Chapter 3
Amphibious Robotic Propulsive Mechanisms: Current Technologies and Open Challenges

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3.1 Introduction

Much research effort has been dedicated to underwater robots, as evidenced by numerous papers and the contents of this book [1]. An even larger body of literature concerns terrestrial robots. But what about amphibious robots that can operate both in water and on land? From the literature, we glean that amphibious robots are fantastic vehicles for studying autonomous navigation strategies in unstructured, complex environments [2]. Furthermore, they have proven useful as physical models for gaining deeper insight into the gait patterns and mechanics of animal locomotion [3–5], analyzing the health of ecosystems [6, 7], and understanding physical principles underlying propulsion in various media [8, 9]. Beyond the academic space, advances in amphibious robotics are projected to be a significant boon to industries such as reconnaissance, surveying, offshore mine detection, and water quality monitoring, where seamless transitioning between locomotion modes is critical to success [10–13].

In spite of their versatility, relatively few amphibious robots have been reported in the literature. Significant challenges remain for designing, building, and implementing amphibious systems outside of the laboratory setting. Central to realizing an amphibious robot is designing propulsive mechanisms for effective water- and land-based locomotion. In doing so, the engineer must strive to balance conflicting features. As we shall investigate in this chapter, both in natural and physical systems,

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functional shapes conducive to load bearing and terrestrial maneuverability often detract from hydrodynamic efficiency and water compatibility.

The transition between water and land, called the littoral zone, also presents challenges. The littoral zone is characterized as a turbulent environment due to wave action, intermixing of heterogeneous substrates, suction forces, and abrasive flows imposed by fluidized sediment. Rocks, shoals, uneven slopes, dense algal beds, and reefs are all obstacles that an amphibious robot might encounter and have to negotiate in a transition zone [14, 15]. The dynamic onslaught of physical phenomena and obstacles in the littoral zone constitute a multi-faceted problem for which there are no obvious robot design solutions.

To provide biological inspiration in the design of amphibious propulsors, this chapter first analyzes animals' body plans and their locomotor adaptations in Sect. 3.2. Animal morphology and physiology is, in fact, chiefly influenced by evolutionary pressures for effective movement in an environment [16]. For the sake of brevity, we hone in on key examples from semi-aquatic, semi-terrestrial, and highly specialized species that typify the range of propulsive modes exhibited by animals.

With biological context, we transition to a survey of existing amphibious robotic platforms in Sect. 3.3. Designs striving to address the slew of environmental challenges amphibious robots face can be broadly classified into systems that locomote using separate or united propulsive mechanisms. We define separate to mean that distinct subsystems move a robot on land and though water, whereas movement with a united mechanism is achieved in both media via the same subsystem. While separating propulsive mechanisms is a more traditional approach and may allow robots to locomote with specialized modes of transit in each environment (i.e., using wheels to move on land and jets to move through water), uniting propulsive mechanisms has gained popularity as a means of reducing system complexity and exploring propulsive architectures inspired by amphibious animals (i.e., using snake-like undulations to move in water and on land) [17]. Beyond separate and united propulsive mechanisms, we further sort robots into (1) wheeled, (2) legged, (3) undulatory, or (4) soft categories, based on their body plans and primary means of propulsion. Section 3.3 further expounds on what distinguishes these classifications from each other.

After a synthesis of existing work, Sect. 3.4 identifies promising avenues for future research on amphibious robotics. Lastly, Sect. 3.5 presents a case study: our research on a variable stiffness morphing limb, a design that seeks to unite various propulsive functionalities into a single cohesive mechanism.

3.2 Biological Perspectives on Amphibious Locomotion

3.2.1 Movement through Different Media

There are physical differences between water and air that determine the different mechanisms of animal locomotor modes in either environment. Density and viscosity are the most important physical properties [18]; water is 800 times denser than air and 55 times more viscous. The ratio of inertial to viscous effects is also of paramount importance to aquatic locomotion [19], and can be expressed quantitatively via the Reynolds number:

$$Re = \frac{\rho U L}{\mu}, \tag{3.1}$$

where ρ is the fluid density, U speed, L characteristic length of the body in the fluid, and μ dynamic viscosity. We will touch on the ramifications of scale with regard to specific propulsive mechanisms later. Regardless of scale, swimming animals tend toward a density close to that of water to support their body weight via buoyancy. They use the high density and viscosity of the medium to generate hydrodynamic forces for propulsion. Swimming is accomplished by propulsors that can be broadly classified as undulatory, lift-based oscillatory, drag-based oscillatory, or jetting [20–22].

On land, an animal moves through air, so gravitational forces predominate and the weight of an animal has to be supported by rigid or hydrostatic skeletons. Animals apply frictional forces from contact of a body or limbs on the solid ground for propulsion. Broadly speaking, terrestrial locomotion is enabled by propulsors that induce undulatory motions, limbed locomotion, a combination of both undulating and limbed locomotion, or rolling [23–26].

Many animals are capable of moving between water and land [22]. The reasons why animals adapted for multi-modal locomotion between water and land stem from survival adaptations, including catching prey, escaping from predators, mating, and searching for food [27]. For vertebrate animals, the shift from finned swimming to legged terrestrial locomotion in the transition from fish to amphibians is considered one of the watershed events in evolution. Aside from amphibians, mammals, reptiles, and birds have amphibious species exhibiting varying degrees of terrestrial and aquatic locomotor adaptations. Amphibious behaviors are also exhibited by invertebrate lineages, most notably mollusks and arthropods. All amphibious animals, regardless of classification, must strike a balance between being both semi-aquatic and semi-terrestrial, and utilize united or separate propulsive mechanisms for locomotion in either media.

