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AMPHIBIOUS ROBOTS LOCOMOTION STRATEGIES IN UNSTRUCTURED COMPLEX ENVIRONMENTS: A REVIEW

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ABSTRACT

In the previous literature, amphibious robots focused mainly on locomotion in underwater and flat land surface manoeuvring. Few amphibious robots focused on unstructured land environments. The amphibious robot designs were more emphasised in academics, leading to more work done in building amphibious robots that mimic biological amphibians, imitating the geometry and overall functionality of the amphibious robots. Developing amphibious robots with propulsive mechanisms for manoeuvring in a water environment received more attention than other functionalities like adaptability on rough natural terrain and obstacle repositioning capability. However, practical applications like reconnaissance and surveying posed challenges in the ground environment, which had unstructured and complex terrain profiles, especially in the transition area. Therefore, reviewing the amphibious robots focused on manoeuvring complex uneven surfaces was essential. The literature had comprehensive review papers on navigation strategies encompassing manoeuvring on flat ground surfaces and underwater locomotion. There was a need for a focused study that highlighted the amphibious robot that manoeuvred in an unstructured land environment. The open challenges and recent solutions by designing new mechanisms and deployment issues were highlighted and reviewed. Hence, the paper addressed a more specific review of amphibious robot locomotion in an unstructured environment. The paper also discussed a case study of an amphibious robot capable of locomotion in unstructured environments. It was envisaged that the review would provide directions and insights to researchers and robotic system designers on developing robust propulsive mechanisms for amphibious robots capable of locomotion in unstructured environments.

***Keywords**: manoeuvrability, mobility, terrain, unified locomotion, mechanism, propulsion*

INTRODUCTION

Amphibious robot research in the past two decades has had exponential growth. Amphibious robots' versatile locomotion and ability to manoeuvre in multiple environments and on various terrain profiles inspire researchers to focus on their design, functionality, and applications [1]. There is a shifting trend from employing traditional mobile robots and underwater robots for ground and water operations to complex applications like reconnaissance, surveying, offshore mine detection, and water quality monitoring, which require advanced capabilities that are fulfilled using amphibious robots [2]. The versatile locomotion of amphibians inspires many amphibious robot designs. Some of the recent developments include wheeled amphibious robots like LMAR [3], legged crawling amphibious robots like rugged Rhex [4] inspired by cockroaches [5], or basilisk lizards [6] employ legs for locomotion, hybrid mechanism with separate propulsive mechanism for each environment like wheel leg propeller [7], wheel paddle fin [8], hybrid mechanism with unified propulsive mechanism for both the environment like tumbling aquapod robot [9] and Roboterp [10] and hybrid mechanism with hovercraft capability transversing in water, land and aerial environment [11].

Another critical aspect of amphibious robots where the studies have little focus and few works have been reported is in the area where successful switching between locomotion modes is essential [12]. The surf zone area, a transitional zone, includes an unstructured environment with various terrain profiles. The terrain profiles like bumps, slopes, ditches, shoals, rocky and loose surfaces are encountered while locomotion on natural terrain. Natural terrain locomotion may also involve obstacles of various sizes and shapes. Negotiating and overcoming these obstacles to perform the assigned task is essential for the robot's capability in these challenging environments. Most of the robots reported in the literature that address the unstructured environment locomotion are highly efficient using legged amphibious robots [13]-[14]. However, legged amphibious robots have limitations in terms of lower speed performance. The designers have continuously searched for new possibilities and a hybrid mechanism that balances tradeoffs with adaptability and mobility in these unstructured environments.

Despite their versatility, few reports of amphibious robots are in the literature. The literature focused more on lab testbed environments and imitating the propulsive behaviour of underwater animals to increase propulsive performance in underwater environments, compromising the development of separate simpler mechanisms suitable for only flat, smooth land environments. The studies do not consider more natural terrain and practical applications that encounter transition zones with unstructured environments with irregular paths and obstacles of varying size and shape to accomplish the assigned task. Outside the lab in the real environment, designing, developing, and implementing amphibious systems still presents significant problems.

