipulator system with an AUV VORTEX and a 7-DOF robotic arm. ALIVE I-AUV described in Evans et al. (2003) is one of the early projects to use autonomous manipulator system in the field. The I-AUV was aimed for docking to sub-sea structure autonomously, using sonar, vision sensors and manipulators. SAUVIM Marani et al. (2009) was the first project to perform free floating intervention task to retrieve the object after identifying the target. Sanz et al. (2010) presented the road map and challenges for the "TRIDENT" project for developing an Underwater Vehicle Manipulator System (UVMS) for autonomous intervention task in unknown underwater environments. It is proposed to use different AUVs as surface vehicles and one I-AUV for simple intervention applications such as picking of objects without a ship. Sanz et al. (2012) Presented multi-purpose intervention task such as object search and retrieval initially with 4 DOF arm and later with a 7 DOF arm with three-fingered hand under the TRIDENT project. Prats et al. (2012) presented a case study of black box retrieval by the I-AUV, and Sanz

Table 3
Standard SNAME (1950) notations for Marine vessels.

DOF	Motion Descriptions	Positions and Orientations	Linear and Angular Velocities
1	Motions in the X- direction (surge)	x	u
2	Motions in the Y− direction (sway)	y	v
3	Motions in the Z- direction (heave)	z	w
4	Rotations about the X-axis (roll)	ϕ	p
5	Rotations about the Y-axis (pitch)	θ	q
6	Rotations about the Z-axis (yaw)	ψ	r

et al. (2013) presented the shallow water trial. Ridao et al. (2014) presented a detailed review of different major I-AUV projects such as "AMADEUS", "ALIVE", "SAUVIM" and 'TRIDENT" etc. The first lightweight GIRONA 500 I-AUV is presented in detail along with its software architecture. A detailed discussion on different experimental intervention tasks performed with the I-AUV such as locating a target object and picking up, docking, turning a valve, plugging a connector etc. Is presented. Some of the major challenges highlighted are the current limitation in high bandwidth communication with multiple I-AUVs and AUVs for cooperative intervention missions and limitation of sonar and visual sensors for intervention tasks close to the ocean floor.

Simetti et al. (2014) presented the control architecture of a multipurpose intervention AUV. Carrera et al. (2014) demonstrated valve turning operation underwater using the Girona 500 I-AUV. Palomeras et al. (2016) presented a technique for autonomous docking to a sub-sea panel and manipulation tasks such as turning a valve and plugging and unplugging a connector using the Girona I-AUV. Fig. 5 presents Girona 500 I-AUV. Simetti et al. (2017) presented cooperative manipulation and transportation of an object with multiple I-AUV. Simulation results of the mission for grasping, transportation and deployment of a long pipe with two I-AUV is presented. I-AUVs are relatively new and in the future, we will be seeing more complex as well as cooperative intervention tasks being carried out by these systems.

Dynamic modelling of AUVs with manipulator becomes more complex when the hydrodynamic effect of the manipulator on the AUV motion is considered. Following are some study on the dynamic model of AUVs coupled with manipulators and other external accessories. Wang et al. (2016) presented a lightweight multi-link manipulator structure for minimising the dynamic coupling between the manipulator and the AUV. Wilson et al. (2011) presented a dynamic model for AUV coupled with a two-link manipulator with its control design and numerical simulation. Zhao et al. (2008) discussed the mathematical models of individual flipper joints of the turtle-like robot and coupling of the joints for oscillatory cooperative movement for swimming. Shibata et al. (2010) presented a joint mechanism which is a combination of flexible and rigid parts and can be deformed by a prismatic actuator driven by hydraulic pressure for underwater manipulation. Santhakumar and Kim (2011) discussed detailed modelling and simulation of dynamic coupling in an AUV and its manipulator system. Jie and Wang (2009) presented an underwater robot with two hanging torpedoes and developed a dynamic model for the robot considering the forces exerted by the torpedoes on the robot. Generally, underwater robots rely on tethered communication. The cable affects the dynamics of these vehicles. Schjolberg et al. (1996) presented a dynamic model of a robotic system connected to the ship by a cable.

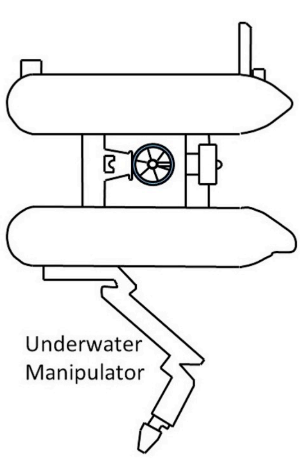

Fig. 5. Girona 500 I-AUV Palomeras et al. (2016).

A flexible AUV such as a robotic fish or snake has a body consisting of multiple links. In the case of such AUVs, kinematic and dynamic modelling becomes more complex. The dynamic model of such robots correlates different forces along with the forces generated because of the link movements and the motion of the AUV. Some studies with Mathematical modelling of such multi-link flexible AUVs are presented here. Yang et al. (2011) presented a dynamic model for a 3 joint 4 link robotic fish. Ashar et al. (2013) used different link movement patterns for a different motion of the fish robot. Kinematic relations have been developed for these movement patterns, which are further used in the control system. Vo et al. (2010), Choi et al. (2012b) and Yu et al. (2016) developed kinematic and dynamic models of their flexible robot for control and navigation. AUVs have to use different control systems and path planning algorithms for navigation in the highly dynamic underwater environment which are discussed in the following section.