3.2.2 Amphibious Animals with United Propulsive Mechanisms

Numerous amphibious animals exist in nature that utilize the same propulsive mechanism in both mediums [28]. Amphibians, notably frogs, hop and swim using a similar movement pattern: maximum extension of hind limbs, followed by a sweeping recovery phase [29]. Mammalian limbs can relatively easily engage in drag-based propulsion in water. Drag-based swimming and quadrupedal walking locomotion modes are embodied by mammals such as muskrats, elephants, and opossums [30]. When swimming in a drag-based regime, propulsive drag force is produced only through half of the stroke cycle by the rearward movement of the appendage, since forward motion is a non-thrust generating recovery phase. Consequently, limbed amphibious mammals demonstrate high locomotor costs due to their inability to specialize for water or land [22].

Amphibious reptiles, like freshwater turtles, also utilize united propulsive mechanisms—swinging of limbs—for drag-based swimming and quadrupedal walking. Amphibious snakes, on the other hand, leverage bodily undulations to move in the water and on land. Evolutionary adaptations that enhance aquatic locomotion at the expense of terrestrial locomotion, such as diminished ventral plates and a flattened tail, can be observed between some species of snakes. [31]. Mollusks like the octopus represent a rather unique case in that they use unsupported limbed locomotion to crawl along the ocean bottom and on land [32].

Propulsive mechanisms for amphibious animals that walk both on the surface of water and on land are very much governed by size. Small animals with hydrophobic surfaces, such as water striders, can exploit surface tension to support the body [33]. As the size of an animal increases, surface tension becomes insufficient to support its weight. The basilisk lizard can run atop water by simultaneously generating surface-level drag and expanding an air cavity underwater [34]. As the size of a basilisk lizard increases, the kinematics of the foot stroke change to keep it atop the surface [35]. For even larger organisms, like aquatic birds, movement atop water requires the addition of broad wings impacting the surface [36].

3.2.3 Amphibious Animals with Separate Propulsive Mechanisms

A less common model in nature than united propulsive mechanisms is to utilize separate propulsive mechanisms for either medium. Among mammals, otters engage in quadrupedal walking and undulatory swimming [37]. Reptiles of the order Crocodilia, including alligators and crocodiles, use tail undulations in the water but rely on quadrupedal gaits on land. Similarly, newts and salamanders undulate their bodies in a standing wave while using their limbs to walk [28]. Some at high speeds will undulate on land with their legs tucked in to their sides.

3.2.4 *Specialization for Water or Land*

Generally, semi-aquatic or semi-terrestrial animals—like those mentioned up to this point—are less energy efficient and slower (in terms of body lengths per second) than animals that are specialized for one environment [22]. Yet in engineering, an amphibious robot is not limited by the same physiological factors that limit animals. Animals must move by oscillations of appendages or body undulations powered by muscles, must respire with gills or lungs for oxygen to fuel cells constituting their muscles, are composed of biomaterials such as bone, cartilage, and chitin that have lower strengths compared to metals used in engineered systems, and have a large portion of the body devoted to reproductive functions. An amphibious robot can take advantage of specialized, rapid, and efficient aquatic and terrestrial propulsive mechanisms, or those that are dangerous for animals [5]. It is thus worth enumerating some of the more optimal propulsive mechanisms and body plans for water and land exhibited by highly derived (specialized for certain environments as a result of evolution) species.

Inhabiting an exclusively aquatic environment, tuna and dolphins have streamlined, hydrodynamic bodies and rely on oscillation of their caudal fins to generate thrust as a vector component of lift. Other fast and efficient aquatic animals with lateral fins and flippers can produce thrust by undulatory (bluegill, sunfish, stingray) swimming, as well as oscillatory wing-like movements (sea lion, sea turtle). Though not sustainable over long periods, jetting can enable rapid accelerations and is seen in jellyfish, squid, and octopus. Larger aquatic animals, like those mentioned above, are considered to be nekton, that is, capable of swimming long distances independent of water currents. Nektonic animals swim at high Reynolds number ($Re > 10^3$ up to 10^8) [38]. At high ranges of Re, swimming is performed by accelerating a mass of water for propulsion. Viscous forces are small, whereas inertial forces are large [38]. Yet the overwhelming number of animals that exist in the oceans are small, like plankton, and use ocean currents pushing on their bodies as a propulsive mechanism to move long distances. Most planktonic animals (e.g., copepods) lie within an intermediate range of Re ($1 < Re < 10^3$), where viscous and inertial forces are both important [39]. At even smaller scales, bacteria cilia and flagella operate between 10^{-5} and 10^{-6} Re, where viscous effects dominate [40].

Terrestrial vertebrates are generally not streamlined. They have a defined neck, no blubber to contour the body shape, and if they have limbs, the limbs are generally cylindrical with an approximately circular cross section. As size (and thereby mass) of a terrestrial organism increases, gravity becomes a more dominant force, unlike in water where weight is supported by buoyancy. Among limbed terrestrial animals, peak limb stresses can increase with increasing body size, so posture of the skeletal elements of the legs tends toward a more columnar (upright) stance [41, 42]. Such a change in posture maintains a safety factor independent of size, but at the expense of accelerative capability and maneuverability. Horses and cheetahs are exemplar animals with skeletal components disposed to upright walking and high-speed linear galloping. Highly derived terrestrial animals, like the horse and cheetah, exploit spring-like interactions of their body with the ground to enhance thrust produced with each stride [43]. The storage and release of elastic energy as a propulsive mode actually increases in efficiency at higher speeds in some animals [44]. In addition to limbed propulsion aided by elastic potential energy storage, it is instructive to mention another (perhaps more unusual) specialized terrestrial propulsive mechanism that harnesses gravity: rolling. Passive rolling is demonstrated by arachnids, while species of caterpillar actively build up angular momentum during rapid escape maneuvers [26]. Top speeds of rolling animals can be an astounding tens of body lengths per second.

3.2.5 Biological Inspiration for Design of Amphibious Robotic Propulsive Mechanisms

Both environmental medium and scale influence an organism's propulsive mechanism adaptations. The intermediate status of amphibious animals compromises their locomotive performance in either environment, but the mechanics of these intermediate species can potentially serve as a template to develop a new generation of amphibious robots. Furthermore, amphibious robots can be designed to incorporate locomotor mechanics that are specialized for either environment or any scale, expanding upon what nature has been capable of producing through evolution.