Commonly popular studies and development of robots are classified similarly to traditional mobile locomotion systems, each category surpassing the other as it specialises and focuses on a particular metric. High mobility on flat terrains is achieved by wheeled amphibious locomotion; high-performance adaptability is achieved by legged amphibious locomotion, and undulatory locomotion mechanisms are utilised to achieve high manoeuvrability in the water environment. The above-discussed locomotion strategies are exploited to form a hybrid combination, and the tradeoff is aimed at attaining moderate and efficient locomotion performance in both environments. The hybrid mechanism with a separate mechanism achieves considerable performance in both environments at the expense of a more complex control design. However, hybrid mechanism designs are bulkier and require an additional switching mechanism while transitioning between the environment modes. Unified mechanisms adopt a single mechanism for locomotion in both environments by modifying the propulsive mechanism's mechanical design. However, the complexity in a unified mechanism is due to control complexity.

The work proposes a literature review on a specific domain of amphibious robot locomotion in the unstructured environment instead of a generalised comprehensive review of amphibious robots. Also, a case study and our current development of a unified propulsive mechanism to manoeuvre in both environments employing the same subsystem instead of distinct traditional propulsive subsystems are presented. Since each subsystem is utilised separately for transit in different media, the system is bulkier and more complex to control. Combining propulsion mechanisms has grown in favour of simplifying systems and exploring propulsion architectures that move both on land and in water. The review narrows the study area, presents issues of amphibious robot locomotion for deployment, and addresses practicality in implementing these amphibious robots in applications.

This paper is structured with the following sections. The introductory section first discusses recent literature on amphibious robot locomotion in unstructured environments, highlighting the significant challenges in designing, modelling, and developing amphibious robots in an unstructured locomotion multi-modal environment. The second section briefly discusses the metric considered in recent studies for classifying amphibious robot locomotion. Thirdly, there is a discussion on the classification of amphibious robot locomotion detailing wheeled, legged, undulatory, and hybrid unified and separate mechanisms for amphibious locomotion, leading to our case study and future challenges that need to be addressed for the practicability of adopting amphibious robots. Finally, the conclusion summarises the important points.

CLASSIFICATION OF MOBILE AMPHIBIOUS ROBOT LOCOMOTION SYSTEMS

The amphibious robots are agents that can manoeuvre in multiple media and various terrain profiles. In the literature described in the introduction, a variety of amphibious robots are categorised primarily based on the type of mechanism adopted for locomotion, as shown in Figure 1. However, locomotion depends on the application and required performance metric of focus. The researchers for diverse applications classified amphibious robots as wheeled amphibious robots since they provide high-speed mobility on smooth land surfaces, legged amphibious robots since they provide excellent adaptability on uneven ground surfaces, and undulatory and fin-based amphibious robots since they have adequate mobility in water environment.

A combination of the those categories is chosen to trade the mobility in both environments since amphibious robot applications like reconnaissance and transition area manoeuvres require performance in both environments. The category of mechanism is hybrid amphibious robots with separate or unified mechanisms. The separate mechanisms, however, demand increased load, hardware, and control design complexity. The distinct mechanism control complexity is addressed by manipulating the mechanical structure of the mechanism using the transformation mechanism. The unified mechanism reduces load, cost, and hardware. However, the extra requirement of a transformation mechanism also adds up to control architecture. Our current development discussed in the case study is a unified amphibious robot with low control requirements that adopts a rocker-bogie's passive suspension and wheel paddle mechanism.

