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Locomotion Strategies for Amphibious Robots-A Review

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ABSTRACT In the past two decades, unmanned amphibious robots have proven the most promising and efficient systems ranging from scientific, military, and commercial applications. The applications like monitoring, surveillance, reconnaissance, and military combat operations require platforms to maneuver on challenging, complex, rugged terrains and diverse environments. The recent technological advancements and development in aquatic robotics and mobile robotics have facilitated a more agile, robust, and efficient amphibious robots maneuvering in multiple environments and various terrain profiles. Amphibious robot locomotion inspired by nature, such as amphibians, offers augmented flexibility, improved adaptability, and higher mobility over terrestrial, aquatic, and aerial mediums. In this review, amphibious robots' locomotion mechanism designed and developed previously are consolidated, systematically The review also analyzes the literature on amphibious robot highlighting the limitations, open research areas, recent key development in this research field. Further development and contributions to amphibious robot locomotion, actuation, and control can be utilized to perform specific missions in sophisticated environments, where tasks are unsafe or hardly feasible for the divers or traditional aquatic and terrestrial robots.

INDEX TERMS Bioinspired robot, multimodal locomotion, amphibious robot,autonomous amphibious vehicle.

I. INTRODUCTION

The marine environment covers two-third of the earth's habitat and is vital for human development. The habitat is rich in natural and mineral resources, economic value, ecological significance, biodiversity, cultural heritage, and transportation routes. The study of these environments is crucial for resource exploitation and sustainable progress. Traditionally, the above applications employ manned vehicles for operating in this environment. However, shear reliance on a manned mission risks human life operating in dangerous habitat. The challenging environment creates a new possibility for unmanned and autonomous marine vehicles (UMV). UMV has found widespread usage in the marine industry [1] and military applications [2].

In the literature, unmanned marine vehicle terminology is interchangeably used with unmanned underwater vehicles (UUV) [3] or commonly referred as autonomous unmanned vehicle (AUV) [4]. Remotely operated vehicles (ROV) [5] and Unmanned surface vehicles (USV) [6] commonly constitute the AUV class. The marine environment deployed UMV for many applications that necessitate autonomous and unmanned capabilities. Amphibious robotics is a prominent field among the researcher, industrial application, and it is of great scientific importance.

AUV, bio-mimetic, and bio-inspired amphibious robots are a category of robots employed for both aquatic and terrestrial applications. However, most marine robots are designed to operate in an underwater environment. The growing demand for applications like patrolling, surveying, and reconnaissance necessitates maneuvering of these robots in multiple environments like aquatic, terrestrial, and air medium. Diverse environments have different characteristics, features, environmental properties, and locomotion surface (structured and unstructured) to maneuver. The transition between the environment with the same design is also a cumbersome and

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nontrivial problem. These challenges open new technological problems, dimensions, and areas for the researchers. In the past two decades, the research advancements are mainly in locomotion, motion control, planning and navigation, perception, and vision of amphibious robots.

An amphibious mobile robot maneuver both on land and water. The inspiration to build Amphibious robots is based on the amphibian animals present in the nature. The amphibians possess the capabilities that they inhabit both on land and water environment [7]. Amphibians have exceptional locomotion competence in an unstructured, dynamically changing, and uncertain environment. The locomotion of amphibians in these environments is robust and efficient. However, mimicking amphibians and taking inspiration to develop functionality for amphibious robots is challenging and nontrivial. The maneuvering land environment of amphibious robot is on irregular and uneven terrain. Whereas the characteristic of an aquatic environment is dynamically changing, which encounters continuous perturbations; many amphibians conventionally have an exceptional adaptation to the changing terrains and dynamic aquatic disturbances. The challenge in an amphibious robot is its operational capabilities in water and on the ground, working within a single mechanism.

To achieve amphibious locomotion that is adaptable to a different environment, researchers in the past have developed interesting robots broadly categorized into a bio-mimetic and Bio-inspired amphibious robot. In the design of an amphibian inspired robot, Bio-inspiration design approach is a widely accepted pertaining to its realistic development and deployment. Bio-inspired amphibious robots [8] offer transformative performance in maneuvering, specifically a region of transition between water and land, also the high energy waves region, and different substrate types dynamically fluidized sediment. An examination of biological solutions for transitioning between aquatic and terrestrial locomotion suggests that morphological compromise for high-performance locomotion in both terrestrial and aquatic medium has not yet occurred. Robotic designs have greatly benefited from studies of vertebrates' evolution transitioning from water to land; the limb can adapt to terrestrial locomotion. Table 1 highlights some of the bio-inspired amphibious locomotion strategies reported in the past literature, which is taking inspiration from animal locomotion.

The work in the area of amphibious robots in the past two decades has increased. In the past, researchers have reviewed amphibious robot literature. The works reported are reviews or surveys on a specific biological animal-inspired robot-like fish or snake or specific aspects like motion control or vision of amphibious robots. The literature reported in the past are: review of fish-inspired robotics [19], review on snake robots [10], salamander robots sprawling locomotion [20], spherical rolling robots [21], and short reviews on amphibious robots [22], [23]. The difference between earlier review papers and the present review is a comprehensive and state-of-the-art study on amphibious robots.

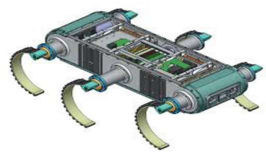
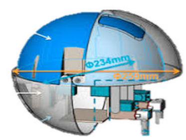
In the current review article, an extensive survey of amphibious robots focusing mainly on the functionality Of their locomotion mechanism.. The discussion outlines the design and deployment of amphibious robots in practice, underlining some of the shortcomings and open research areas. A vast literature exists in the different domains for amphibious robots; therefore, in this work, discussion on amphibious robot locomotion in detail on every published work is not possible due to space constraints. We tried to arrange the literature on amphibious robots based on locomotion modes. Further, we have limited the scope of review to locomotion of amphibious robot. We believe that this review will facilitate robotics engineers to a comprehensive understanding of amphibious robot designs in terms of locomotion, control and actuation, various technical features like operating speed, actuating frequencies, and issues related to locomotion and control. Future robotic engineers and designers will make new designs by adopting features from existing successful designs.

The paper is organized as section one gives a detailed introduction of the amphibious robot. In the second section, a detailed discussion on various locomotion mechanism providing concrete background and outlook. Section three outlines the analysis of amphibious robots. Finally, the research prospects and some of the limitations of previous works are discussed.

II. LOCOMOTION AND MECHANISM OF THE AMPHIBIOUS ROBOT

Locomotion is the primary trait of any organism in nature. Understanding its characteristics and taking inspiration to build a mechatronic system for enhancing motion performance is a growing research area [24]. Amphibious robots' locomotion strategies are inspired by amphibians with multiple functional locomotion capabilities for movement on land and in an aquatic medium. Locomotion of some amphibians like salamander and serpentine inspires connected mechatronics modules undulation motion for the motion in the terrestrial and aquatic environment [25]. Amphibians like salamanders and reptiles like basilisk lizards and crocodiles locomotion using legs laterally appended and elongated to the body for locomotion [26]. Auke *et al.* [20] investigated the sprawling amphibious locomotion of a salamander. The sprawling locomotion of amphibious animals like salamander involves whole-body movement, large trunk, and tail. Amphibious robots' enhanced capability is multimodal (swimming, galloping, walking) locomotion, and switching between these modes makes them the focal in designing robotics systems. The amphibious robot for the locomotion utilizes wheels, leg, track, fins, propellers, or a combination of these for maneuvering. However, each locomotion has limited performance abilities; in the literature, to overcome the limitation, novel hybrid mechanisms like epaddle [27] and Whegs series [28] investigations are inspirational to build efficient locomotion mechanism of amphibious robots. The hybrid mechanism explores either of the combination

TABLE 1. Bio-inspired locomotion of prominent amphibious robots.

Ref	Amphibious Robot	Locomotion	Animal	Physical Robot
[9] [10]	snake inspired	body Undulation motion		
[11]	lobster inspired	claws, abdomen, and swimmerets		
[12]	salamander inspired	limb movements and body undulations		
[13]	basilisk inspired	slapping and stroking of legs		
[14]	frog inspired	dual swing legs with antibias wheels		
[15]	fish inspired	fin wheel propeller		
[16]	cockroach inspired	flexible flipper legs		
[17] [18]	turtle inspired	vectored water jet thrusters with legs		

wheel-leg [27], wheel-track [28], wheel-leg-track [29] to increase the functionality and performance. The unique design of epaddle exhibits a hybrid mechanism with combines wheel, leg, and paddle for amphibious aquatic and terrestrial locomotion found very beneficial in search and rescue operations.