It is thus the charge of the robotic designer to synthesize various propulsive mechanisms and corresponding body plans found in nature—even to look beyond these natural examples to synthetic solutions—to innovate and produce an effective amphibious robotic system. Such a methodology to realizing future amphibious robots is depicted in Fig. 3.1. The next sections review current work in amphibious robotics. An exposé of novel designs, biologically inspired or of purely synthetic origin, as well as the advantages and disadvantages of these designs, supplies additional foreknowledge to synthesize next-generation amphibious robots.

3.3 Classification of Amphibious Robots

A strict template for classification does not necessarily encompass any given robot's propulsive mechanisms. While robots with united propulsive mechanisms may be much easier to classify, robots with separate propulsive mechanisms defy any strict classification. For the sake of review, we sort amphibious robots into wheeled, legged, and undulating based on the most salient aspect of their morphologies. Wheeled, legged, and undulating amphibious robots utilize significantly different mechanisms to move in water and on land. Wheeled systems include rounded entities concentric to axles that, when engaged in rolling, provide leverage based on the radius. Wheels can be driven passively (by gravity) or actively (by motors).

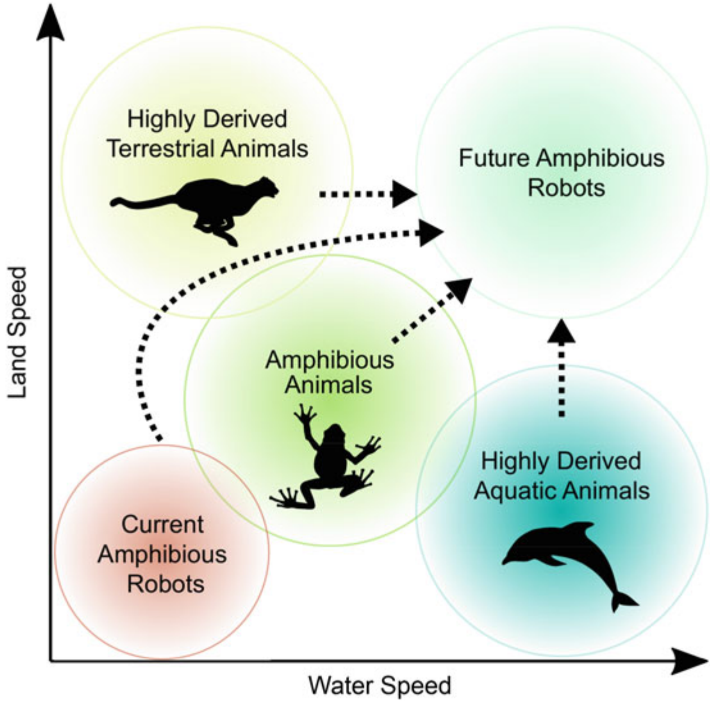

Fig. 3.1 Combining knowledge of the propulsive mechanisms of amphibious animals, the specialized mechanisms exhibited by highly derived species, and existing amphibious robot designs is key to developing the next generation of amphibious robots. Note that the relative positioning of groups is based on the authors' qualitative assessment of performance

In water, movement of treads through the fluid medium can serve as discretized paddles for drag-based thrust. On land, wheels rest on the ground at all times and rely on friction contact force on the substrate at a point and repetitive revolutions to generate a thrust vector.

Legs are a more generic morphology. They can be articulated, multi-degree-of-freedom, or single degree-of-freedom links of various shapes and kinematic configurations. In water, legs engage in oscillations or power strokes to generate thrust. On land, legged systems utilize discrete footholds to move. The body is supported off the ground with either upright or sprawled legs. Having a lower center of mass, sprawled posture is generally more stable than the full upright orientation of legs. A robot's legs must leave the ground in periodic increments to achieve bodily displacement.

Undulating robots come in elongated forms, often consisting of a series of modules connected together. In water, undulatory swimmers display a gradient of propulsive modes for thrust production—from undulatory waves encompassing the total length of the body (anguilliform), through progressively expanded posterior regions of the body (carangiform), culminating in thrust production confined to the

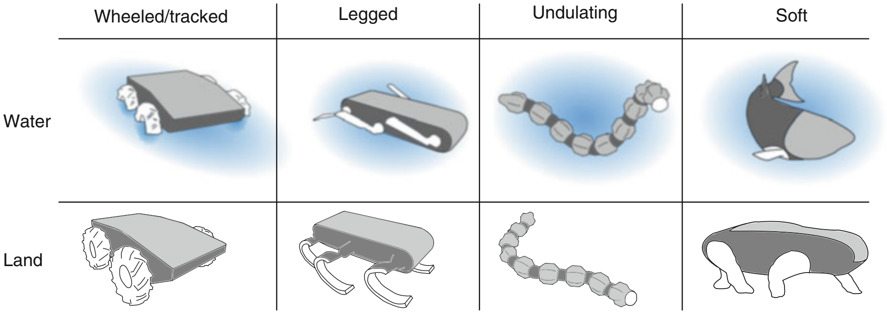

Fig. 3.2 Amphibious robots sorted into four distinct categories based on their primary propulsive mechanisms and structural features: wheeled/tracked (note, wheels are half-submerged in water in the depicted image), legged, undulating, and soft. Here, we illustrate how each category might unite the same propulsive mechanism, or transform its limbs or body plan to accommodate water and land

caudal fin (thunniform). On land, undulating robots move in a fashion characterized by multiple surface contact points. Waves passing posteriorly down the body push on solid substrate for forward movement.

Soft amphibious robots may locomote in a way that is consistent with the previous three delineated categories, but are distinguished by their composition of continuously deformable materials, typically having a Young's modulus on the order of, or less than, one MPa. Consequently, soft robots do not commonly use traditional rigid motors. Reliance on soft actuators [45] is thus another factor that separates them from the other three categories.