4.1. Planning and control

After the development of an accurate dynamic model, one needs to develop a control system for the AUV to work properly. Control system regulates the actuator output to obtain the required velocity and position. AUV controller has three major operations: planning, control and error diagnostic. Depending on the mission objective and environmental constraints, path-plan is developed. Control enables the AUV to follow this path and replanning is done if some constraint is violated. The highly non-linear behaviour of AUV, dynamic underwater environment forces and uncertainties in system parameters are some major challenges faced during the design of a control system for an AUV. Multi-link flexible body AUVs and additional manipulators add more complexity to the problem. AUVs to operate in a highly dynamic environment, controller gains have to be tuned during AUV motion. Thus adaptive or self-tuning controllers are highly desirable. But still, classic control technique such as PID is commonly used in AUVs because of its ease of implementation. Schjolberg et al. (1996) adopted a classical PID control strategy for control of the underwater robot and presented a stability analysis of the system by Lyapunov theory. A simple PID controller was used by Jung et al. (2013) to control the motion of a slide-slipping fish robot on a flow aided path. Fittery et al. (2012) used a simple PD controller with an onboard gyro sensor for estimation of heading angle of the micro-pumps of an egg-shaped AUV. Isa and Rizal A. (2011) developed an open loop controller for a propeller-driven underwater glider. Shome and Das (2012) implemented a PID controller for 'AUV-150'. Wilson et al. (2011) presented a PID controller having linearised feedback. Schillai et al. (2016) used a depth PID control along with sonar to evaluate the terrain collision risk associated with AUVs used in photographic surveys of sea-floor.

Apart from simple controllers, researchers have developed some advanced control strategies such as non-linear control, adaptive control, sliding mode control and neural network control to address complex dynamic control problem associated with AUVs. Some of these control methods adapted for AUVs are discussed by Parhi and Kundu (2012) and Yuh (2000). Hyakudome (2011) used a linear quadratic optimum controller with integral action. Sarhadi et al. (2016) proposed an adaptive PID control with an anti-windup compensator for an AUV. Such adaptive control strategies are better equipped to handle variable system parameters. Xiang et al. (2015) developed a control strategy to move an AUV along a horizontal path in both fully-actuated and under-actuated configurations. A non-linear controller was used for an under-actuated AUV which was later adopted for the fully-actuated system.

Fuzzy controllers based on fuzzy logic are most popular control techniques. Fuzzy logic is a mathematical system which considers analog inputs in the form of a logical variable which can take continuous values between 0 and 1. This method reduces mathematical complexity. Kato et al. (1994) developed a PID and a fuzzy controller for maintaining the altitude of a cable tracking AUV and also discussed the cable tracking experiment with sensors, sonar and PID control. Hung et al. (2008) used a Hybrid fuzzy PID controller where the incremental fuzzy logic controller is used in place of the proportional term with integral and derivative terms intact. Yu et al. (2016) used two-stage control law for posture control of the robotic fish. First one is the fast position approach, which is a modified proportional control for the fish to swim faster towards the target and the second one is the accurate posture adjusting using a time-varying feedback stabilization control for position and directional accuracy. Here fuzzy logic and behaviour based control were used for coordination of multiple fish robots. Vo et al. (2010) developed the dynamic model of a fish robot based on Lagrange's method. The Sliding Mode Controller (SMC) and the Fuzzy Sliding Mode Controller (FSMC) were proposed to achieve the straight and turning motion of the fish robot. Feasibility and the quality of the controllers were verified using numerical simulations. Li et al. (2017) used Fuzzy Sliding Mode Controller for a spherical AUV to control the direction of the water-jet thruster for navigation. Yu et al. (2017) proposed a non-linear single input fuzzy controller coupled with a 3D guidance law for path following problem of an under-actuated AUV. Londhe et al. (2019) designed an adaptive fuzzy sliding mode control for trajectory tracking AUV considering the system non-linearity. Yan et al. (2019a) discussed an adaptive integral sliding mode control for under-actuated AUVs with unknown dynamics. A dual closed-loop integral sliding mode control design is used with an outer loop for velocity estimation and an inner loop for actual control input to actuators for trajectory tracking.

Neural network controllers have gained popularity and seen a large scale adoption in recent years because of exponential advancements in computer infrastructure. Artificial neural networks are computing systems inspired by a biological neural network with machine learning algorithms for data processing. Li and Lee (2005) designed a neural network adaptive controller for an AUV. Here neural network was used to approximate unknown dynamics in the pitch motion. Wang et al. (2014) proposed a neural network PID controller for an amphibious spherical robot. The stability of the controller was analysed according to the Lyapunov method. Shojaei (2019) studied a 3D target tracking control for an under-actuated AUV with a multilayer neural network.

As discussed above the control strategies, in general, are developed with an objective to make the AUV follow a predefined path or target taking care of the unknown dynamics, system non-linearity and unknown disturbances. Shen et al. (2016) presented a non-linear model predictive control for trajectory tracking AUV. Here six DOF AUV model was presented in three coupled subsystems and distributed model predictive control was implemented. Xia et al. (2019) presented a line-of-sight (LOS) based adaptive trajectory tracking controller for an under-actuated AUV with consideration of system non-linearity, uncertain ocean currents and input saturation etc. Here kinematic and dynamic models of AUV are developed with ocean currents and extended disturbance observers (EDO) are utilised to estimate the ocean currents. Lamraoui et al. (2019) presented an active disturbance rejection control strategy for a path following AUV in presence of fast-varying disturbance by waves and ocean currents. Here the generalized extended state observer (GESO) and Harmonic ESO (HESO) is used for disturbance estimation. Yan et al. (2019b) presented a coordination control for multiple AUVs for trajectory following problem. In this work, a leader AUV with accurate sensors leads the fleet of multiple AUVs. Kimura et al. (2013) presented a control strategy for SOTAB-I (SOTAB; Spilled Oil Tracking Autonomous Buoy) Allibert et al. (2019) presented a vision-based non-linear control technique for pipeline following. Apart from following a path or target, control strategies can be developed to control depth, increase energy efficiency, achieve biomimetic propulsion, autonomous docking etc. Hong et al. (2010) presented a depth controller design for a positively buoyant torpedo-shaped AUV named as 'STARFISH'. Here, the effect of buoyancy on both pitch and heave dynamics of an AUV was studied and a controller scheme was proposed that specifically compensates for the positive buoyancy. A cascaded dual loop design with inner sliding mode control and outer proportional control with feed-forward loop was used for depth or altitude control for the terrain following AUV for collision avoidance. Yang et al. (2011) described a control method according to the propulsion algorithm for improving energy efficiency and obstacle avoidance of the fish robot 'Ichthus'. Zhao et al. (2008) presented a central pattern generator (CPG) based control model for the propulsion of a turtle-like robot. The controller generates oscillatory movement of the four mechanical flippers which results in different swimming gaits. Liu et al. (2019) presented a convolutional neural network control for detection and pose estimation for docking.