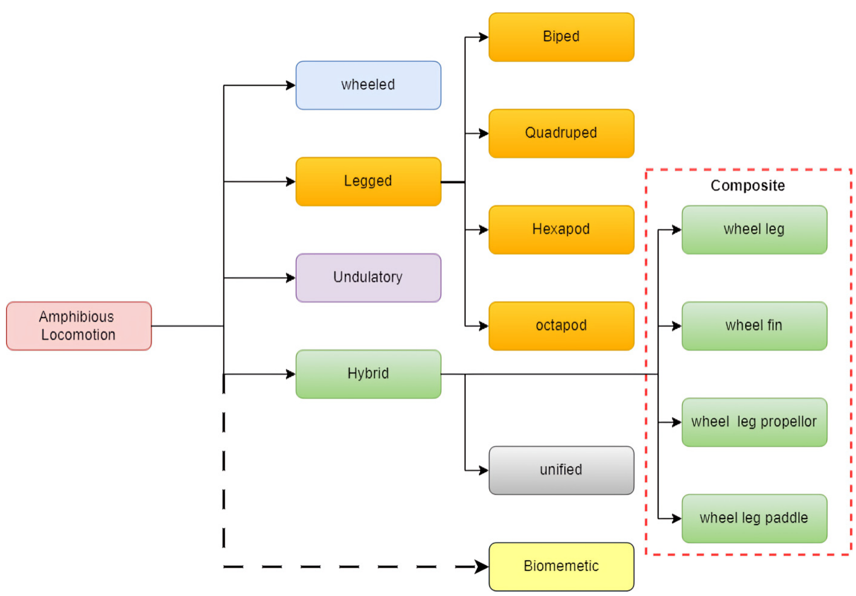
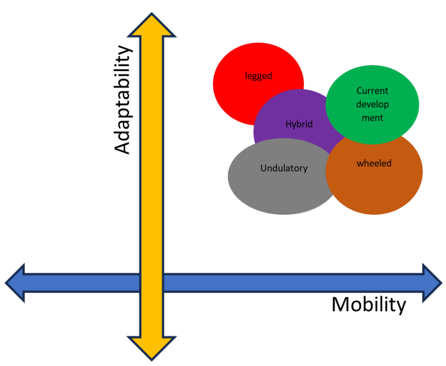


Figure 1 Classification of amphibious robots locomotion

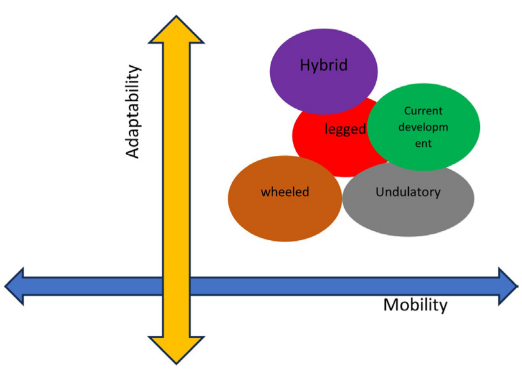
Description of the Features Considered in the Comparison of Locomotion Systems

Amphibians inspire the development of amphibious robots. The propulsive mechanism employed by amphibious animals often involves the fins, limbs, tails, and full-body trunks for locomotion in the land and water environment. The fins act as paddles that generate enough thrust to create forward propulsion in the water; the limbs are also used to paddle, although they are more often employed for manoeuvring in the ground environment. Also, the legs are flexible to uneven terrain and can overcome obstacles to reach the destination. The body trunk and tail parts are utilised for high-speed manoeuvring in the water environment. Adaptability and mobility are two important performance metrics that compare and classify amphibious robots in land and water environments. Figure 2 shows the amphibious robot groups classified in the past literature. The land environment mobility and adaptability performance metric is plotted for different classes of amphibious robots in Figure 2a and for the water environment in Figure 2b. For instance, legged robots have high adaptability in the land environment. Wheeled robots have higher speed or mobility performance. Undulatory robots have high mobility in the water environment, and hybrid robots adapt more to changing environmental conditions. The features of adaptability and mobility interpret the tradeoff made while designing and developing a class of robots. By exploiting the best mechanism functionalities, we aim to establish an amphibious robot with high mobility and adaptability capabilities.

Some amphibians use limbs for motion using surface tension or stroke cycles of the limbs to locomote in a water environment. The functionalities are imitated in the form of wheels, legs, fin-paddles, propeller, tail, modular body, and a combination of these to develop hybrid, unified, and separate mechanisms for propulsion and locomotion in water and land environments. Also, the transition region that involves complex terrains like rocky, bumpy, valley, and shoal terrains requires the locomotory mechanism to adapt to the natural terrain and negotiate obstacles for traversing the path. The locomotory mechanism changes its shape to adapt to the environment while transitioning.