Figure 3.2 depicts how each category might unite the same propulsive mechanism, albeit with morphological transformations present in the legged and soft categories. Each category is associated with a unique set of advantages and disadvantages that motivate discussion on what constitutes an effective amphibious robot design. The following subsections address each of the classes of robots in the listed order. For each, we open with a discussion of its respective advantages. We then highlight seminal amphibious robots belonging to that class. Our intention is to not to detail every amphibious robot reported in literature, but to summarize key innovations as embodied by the seminal designs. Aspects we focus on when appraising an amphibious robot are its capacity to bear payloads (i.e., sensors, camera, equipment; this criteria is of course dependent on size), ease of control, efficiency, maneuverability, and speeds in water and on land. Aside from absolute speeds in water and on land, which we have plotted against each other for a number of designs and comparably sized animals in Fig. 3.3, the other metrics are not consistently reported for amphibious robots throughout literature. We instead provide a qualitative assessment of these metrics. Each section closes with a synopsis of a particular class' drawbacks, and therefore opportunities for future research.

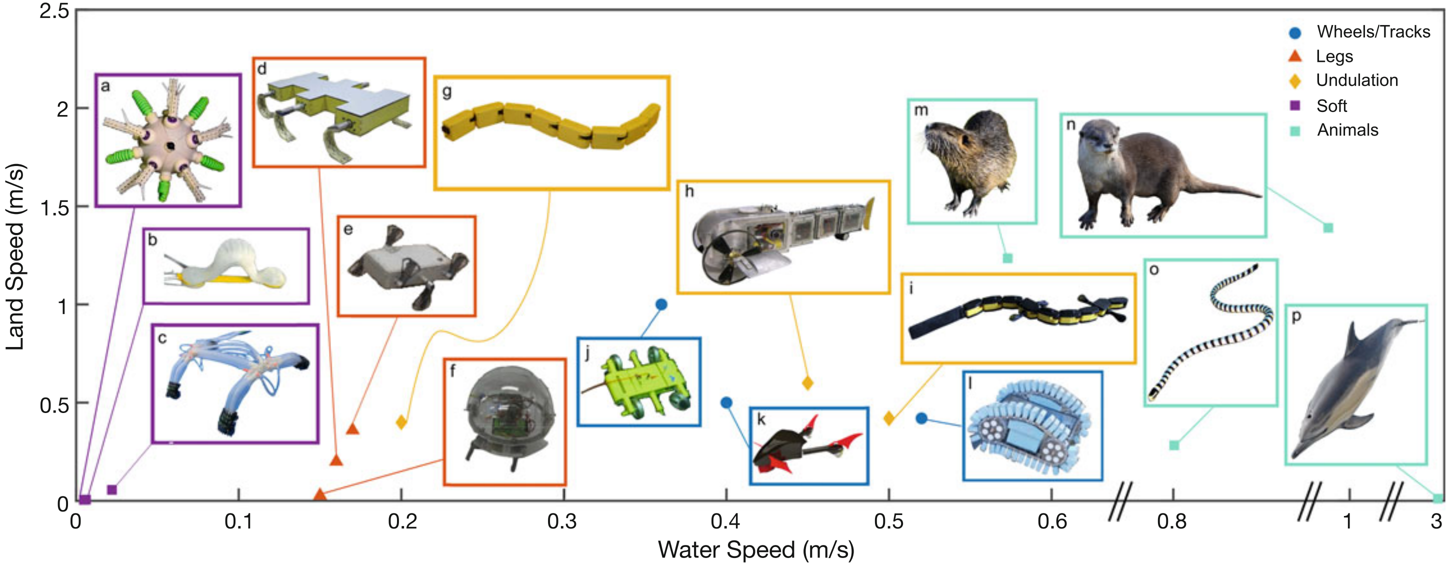

Fig. 3.3 A comparison of absolute sustained speeds between representative amphibious robots from each of the delineated categories, as well as semi-aquatic, semi-terrestrial, and aquatic animals. Note that many of the increases in robots' speed have naturally come hand-in-hand with improved research hardware, such as higher torque motors and lower footprint microcontrollers. We try and account for this factor by featuring a variety of older and newer published work from each category. Citations for (**a**–**l**) are [4, 6, 9, 46–54]. We include comparably sized animals operating in a similar Reynolds regime (thus excluding whales, bacteria, etc.) for comparison to the robots. The animals are from (**m**–**p**): muskrat, river otter, yellow-lipped sea krait, and bottlenose dolphin. Citations for speeds (**m**–**p**): [37, 55–59]

3.3.1 Wheeled and Tracked Amphibious Robots

Wheels represent a unique propulsive mechanism for amphibious robots since, compared to legs and undulations, wheel-like forms are less readily used in nature [26]. On land, wheels pose an energetic benefit because when traveling at a constant speed, the kinetic energy remains constant [40]. Compare this energy profile to most other natural propulsive mechanisms that necessitate trajectories of cyclic acceleration and deceleration that may incur a sizable energy cost. It is not surprising then, that a common—and perhaps the simplest—propulsive mechanism for amphibious robots is wheels or tracks.

A ubiquitous amphibious robot design, similar to many amphibious vehicles, uses wheels to move on land and on top of water. Such robots are far along in the development pipeline and are commercially available [60]. Though rotating wheels to move in water and on land unite the same propulsive mechanism, simplifying control, it comes at the expense of speed in water. Speed is limited because wheels increase drag due to the heightened relative velocity from the rotation of the wheel, which can induce flow separation [61].

Yamada et al. built what appears to be a quintessential wheeled amphibious robot, but with a clever twist for improved aquatic locomotion. Their four-wheeled platform, R-Crank, incorporates a ribbed crank link between its front and back wheels on each of its sides. The crank link generates thrust for surface-based aquatic locomotion as the tires spin [62].