I-AUVs are autonomous manipulator systems used for intervention tasks. Such AUVs need to incorporate robust control architecture for autonomous manipulation tasks such as self-docking, object search and retrieval etc. Simetti et al. (2014) presented the control architecture of a multi-purpose intervention AUV. Carrera et al. (2014) presented the control of the Girona 500 I-AUV for valve turning operation with learning by demonstration algorithm. Simetti et al. (2017) discussed individual and also cooperative control of multiple UVMS for different intervention tasks such as picking up, transportation and deployment. Antonelli (2014) presented a detailed discussion on I-AUVs and different control strategy for UVMS such as Feed-forward Decoupling Control, Feedback Linearisation, Nonlinear Control, Non-Regressor-Based Adaptive Contro and Virtual Decomposition Based Control etc. Along with the control systems, certain navigation and localization techniques are essential for the AUVs motion, which is discussed in section 7.

5. Navigation and localization

AUVs navigate underwater autonomously based on predefined strategy. Localization is a vital component in navigation which helps an AUV to follow the predefined path precisely and reach the final destination. Non-availability of Global Positioning System (GPS) and high-frequency radio signals in the underwater environment makes localization and navigation very challenging for AUVs. Maintaining accuracy in AUV's position for a long mission is a difficult task. Accuracy in position deteriorates over time because of variations in AUV motion and absence of an external reference. Therefore, over time different innovative methods have been developed to tackle these problems using a combination of numerical technique and real-time sensor data. As discussed by Stutters et al. (2008) AUV navigation can be broadly classified as:

- *Inertial navigation*: Inertial navigation uses different sensor data to estimate vehicle's relative velocity and position. Acceleration, rotational speed and magnetic field intensity data are obtained from

accelerometer, gyroscope and magnetometer sensors respectively. These three sensors are part of the Inertial Measurement Unit (IMU). Other sensor data such as relative velocity from Doppler velocity log (DVL) sonar, positioning data from GPS, depth data from pressure sensor etc. are used to minimise the error in estimated position.
- *Acoustic navigation*: Acoustic navigation uses multiple acoustic transponders to estimate AUV's position using time of flight concept.
- *Geophysical navigation*: Geophysical navigation uses unique features in the surrounding as a reference to estimate AUV's position and navigate. Different sensors capable of detecting and identifying these features are used.

AUVs are equipped with different sensors which can provide real-time quantitative data of the surrounding. All these sensor data have to be processed together using some techniques to obtain an optimal estimate of the vehicle position. Some of those techniques are Kalman Filters (KFs), Particle Filters (PFs), and Simultaneous localization and mapping (SLAM). From these techniques, KFs and PFs are numerical techniques for sensor fusion. These numerical methods are prone to drift over time. In SLAM method localization is achieved by identifying areas of the environment, the robot has already passed through. Stutters et al. (2008) and Paull et al. (2014) discussed different navigation and localization methods in detail.

5.1. Inertial navigation systems

INS calculates relative position and orientation of a dynamic system relative to a known starting point, orientation, and velocity using the data from motion sensors (accelerometers), and rotation sensors (gyroscopes). INS is a compact, inexpensive and self-contained system which does not require external references. Therefore It can be used for inexpensive small AUVs. However, INS can accumulate error over time because the estimated relative velocity and position are the result of mathematical integrations of the accelerometer and gyroscopic sensor data. Errors in the measurement of this sensor data and errors introduced in integration lead to a significant drift in the estimated position and velocity. Therefore, the estimated position from INS needs to be compared with the data from other systems such as depth sensor, compass, DVL sonar, acoustic Doppler current profiler (ADCP) Sonar for short missions and from GPS on long missions. Depth sensor, compass, GPS costs between 100 and 1000 USD whereas DVL and ADCP Sonar cost 20k-200k USD. A low-cost INS set-up uses GPS, but the AUV has to resurface in intervals. When operating in greater depth resurfacing is not an option AUV has to relay on INS with DVL or ADCP Sonar.

P-SURO AUV Li et al. (2010) used an INS system along with depth sensor, sonar and vision system with Kalman filter for navigation. Thompson et al. (2012a) used Kearfott inertial navigation system (INS) in their mapping AUV. Shome and Das (2012) used EKF with INS and DVL for navigation of ‘AUV-150’. Ashar et al. (2013) used an INS using a 10-DOF IMU for a fish robot. Tal et al. (2017) proposed a navigation system for small AUV using INS and DVL fusion with partial DVL measurement.

5.2. Acoustic navigation systems

The range is estimated from the time of travel of the acoustic signal for localization. Some of the popular Acoustic navigation systems are:

- *Ultra-Short Baseline(USBL)*: AUV is localized relative to a surface vehicle fitted with an array of acoustic transducers (Fig. 6(a)). Relative distance is calculated from the time of travel of the acoustic signal and direction from the phase difference of the signal received by different transducers. Here the transducers are placed close to one-another and major disadvantages is the range. the time delay in acoustic communication can cause an error in localization. Xiao et al. (2017) proposed a time delay compensation approach for multi AUV cooperative navigation with an ultra-short baseline acoustic positioning system.
- *Short Baseline(SBL)*: Here the transducers are placed in front and back of the surface vehicle (Fig. 6(b)). Thus the baseline is limited to the length of the vehicle which limits the positional accuracy of the AUV.
- *Long Baseline(LBL)*: In this case, the transducers are widely placed over the mission area on the seabed. Localization is done by triangulating the range estimated by acoustic transducers. The major limitation is the huge cost and time involved in placing the transducers on the seabed. Siddiqui et al. (2015) used LBL acoustic ranging. Sound speed profile was shown to affect acoustic localization and such environmental parameters were considered for effective path planning.
- *GPS Intelligent Buoys (GIBs)*: Limitation of LBL can be eliminated by putting transducers with GPS buoys on the surface (Fig. 6(c)). Two-way communication is used between the AUV and GIBs. The ranges are estimated by using two way travel time of the acoustic signal.
- *Single transponder*: To minimise the cost single transponders can be used instead of multiple systems. Here the baseline is simulated by extending the range with time until the next signal is received. Straight trajectory towards or away from the transponder results in large positional errors. For this case trajectories tangent to the transponder is ideal. Crasta et al. (2015) presented an observability study of an AUV with a single transponder in the presence of ocean current using depth measurement and range from the transponder data.
- *Acoustic Modem*: With these modems, information can be transmitted along with the signal used for range estimation using time of flight. Therefore the transponders need not be fixed and located in the global frame before starting the mission. This navigation technique can be used for cooperative navigation with multi AUV systems. A cooperative localization technique using a minimum of three AUV by a tetrahedral geometric method is proposed by Allotta et al. (2014). Three AUVs were equipped with cheap INS modules, but one had DVL whose benefits were extended by using acoustic communication towards cooperative localization. Munafo et al. (2014) included time information in the acoustic signal which helped in improving AUV localization using underwater acoustic sensor networks. Some of the commercially available acoustic modems are presented in Table 4.