(a)



(b)

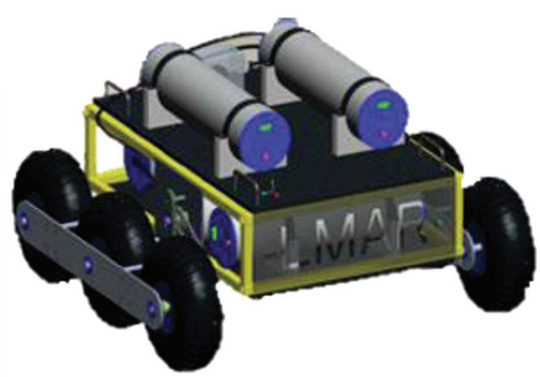
Figure 2 Amphibious robots' manoeuvrability on (a) land (b) water environment

AMPHIBIOUS ROBOT LOCOMOTION SYSTEMS

Wheeled Amphibious Locomotion Systems

Wheeled locomotion systems are the most commonly employed in mobile ground robot operation. High-speed manoeuvrability allows the wheeled robot to navigate on smooth, flat surfaces. However, they are unsuitable for unstructured and irregular terrains. The wheels are also appended to the modular body of an undulatory snake-type robot for high-speed manoeuvrability on land surfaces and body undulation in a water environment. The wheeled robot-like ARGO carries heavy loads and is employed in military applications, as shown in Figure 3 [15]. Primarily, the wheel mechanism in wheeled amphibious robots is only utilised for ground locomotion, and secondary mechanisms like propellers or water jet thrusters are employed for amphibious vehicles for manoeuvring in a water environment. Switching between the modes requires the robot to switch the mechanism from wheel to propeller type of locomotion.

(a)



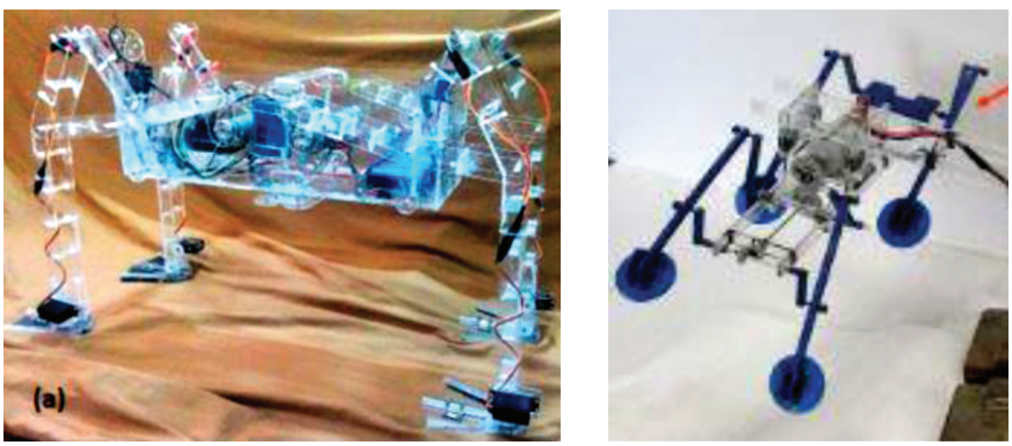
(b)

Figure 3 Wheeled amphibious robot (a) ARGO (b) LMAR [16]-[17]

Besides avoiding the separate mechanism that burdens the overall system, Yu et al. [7] attempted to incorporate wheels with propellors in which wheels are used for land, and changing the orientation of wheels integrated with the propeller provides propulsion in the water environment, as shown in Figure 3. Amphibot robot employs wheels with a propeller at the front and fins to increase the propulsion at the middle and freewheel at the rear end of the body. The limitation of a wheeled robot is its adaptability to uneven terrain profiles, and tyres provide limited propulsion in water. Wheeled robots with passive suspension mechanisms can provide adaptability on the ground and with paddle propulsion in the water environment.

Legged Amphibious Locomotion Systems

Legged amphibious locomotion systems are inspired by amphibians that employ limbs for locomotion in transition regions and both environments. Legged amphibious tough achieves moderate speed performance in both environments. It is highly suitable for uneven terrain land surfaces since it accommodates irregular surfaces and obstacle negotiating capability. Legs are also used for propulsion for the environment; amphibians like basilisk lizards and water striders locomote on the surface of water using a leg stroke cycle similar to paddle rotation, and water striders use surface tension on the surface of water for forward propulsion as shown in Figure 4 [6],[18]. The opossum uses legs for locomotion on the water surface. The mechanics of the leg are complex; hence, the control complexity also increases. Legged robots based on some limbs are categorised as biped, quadruped, hexapod, and octapod robots. This robot uses various gate structures in different environments; the gait pattern changes while adapting to the environment. The speed performance of a legged robot on a smooth surface is increased by attaching wheels to the legs. Legged amphibious robots have excellent stability on uneven surfaces. Webbed feet of legged robots are employed to increase propulsion in water using drag-based paddling.