The Hexapod robot is an advanced legged amphibious robot, which imitates octopus Vulgaris' locomotion. The synthesized mechanical and control features represent the crawling locomotion of the octopus [30]. Recent studies employ deformable structures for locomotion. Baines *et al.* [25] demonstrate the transformable morphing limb for amphibious locomotion. The limb is suitable for legged locomotion because it can sustain higher compression loads. A substantial number of reviews were done in the past for amphibious robots but only a few studied locomotion, in particular the comprehensive study is on bio-mimetic robots [22]; general review on amphibious robots [23]. In addition a review of a particular class of amphibious robot locomotion on bionic fish by Raj and Thakur [19] and yu *et al.* [31],instead a review of snake robot or serpentine locomotion reported by Liljebck *et al.* [10], Sprawling locomotion [20], and review of gecko locomotion [32]. The other surveys reported are performed, considering metrics like motion control of underwater robots studied by [33]. However, this study focuses on a comprehensive understanding, state of the art and overview

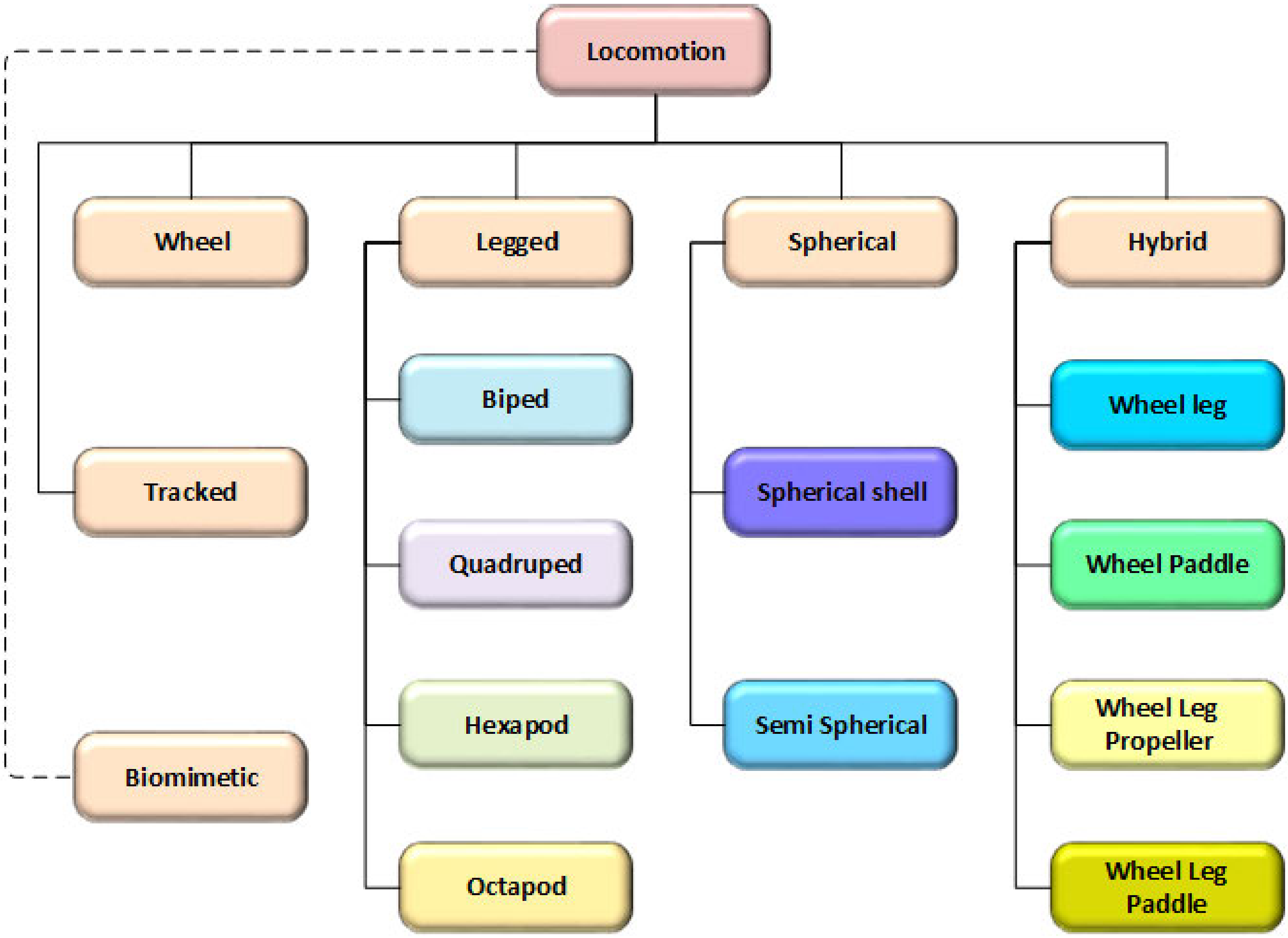


FIGURE 1. **Classification of amphibious robot locomotion strategies.**

of amphibious robot locomotion reported in the past literature, and systematic classification of amphibious robot is performed as shown in Figure 1 and discussed in detail in this section.

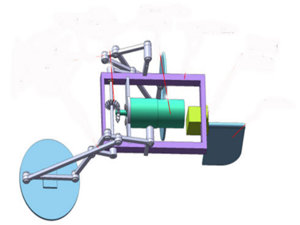
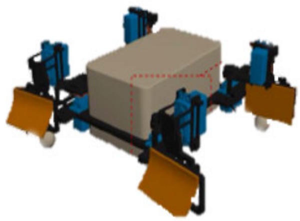
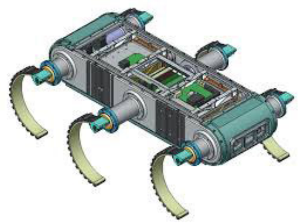
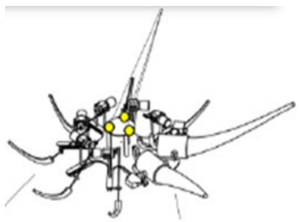
A. LEGGED AMPHIBIOUS ROBOT

Legged mobile robots are designed for highly rugged environments with irregular terrains. Legged robot locomotion is discrete with varying leg configuration than other mobile locomotion like wheel or track that requires continuous support on the terrain's surface. Additionally, legs are outstanding sensor platforms as the foot is in contact with the floor, making the legged robot highly adaptable to uneven surfaces. Many amphibians like basilisk lizard, gecko, and others utilize legs for locomotion for terrestrial movement and aquatic swimming or underwater walking. The significant metrics that define the performance of legged amphibious robots are stability (stability on irregular terrain on land and stability in water), speed (speed on land and forward thrust in water), and energy requirement (actuators power consumption or torque requirement on land and water) for the locomotion. The legged robots have the outstanding capability of obstacle negotiation while locomotion in the work space [34]. Legged amphibious robots locomotion in the aquatic environment have slower cruising speed compared to other locomotion methods. The categorization of legged robots is done considering number of legs used for locomotion on terrestrial and aquatic environment as in Table 2.

1) BIPED AMPHIBIOUS LOCOMOTION

Biped legged robot is inspired by the basilisk lizard that utilizes lift force instead of surface tension or buoyancy force to overcomes the weight of the body and propel it forward when the foot of the basilisk lizard splash on the water surface, while pushing the volume of water creates air vacuum which generates lift force and forward thrust. Xu *et al.* [35] performed an analysis using fluid-structure interaction dynamics considering cylindrical coordinates, depression motion, and air compression flow on the water surface to obtain reaction pressure by water surface on foot when the feet slaps on the water surface. The biped robot accomplishes water walking with a forward thrust and lift force generated by an air pocket above and around the foot because of foot pressure displacing the water in a downward direction.

TABLE 2. Legged amphibious locomotion.

Type	Locomotion	Physical Robot
biped	two legs	 [36]
quadruped	four legs	 [37]
hexapod	six legs	 [38]
octapod	eight legs	 [30]

Floyd *et al.* [36] reported that, to achieve bipedal locomotion on the water surface, developed a robot that employs a pair of similar four-bar mechanisms as leg mechanism, with a 180° phase shift between the legs. However, biped robots are less stable than quadruped or hexapod robots since they use only two legs for locomotion. The propulsive force is the decisive limiting factor for the load capacity of the robot. Consequently, bipedal locomotion is studied to understand animal locomotion instead of practical applications of biped amphibious robot.

2) QUADRUPED AMPHIBIOUS LOCOMOTION

Quadruped amphibious locomotion is employed for applications that require increased payload capacity, flexibility, environmental adaptability, and safety since they use four legs compared to bipeds. The amphibious quadruped robot legs are multi-functional in the terrestrial environment with crawling, walking, climbing, and throttling gaits [39]. In the aquatic medium, the legs are used for seabed walking [40], underwater walking [41], flipper legs as swimming gait (oscillating and adulating) [42], and complaint feet as water runner on the surface of the water [43]. The formation of a triangular polygon with a minimum number of legs of a quadruped amphibious robot makes them statistically stable. Quadruped amphibious robots (QAR) emulate various amphibians with four legs; hence, simulations and analysis of QAR benefit these animals' studies and development of systems. With the increase in the number of legs, control complexity also increases. However, quadruped robots preserve a decent balance between stability and control complexity.

Roboterp is a quadruped amphibious robot that can locomote both in water and land by switching gait to match terrain mode. The robot has a novel design that provides splash-free locomotion using the quadrupedal in the oscillatory mode rather than in rotary mode used in conventional legged or wheel on leg robot design. The latter generates high disruptive turbulence due to the leg lift and splashing on the water surface for the forward motion. In the semi-aquatic environment, the trust is created by four legs on the surface of the water. The main idea of Roboterp is on the lower part of leg structure, passive complaints have appended the acts as a valve for thrust generation. Four legs' rhythmic oscillations create a net forward thrust with directed control by valves [37]. Luo *et al.* [44] proposed the QAR applying a five-bar mechanism (one flipper and three links) for the locomotion on land and water. The robot has limited gait transitioning, less suitable on irregular terrains, and smaller size obstacle negotiation. To increase the quadruped robot stability complaint foot-pad where the design is inspired by duck feet. Saad *et al.* [45] the proposed duck feet inspired design imitating the duck feet movement's operational behavior on land and water environment. The duck feet' critical analysis for motion inspires improved Klann linkage design mechanism which is trying to replicate the duck feet. The proportional body design of the robot carried four duck feet for locomotion. Small and lighter amphibious quadruped [46] like water strider inspires robot locomotion on the water surface utilizing surface tension force instead of buoyancy force that other animals use; it takes advantage of the scaling effect on water surface motion. The water striders [47] are lightweight, just weighing 0.01 g, which benefits them for high-speed locomotion capability up to 1.5 m/s. The author proposes studying static and dynamic interaction between the legs of the water strider and the water surface. It has benefits over buoyancy force-based design. It is power efficient due to reduced drag force on the water surface and reduced disturbances in the shallow water (upto 5mm),improved maneuverability. However, it is unsuitable for the environment with higher disturbances. The robot is stable on the water surface utilizing T—shaped mechanism for propulsion on the water surface [48]. Quadruped robots are designed and developed for higher stability, adaptability to rough terrains, and simplicity in control design.