While the previously mentioned robots include wheels as a part of their hardware, other robots are, by no stretch of definition, wheels. A design perk of wheel-bodied robots over robots with wheels is that the need for a bulky chassis is eliminated, reducing weight, and potentially conferring hydrodynamic benefits. Consider that the drag force on a body is

$$F_D = C_D A \frac{\rho V^2}{2}, \tag{3.2}$$

where C_D is the drag coefficient, ρ is the density of the fluid, V is the flow velocity relative to the body, and A is the reference area. Note removing a chassis will substantially decrease A. Also, the C_D of a wheel, typically shaped like a sphere or disk can be much lower than typically angular, rectangular chassis.

One wheel-bodied system, Groundbot, was developed by Rotundus AB in Sweden as a multi-terrain surveillance robot. Spherical, treaded, made of rubber, and fully resembling a tire, Groundbot can roll and steer itself using an offset internal weight actuated by motors. It boasts up to 3 m/s (5 bl/s) sustained speeds on level ground. It employs the same rolling mechanism to traverse water as it does for land, floating atop the surface and generating thrust with its specifically engineered treads that essentially serve as a series of paddles [63].

Another robot with a wheel-like body is the triphibious MUWA. MUWA consists of a ring of polystyrene foam surrounding a multicopter. The polystyrene ring gives

MUWA enough buoyancy to float atop water, but also provides geometry conducive to rolling. When rolling on land, MUWA controls its trajectory by adjusting the pitch of its rotating propellers [64].

Transition areas rife with loose or fluidized sediment threaten to ensnare wheels. Rolling resistance of wheels increases in proportion with soil compliance [65]; in fact, one study found that rolling resistance on concrete can be 10–15 times less than that of sand [66]. Terramechanics research models physical interactions with the substrate and provides an estimate of the extent to which sinking into the substrate impedes motion [67]. Concentrated weight is a primary cause of local soil fracture, causing ensnarement. Tracks distribute the weight of a robot over a larger area to mitigate sinking and improve locomotion across muddy terrain, but may sacrifice some speed and maneuverability.

Tracked amphibious robots have been built that are intended to sink below the surface to crawl on lake beds [11]. Sinking to the bottom is not always practical, though. Motivated by the need to monitor an estuary system composed of multiple rapid transitions from shallow water to soggy land, one robot was designed with buoyant tracks so it can engage in surface swimming while retaining the ability to navigate muddy sections [6]. This surface-swimming robot has the fastest speed on water reported in Fig. 3.3.

The aforementioned wheeled or tracked designs have not demonstrated ability to swim in 3D. For certain applications, amphibious robots need to be able to engage in 3D swimming so that they can transition between the surface and underwater and explore the water column in between. In order to enable 3D swimming while retaining the merits of wheels on land, one group introduced a class of robot with hybrid wheels/propellers and separate fins [53]. The hybrid wheels/propellers have spokes emanating radially from the termination of their axle, effectively providing the hydrodynamic thrust of propellers and generating sustained speed of up to 0.36 m/s (0.375 bl/s) in water (Fig. 3.3j). The fins on the robot are used to steer when swimming. Owing to its wheeled design, this robot also exhibits the top speed on land out of all designs in Fig. 3.3, at 1 m/s (1.04 bl/s). Transitions from aquatic to terrestrial locomotion are accomplished by orienting the wheels/propellers so their revolution will provide forward thrust in water or serve as a wheel on the land.

Another hybrid wheel/propeller mechanism that allows for 3D swimming, dubbed the eccentric paddle, consists of a shaft embedded in a wheel on which paddles are radially distributed. The paddles move in and out of the wheel to adjust the extent of their interaction with the environment. Equipped with eccentric paddles, the robot demonstrates an unusual capability: a quasi-walking mode of locomotion by cyclically protruding the paddles from the wheel [68–70]. Offering the speed of wheels as well as aquatic mobility, hybrid approaches, like combined wheels/propellers and separate fins or the eccentric paddle, nonetheless rely on complex agglomerations of mechanisms that are difficult to control. Such intricate hybrid mechanisms with many moving components may also be susceptible to debris in the littoral zone compromising their function.

Overall, although they offer efficiency and high top speeds on flat land and the requisite structural integrity to support large payloads, a major drawback of wheeled and tracked robots is their lack of ground clearance and consequently diminished ability to traverse uneven terrain [71, 72]. Heavy systems with wheels, specifically, have a propensity to become trapped in shallow, fluidized sediment [73]. Moreover, wheels do not scale well to small sizes because they become sensitive to substrate compliance and uneven terrain impacting forward motion [40]. A promising design strategy, creating a wheel-bodied robot or a hybridized paddle-wheel mechanism, can reduce mass, enable 3D swimming, and address minor challenges posed by uneven terrain [53, 70]. Yet, hybrid mechanisms can be plagued by their host of moving parts, especially in the littoral zone rife with obstacles. If creating hybrid mechanisms, designers should err on the side of simplicity to provide resilience against environmental detritus. Lastly, robots with wheels or tracks can leave destructive trails behind them—a heavy wake or dislodged soil. While observing fragile ecosystems or trying to maintain stealth, disturbances to the environment can undermine mission success. More work on wheeled systems that minimize environmental impact thus represents an open area of research. When navigation of uneven terrain or stealth are prerequisites to a successful mission, other types of amphibious robots might be better options than current designs with wheels or tracks.

3.3.2 Legged Amphibious Robots

Legged amphibious robots tend to be more complex in design and control architecture than wheeled robots due to the multiple controlled degrees of freedom associated with each leg. Primary advantages of legged robots include their capability to traverse obstacles wheels or tracks cannot, and need for only discrete footholds to locomote, as opposed to a continuous supporting surface. On especially soft ground, legged robots deform terrain less than wheeled or tracked systems and thereby can diminish the energy required for traversal [74]. Due to their multiple degrees of freedom, legged robots can also change direction without slippage. Like wheeled robots, legged robots can sustain concentrated payloads undulating robots cannot, since their motion is not dependent on dynamic oscillations of interconnected bodily modules.