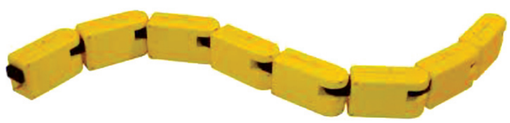
(a) (b)

Figure 4 Legged amphibious robot (a) duck feet (b) basilisk lizard robot [19]-[20]

Undulatory Amphibious Locomotion Systems

Another class of amphibious robots is undulatory robots, which are employed in applications that require flexible manoeuvres or are difficult to reach by traditional mechanisms like underwater pipelines and passing through disaster areas. Undulation is achieved using part of the body's undulation and the tail. The body is uniformly formed or arranged as a modular structure connected and controlled by a single control architecture. Adulatory locomotion is suitable for underwater locomotion as it achieves high propulsion using body undulation. The forward propulsion depends on the part of the body involved in the locomotion and is measured by body lengths. Snake robots are more commonly categorised as undulatory amphibious robots. The popular amphibious robots are Amphibot I and II, as shown in Figure 5 [21]-[22]. ACM-R5 is a typical illustration of undulatory locomotion that aims for high-speed locomotion in underwater environments [22]. The robot has high flexibility due to its modular design traversing complex pathways, but controlling each module increases control design. ACM uses body undulation to increase propulsion, and undulatory motion uses body, tail, and fin undulation motion. Undulatory fin-based amphibious robots are employed in marine environments due to their water surface stability [24]. Salamander-inspired robots are complex amphibious robots that employ undulatory locomotion for swimming in water and limbs for crawling on the land surface. Salamander-I, Salamander-II, and Pleurorobot series developed by Ijspeert et al. [25] are modular design-based undulatory amphibious robots capable of locomotion over smooth, unstructured land and water environments.

(a)

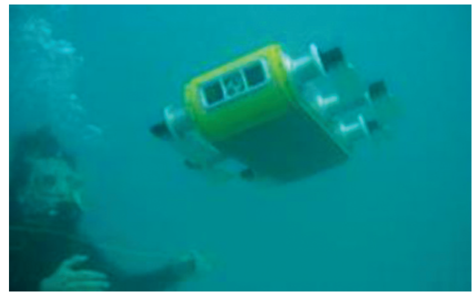


(b)

Figure 5 Popular amphibious robot (a) Amphibot-I and (b) Amphibot-II [21]-[22]

Hybrid Amphibious Locomotion Systems

Hybrid locomotion systems are employed since a single mechanism suits specific environment locomotion. Also, the mechanism tradeoff could be higher, revealing that the mechanism mobility performance is superior in one environment but inferior in another. As discussed in the above sections, the performance metric mobility and adaptability are compromised using a specialised mechanism for the environment. A hybrid environment exploits the best feature of the mechanism, and a new mechanism is developed, integrating two or more mechanisms, each operating in a different environment. The integrated mechanism wheel and fin paddle are employed in flat land surfaces and water environments. Similar configurations are adopted, like in Aqua, shown in Figure 6. the combination of leg and fins. Legs are used to manoeuvre irregular terrain, and fins are used as paddles in water environments.



(a)

(b)

Figure 6 (a) Aqua and (b) Frog-inspired amphibious robot [13],[26]

However, the frog-inspired robot has a hybrid mechanism that involves two fins and a wheel, as shown in Figure 6. Snake-type robots have wheels for locomotion on land and undulating the body in the water. Limb and body and tail undulation complex robot-like salamander amphibious robot is a typical example of a hybrid mechanism amphibious robot; since the modulation of the body, the control complexity is very high, like CPG is utilised for control architecture [27]. An amphibious spherical turtle robot has separate propulsive mechanism legs for crawling on land and waterjet while manoeuvring underwater [28]. Shi et al. [29] proposed an amphibious spherical robot capable of locomotion on slopes and inclined surfaces. The hybrid spherical amphibious crawling speed is much lesser than the high-speed amphibious robot like Amphistar proposed by Cohen et al. Although the speed performance is higher in both mediums, practical applications involve the operation that carries a manipulator or equipment for repair and rescue that puts additional load on the locomotion mechanism. Amphistar with wheel propellor design would encounter wear and tear in the locomotion mechanism [30]. Ma et al. [31] propose a shoalbot that employs a composite wheel propeller leg, unlike the amphistar leg mode, for increasing unstructured environmental ability.