Tang et al. (2019) studied a positioning method for AUVs in Arctic seawater using an electromagnetic field. It uses direction-of-arrival triangulation based on the polarization of near field from three nodes. AUV estimates its position by comparing the polarized field obtained from three monochromatic sources with different frequencies.

5.3. Geophysical navigation

External environmental features are used as landmarks for localization. Optical and Sonar are the two major categories for geophysical navigation. SLAM is predominantly used for this navigation.

5.3.1. Optical

Monocular or stereo cameras can be used to take images of the underwater environment and features extracted from the images can be used for SLAM. Visual odometry technique uses dual camera set-up for relative velocity and orientation estimation from images captured. Negahdaripour et al. (1991) described a method for orientation and motion estimation using optical sensor and illustrated some examples with real images. Hildebrandt and Kirchner (2010) presented a visual odometry algorithm using stereo vision setup and data from an Inertial Measurement Unit to be used in a SLAM system. Calibration is a major problem for visual odometry techniques. Kunz et al. (2010) presented a system for recovering the 7- DOF relationship between the AUV's

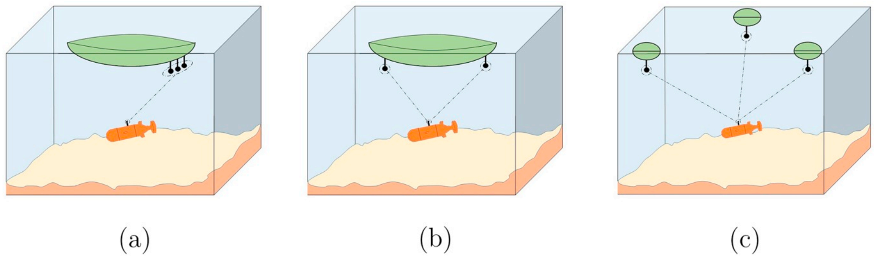

Fig. 6. Acoustic navigation (a)Usbl (b)SBL (c)LBL.

estimation frame and the camera rig in order to produce a self-calibrated stereo vision setup for Sea-floor Mapping. This led to a detailed 3D reconstruction of the underwater structures. P-SURO AUV presented by Li et al. (2010) used an underwater vision system for localization and path planning. During the vision test, the template matching method with 'OpenCV' library is used for detecting number patterns. Wirth et al. (2013) presented a vision-based motion estimation algorithms combined with inertial measurement units as a low-cost sensor for velocity and incremental pose estimation for AUV. In this work 'libviso2' and 'fovis' two visual odometry algorithms are used during the experimentation. Carrasco et al. (2015) presented the integration of a stereo-vision Graph-SLAM system in the navigation and control architecture of the AUV 'SPARUS II' and showed improvement in localization compared with the fusion of DVL, pressure sensor, GPS and IMU sensors with EKF. Perez et al. (2015) presented a benchmarking process used for easy comparison and replication of the results of two 3-D reconstruction algorithms in simulated and real scenarios. Sukvichai et al. (2016) successfully implemented a visual odometry estimation algorithm into the single-board computer RaspberryPi 2 with the Robot Operating System (ROS). Lin et al. (2017) developed a 3D reconstruction method using the laser line scan technique using a binocular stereo-vision camera for obstacle avoidance for the AUV. Liu et al. (2019) presented a short range vision based docking system for AUV. A convolutional neural network is used for detection and pose-estimation for docking. The Experiment was carried coupled with a USBL acoustic sensor to evaluate the proposed framework. Allibert et al. (2019) presented a vision-based non-linear control technique for pipeline following fully actuated AUV. Apart from kinematics, full system dynamics have been considered for stability analysis. The proposed system was demonstrated with a fully actuated Girona 500 AUV.

Dark underwater environment, scattering of light, low visibility range are some major challenges for underwater vision systems. Lu et al. (2017) discussed the issues related to the underwater vision such as poor visibility due to the medium scattering and light distortion, and its solution using computer vision. Recent trends of ocean exploration approaches using optical imaging sensors and computer vision were also discussed. Hoth et al. (2017) proposed a colour reconstruction of underwater images with machine learning so that vision systems can be used for underwater SLAM. Cho et al. (2018) proposed visibility enhancement technique for visual SLAM in a turbid environment. In most of the AUVs object detection systems uses sonar. Expensive sonar systems can be replaced with optical sensors for object detection in case of small-scale AUVs. Advancement in compact high-quality cameras, techniques such as computer vision and artificial intelligence vision systems have become more reliable over time.

5.3.2. Sonar

Sonars are most preferable sensors for underwater mapping and being used for such applications from ages. Sonars can be used to detect and identify different underwater structural features to be used for navigation. Imaging Sonars produces bathymetric information as a black-and-white image with hard rocks being dark with maximum reflection and mud lighter with less reflection. Multi-beam bathymetry Sonars used for ocean floor mapping by detecting sound reflected back from the sea-floor by the multiple arrays of traducers with time delay. After processing this information water depth is determined and bathymetric map is developed, which can be used for Terrain-Aided Navigation (TAN). Morice et al. (2009) developed a terrain aided

Table 4
Underwater communication modems.