Spurred by calls to develop systems to locate and destroy mines in the surf zone, one of the first examples of a legged amphibious robot—let alone one of the first amphibious robots—was published in 1996. The report detailed a hexapod robot, Ariel, inspired by the crab that walks at a shallow depth along the seabed [12]. Since Ariel, similar work has been published focusing on the creation of lobster-inspired robots with the same purpose [75]. A major concern for benthic walking robots is the large hydrostatic pressures associated with great depths—not only for water-proofing but also for feasibility of walking. Large moments would be created about the leg joints at depths, and it is unlikely compact actuators could overcome such moments.

In contrast to robots that crawl along the seabed are surface walkers: amphibious robots inspired by insects and reptiles (mentioned in Sect. 3.2) that are able to walk on the surface of water by exploiting the physical properties of their feet, and/or their small body mass. Park et al. presented a platform inspired by the basilisk lizard. The crux of their design revolves around a light-weight robot body and a compliant foot pad, which transfers elastic energy to propulsive momentum [76–78]. Yet such a robot cannot bear payloads that would compromise its light weight and would therefore be limited to minimal integrated circuits. Another surface-walker-inspired robot is bulkier and able to bear payloads, compensating for its increased weight via Styrofoam spherical feet that provide buoyant forces [79]. A cockroach-inspired microrobot fabricated by Chen et al. uses partially submerged foot pads to paddle on the surface of the water, exploiting surface tension. Unlike the previous two mentioned platforms, it is able to dive from the surface to the bottom by emitting high voltage from its padded feet to temporarily break surface tension. It can then walk on underwater surfaces as it does on land [80]. Nevertheless, the robot is unable to replicate the speed and dexterity of an actual water strider due to constraints on the force density of such small actuators. In addition to those mentioned, there have been a variety of other surface-walking robots [81].

Though bottom and surface walking may be sufficient in some scenarios, 3D swimming offers greater surveying capability. To this end, a new chapter in amphibious legged robotics started with AQUA [82, 83]. AQUA, based on Boston Dynamics' R-hex platform [84], utilizes six independently controlled paddles on single degree-of-freedom (DOF) joints as control surfaces during swimming. It also has interchangeable, curved cockroach-style legs for walking that act as springs, efficiently storing and releasing potential energy with each stride. AQUA represents the first robot of its kind—legged, able to proficiently move on land and traverse obstacles, but also able to engage in 3D swimming to fair depths. There are many subsequent amphibious robots that drew design inspiration from AQUA's body plan and leg design.

One series of robots inspired by AQUA are hexapods equipped with Whegs™ (a portmanteau for wheel-legs). Whegs™ integrate swimming and walking mechanisms, combining the simplistic control of a wheel with the articulated cadence and ability to traverse some obstacles that legs typically can [85]. Whegs™ are similar to the cockroach-style legs initially equipped to AQUA, but are built with three protruding paddles equally distributed radially about the center shaft, as opposed to AQUA's single paddle. Whegs™ have been implemented on amphibious robotic platforms as a combined propeller/wheel with great success [86–88]. Despite their critical appeal, it should be noted that the drag-based propulsion supplied by Whegs™ is inefficient relative to lift-based locomotion [30]. Also, like propellers, Whegs™ induce turbulent vortices that may pose too much of an environmental disturbance for some applications. Lastly, the geometry of Whegs™ does not allow backwards locomotion on land (the paddles contact the ground at a point, acting as a rigid rod and stunting motion), which detracts from their terrestrial mobility.

Bearing strong resemblance to Whegs™-style robots but with modifications to address the fact that Whegs™ are not able to back-drive, Ninja Legs incorporate a thin circular wire enclosure around flippers. The enclosure protects the compliant flippers and simultaneously serves as an offset wheel for hybrid rolling/walking [89]. In a similar vein as Ninja Legs, one robot named RoboTerp unites flippers and legs into a single hybrid propulsion mechanism. The structure of one limb consists of a flap passively hinged to a grate. The grate serves as a rigid load-bearing leg to support the robot's weight on land. While swimming, during the robot's power stroke, the flap flattens against the grate thereby increasing paddle surface area and producing forward thrust. On the upstroke, the flap freely swings back, reducing drag [90].

RoboTerp's passive paddle mechanism is not conducive to high aquatic mobility. This reinforces the observation that walking legs, in addition to producing less thrust compared to more hydrodynamic, high aspect ratio surfaces, are far from optimal forms for maneuvering in the water. Indeed, the original AQUA platform had separate flipper and leg modules for water and land, respectively, optimized independently of one another. However, the need for human intervention to manually exchange limb designs undermines a system's ability to autonomously transition between environments.

One group introduced AmphiHex-I (Fig. 3.3d) and in doing so initiated a new amphibious legged robot design paradigm. AmphiHex-I [48, 91, 92] features a transformable leg-flipper propulsion mechanism. The leg-flipper consists of interlocking rigid segments connected via a cable. When the cable is pulled, the interlocking segments are compressed to create a curled cockroach-style leg. When released from tension, the limb becomes a compliant flipper. Although the robot's speeds of 0.16 m/s (0.18 bl/s) underwater and 0.2 m/s (0.23 bl/s) on land rank lower middle-tier in Fig. 3.3, the AmphiHex-I design philosophy seems promising in terms of efficiency. Namely, as opposed to relying on separate propulsive mechanisms that may impede each other's performance, or a united propulsive mechanism that sacrifices specialization for average performance, transforming a propulsive mechanism's shape offers the ability to greatly hone locomotive performance in both environments.

After AmphiHex-I came AmphiHex-II (Fig. 3.3e). This robot introduced an entirely different mechanism than AmphiHex-I: manually adjustable variable stiffness legs. Its semi-circular legs are rigid, fan-shaped frames, and protect flexible flippers within. By adjusting a pin joint along the leg's length and the robot's chassis, one can set the leg to five different stiffnesses. Experiments with the robot underscore that modulating the stiffness improves locomotive performance based on fluid content in a soil-like terrain. It was found that higher stiffness limbs allow the robot to locomote fastest in sandy substrates and soft soils. An intermediate stiffness was found to be more efficient for locomotion in fluidized (25%) soil reminiscent of the littoral zone. Lastly, for swimming, the researchers found the highest stiffness elicited maximum achievable, sustained velocity [9].