Amphibious Animals with Unified Propulsive Mechanisms

The Aqua robot is a Rhex type of unified mechanism with a transformation mechanism. The fin wheel propeller is also a unified mechanism with a transformation mechanism. Li et al. [32] employed an integrated mechanism guiding the fin and wheel together for multi-modal locomotion. The same actuator drives the integrated mechanism, therefore avoiding the switching mechanism. However, the robot could be more suitable for an unstructured environment. The Whegs series is inspired by cockroaches' locomotion, which encompasses the combination of wheel and leg. Also, body flexion is employed while climbing the stairs or step type of obstacle negotiation. Whegs' type of robot represents a unified hybrid mechanism, as shown in Figure 7 [33]-[34]. RoboTerp is a passive paddle mechanism, and epaddle is an active one; both are a combination of leg and paddle that illustrates a hybrid unified mechanism, as shown in Figure 8 [10]. Ge et al. [35] proposed a unified mechanism for locomotion in the unstructured environment using a transformable wheel spoke paddle mechanism; the robot has stable locomotion due to the wheel and cranks slider mechanism transforming to a wheel spoke to leg type for adaptability on rough surfaces. However, the mechanism required an additional crank slider, adding mechanical complexity and actuator requirements. An unstructured environment requires the capability of obstacle negotiation. Kim et al. [36] employed an angled-spoke paddling wheel for locomotion on land using the wheel and rotational mechanism that turns the wheels to achieve paddling force in a water environment; the amphibious robot could negotiate obstacles of height equal to wheel size. However, the speed performance is much lower, 0.47 m/s, compared to other amphibious counterparts.

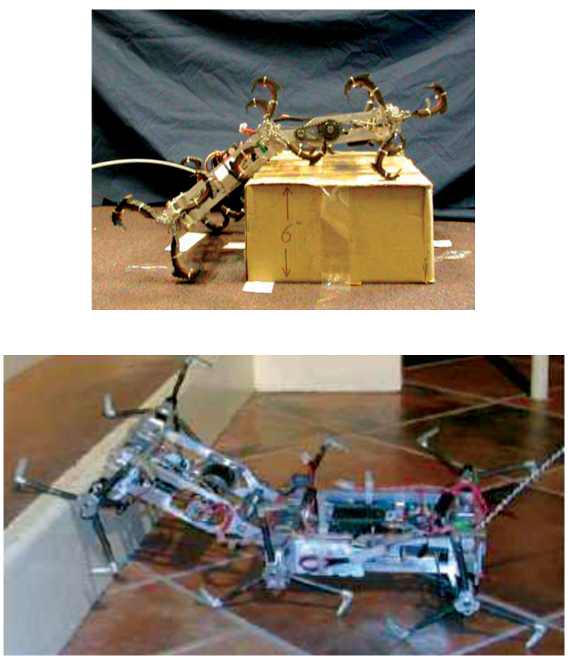
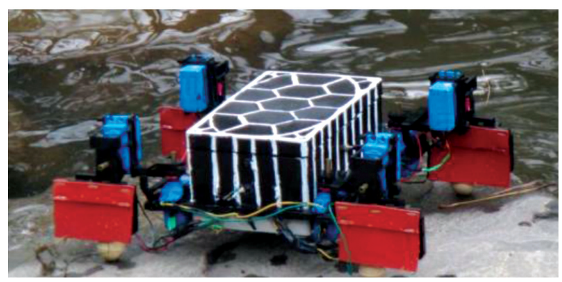


Figure 7 Whegs amphibious robot while climbing step obstacle [34]



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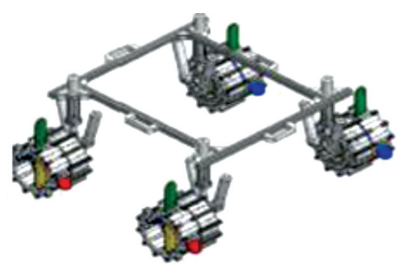