Modem	Category	Maximum Range	Data rate	Operating Frequency	Dimensions
Acoustic Modem by Nortek AS	Acoustic	200 m	4000 bps	9–14 kHz	Dia: 9.4 cm Length: 40 cm
Acoustic Modem by Sonardyne. 2012a, b	Acoustic	3000 m	9000 bps	26 kHz	Dia: 133 mm Length: 211 mm
AquaComm by Dspcomm	Acoustic	3000 m	480 bps	16–30 kHz	8 cm × 7 cm x 1.5 cm
UWM 2000 by LinkQuest	Acoustic	1500 m	9600 bps	26.775–44.625 kHz	Dia: 126.2 mm Length: 252.4 mm
S2C R 42/65 by EvoLogics. 2012	Acoustic	2000 m	31.2 kbps	42–65 kHz	Dia: 170 mm Length: 265 mm
ATM-966 Benthos by Teledyne Marine. 2018	Acoustic	2–6 km	140-15,360 bps	9–14 kHz	Dia: 88.9 mm Length: 378 mm
Tritech Micron by Tritech Int. Ltd. 1987	Acoustic	500 m	40 bps	20–28 kHz	Dia: 50 mm Length: 79 mm
Optical Modem by Sonardyne. 2012a, b	Optical	150 m	2.5–12.5 Mbps	–	Dia: 135.5 mm Length: 197.4 mm

navigation correction system for AUV. Here drift was measured by comparing the bathymetric data from the multi-beam sonar and previously collected reference map. Ferguson (2009) and Kaminski et al. (2010) presented the development of an AUV for under-ice seabed mapping in the Canadian border using echo-sounders. Curado Teixeira et al. (2016) presented a TAN with a bi-dimensional particle filter (PF) and a four-dimensional Rao-Blackwellized PF coupled with DVL sonar and IMU. The major issue with geophysical navigation is the shortage of unambiguous reference landmarks. To address such problems Teixeira et al. (2017) presented three novel practical filter algorithms for TAN. Norgren and Skjetne (2018) proposed bathymetric distributed particle filter SLAM (BPSLAM) algorithm for mapping of undersea iceberg topology. This method estimates AUVs pose in an iceberg fixed coordinate system for AUV guidance to cover the iceberg and producing consistent topology. Ma et al. (2018) proposed a robust bathymetric SLAM (BSLAM) to properly estimate inter-frame motion and avoid invalid loop closers. The algorithm is verified with experimental data set.

5.4. State estimator

As discussed above Kalman Filters (KFs), Particle Filters (PFs), and Simultaneous localization and mapping (SLAM) are some of the popular state estimators used for AUV localization with available sensor data. KFs and PFs commonly used with INS and acoustic navigation whereas SLAM with geophysical navigation. Kalman Filter (KF) is used to derive the best estimate of position from different sensors used. The KF estimates the state of a system from multiple uncertain observations using a predict–update cycle. A physical model describing AUV motion can be highly non-linear where the KF fails. In such a non-linear model case, an Extended Kalman Filter (EKF) can be used. EKF uses a first-order Taylor series to approximate the nonlinear processes. Xiaoping Yun et al. (2000) developed an INS navigation system for small AUV using low-cost IMU and GPS unit. An Asynchronous Kalman Filter is used to improve position estimation. Allotta et al. (2012); Choi et al. (2012a) Used EKF for AUV localization. Font et al. (2016) developed a navigation system with two parallel EKF, one using the positioning system GPS and other Ultra Short Base Line (USBL) acoustic modem. Panish and Taylor (2011) presented the development of a high accuracy INS for AUVs developed by Bluefin Robotics using different sophisticated laser and fibre optic gyros with sonar. Mu et al. (2017) proposed a modified algorithm combining least square method with EKF. This proposed LS-EKF is compared with EKF and observed to reduce localization errors. Ngatini et al. (2017) presented position estimation of AUV based on the dynamic model using the Ensemble Kalman Filter (EnKF) and the Fuzzy Kalman Filter (FKF) and shown that EnKF is better in estimating the trajectory of dynamic equation of AUV motion. Choi and Lee (2012) proposed an effective movement for the navigation of the fish-like robot using the heuristic method. Kinsey et al. (2014) presented a system to estimate the position and velocity of an ROV for the navigation using a non-linear dynamic model. Here EKF and non-linear observer (NLO) methods were used for position estimation, and it is observed that NLO performed better than KF. Shao et al. (2016) used an adaptive EKF for AUV navigation. Allotta et al. (2016a, b) used Unscented Kalman Filter (UKF) for AUV navigation and presented a comparative study with EKF approach. Jung et al. (2013) presented a navigation strategy for an AUV in a flowing medium. A biomimetic robot moving in uniform flow using a side-slipping manoeuvre was used to showcase the stability of the proposed strategy. An accurate dynamic model of AUVs are essential for navigation, but the error in parameter estimation and some unknown parameters introduce error in navigation. Shariati et al. (2019) proposed a method to estimate the non-linear dynamic model of the AUV using PF combined with EKF. Simulated results by the estimated model are compared with the experimental results to validate the model.

Navigation algorithms can also be target-specific such as tracking oil spill, gas leakage or underwater communication cables etc. In these cases different visual and chemical makeup sensors data are incorporated in the navigation algorithm to track these specific targets. Kimura et al. (2013) described the guidance control simulation for designing the underwater robot SOTAB, that tracks oil-spill autonomously and gathers oceanographic data. Numerical simulation was adopted to estimate the manoeuvrability of this robot. To compute the hydrodynamic derivatives of the robot, USAF DATCOM Method and CFD were used. Kato et al. (1994) presented an autonomous underwater robot "AQUA EXPLORER 1000" (AE1000) used for inspection of underwater telecommunication cables. AEl000 can find and track buried underwater cables with a cable tracking sensor, and the underwater footage of the sea-floor is saved on a built-in Video Cassette Recorder (VCR).

Among the three navigation systems, INS is suitable for low-cost small-scale AUVs for short missions and long missions with GPS where resurfacing is allowed. Acoustic navigation is costlier with better accuracy. This need transponders to be fitted to support surface vehicles, GPS buoys or to be placed on the seabed. Which are time-consuming process and before starting each operation the transponders has to be referred globally. These limitations can be eliminated by using acoustic modems. Acoustic modems are suitable for cooperative navigation. When existing information of the environment is available such as repetitive routine operations geophysical navigation can be utilised with low-cost optical sensors or high precision costlier sonar sensors and different SLAM techniques.