3) HEXAPOD AMPHIBIOUS LOCOMOTION

Bio-mechanics of insect arthropods like a cockroach inspires hexapods design [49], and these stick insects have the spectacular walking ability over irregular and unstructured terrain. Hexapods emulate the insects mimicking them in the structure of a limb and motion control aspects. The hexapods achieve high stability goals over uneven terrain or unstructured environment by adopting distinguish gaits, and continuously switching between the gait makes them the most obvious choice for locomotion [38]. Amphibious hexapods are capable of walking on land [49], crawling on the seabed [50], swimming on the surface of the water, and underwater environment [51].

The literature reports amphibious hexapods leg designs, all-terrain walking legs for terrestrial locomotion [42], efficient flipper for swimming, and transformable morphing limb design [52]. Amphibious hexapod robots have exploited design from other robots classes to achieve versatile locomotion in the terrestrial mode and outstanding mobility in the water mode. Among the legged robot, hexapods are most prevalent since they are more stable and compliant. AQUA is the most versatile hexapod robot. The locomotion of AQUA has six flipper legs appended to the body. The robot propels in water using legs as paddles in swimming mode. AQUA uses the same legs for seabed walking or uneven terrestrial unstructured terrains in the walking mode. It also equipped with visual sensors that facilitate the robot to locate its position, estimating local features and global framework for navigating in an aquatic and terrestrial medium. AQUA2 is an improved design of AQUA with more sensors [50].

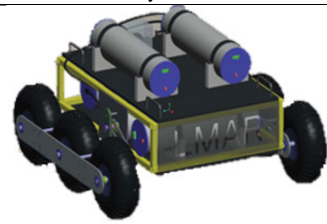
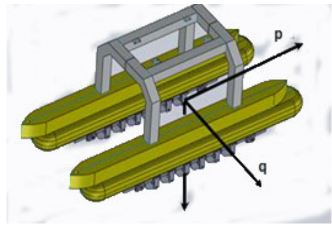
The wheel-leg robots designed by Harkins *et al.* [53] to ensure higher running speed in the wheeled mode and superior adaptability in legged mode and switch accordingly to the different operating environments for different operation modes. Ninja legs are built to take heavy loads; a design utilizes a structure enclosing the current flipper. Ninja legs are aqua class-based hexapods that employ semicircular walking legs and swimming flippers. To protect flippers, the leg mechanism encloses to form walking legs during terrestrial operation [51].

Amphihex-I [52] and Amphihex-II [42] are hexapod robots with a single propulsion mechanism. The amphihex-II unique feature is a rotary leg mechanism that compromises the flexible flipper and fan-shaped rigid leg structure. The robot can maneuver on muddy terrain, sandy area and can swim underwater. Flexible flipper legs operate during locomotion on sandy terrain and underwater swimming. The rigid leg structure of hexapod operates for terrestrial smooth or muddy terrains. The feature also benefits transitioning between terrestrial and aquatic medium.

4) OCTOPOD AMPHIBIOUS ROBOTS

Octopod amphibious robots are inspired by amphibians possessing more than six legs. The octopods are complex and versatile locomotion. With eight flexible arms, the Octopus robot is one of the first soft robots [30]. The locomotion is versatile; it can swim in the water, and locomotion over different complex terrains, pass through confined spaces and shapes. The arms can grasp different size objects because of its the mechanical design, and material technology is soft, it can be highly interactive. The Octopus robot is an entirely soft robot with front arms to grasp, manipulate, elongate, and rear arms for locomotion. Silicone and cables make the locomotive arms, and swimming in water utilizes all the arms with almost neutral buoyancy [30].

TABLE 3. Wheeled and tracked amphibious locomotion.

Type	Locomotion	Physical Robot
wheeled	six wheels	 [56]
tracked	track wheels	 [57]

B. WHEELED AND TRACKED AMPHIBIOUS LOCOMOTION

1) WHEELED AMPHIBIOUS LOCOMOTION

Wheeled robots are the most common conventional mechanism for locomotion over flat and smooth terrains or structured environments. Wheeled robots have high mobility over these surfaces as compared to other mobile robots [54]. A wheeled robot structure has a set of wheels connected to the main body by linkages and joints. Wheeled amphibious robots utilize wheels for crawling on terrestrial ground or seabed crawling. Wheels with combinations of other propulsion mechanisms like fins or thrusters are used for aquatic propulsion while wheels are utilized as active or passive elements on the terrestrial terrain, and for the transition between land to water [55] as shown in Table 3. At Surf Zone, operations and Environmental monitoring employ an amphibious robot as a tracking vehicle. Instead of theodolites and total station at the beach, Consi *et al.* [58] developed LMAR-I an amphibious robot, and an improved version is LMAR-II eliminating the limitations of LMAR-I. LMAR-II [56] employs six pneumatic rubber wheels with four cylindrical aluminum pressure housings on the frame of the vehicle for locomotion and propulsion.

Toha and Zainol [59] focused on adaptability over uneven terrains and propulsion in shallow water. Michael Clarke and Tom Blanchard developed an all-terrain robotic platform, an ARGO 6 × 6 amphibious petrol-powered skid-steer vehicle. Sea-Dragon an amphibious tracked robot vehicle designed to operate in littorals. It carries a tele-operated weapon and operational by the remote operator using standard R/C gear and camera feedback [60]. Wheeled amphibious robots are suitable to work on smooth terrains. Wheel with separate propulsion-such as jet propulsion-based robots has high performance as compared to other locomotion. Instead, the amphibious operation expects a unified mechanism that combines locomotion on terrestrial and aquatic media.

2) TRACKED AMPHIBIOUS LOCOMOTION

Tracked mobile robots are employed because the track design spreads out the entire weight of the robotic platform on the multibloks. The larger surface area in contact with the ground and even spread of weight features to have a smaller impact on ground, making tracked robots suitable for ground locomotion. Tracked robots have high adaptability than wheeled robots but are less performing than legged locomotory over irregular terrains. Tracks fixed with floats provide buoyancy and propulsive force on the water, and on land, the tracks make a larger contact area with the ground creating low pressure and effective actuation in the terrestrial environment.

Amphibious tracked vehicles are illustrated in Table 3 these are employed to maneuver over diverse terrains like cross-country terrains like bogs and swaps of diverse nature and terrain obstacles, having varying inclination angles. The widely used all-terrain vehicle (ATV) for traversing utilizes a pair of extended pontoons aligned parallel to each other. An endless chain passes over, each pontoon relates to crossing the driving shaft to which sprockets are mounted, the chain runs over the sprockets for traversing. The ATV encounters some operational problems such as rapid chain wear and lubrication of chain elements as they are exposed to mud, water, and sandy terrains. Chain made of rubber have track throw issues over terrestrial surfaces, track sag problem over marsh surfaces. Several literature provide solutions to the above problems. In [61] author proposes ATV track with a retainer system and a T shaped hanger supported to the track, that secures the pontoons with corrosion and guide driving means, the resistant track passing over each pontoon also circumvent lubrication requirement of the track. The ATV [62] employs vegetation shredded above and below the surface of shallow water. The ATV consist of an endless track mounted on the buoyant hull and shredding assembly with a higher load-carrying capacity.

The characterization of track forces acting on DUKW-Ling ATV during transitioning from land to sea and sea to land is performed by marquardt *et al.* In the waterborne area, the modified tractive force model reduces the weight of vehicles supported with tracks; the wave forces during the transition on the vehicle are higher than measured forces on the track of DUKW-Ling [63]. Tracked ATV with adaptable pontoons are employed to navigate through closed narrow surfaces with reduced footprints. The adaptable ATV design has a lessened impact on the traverse environment [64].

A large-scale high mobility multi-purpose ATV with four articulated legs, two at the front and two at the rear end, each articulated leg appended to the vehicle's body has a track assembly,which is independently driven by motors. The articulated leg facilitates the height adjustment with reference to track assembly and variation in distance between the track assembly leg (width adjustment between the legs). Amphibious capability with a hull structure that enables floating on the water surface and tracks used for terrestrial maneuvering configures the vehicle. The driving cabin is made rotational, so that it benefits ground visibility while traversing inclined surfaces upward [29]. Ambot is a bio-inspired amphibious robot employed tracked locomotion inspired by centipede for the swan-canning estuary monitoring. The tracks are constructed using aluminum at the base, and a polystyrene-block float is appended to the base [65]. An amphibious operation with single propulsion methods widely employs a tracked locomotion. Tracked locomotion is advantageous in balancing, between mobility and adaptability within the environment.

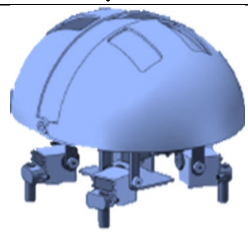
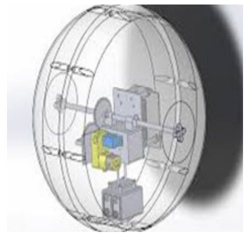
C. SPHERICAL AMPHIBIOUS LOCOMOTION

Spherical rolling robots are highly maneuverable, holonomic, and omnidirectional; that makes them suitable for multi-mode amphibious applications. The spherical robot design as illustrated in Table 4 encloses a closed spherical surface shell; inside the shell, the drive unit and other components are mounted in axial or other forms. The spherical shell is single or multi hemispherical for different applications and designs. The propulsion for spherical amphibious locomotion is achieved by displacing the center of mass either with wheeled design [66] or pendulum design [67], or hybrid design. The spherical morphology has a limitation of upward motion problem, making them unsuitable for maneuvering steep surfaces upward. Placement and stabilization constraints of sensors, cameras, and payloads on a spherical ball-shaped robot pose significant research challenges.

Crossley *et al.* [21] reviewed and discussed Spherical robots in detail. Groundbot is a popular spherical robot that uses a propulsion mechanism based on a controllable internal pendulum. In the past, researchers proposed several other spherical robot designs. However, they achieve propulsion in different ways, but all these have propulsion mechanisms are based on displacing the system's center of mass. The work proposed by Ho *et al.* [68] for spherical motion utilizes a single drive wheel pushed down onto the sphere's bottom by a spring. The turning drive wheel mechanism steers the robots. Bicchi *et al.* [69] discuss rotundus, a car-based unmanned amphibious vehicle design with unicycle kinematics resting on the bottom of the sphere. The propulsion system of the Bhattacharya and Agrawal [70] design utilizes a set of perpendicularly mounted rotors [71] and works on the principle of the conservation of angular momentum locomotion in the environment. The Table 4 highlights the classification and design of the amphibious spherical robot.