Though legs give a robot the ability to skillfully traverse a wide swath of terrain, legged robots are generally slower and less energy efficient on flat land, especially when compared to wheeled robots [5]. Moreover, control of legged robots is much more complex than that of wheeled robots. Particularly in the aquatic environment, controlling legs as hydrodynamic surfaces for efficient propulsion represents an open area of research. Whegs™-style legs simplify the control problem by replacing articulated joints with just 1-DOF. However, Whegs™, as well as a majority of the legged amphibious robot designs mentioned, employ drag-based paddling to move through water. As mentioned, paddling is not an efficient mode of swimming, because thrust is only generated in half of the stroke [30]. Thus, alternative modes of aquatic locomotion must be explored and mechanisms developed to achieve those modes. One example of an alternative locomotion mode, incorporating separate jet nozzles on the bottom of a robot's legs [49, 93], seems like a promising strategy but requires highly complex modeling of jet orientation to optimize locomotion (moreover, this specific robot is extremely slow, as seen by its relative position in Fig. 3.3f). If land speed, hydrodynamics, or control complexity are precursors for a successful mission, legged amphibious robots may not fare well.

3.3.3 Undulating Amphibious Robots

The third class of amphibious robots is undulating robots, often those with a serpentine body. Key advantages of undulating robots are their high maneuverability in water, small turning radii on land, and multiple DOF that lend themselves to novel locomotion strategies and negotiation of restricted spaces. Arguably one of the most significant jumps in amphibious robotics coincides with the advent of the snake-inspired robot, AmphiBot. Unlike other land-based snake robots of the time, AmphiBot is capable of swimming and crawling, all with the same mechanism: undulation [17, 94]. AmphiBot's body is composed of interconnected, independently actuated modules. Selective actuation of each of the modules via a central pattern generator allows AmphiBot to undulate to move smoothly through water with a speed of 0.2 m/s (0.26 bl/s). However, it has wheels to overcome friction and attain higher speeds on land. In terms of relative speed to other robots, AmphiBot falls into the middle of the pack (Fig. 3.3g). Subsequent to AmphiBot, there have been a fair number of snake-like robots capable of amphibious locomotion. These follow-ups make slight variations to hardware in efforts to generate more productive thrust with each oscillation, such as including radially distributed wheels around the body, and placing continuous ridges along the body [95–97].

One group sought to integrate undulatory caudal fin swimming, propeller-generated thrust, and flipper-like control surfaces for locomotion in water with wheels for locomotion on land: the results were Amphirobots-I and II [98, 99]. Amphirobots are composed of a multi-link serial chain whose units possess passive wheels and has axles that can swivel both laterally and dorsoventrally, unlike previous amphibious undulating robots. This clever mechanism enables both dolphin- and fish-style swimming up to 0.45 m/s (0.64 bl/s) as well as serpentine crawling on land of 0.6 m/s (0.86 bl/s), positioning Amphirobot-II near the top of those surveyed in both categories (Fig. 3.3h). Caudal oscillation in the fashion of some fish happens to yield one of the lowest costs of transport among swimming modes as mass increases [22]. Yet, Amphirobot's agglomeration of components increases the projected area in Eq. (3.2), proportionally increasing drag, countering to some extent the merits of the efficient propulsive mode. Additionally, as mentioned, having multiple separate propulsive mechanisms obfuscates control, which the authors concede reduces the efficacy of their system [98].

The most recent amphibious undulating robot at the time of this writing originated at Pliant Energy Systems, an energy firm based out of Brooklyn, NY. Their robot, Velox, consists of a static, rigid body lined with two sets of dynamically undulating, elongate fins [100]. These fins are based on Pliant's blade-less energy-harvesting turbines that passively harness fluid flow. A geared transmission system internal to the robot pulls parts of the flexible fins up in a wave. The resulting coordinated undulation endows the robot with high mobility over a variety of terrain. Videos of the robot traversing snow, flat ground, and swimming freely in three dimensions testify to its effective united propulsive mechanism design [101].

Despite its superiority in water, undulating propulsion over land has several drawbacks. First, ongoing challenges with snake-like robots are to get them to traverse uneven terrain, and developing appropriate contact models for such traversal [102]. Second, undulation relies on high surface area contact between a robot's body and the underlying substrate. Friction or smoothness of a substrate therefore governs cost of transport much more than a legged robot experiencing less surface contact. Although friction issues have been partly addressed via the incorporation of passive wheels onto multi-segment robots, wheels are bulky protrusions to a robot's body plan that may further reduce ability to clear obstacles. From a hydrodynamic perspective, wheels can incur undesired drag forces. Thus it stands as an open challenge to devise undulating robots that modulate their substrate friction coefficient without negatively impacting other aspects of locomotion. Third, serpentine undulating robots do not generally have the capacity to bear large, centralized payloads due to size limitations of the modules composing their bodies. More work on centralized chassis-based undulating systems, like Pliant Energy Systems Velox, represents a promising future direction in this regard. In brief, if desiring a simplistic platform for transporting larger payloads or navigating uneven ground, current undulating robot designs may fall short.

3.3.4 Soft Amphibious Robots

The fourth and final class of amphibious robot, ones made primarily of soft materials, constitute a subset of the already small body of literature pertaining to amphibious robots. It is well-established that robots can benefit from new research in soft, responsive materials [45, 103]. The properties of soft materials—compliance, continuous deformation, stretchability, incompressibility, conference of hydrodynamic benefits [104, 105], and resilience to damage and harsh conditions [106]—make them apt candidates for incorporation into amphibious robotics.