5.5. Path planning with object detection and obstacle avoidance

Navigation algorithm must incorporate object detection and obstacle avoidance mechanism so that the AUV does not collide with objects in the underwater environment and damage itself. These systems are used for path planning to find an optimal and suboptimal path for navigation. Navigation algorithms can be deterministic, non-deterministic or hybridization of both called evolutionary algorithm. Navigation can be global or local. In global navigation, prior knowledge of the environment must be available. In case of local navigation, AUV decides and controls its motion and orientation using the available sensor data such as sonar, infrared range finder, lasers, acoustic sensors and stereo vision cameras. Path planning is simply a multobjective optimization procedure with an objective to reduce travel-time, shorten path length with safety and smooth trajectory. Path planning algorithm must quickly adapt to the changing underwater environment and select trajectory based on the surrounding information, avoiding obstacles with either minimum time or energy use. 3D optimal path planning is essential for AUVs. But large scale 3D optimization problem has a high computational requirement. Different optimization algorithm has been developed to address these problems but still, more research is required towards the development of AUV path planning systems to be used in the highly dynamic underwater environment. Li et al. (2019) presented a detailed review of different path-planning techniques used for AUVs, highlighting the advantages, disadvantages and application scenario of different methods. Waypoint navigation is a simple path planning technique in which path is generated by connecting the static via-points or way-point by straight-lines with arcs at the joints. Line-of-Sight (LOS) is a very popular method to follow the generated paths or some target. Ataei et al. (2015) presented a guidance system with 3D optimal path planning for AUV. The Guidance system inspired by LOS strategy can be used to follow a predefined path. Target tracking is a path planning problem where the path of the target is unknown. Breivik et al. (2008) presented a motion control system for tracking a target moving in a straight line at high speed. Zeng et al. (2016) proposed a B-Spline based quantum-behaved particle swarm optimization algorithm for optimal trajectory planning for AUV in the presence of ocean current. In this work, a performance study of the proposed method compared with different optimization techniques such as 'Graph search schemes', 'Fast Marching and Level Set Methods', 'Artificial Potential

Field', 'Rapidly-exploring Random Tree' and 'Evolutionary algorithms' was also presented. Eichhorn (2015) implemented a path planning algorithm in a transient environment based on graph-based search methods. Jacobi (2015) used adaptive path planning for navigation of an AUV used for inspection of the underwater structure. Brito et al. (2012) presented a study of adaptive mission planning and controls such as probabilistic approach with machine learning, MOOS-IvP software which used behavioural-based architecture and T-Rex software framework which used model-based architecture etc. Failure analysis is also presented which discussed different reasons for low adoption of the methods such as uncertainty in vehicle behaviour, expensive technology and insignificant advantages. Abbasi et al. (2010) used the fuzzy approach to avoid fixed or moving unknown obstacles by AUV. Choi et al. (2012b) proposed an algorithm for safe navigation of an AUV avoiding the obstacles on its path. The low-risk direction for collision is selected using the fuzzy theory. Xiao et al. (2007) used the sigmoid fuzzy neural network for high manoeuvrability and obstacle avoidance capability of a mini underwater robot. Chew et al. (2013) presented object detection using a sector scanning sonar and proposed adaptive thresholding methodology for object detection. Modalavalasa et al. (2015) developed a tracking algorithm for underwater application where EKF has been extended to the Bearing and Elevation only Tracking (BEOT) method. Monte Carlo approach was used for the evaluation of the algorithm. Jacobi (2015) used sonar for obstacle and target detection along with the camera, laser measurement and multi-beam echo sounder for crack and defect detection to develop an autonomous inspection robot. Kaeli (2016) presented an anomaly detection framework based on saliency and rarity and demonstrated the system with a set of side-scan sonar data. These adaptive planning can help AUVs to scan the anomaly with higher resolution and transmit only the anomaly to the operator for inspection which will decrease data congestion. Wang et al. (2013) presented a vector polar histogram method for obstacle avoidance of an AUV. In this work , the distance between the AUV and obstacles measured by sonar in a different direction and their distribution were expressed as the histogram in polar coordinate which was later transformed to the dualistic histogram, and optimal travel direction was determined by calculating the cost function. Gaya et al. (2016) described a vision-based obstacle avoidance strategy for AUVs using deep learning with a simple monocular camera. The system was evaluated using two underwater video sequences and it successfully avoided coral reefs, fish and seafloor. Schillai et al. (2016) presented a simulation for evaluation of collision risk for terrain following AUV. Yan et al. (2018) proposed a real-time path-planning algorithm for an AUV in an unknown environment. The algorithm is a combination of particle swarm optimization and way-point guidance system. A multi-beam forward-looking sonar is used for obstacle detection. The algorithm is compared with the artificial potential field and genic algorithm for validation. Sonars are being used for sea-floor mapping Thompson et al. (2012a, b). He and Seet (2001) presented a laser gated-ranging system for underwater robot vision and experimentally verified the system in turbid water. Section 9 highlights the different communication systems used by AUVs.