Amphibious spherical robots (ASR) are inspired by freshwater or sea turtle that can locomote both on land and water. Pan *et al.* [72] built ASR-I at kasaga university, having a hemispherical shape with a diameter of 0.25m, and the movable retracted legs upward or downward swing. ASR-I was less stable as compared to ASR-II. The introduction of active wheels to the previous version increases ASR-II locomotion terrestrial speed [73]. To have better locomotion in an unknown environment, Pan *et al.* [73] developed an

TABLE 4. Spherical amphibious locomotion.

Type	Locomotion	Physical Robot
semi spherical	shell and legs	 [22]
spherical rolling	rolling shell	 [21]

active wheel leg robot with reinforcement learning. Active wheels with DC motor actuator increase robot size, and redundant propulsion poses difficulty while walking mode. Li *et al.* [74] proposed a roller walker robot with a passive wheel leg. The robot with a transformation mechanism rotates the ankle joint with a passive wheel on the leg to locomote on a flat surface with high speed and quadruped walking mode on uneven terrain. The robot could locomote by walking or on the roller-skating mode. ASR with active wheels that are heavier in weight and consumes more energy, ASR with passive wheels were adopted. However, the issue of robot swing exists during skating and walking mode. The control and steering are sophisticated in the passive wheel mechanism as compared with the active wheel mechanism. The ASR-III [75] overcomes the above-listed limitations by introducing a composite driving mechanism (lifting and support mechanism), omnidirectional passive wheel legged amphibious robot. Legs encompass water jet thrusters for propulsion in an aquatic medium. The robot introduced a unique feature of sliding mode; in the sliding mode, the robot mechanism is lowered for locomotion on flat surfaces and raised for the walking mode for rough terrain. The spherical amphibious robot has versatile locomotion capabilities, with the development of enabling technologies and proper mounting ability enables ASR for practical applications.

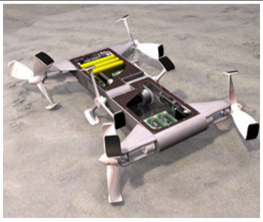
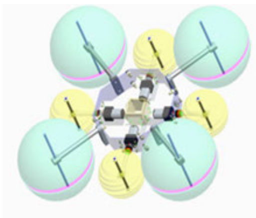
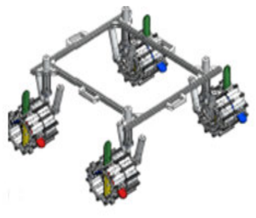
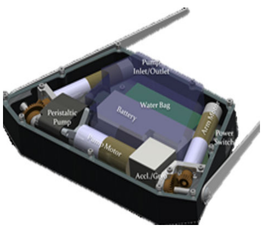
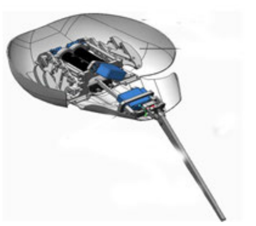
D. HYBRID AMPHIBIOUS LOCOMOTION

Hybrid and multi mechanism locomotion are categorically presented in this section because the locomotion in a multi-environment is executed by combining two or more mechanisms combination like the wheel, leg, fin, paddle, and track mechanism. In a hybrid mechanism as illustrated in Table 5 like whegs the wheel used for locomotion on land, the same wheel structure design operates as a propeller on the aquatic medium. Wheg series is the prominent work reported with hybrid locomotion. Wheg derives its name from the mixture of wheel and leg locomotion [76]. Wheg-I is designed based on Rhex [38] conceptual locomotion mechanism. However, it uses a wheel made up of equally spaced spokes. The rigid body appends by six wheels. Cockroach locomotion inspires the Wheg-I design [38].The two-servo motor and a single DC motor are used as actuators to the passive wheels operating in the tripod gait, achieving robots direction control. The Wheg-I has limitations of a smaller distance from the ground, and the spokes in certain obstacles have chances of entanglement. However, among other families of Whegs series, Wheg-I is the fastest.

The abstract form of cockroach studies inspires the design of Wheg-II. The main characteristic of Wheg-II is that it uses a body flexion join that gives the capability of implementing cockroach functionality of bending part of the body during obstacle climbing [53]. Similar to cockroach for obstacle climbing operation, the body flexion joint of Wheg-II uses a bidirectional servo motor ascending or descending the front part of the body to reach the surface in the vertical direction and after climbing to keep contact with the surface, respectively. Wheg-III and an improved version Wheg-IV performs autonomous locomotion and navigation of ocean floor, locomote underwater up to 40 feet, surf zone area, and beach environment. Wheg-IV adopts a fully waterproof enclosed chassis for development. The Wheg series previous designs were an open frame that facilitates easy service of all the components attached to the chassis. Also, the chassis is lightweight but prone to dirt and debris accumulation. Wheg IV [53] body joint has worm gear in series with the transmission and motor that withstands impact loading. The mechanical design of the wheg-IV robot has significantly reduced control problems and it is more versatile than other Wheg platforms. Seadog is an amphibious hybrid robot representing the class of Whegs; they demonstrate maximum speed and turning radius, maximum speed on the grass, and transitioning from grass to lose grit has increased adaptability compared to previous Whegs series. Obstacle climbing of sea dog is at a maximum of 48 cm (2.5 times leg height), allowing it to approach more closely, placing the center of mass in a better position, and mobility in water with turn. The tail design is a unique feature that gives Seadog stability and a higher capability of obstacle negotiation [80].

Frog breaststroke and scooter inspires frobot hybrid locomotion. The unique feature of frobot is that it uses dual swing legs as propulsion mechanisms in aquatic medium and unusual universal wheels appended to the legs for terrestrial locomotion. The dual swing legs are pair of flexible flipper legs like a caudal flipper foot used by the frog for swimming in water. Frobot exploits the wheeled locomotion for high-speed motion on flat surfaces on land and undulating motion with high energy conversion utilizing the surrounding fluid's energy for aquatic locomotion. Frobot symmetrical structure of dual swing legs gives more stable underwater locomotion, lesser actuators, and simple control. However, frobot has limitations on uneven terrains and difficulty in steering [14]. Omipaddle hybrid amphibious robot utilizes a compound driving mechanism of wheel ground and paddle. The hybrid driving mechanism is proposed for efficient land

TABLE 5. Hybrid amphibious locomotion.

Type	Locomotion	Physical Robot
wheelleg	four wheelleg	 [77]
wheelfin	dual fin wheels	 [14]
omnipaddle	four wheel paddle	 [78]
equad	four epaddle	 [37]
finned	two fin legs	 [46]
leg tail	leg paddle	 [79]

and water transitioning. The maneuvering at the coast in the application of disaster relief is essential and requires an effective mechanism. The combined mechanism of wheel ground and paddle is a basis for developing an amphibious spherical rotary paddle mechanism. Omni paddles are fabricated in a different configuration with or without passive wheels [78]. Equads(epaddle) hybrid amphibious robot is inspired by an opossum, which utilizes hind limbs for propulsion and moves on the parasagittal plane when paddling. The inspiration is due to legged walking and paddling gaits have similar motion patterns [27]. Epaddle has versatile motion because of the eccentric paddle utilizing the actuated side screw inside the shell alters the paddle shaft. The paddles are attached to a common paddle shaft that is eccentric from the center of the shell. Individual paddles can be routed around the center of the paddle shaft. A quadruped robot is build using appending four eccentric paddle mechanism to the chassis body [81]. Novel Equad have high locomotion versatility for amphibious locomotion. For epaddle, two aquatic and three terrestrial gaits are available. A wheel-like gait is one option where the outer surface is a shell acting as a wheel suitable for flat surfaces. The up-most point relocates the paddle shaft avoiding paddles to hit the ground.

The paddle shaft acts as a leg, and its tip touches the ground surface to achieve a legged gait. A sophisticated control relocates the position of the paddle shaft. The rough terrain with an uneven surface utilizes this gait, and the legged gait gives better adaptability with the terrain. Wheel leg gait is a unique feature of epaddle, a supportive mechanism that utilizes paddles gives additional tracking forces to wheel paddle gait; this is suitable for muddy or sandy surfaces. The shell's actuation realizes rotational paddling gait, and the epaddle is rotated that generates thrust for swimming by placing the paddle shaft at a distance eccentrically. In the oscillation paddling, one of the paddles oscillates; however, all paddles' oscillations may create a disturbance that should be considered while swimming. Hybrid amphibious locomotion increases the capability of locomotion over diverse terrain and environment exploiting the mechanical design of hybrid mechanism.

Underwater vehicles popularly utilize propellers for propulsion. However, for hybrid mechanism rotatable and adjustable propulsion method is becoming a widely used method for steering, for lifting (ascend and descend) operations. Chocron *et al.* contribute immensely to vectorial propulsion techniques that can be applied to underwater robots. To maneuver the vehicle and steering operation without control surface, trust vector from set of propellers gives vectored thrust propulsion [82]. Fixed thruster or reconfigurable thrusters have limitation of trajectory tracking therefore combination of fixed thrusters in different direction and thrust capacity overcome the above problem. However, novel Flat- reconfigurable magnetic coupling thruster provide greater restoring torque with the vectorial reconfigurable thruster developed by Chocron *et al.* [83]. A joint is employed with magnetic coupling as basis not to directly connect to motor for rotation. AUVs with growing application faces new challenging tasks, finding optimal topology requires optimization for respective task, vega *et al.* [84] proposes optimization of propulsive configuration considering developments in reconfigurable thruster technology that improved AUV design. The amphibious spherical robot employs multiple vectored water jet thrusters developed by Guo et al. [75] for amphibious underwater locomotion.