(b)

Figure 8 Unified amphibious robot (a) robterp (b) epaddle [10],[37]

COMPARISON AND DISCUSSION

Amphibious robot classification and performance metrics considered for evaluating locomotion performance discussed in the above section are compiled in Table 1. Table 1 lists the mobility and adaptability of various robots in both environments. Nevertheless, these are other parameters and environmental conditions also correlated while determining the overall propulsive performance of the amphibious robots. The lower and higher counts of star markers indicate the performance of robots. The comparison metrics for amphibious robots are adopted from [22] for evaluation, and water locomotion shows mobility performance like trust force achieved in a water environment for a robot. Undulatory motion has the highest thrust forces or lowest drag in aquatic environments. Wheeled locomotion has peak average velocity for smooth land surfaces, as represented in the second row. The design, structural and environmental metrics are considered while developing these mechanisms and tradeoffs in speed performance or control complexity are aimed at particular applications. Moderate performance is achieved by using hybrid mechanisms in both environments since they exploit and integrate the capabilities of multiple mechanisms in a single design. Adaptability is considered for unstructured environments; legged robots have the highest terrainability and can negotiate obstacles during the traverse cycle.

Table 1 Comparison of different amphibious robots using popular metrics

Robot / Metric				Hybrid	
	Wheeled[16]	Legged[20]	Undulatory[22]	Separate[29]	Unified[10]
Water locomotion	*	**	****	***	**
Land locomotion	****	**	**	***	***
Control complexity	*	**	***	***	**
Endurance	****	**	***	***	***
Simple structure	****	***	*	**	*
Environmental	**	***	**	**	**
Adaptability	*	****	**	***	**

Case Study: Example of Propulsive Mechanism for Efficient Amphibious Locomotion

Our group is building an amphibious capable of locomotion in the environment using a unified propulsive mechanism. Unlike the amphibious robot discussed in this paper, the mechanism focuses on a complete body structure involving the main body and propulsive mechanism rather than only imitating the bio-inspired functionalities at the wheelbase or leg assembly. The amphibious robot integrates a rocker-bogie mechanism in the main body and independently driven wheels with paddles. The rocker-bogie mechanism provides passive suspension while manoeuvring on the uneven ground surface, providing sufficient adaptability on unstructured terrain profiles with obstacle-negotiating capability. Also, the wheel axial paddle mechanism provides competent speed performance on smooth, flat terrestrial surfaces. The unified propulsive mechanism combines wheels with axial paddles; paddles are involved in the propulsion on the water surface environment using drag-based locomotion. The unified mechanism has lower control complexity since the same wheel drive drives the axial paddles, avoiding an independent control requirement.

Overarching Challenges in Amphibious Robotics Locomotion

The metric speed performance focuses primarily on designing and developing amphibious robot locomotion. However, practical shoreline monitoring and other applications require robots to manoeuvre complex terrain. Hence, there is a requirement for the design and development of robot structure, propulsive mechanism, and control architecture considering complex irregular terrestrial terrain profiles in actual application transition regions. Therefore, an amphibious robot with cross-medium agility is still a challenging task to achieve. Soft amphibious robots like origami robots are well-suited to adapting their shape and stiffness to the environment and gecko-inspired adhesive structures for amphibious soft robot locomotion on inclined surfaces [38]-[39]. Therefore, soft amphibious locomotion represents an untapped reservoir of potential for addressing the multi-faceted challenge of transitions between aquatic and terrestrial locomotion.

CONCLUSION

This paper outlined the literature on amphibious robot locomotion, comprehensively discussed the significant categories of amphibious robots, and detailed the mechanisms employed for propulsive mechanisms in the land and water environment. The discussion also focused on the challenges in the uneven terrestrial terrain profiles and the mechanism adopted to achieve high mobility and adaptability in the irregular terrain profile with obstacle negotiating capabilities. Finally, we presented our current development of an amphibious robot capable of manoeuvring in multiple environments, integrating the capability of traversing on uneven terrains with lower control complexity by addressing the robot's main body rather than only focusing on the propulsive mechanism. The review and proposed development gave direction in looking into overarching challenges in designing and developing amphibious robot locomotion.

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