5.6. Underwater communication

Most of the underwater robotic systems rely on tethered communication using LAN, coaxial or fibre-optic cables. These cable brings hydrodynamic instability to the AUV, increases drag and also limits its manoeuvrability and accessibility. Wireless underwater communication with high speed, high volume data is still a major challenge. Researchers have experimented with different modes of communication for this purpose such as low and high-frequency radio, acoustic and laser communication. Vk5br (1987) presented a study on underwater radio communication along with its limitations and solutions. Shaneyfelt et al. (2008) described the problems associated with the underwater radio communication due to loss of signal for the skin depth associated with the conductivity of water. Skin depth gives the distance up to which a radio signal can travel through a medium before deteriorating to some factor of the original signal power. It was experimentally verified that communication in a salt-water pool is more difficult than in a chlorinated pool, as the conductivity of the salt water is higher. Goh et al. (2009) shown that the propagation of electromagnetic waves at high-frequency in the water is possible. For short range applications, the higher frequencies and much higher velocity can have a higher range. Hung et al. (2008) presented a remote control system for a 6 DOF underwater robot by using 8–16 kHz acoustic signal. It used two acoustic transducers viz., transmitter and receiver. The transmitter generates acoustic wave signal when commanded by the controller and receiver receives these signals and convert them to pulse signals. Li et al. (2017) used Tritech International Ltd Micron acoustic data modem for underwater point to point communication. Afzulpurkar et al. (2015) presented the field test results of the AUV named 'MAYA' with 'EvoLogics. 2012' acoustic modem pair for communication to the surface. The modem was successfully tested at the sea up to 20 m depth. Benson et al. (2010) designed a low-cost underwater acoustic modem for short-range sensor networks. Borden et al. (2012) demonstrated successful underwater communication over long distances using two commercially available acoustic modems 'Teledyne Benthos ATM-903 and ATM-916' for compact AUVs. Claus (2014) developed a low cost acoustic underwater communication and control system. Hyakudome (2011) used acoustic telemetry for underwater communication between the AUV and support vessel. Shome and Das (2012) used an USBL system with an integrated acoustic modem for underwater wireless communication with 'AUV-150'. Reddy and Rao (2014) developed an underwater communication system using 'Zigbee' protocol and successfully tested its performance. Acoustic waves are most commonly used underwater communication method employed nowadays because of the lower attenuation in sea water. Commercial acoustic underwater wireless communication modems are available for low bit rate data transfer. The low data rate, delay in communication and high energy requirement are some of the disadvantages of the acoustic communication. High attenuation in conducting salt water limits the use of high-frequency radio waves and low-frequency radio waves can be used in shallow waters. Constant requirement of high data rate, low energy consumption gave rise to optical, light-based communication and hybrid acoustic, Radio Frequency (RF) communication technique. Saini et al. (2017) presented an analytical study showing the use of radio waves for deep water communication by using an acoustic signal as a complementary part. Soomro et al. (2018) presented an underwater network control system with a hybrid acoustic and RF communication with an acoustic link for long range and RF link for short = range communication. Results showed lower delay and energy consumption with similar steady-state errors over acoustic communication. Laser and light wave based optical communication for high-speed data transmission in the underwater environment is one of the new research directions and in its early stages. Oubei et al. (2018) presented a numerical analysis of the underwater optical communication system with different optical disturbances. Sharifzadeh et al. (2018) presented an overview of different Underwater Wireless Optical Communication (UWOC) research around the world and also highlight the different major components of UWOC systems such as transmitters and receivers and their details. Real-time wireless video streaming is a major challenge in the field of underwater communication as it requires high bandwidth. Han et al. (2019) presented a hybrid solution with acoustic and optical communications. Here optical channel provides a real-time quality video transmission and acoustic channel with control and network parameters. In the failure of the optical channel, the acoustic channel transmits a video signal frame by frame after some image processing. The study also highlights the smooth transition between the channels during the switchover and presented experimental validation of the acoustic channel transmission with image processing. Table 4 presents some of the commercially available underwater communication modems.

6. Discussion

In this work different possible applications of AUVs are discussed along with few examples, which show the usefulness of the underwater robotic systems. Different aspects of an AUV such as structural design and analysis, propulsion, dynamics, control, navigation, localization, path planning and communication are presented in detail. Current developments and limitations in the field of AUVs are discussed below. This will provide an overview of possible research directions.

AUVs can be found in various shapes and sizes from large-scale torpedo-shaped submersibles (Jun et al. (2009); Shome and Das (2012); Ferguson (2009); Hiller et al. (2012); Hyakudome (2011); Hong et al. (2010); Desa et al. (2007)) to different bio-mimetic AUVs (Yang et al. (2011); Parameswaran and Selvin (2011); Ashar et al. (2013); Vo et al. (2010); Choi and Lee (2012); Listak et al. (2008); Yu et al. (2016); Jung et al. (2013)). Generally, large-scale AUVs dominate this space. Most of these bulky expensive AUVs are difficult to deploy and operate, require a lot of energy and can not be used in narrow pathways. Over the years form-factor of computers, controllers and sensors have been reduced which can help reduce the size of the AUVs significantly. Till date compact small-scale AUVs are rare and most of them are bio-mimetic AUVs. These Bio-mimetic AUVs are silent in operation, can integrate well into the natural habitat, therefore they are mostly used for survey and monitoring purpose. In recent years soft and flexible materials have been used to develop lifelike bio-mimetic AUVs(Katzschmann et al. (2018)). Such AUVs can effortlessly integrate into the habitat and therefore used for close observation of aquatic life. However, these robots are slow and have very less load carrying capacity. A host of research can be done towards the development of compact hybrid AUVs with bio-inspired aquatic structures and powerful thrusters.

With ever-increasing computational power, techniques like CFD and constantly upgrading sophisticated CAD modelling software like SOLIDWORKS and finite element analysis software like ANSYS, researchers can come up with AUVs with shape-optimized hydrofoil profiles (Nguyen et al. (2018); Sun et al. (2017); Alam et al. (2014)) to increase efficiency and decrease drag and other unbalancing forces. The AUV designs can incorporate more bio-mimetic components to further increase the efficiency. Such complex designs can become reality using sophisticated 3D-printing techniques. Composite (Kang et al. (2018)), smart and functionally graded materials with higher strength, energy harvesting ability have not much used in AUVs. Investigation in this direction can help in increasing the efficiency which will enhance the range of operation in terms of time and distance. Compact micro-robots and bio-mimetic AUVs can find large applications in surveillance and reconnaissance.

Use of different system identification techniques and sophisticated CAD modelling software have enabled researchers to develop accurate dynamic models for the highly non-linear dynamic behaviour of the AUVs. Using Accurate dynamic models, better control systems can be designed. Increase in the accuracy of the dynamic model increases its complexity and they have become highly non-linear. Apart from simple PID controllers (Schjolberg et al., 1996; Jung et al. (2013); Shome and Das (2012); Wilson et al. (2011); Schillai et al. (2016)) advanced controllers like non-linear (Xiang et al. (2015)), fuzzy (Kato et al. (1994)), sliding mode (Vo et al. (2010)), fuzzy sliding mode (Li et al. (2017)), adaptive (Sarhadi et al. (2016)) and neural network (Wang et al. (2014); Li and Lee (2005)) controllers have been developed to handle the non-linear models. More research has to be carried out for developing adaptive controllers, suitable for AUVs operating in the dynamic underwater environment.