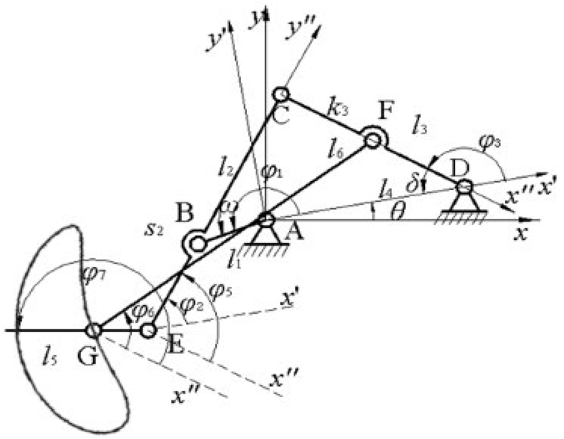


FIGURE 2. Kinematic model of bipedal whatt-I linkage [35].

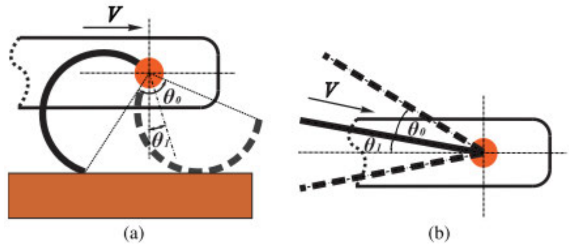


FIGURE 3. Kinematic during a) rotation b) oscillation [86].

E. KINEMATIC AND DYNAMIC MODELS OF AMPHIBIOUS ROBOT

Amphibious locomotion is inspired by robust motion abilities of amphibious animals. The leg mechanism of the legged Amphibious robot is serially connected links that undergo swing and stride phase, each link joint provides a single degree of freedom achieving reversibility over irregular terrain. The kinematic and dynamic models of the amphibious robots have different behavior on different environments while crawling on land and swimming in water. The kinematic analysis of bipedal robot is performed by Xu *et al.* [35], the propulsion mechanism employs six bar plane Watt-I linkage mechanism as shown in Figure 2. The trajectory of point end effector G in the world coordinate frame is derived from Equation (1)

$$\begin{pmatrix} x_G \\ y_G \end{pmatrix} = \begin{pmatrix} x'_G cos\theta & -y'_G sin\theta \\ y'_G sin\theta & y'_G cos\theta \end{pmatrix} \tag{1}$$

Wadoo *et al.* [85] analyzed the kinematic model of the amphibious robot which is non-linear and underactuated. The system is subjected to nonholonomic constraints like Pfaffian constraints. The system considers constrains on linear velocities in y and z direction therefore $v = [v_x 00]^T$ be is linear velocity only in x direction. The kinematic model in generalized coordinate form is given by Equation (2)

$$\dot{q} = G(q)v \tag{2}$$

Zhang *et al.* [86] experimentally evaluates the locomotion performance of flipper leg of the amphibious robot considering the kinematic parameters, terrain muddy surface characteristics and leg shape impact. In the leg walking experiment, Zhang observed semicircle leg shape is suitable for greater stability and lower loss of locomotion speed in the muddy substrate. Straight flipper design provides kinematic parameters suitable for oscillation in the underwater swimming mode. The transformable flipper kinematic model illustrated in Figure 3 provides higher maneuverability on walking mode and oscillation as vectored thrusters are employed in the swimming mode. The kinematic parameters that describe the oscillation of the flipper leg include θ_0, θ_1, and T, where θ_0 represents the flipper oscillation amplitude and θ_1 represents its propulsion direction, calculated from the vertical line to the center of the oscillation. T represents the oscillation period.

The kinematic model of swing leg of the bio-mimetic hexapod robot [87] can be considered as open kinematic chain with three degrees of freedom appended to a stationary base as illustrated in the Figure 4.The position of hexapod toe is obtained using Equation (3)-(5)

$$\begin{aligned} p_x &= c\psi(l_1c\theta_1 + l_2c\theta_1c\theta_1 + l_3c\theta_1c\theta_23) \\ &\quad + s\psi(l_2s\theta_2 + l_3s\theta_{23}) + c_x \end{aligned} \tag{3}$$

$$p_y = (l_1s\theta_1 + l_2s\theta_1c\theta_2 + l_3s\theta_1c\theta_{23}) + c_y \tag{4}$$

$$\begin{aligned} p_z &= -s\psi(l_1c\theta_1 + l_2c\theta_1c\theta_1 + l_3c\theta_1c\theta_23) \\ &\quad + c\psi(l_2s\theta_2 + l_3s\theta_{23}) + c_z \end{aligned} \tag{5}$$

D-H coordinate system is used for kinematics analysis, and the constructed kinematics model of wheel leg amphibious robot is used to solve these joint variables for redundant robot [88],wheel leg is illustrated in Figure 5 and also inverse kinematics calculation is carried out, the middle plate variable θ is assumed fixed. The angles of the wheel plate are obtained by a series of 3 operations, these variables θ_2, θ_3 and θ_4 are solved by inverse kinematics using Equation (6)-(8)

$$\theta_2 = arccos(N/W) \tag{6}$$

$$\theta_3 = \theta \tag{7}$$

$$\theta_4 = arccos(X/\sqrt{A^2+B^2}) - \theta_3 - \alpha \tag{8}$$

where $W = (l_2b+2l_2P_z+2l_1l_2)$; $A = 2l_2l_4+2l_3l_4cos\theta_3$; $B = 2l_3l_4$; $\alpha = arcsin(B/\sqrt{A^2+B^2})$; $M = (a/2-P_x)^2 + (b/2+P_z)^2 + l_1^2 + (bl_1+2P_zl_1) - (l_2^2+l_3^2+l_4^2+2l_2l_3cos\theta_3)$; $N = l_3^2+l_4^2+2l_3l_4[cos(arccos(M/\sqrt{A^2+B^2})-\theta_3-\alpha)] - [(a/2-p_x)^2 + (b/2+p_z)^2 + l_1^2 + l_2^2]$;

The kinematic model of the amphibious spherical robot [75] is obtained using DH homogeneous transformation to obtain position of the leg toe as in Equation (9) and Jacobian matrix of coordinate transformation is given in Equation (10)

$$P^1 = \begin{bmatrix} p_x^1 \\ p_y^1 \\ p_z^1 \end{bmatrix} = \begin{bmatrix} l_3s_1^1c_2^1 + r_3s_1^1s_2^1 + l_2s_1^1 + l_1 \\ -l_3c_1^1c_2^1 - r_3c_1^1s_2^1 - l_2c_1^1 - l_1 \\ -l_3s_2^1 + r_3c_2^1 + r_3 + r_1 \end{bmatrix} \tag{9}$$

$$J = \begin{bmatrix} c_1c_2l_3 + c_1s_2l_4 + c_1l_1 & -s_1s_2l_3 + s_1c_2l_4 \\ s_1c_2l_3 + s_1s_2l_4 + s_1l_1 & c_1s_2l_3 - c_1c_2l_4 \\ 0 & c_2l_3 + s_2l_4 \end{bmatrix} \tag{10}$$

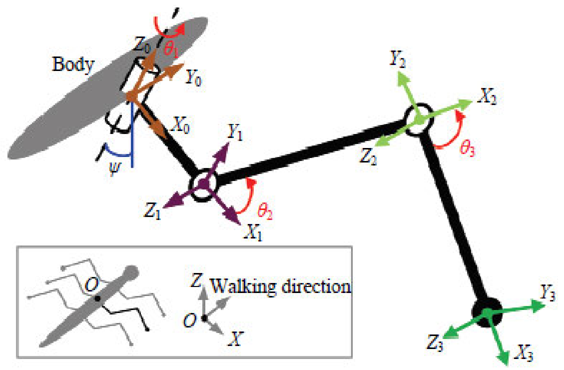


FIGURE 4. Kinematic model of the robot leg [87].

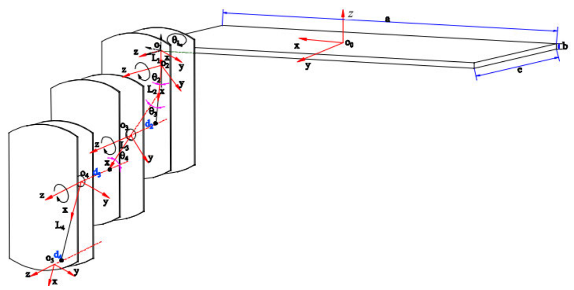


FIGURE 5. Kinematic model of adaptable wheel leg [88].

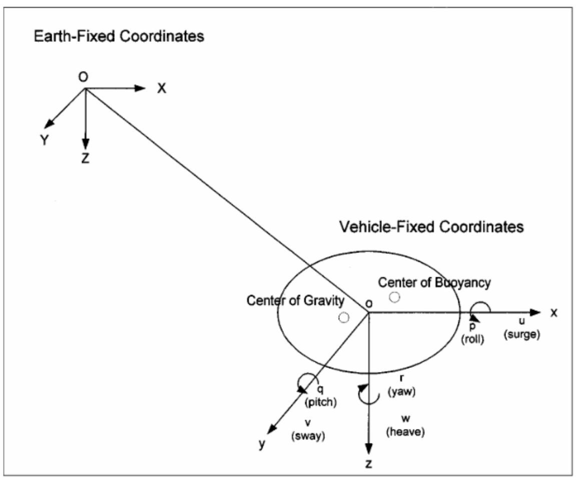


FIGURE 6. Coordinate system [91].

Here left foreleg is chosen for analysis therefore forward and inverse kinematic relation succinctly are written as in Equation (12) and using the same procedure, kinematic relations are obtained for other three legs of ASR. The initial kinematic relations are derived by Fossen [89].

$$ {}^{B}P_{toe} = FK(\theta) \tag{11} $$

$$ \theta = IK({}^{B}P_{toe}) \tag{12} $$

The amphibious robot model are subjected to uncertainty in kinematic parameters and external interference. The complexity of amphibious robot increases with manipulators attached [90]. The kinematic model of amphibious robot with a manipulator is expressed as

$$ \dot{\xi} = J_a, s\zeta \tag{13} $$

where $\xi = [\eta q]^T$ represents the absolute position and Euler angles of the vehicle body $\eta = [xyz\phi\Theta\psi]^T$. The velocity of an end effector with respect inertial reference frame is

$$ V_{oe} = J_{oe}\zeta = [Ad_{g_{be}}^{-1} Ad_{g_{be}}^{-1} J_n]\zeta \tag{14} $$

Dynamics of underwater vehicles are proposed by researchers like Fossen [91] taking into consideration hydrodynamic parameters and uncertainties in dynamic environments. Figure 6 shows the coordinate system to derive equations of motion for underwater robots in generalized form is given by Equation (15) and (16)

$$ \dot{x} = J(x)\dot{q} \tag{15} $$

$$ M\ddot{q} + C(\dot{q})\dot{q} + D(\dot{q})\dot{q} + G(x) = \tau + \omega \tag{16} $$

where $\dot{x} = [xyz\phi\theta\psi]^T$ uses Euler parameterization representing rotational and translation movements expressed in inertial reference frame and $\dot{q}$ is velocity vector $\dot{q} = [uvwpqr]^T$ expressed in body the coordinate frame. J(x) is Jacobian matrix of order 6×6 representing velocity transformation in coordinate frame. M in the equation is a combination of M_R(inertial matrix of rigid body) and M_A(added mass inertia matrix due to hydrodynamic coefficients). Coriolis and centripetal terms are indicated by $C(\dot{q})$ matrix of order 6×6 that includes $C_R(\dot{q})$ represents body terms and $C_A(\dot{q})$ represents added mass; restoring terms developed by the rigid body buoyancy and drag forces is indicated by 6×6 damping matrix $D(\dot{q})$; gravitational vector of order 6×1 is denoted as G(x); external forces such as environmental moments is represented by 6×1 vector τ; disturbance such as wave and fluid current produced on the vehicle body is denoted as ω a 6×1 vector. The amphibious spherical robot uses Lagrange approach to arrive at dynamic equations that serves as theoretical foundation for simulation using virtual prototype build in dynamic simulation software like ADAMS [92]. These general equations have been simplified and represented by their simple matrix forms as in Equation (17)

$$ \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta_1} \\ \ddot{\theta_2} \end{bmatrix} + \begin{bmatrix} D_{111} & D_{122} \\ D_{211} & D_{222} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \end{bmatrix} + \begin{bmatrix} D_{112} & D_{121} \\ D_{212} & D_{221} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1\dot{\theta}_2 \\ \dot{\theta}_2\dot{\theta}_1 \end{bmatrix} + \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \tag{17} $$

where D_{11} and D_{22} terms in matrix represents effective inertia terms;D_{12} and D_{21} terms in represents coupling inertia terms;D_{111},D_{122}, D_{211} and D_{222} represents Coriolis coefficient;D_{111},D_{122}, D_{211} and D_{222} represents centripetal acceleration coefficient; D_1 and D_2 indicate gravity terms.

III. COMPARISON AND ANALYSIS OF AMPHIBIOUS ROBOT LOCOMOTION

Most mobile robots built for industrial and commercial applications utilize a single mode of locomotion for their mobility. The locomotion mechanism is either wheel, legged, or hybrid.

TABLE 6. Comparison of speed performance of amphibious robot on land and water.

Ref	Locomotion Feature	Robot Type	Maximum Speed on Land	Maximum Speed on Water
[39]	leg flipper	miniturtle	200 mm/min	0.15 m/s
[86]	leg flipper	amphihex-I	0.20 m/s	0.19 bl/s
[42]	varible stiffness leg flipper	amphihex-II	0.36 m/s	0.37 bl/s
[93]	modular body with passive wheels	amphibot-I	0.035m/s (0.06 bl/s)	
[94]	modular body	amphibot-II	0.201m/s (0.26 bl/s)	0.147m/s (0.191 bl/s)
[95]	fins	boxybot		0.37m/s (1.4 bl/s)
[96]	Segmented anguilliform	envirobot		0.52 m/s(average)
[38]	legs	Rhex	0.55m/s(1.04 bl/s)	
[16]	leg wheel propeller	amphirobot-II	0.6 m/s	0.4 m/s
[48]	leg	waterstrider		45 mm/s
[97]	wheel and water-jet	AAPC		10.5 km/h
[61]	track and water-jet	ATV		10 km/h
[98]	leg and body undulation	salamander-II	0.42m/s	0.28m/s for(k=1.5)
[99]	modular unndulatory	amphibot-III		0.59m/s
[100]	spherical shell	groundbot	3m/s	3m/s

Figure 9 and 10 illustrates the mobility and endurance of amphibious robot on terrestrial and aquatic environment respectively. Each locomotion mechanism has its advantage; although wheel type mobile robots have high mobility on the smooth surfaces, their usage was confined to the environment with flat surfaces. In the case of the legged robot, their mobility is less as compared to the wheeled robot. However, their locomotion capability on uneven rugged surfaces is excellent as compared with wheeled robots. Legged mobile robots are suitable for the unstructured rough environment. Researchers have exploited the advantages of two and have built configurations and mechanisms with hybrid combinations. The wheel on legs is commonly referred to as Whegs, is one such hybrid mechanism utilized to achieve greater mobility and adaptability. The Whegs have enhanced mobility and adaptability to rugged and volatile surfaces. Most of the terrestrial and aquatic robots reported in the literature are suitable for a single mode of locomotion in the applications where the capability of multi-mode locomotion is required, for instance, locomotion both on land and water or water and air or air and land or water air and land [23]. Amphibians have developed agility, robust maneuverability on the surface of land and water and in the water. This section gives perspectives, challenges, open research areas, some of the shortcomings, and recent advancements on locomotion and mechanisms, briefly on actuation and control of amphibious robots.

A. AMPHIBIOUS ROBOT PUBLICATION ANALYSIS

The amphibious robot locomotion research area has attracted enormous researchers and roboticists to work on amphibious robots' design, structural, control, motion planning, and navigation problems. Many researchers have proposed their works to address the complex, interesting, challenging problems of amphibious robot locomotion. The scopus database in figure 7 illustrates the research publication in last two decades. An amphibious robot's growing application areas are search and rescue, survey and monitoring, and military operations. The functionality requirement to locomote in multiple environments created new designs and technologies to enable operations using amphibious robots. The Locomotion strategies used by autonomous marine robots had single designed for motion in a single environment.

The publication data of Scopus database and IEEE explore database is selected for understanding the growth of amphibious robots' development and their application in various domains. The Scopus database provides an analysis tool to extract information data like the number of documents published by choosing a keyword. The documents published in Scopus database on amphibious robot keyword is extracted and for last decades number of articles published is plotted against each year. Similarly, in IEEE explore database is chosen because the conference articles on amphibious robots are predominately available in IEEE explore database. The four keywords are chosen for publication data extraction amphibious robot, control, modeling and bio-inspired amphibious and in last two decades number of documents published is plotted against year. The early development of amphibious robot models in late 1990, and following developments in last two decades as illustrated in figure 7 and 8. The trend is exponential rise due to reason being with the parallel development of mechatronics engineering technologies and applications in various fields. The researchers focused on novel hybrid mechanism designs for challenging terrain capabilities and control models for the designed system and their applications in various application. Recent publication trends focused on multi-robot amphibious robots. The locomotion style selection and biological animal morphology inspire designs and systems integral to the bio-inspired or bio-mimetic inspired robotic platform. The kinematic, dynamics, and hydrodynamic analyses of amphibian's locomotion facilitate the creation of a functioning amphibious robot, also each of these constrains the design of the amphibious marine robot.

B. DISCUSSION

To give more insights for research enthusiasts, some of the excerpts prominent research problems and directions are also discussed. Amphibious robots have seen continued developments in the last two decades because of parallel developments in mechatronic designs, sensor and vision technologies, and advancements in control strategies and algorithms to control dynamic motion and environmental designs. The amphibious robots have improved mobility performance over time. The robot maneuver faster demonstrates more endurance and adaptability to diverse environments. However, amphibious robots' speed and endurance performance compared to animals is still having a wider gap. Bio-mimetic

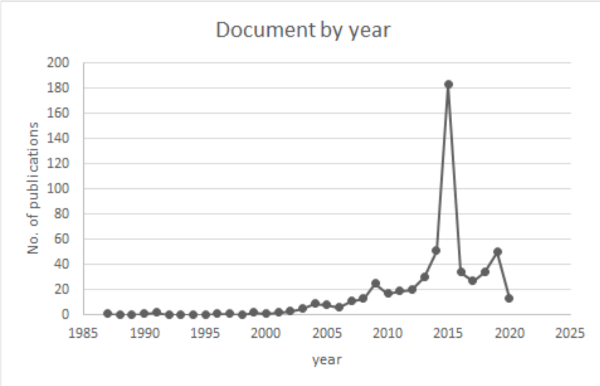


FIGURE 7. Publication on amphibious robot in scopus database.

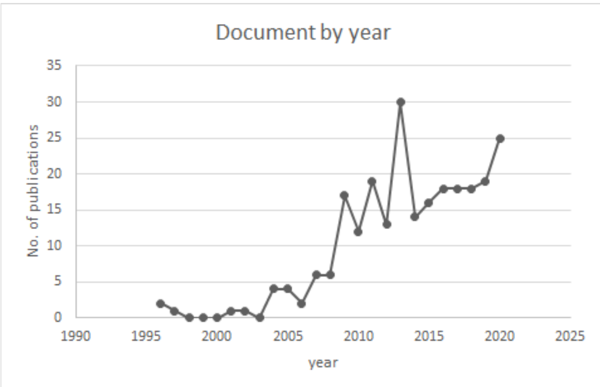


FIGURE 8. Publication on amphibious robot in IEEE explore database.

and bio-inspired robots are investigated to understand animal morphology or develop systems with exceptional functionality like animals for maneuvering, control, and navigation of mechatronics systems.