Different innovative navigation methods have been developed over time to have better localization in the underwater environment in the absence of GPS and external references. From these methods, INS is best suited for small-scale AUVs with short range mission and accuracy can be improved by using DVL sonar, stereo vision and other sensors with IMU. For long missions, AUVs have to resurface to use GPS. Generally Practical and Kalman filters are used to estimate the best position using these multiple sensor data. In last decade modified Kalman filters such as EKF(Allotta et al. (2012); Choi et al. (2012a); Font et al. (2016); Shome and Das (2012)), Asynchronous KF(Xiaoping Yun et al. (2000)), Ensemble KF(Ngatini et al. (2017)), Fuzzy KF(Ngatini et al. (2017)), Unscented KF(Allotta et al. (2016a, b)) have seen extensively used in underwater localization and navigation of AUVs with complex non-linear dynamic model. Research towards the development of algorithms such as modified Kalman Filters with accurate and precise sensors can minimise the localization error. Previously deployed features or use of acoustic transponders (Munafo et al. (2014); Siddiqui et al. (2015)) can help improve AUV navigation. New generation acoustic modems can be used for cooperative navigation and save cost and time of deploy, recovery and tracking of fixed beacons. For repetitive mission on a small locality, different SLAM(Carrasco et al. (2015); Hildebrandt and Kirchner (2010)) techniques can be used as in this system AUVs map the surroundings in each pass and use this information for localization. Cooperative navigation with multi AUVs (Allotta et al. (2014); Xiao et al. (2017)) can help extend the benefit of one AUV's hardware capabilities to others. Sonar and optical sensors with hybrid EKF-SLAM can further minimise localization errors.

I-AUVs have seen significant development in the last few years. Such autonomous manipulator systems can effectively replace costly and complex semi-autonomous and manual intervention missions. These systems are in the early stage and need significant research towards the development of fully autonomous systems for complex intervention tasks. Current research in this field showcased simple intervention task such as self-ducking (Palomeras et al. (2016)), valve turning (Carrera et al. (2014)), search and retrieval of a target object (Prats et al. (2012); Sanz et al. (2013)) and cooperative transportation of payload to ocean floor (Simetti et al., 2017) etc.

3D optimal path planning with obstacle avoidance is essential for an AUV. Path planning algorithm must quickly adapt to the dynamic underwater environment. Various evolutionary optimization algorithm such as genetic algorithm, particle swarm optimization and quantum-behaved particle swarm optimization has been used for AUV path planning. Graph search schemes, fast marching and level set method, Artificial potential field and Rapidly-exploring random tree are some of the other optimization methods used for AUV path planning. Evolutionary algorithms are better suited to handle dynamic environments. Most of the AUVs used 2d path planning to avoid the high computational requirement. More research has to be carried out towards the development of 3D optimal path planning algorithms for trajectory selection of AUVs operating in an unpredictable underwater environment.

Generally in AUVs sonars (Chew et al., 2013; Jacobi (2015)) with different selection algorithms such as fuzzy (Abbasi et al. (2010); Choi et al. (2012b)), sigmoid neuro-fuzzy (Xiao et al. (2007)) are used for object detection and avoidance. Other Such systems are laser gated-ranging system (He and Seet (2001)), infrared range finder and acoustic sensors (Munafo et al. (2014); Siddiqui et al. (2015)). For compact low-cost AUVs, such expensive systems can be replaced with vision systems but it always has challenges in the underwater environment such as low visibility, turbidity and light distortion which decreases the efficiency of the systems underwater. Techniques like computer vision (Lu et al. (2017)) can be used to overcome some limitations. More research and development in computer vision, neural network and image recognition hardware and software will encourage the development of less expensive object detection, obstacle avoidance (Lin et al. (2017)) and visual odometry systems (Hildebrandt and Kirchner (2010); Sukvichai et al. (2016)). These systems coupled with INS (Wirth et al. (2013); Li et al. (2010)) can be used for accurate localization and mapping (Li et al. (2010)). Compact high precision sensors can provide quantitative information of the surrounding which will help navigate these uncertain dynamic underwater environments.

Data-intensive wireless underwater communication is still a challenge. Low-frequency acoustic signals are being used for communication with the data transfer rate in the kbps range and average transmission range of 1–2 km. The requirement of high data rate and low energy consumption encouraged researchers to revisit RF communications. Wireless optical communication (Oubei et al. (2018); Sharifzadeh et al., 2018) and hybrid acoustic and RF communication (Soomro et al. (2018)) are some of the new trends in this field. Compact modems with high speed and long-range data transfer will play an important role in long-range AUV missions.

7. Conclusion

A critical review on AUVs has been carried out considering the past literature. In the present review investigation, a detailed study of AUVs with applications and different research aspects such as structural design and analysis, propulsion, dynamics, control, navigation, localization, path planning and communication are discussed. In recent times, autonomous underwater manipulator system has gained its popularity because of its cost-effective and simplified solution towards various intervention tasks. Cooperative manipulation and navigation with multi AUVs systems can bring functional solutions to various underwater challenges. Such cooperative systems require high data rate and energy efficient wireless communication systems which can be realised with optical, hybrid RF and acoustic communication. Compact efficient AUV structures; better adaptive control techniques using fuzzy logic and neural networking; accurate localization using improved INS with nonlinear Kalman filters, cooperative, aquatics localization, SLAM etc.; 3D optimal path planning with obstacle avoidance; low cost vision systems with AI and computer vision for object detection and odometry; and underwater wireless communication are some of the topics which require attention from research community. A few years back underwater robotic systems were very expensive and bulky. With the development of affordable manufacturing techniques like 3D printing, cheap one-board computers like 'RaspberryPi' underwater robots are becoming popular in the scientific community. Affordable underwater drones such as 'Trident' by OpenRov and 'PowerRay' by Powervision have come to commercial space and become accessible to students, small industries. These drones are tethered and manually controlledstill, such systems can create research interest in young minds. Improvement in sensors, high-density batteries, energy harvesting techniques, high-strength materials, highspeed wireless underwater communication, artificial intelligence, computer vision, neural network, adaptive control, improved localization will help towards the development of long-range fully autonomous underwater robots which can explore deepest corners of the oceans.

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