Table 7 and Table 8 analyses the locomotion mechanism used for amphibious robots. The performance analysis of each amphibious robot is gauged on parameters such as the ability to maneuver in multiple environments and types of terrain, kinematic analysis, and results produced in simulation and real-time mode. The detailed analysis and taxonomic listing of amphibious provide research enthusiasts to identify the open research gaps and different locomotion mechanisms used in the past to create new designs and mechanisms to meet the unresolved dynamic and challenging environment maneuvering issues. Amphibious robot performance varies with its locomotion feature Table 6 provides different locomotion features analyzing mobility performance in multiple environments. The maneuvering performance parameter chosen for comparison is speed. The amphibious robot's speed performance on land and thrust (speed) water in the environment is provided for analysis. The maximum speed and thrust are presented for each locomotion feature. The maximum speed of the amphibious robot in comparison with biological animal locomotion feature still has a wider gap and yet to be achieved. Snake-inspired Amphibot-II has good performance maximum speed on land 0.201 meter/second(m/s) or 0.261 bodylength/second(bl/s), and water is 0.147 m/s (0.191 bl/s). However, its performance is far less than the real snake amphibious locomotion.

Legged amphibious robot (LAR) is employed for unstructured, uneven, and diverse surfaces. The legged amphibious robots are robust in operation on these surfaces and at the transition zone between rough terrestrial surfaces to shallow water and aquatic medium. Legged robots exploit gait transition between the legs for adaptability on various terrain profiles. Some of the popular gaits of legged robots are tripod, tetrapod, and trot gait. However, the LAR has a slower speed as compared to other locomotion types of robots. The legged robot on soft terrestrial terrains encounters compaction resistance, and the thrust in the legged robot's water is lower because the legs utilize the drag force or surface tension or flapping of legs that create whirls and water splashing, reducing its speed during locomotion in an aquatic medium.

Biped amphibious legged robots employ two legs for locomotion, they are less stable, and they have lower running speed on the ground and propulsive thrust on the water among legged amphibious robots. The dynamic stability requirement limits the applications of biped for amphibious operations, lower payload carrying capacity. The work reported by Floyd *et al.* [36] can move on water only up to 4 seconds sink after that. Biped with improved motion control and composite propulsion mechanism can enhance flexibility and environmental adaptability. Quadruped-legged amphibious robots are more stable and have improved endurance, making them suitable for locomotion on uneven terrains profiles and transition areas between dissimilar environments. The single-leg mechanism operates differently in water mode and land mode. The quadruped amphibious robot has higher propulsion speed because they utilize momentum transfer or drag force of water and lifting forces for locomotion in an aquatic medium. However, quadruped legged robots have lower speed on land than wheeled locomotion and lower thrust on the water than the undulation motion of salamander type or snake robots. Leg design utilizes a mechanism that creates a trajectory motion path suitable for land and water locomotion. Water running quadruped robots are modeled build using a four-bar mechanism, with increased stability and upward lifting capacity.

QAR with compliance assisted legs [79] contributes to splash-free swimming. However, further work on concurrent gait and optimizing the oscillatory flap mechanism is still to be addressed. Obstacle negotiation or avoidance is still an improvement area of research. With a unique mechanism like a five-bar mechanism [47], QAR has evaluated gait trajectories adaptable to multiple environments. However, the design limits its walking speed on the ground and smooth gait transition between the medium for practical applications. QAR with improved Klann mechanism imitating duck feet [79] presents a unique single design mechanism for swimming and walking; though the design is novel, it is less efficient. Besides, the design can be improved with a rigid

TABLE 7. Comparison and analysis of amphibious robots locomotion.

Reference	Amphibious Robot	Year	Locomotion	Environment	Real-time results	Simulation results	Kinematic results
[38]	Rhex	2001	six-wheel legs	land and water	Y	Y	Y
[101]	wheg-I	2002	wheel spokes	land	Y	Y	Y
[102]	seatalon	2003	track and waterjet	land and water	Y	Y	N
[103]	wheg-II	2003	wheel spokes	land and stairs	Y	Y	Y
[27]	miniwheg	2003	wheel spokes	land and stairs	Y	Y	Y
[50]	aqua	2004	six legs	land,seabed and underwater	Y	Y	Y
[41]	acm	2004	wheel and body undulation	land and underwater	Y	Y	Y
[41]	robolobster	2004	decapod with tail	surfzone and littorals	Y	Y	Y
[77]	wheg-IV	2005	wheel and legs	land and seabed walking	Y	Y	Y
[93]	amphibot-I	2005	passive wheel and body undulation	land and underwater	Y	Y	Y
[104]	salamender-I	2006	legs and body undulation	land and underwater	Y	Y	Y
[95]	boxybot	2008	pectoral and caudal fins	land crawling and underwater	Y	Y	Y
[105]	sea-scout	2004	wheels	land and water surface	Y	Y	N
[106]	aquamonkey	2007	wheel and fin	land and water surface	Y	Y	N
[107]	aqua2	2007	legs	land and underwater	Y	Y	Y
[48]	waterstrider	2007	hydrophobic wire legs	land and water surface	Y	Y	Y
[94]	amphibot-II	2008	passive wheel and body undulation	land and underwater	Y	Y	Y
[108]	asguard	2008	wheel and legs	land and stairs	Y	Y	N
[109]	seadragon	2009	track and wheels	land and sea	Y	Y	Y
[58]	LMAR-I	2009	wheels	land and water	Y	Y	N
[16]	amphirobot-I	2009	wheel fin propeller	land and underwater	Y	Y	Y
[43]	water runner	2009	complaint footpad	land and water	Y	Y	Y
[110] [111]	ALUV	2010	track and waterjet	land and water	Y	Y	N
[63]	ARGO	2010	wheels and waterjet	land and water	Y	Y	N
[56]	LMAR-II	2010	wheels	land and water	Y	Y	N
[44]	QAR-fivebar mechanism	2010	flipper legs	land and water	Y	Y	Y
[71]	groundbot	2010	spherical shell and wheels	land,ice and water	Y	Y	Y
[112]	amphirobot-II	2011	wheel fin propeller	land and water	Y	Y	Y
[97]	amphibious assault vehicle	2011	track and waterjet	land and water	Y	Y	N
[81]	eQuad	2011	eccentric paddle	land,stairs and water	Y	Y	Y
[97]	AAPC	2011	wheel and water-jet	land and water surface	Y	Y	N
[80]	seadog	2012	wheel and legs	land,stairs and water	Y	Y	Y
[113]	aquapod	2012	wheel and tumbling tail	land and sea	Y	Y	Y
[67]	rotundus	2012	spherical shell and single pendulum	land,ice and water	Y	Y	Y
[98]	salamander-II	2013	leg and body undulation	land and water	Y	Y	Y
[51]	ninjalegrobot	2013	legs	land and water	Y	Y	Y
[63]	DUKW-Ling	2013	track,wheel and water-jet	land and water	Y	Y	N
[114]	ASR-I	2014	legs and water jet thruster	land and water	Y	Y	Y
[99]	amphibot-III	2014	body undulation	land and water	Y	Y	Y
[115]	QAR-fourbar mechanism	2014	legs	land and water	Y	Y	Y
[65]	ambot	2014	track	land and water	Y	Y	N
[116]	AIROS	2014	legs and trusters	land and water	Y	Y	Y
[37]	roboterp	2014	complaint legs	asphalt land and water	Y	Y	Y
[117]	origamibot	2015	origami wheels	land and water	Y	Y	Y
[118]	ASR-II	2015	active wheels and legs	land and underwater	Y	Y	Y
[119]	dogfishshark	2015	legs	land and water surface	N	Y	N
[30]	octopus robot	2015	soft arms	water	Y	Y	Y
[86]	amphihex-I	2015	flipper legs	muddy land surfaces and water	Y	Y	Y

Klann mechanism with a reconfigurable [100] design for flexible operation. Reconfigurable mechanism with shape morphing joints is also reported that changes motion trajectory with shape and length of links. Leg mechanism with reconfigurable mechanism is potential research that can be employed for soft robots in the near future.

Hexapod legged amphibious class of robots are extensively reported in the literature. The prominent AQUA amphibious robot is Rhex based robot with six spherical legs utilized for walking on terrestrial and swimming in water with the same legs rather than thrusters or propellers.

Additionally, AQUA uses a trinocular vision system, various navigation sensors and extends SLAM for six DOF. Some of the hexapod amphibious utilize single propulsion designs and a simple control framework; these include amphihex-I [52] and amphihex-II [42], which are field-tested for a variety

TABLE 8. Continue of Table 7 comparison and analysis of amphibious robots locomotion.

Reference	Amphibious Robot	Year	Locomotion	Environment	Real-time results	Simulation results	Kinematic results
[120]	envirobot	2016	modular body segments	water surface	Y	Y	Y
[120]	pleurobot	2016	legs	land crawl and water	Y	Y	Y
[40]	crabster	2016	legs	land and water seabed	Y	Y	Y
[121]	guardbot	2016	flywheel with pendulum	land and water	Y	N	N
[122]	ATV	2016	track and water-jets	land and water	N	N	Y
[26]	water ground runner	2016	spherical footpads	land and water	Y	Y	Y
[55]	AAR	2016	wheels and water jet	land,ice and water	Y	Y	N
[123]	scorpio	2017	leg wheel	land	Y	Y	Y
[79]	horseshoe crab	2017	shell and legs	granular land and surfzone	Y	Y	Y
[124]	robocrab	2017	legs and telsonwheels	land and water	Y	Y	Y
[42]	amphihex-II	2018	variable stiffness legs	granular land,open water and surfzone	Y	Y	Y
[42]	ASR-III	2018	wheel leg with LWSM	land and water	Y	Y	Y
[125]	small intelligent amphibious robot	2018	oars and crank rocker mechanism	land and water	Y	Y	Y
[88]	adaptable amphibious wheel legged robot	2018	three wheel-leg	land and water	Y	Y	Y
[126]	amphibious vehicle hovercraft	2018	rotor and propeller	land,air and water	Y	Y	N
[127]	ASR-IV	2018	wheel leg with LWSM	land and water	Y	Y	Y
[128]	spherical robot	2018	flywheel,pendulum and propeller	land and water	Y	Y	Y
[129]	natatores amphibious robot	2018	powered leg with webbed feet	land and water	N	Y	Y
[130]	orobot	2019	modular body segments	land and water	Y	Y	Y
[45]	duck feet amphibious robot	2019	webbed duck feet	land and water	Y	Y	N
[131]	articulated ASR	2019	mecanum wheels	land and water	Y	Y	N
[132]	crab-like hexapod	2019	six leg	land and water	Y	Y	N
[133]	EELWoRM soft robot	2020	elastic inflatable legs	land and water	Y	N	N
[134]	amphistar	2020	propeller	land and water	Y	Y	N
[135]	crab-like amphibious	2020	paddle legs	land and water	Y	Y	Y
[136]	velox	2020	fins	land ice,snow and water	Y	N	N
[137]	ASR LMWCDM	2020	leg and waterjet thruster	land and water	Y	Y	Y
[138]	POSTECH AU robot	2020	paddle legs	land and water	Y	N	N

of terrains locomotion includes a soft, staircase, rough, and water surfaces. With improved sensor integration, the autonomy of the amphihex makes a suitable robot in practical applications. Ninja legs are hexapod robots developed for smooth terrain applications. However, the increased weight of the legs makes them less suitable for new terrain profile. The ninja legs can be utilized for maneuvering a variety of terrains.

Wheel and track-based locomotion are preferred for higher speed and moderate adaptability to unstructured environments. However, the wheel based amphibious robots are suitable for smooth terrestrial surfaces and locomotion in water require separate jet propulsion mechanisms for locomotion in an aquatic medium. LMAR-I and LMAR-II were deployed for near-shore observation of foreign vehicles, monitoring animals like dolphins, and conduct scientific studies in the near-shore environment. Building a computer model as the environment near shore is varying and dynamic building models, and investigation of near-shore physical characteristics requires effective systems since the environment is challenging with high water tides and transition zone. Tracking of objects like vehicles or machines finds application in the military and naval arena. The coastal robot requirement would be high precision for such missions as target tracking required precision and unmanned capability. LMAR-I design is tracked based, the locomotion demerits of LMAR-I were improved in LMAR-II design. Some of the prominent improvements were that wheels replaced the track because of sand accumulation problem at the tracks, to increase the torque, gear ratio of 100:1 was adopted, lesser weight and enhanced computing capabilities are some of the wheel's features tracked robots.

Spherical robots have camera mounting and disturbance issues. For ground, locomotion sensors can be placed inside the spherical shell. However, locomotion on water sensors like sonars is mounted at the outer part of the shell, limiting spherical robots' capability. The other major factor affecting spherical robot application is measurement errors

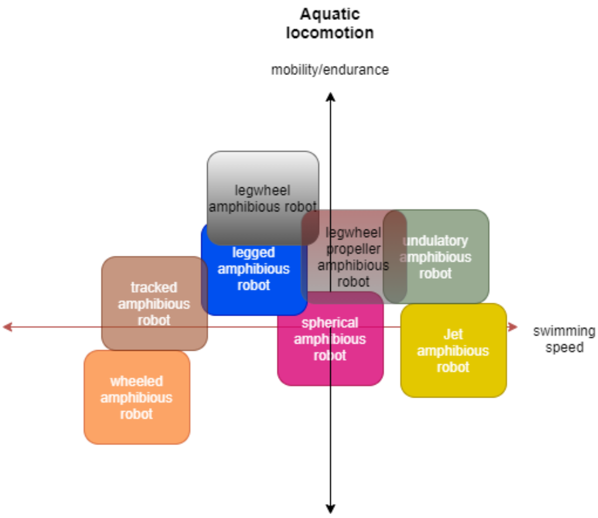


FIGURE 9. **Mobility performance of amphibious robot in aquatic environment.**

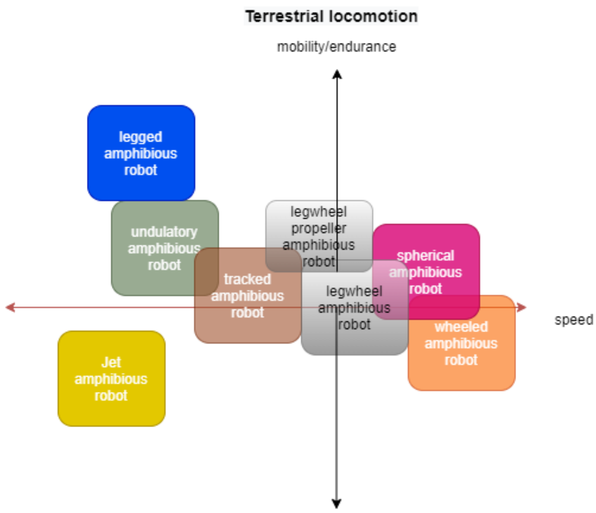


FIGURE 10. **Mobility performance of amphibious robot in terrestrial environment.**

due to disturbance and noise oscillation while in motion. The load-carrying capacity also is a challenging issue for an amphibious spherical robot. The open research areas for spherical robots for obstacle avoidance are mounting of vision-based camera, waypoint techniques, and stereo vision usage for extracting 3D features. Obstacle negotiation using deformable structure is the research problem yet to be explored. While maneuvering the spherical robot on inclined surfaces it is less efficient due to the control problem.

Whegs class of robot utilizes leg wheel combination for locomotion on both land and water. Built explicitly for surf zone application, the latest in series is Seadog. Whegs robots operate with a simplified actuation mechanism without negotiating their functionality. Whegs are sturdy in terms of mechanical design. The wheels are used as paddles to swim, optimized wheel leg designs, and hydrodynamic analysis are investigated for improve locomotion of amphibious robot. The other combination of a hybrid type of locomotion is fin based. The fins are used for utilized for swimming and wheels for traversing on the ground. Frobot employs dual sing fins and anti-bias wheels for maneuvering. The new wheel design restricts locomotion on smooth and inclined surfaces. Besides, fin-wheel mechanical design limits momentum and propulsion in an outward swing. A rotary paddle, a wheel ground hybrid [78] designs encourage transitioning between the environment. Omnidirectional paddle design inspires innovative designs for mechanisms; some of them reported are gear and gripper. The most versatile hybrid mechanism for amphibious operation is the wheel's eccentric paddle grouping, paddle, and leg. Additionally, multiple gaits and gait sequencing makes epaddle perform on diverse terrains. Terrestrial and aquatic gait model optimization benefits the development of versatile amphibious locomotion operations at locations such as search and rescue missions that necessitate mobile platforms with varying terrains. Furthermore, the epaddle mechanism is a reasonable possibility for obstacle negotiation.

Most of the amphibious robots are tested experimentally at the lab at the prototype level and some of them are tested in the field in the scaled model. The fewer companies developed amphibious robot in last two decades making them commercially available in the market. However, they are used for scientific discovery and military applications. Some of the amphibious robot deployment issues in real- time is briefly discussed. The following technological problems in real application studies among amphibious robots are as follows: dynamically changing environment, nonlinear behavior of the system, uncertainties in robot body, issues of controller implementation in practice. In conclusion, amphibious robots are tested in water-tank trials of controllers with scaled models; amphibious robot like Seadog is rarely tested sea-going trials and for full set of application trials.

Kongsberg Maritime and Bluefin Robotics Corporation are leading companies and manufacturers of amphibious vehicles. Other companies are International Submarine Engineering Ltd. and GAVIA autonomous underwater vehicles are also competing in commercial markets as manufacturers. Recently, deployment of amphibious robots from the beach area and small boats was made possible, sea otter amphibious robotic crawler developed by Survae inc and C-2i Innovations for application like geospatial data visualization. Clearpath Robotics Inc., developed amphibious robot like Warthog. Independent Robotics a McGill spinoff company announced Aqua2 to be soon available for commercial applications. Pliant Energy Systems, a marine robotics company developed an amphibious robot based on concept of velox that maneuvers efficiently on multiple terrains and aquatic environments. At offshore renewable energy facility deployment and testing of an amphibious robot Ifrog for a monopile foundation inspection and cleaning is successfully completed [139].

The most challenging task for amphibious robots deployment in real time is communication. Recently, Ad's serial hardware with cloud-based transmitter established efficient communication with Guardot surveillance amphibious robot.

Spherical rolling robot Rotudnus (groundbot) is commercially available amphibious robot for security and surveillance application, it was developed by Swedish company. The Rotudnus employs pendulum type propulsion mechanism for locomotion. The versatile locomotion of Groundbot make it suitable for ice, water and uneven terrain on land. However, the camera mounting and disturbances while locomotion is critical in real time deployment.

IV. CONCLUSION

Amphibians outstanding locomotion and performance capabilities inspire researchers, scientists, and engineers to design and develop platforms imitating and exploiting amphibians' close characteristics for improved locomotion and control of next-generation robotic systems. This review article presents a general comprehensive overview of amphibious locomotion and analyzes the mobility and endurance of amphibious robots. An outlook of the future research focus and significant challenges are highlighted in the context of integration of various research streams from kinematics and dynamics, hydrodynamics, actuation, control, navigation, and vision of amphibious robots. The problems at the diverse environment and transition between the medium pose challenges and further requirement of developments in enabling technologies will pave forward the future generation of amphibious robots. Future amphibious robots locomotion requirement will consider the design of multi-robot amphibious capabilities and cooperation. Also, modeling of a soft amphibious robot will greatly increase amphibious locomotion capabilities in the near future. Amphibious robot locomotion is potential area of future research significant in developing fully autonomous amphibious robots with advancement in design, dynamic and hydrodynamic modeling, control strategies, soft actuation materials, battery power optimization, navigation and vision techniques the growth of amphibious is imperative maintaining the trend to achieve high performance and robust locomotion functions.

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