To the best of our knowledge, the first explicitly declared soft amphibious robot was developed by Faudzi et al. Inspired by the salamander, the robot has an elongated body with short legs. The body and legs consist of McKibben pneumatic actuators. Though quite slow, selective contraction of McKibbens on various parts of its body enables the robot to traverse solid ground, sand, and patches of shallow water [47]. To enable underwater crawling of an amphibious soft robot, Tang et al. integrated two switchable adhesion actuators on distal ends of a bending actuator. Their robot can execute inchworm-style gaits while adhered to both submerged and dry substrates [46].

The salamander-inspired robot and the underwater inchworm-like crawler, being composed of entirely soft actuators, likely cannot bear significant payloads. Another amphibious crawling robot that demonstrated payload capacity and separated its soft actuators from its body is the un-tethered sea urchin-inspired robot developed by Paschal et al. [107]. The sea urchin bot consists of a rigid body, rigid spines, and soft bending actuators (analogs to tubercle feet on a real sea urchin). A unique aspect of the sea urchin robot is that it uses actuation of rigid spines in tandem with bending actuators to engage in bio-mimetic, in-place turning motions. The robot is also able to drag itself on land or under the surface of water. In spite of its high mobility, the robot is confined to ferrous surfaces because it relies on embedded magnets in the tips of its bending actuators for anchor points while dragging [107].

In another instance of utilizing separate soft actuators on a rigid robot body, soft pneumatic bending actuators were equipped as legs to an amphibious dog-inspired robot. The soft actuators were not implemented in a traditional sense, as with the previous two examples. Instead, they are pre-inflated and routed with cables. By pulling on the pre-inflated actuator with the cable, it straightens. Upon release of the tension in the cable, the actuator's stored energy snaps it back into the bent configuration. The researchers leveraged this mechanism to show the dog-inspired robot trotting on land and dog-paddling in water [4]. Though they provide sufficient force to propel the robot to land speeds of 0.18 m/s (0.34 bl/s)—a rate much faster than other soft amphibious robots—the pre-inflated actuators necessitate additional motors to pull the attached cables.

The same material properties that make soft amphibious robots flexible and resilient impede their locomotive performance. Soft amphibious robots substantially lag behind their rigid counterparts in terms of their reported maximum sustained speeds, as indicated by Fig. 3.3a–c. Lack of speed can be attributed to the dissipative effects of soft materials and the low force density of soft actuators relative to motors used on rigid amphibious robots. An open design challenge is thus to enhance speed of soft robots, both in water and on land, while retaining their desirable rheological properties. A wealth of soft actuation schemes that still have yet to be applied to amphibious soft robots, including shape-memory materials, chemically induced volumetric expansion, dielectric elastomers, and combustion [108–110], might facilitate higher speeds. A second drawback is soft robots' lack of payload-bearing capabilities. Even if they could be designed to move faster, entirely soft structures would buckle under external loads. Fortunately, recent work regarding granular and layer jamming and variable stiffness polymers offers novel ways to endow a compliant robot with rapid stiffness-changing capacity [111–115] and might prove useful if applied to amphibious soft robots.

3.4 Overarching Challenges

As evidenced in the literature, the exact design specifications for an amphibious robot traditionally depend on the task it is intended to complete. In some applications, like shoreline monitoring, capability to traverse muddy terrain and surface-level immersion in water with a small camera will suffice to complete all mission objectives. Other applications, however, like routine inspections of offshore rigs, may mandate climbing uneven terrain and deeper dives with specialized sensor suite payloads.

The various presented propulsive mechanism architectures—wheeled, legged, undulating, and soft—bring their own unique sets of advantages and disadvantages to the design table. As research strives to realize increasingly autonomous systems that are not specifically designed for a task, but rather are multi-functional entities, the following question stands: how does an engineer synthesize current amphibious robot propulsive mechanism designs to create new, highly effective ones? To help guide answers to this question, let us observe facts about the current state of robotic technology and review areas for improvement in each category.

Amphibious robots of all categories are outclassed by animals in terms of absolute speed, as shown in Fig. 3.3. Even the state-of-the-art robots that operate exclusively terrestrially or underwater fall short of animals in terms of max sustained speed (both in body lengths per second and absolute speed), operational duration capacity, acceleration, turning ratio, ability to maneuver in compact spaces, cost of transport, and stealth [116, 117]. Though metrics other than speed are not well reported in the literature for amphibious robots, one can infer that amphibious robots suffer from the same shortcomings (maybe more so) as their exclusively terrestrial or aquatic counterparts. With these observations in mind, improvements in the force density and compactness of actuators would be a significant leap for the field.

Wheeled amphibious robots could become much more effective if they are augmented to accommodate uneven terrain, swim in 3D, mitigate flow separation from wheel surfaces in water, and reduce environmental impact. Many of these improvements could be made by creating hybrid mechanisms that augment wheel morphology.

Legged platforms would benefit from simpler control policies (and correspondingly, actuation systems), as their lack of deployment in field missions to-date is attributed to complex control [118]. Existing force models for legged locomotion on granular media rely on assumptions of size and uniformity of particulates [119] that diminish their accuracy in the highly unstructured littoral zone. Thus, more detailed experiments should be conducted focusing on legged locomotion in fluidized sediment to converge on robust physical models that can inform actuation policies. Second, legged systems can be improved by hydrodynamic form factors, or more generally, ways to augment morphology between functional terrestrial and aquatic streamlined shapes.

Undulating robots could be modified for enhanced ground traversal. In contrast to limbless animals that can navigate almost any surface [120], undulating robots struggle with uneven surfaces or low friction coefficients [102]. Snake locomotion strategies of undulation, including concertina motion (used to move through restricted spaces like tunnels), sidewinding (limited to sandy terrain), and rectilinear movement (uses bottom scales to move without undulations of the body; useful for moving along tree branches), have been applied to robotics, but are far from mirroring the fluidity and efficiency of natural systems [102]. Simplified controllers that can replicate the diversity of complex undulating gaits would thus expand the utility of undulating amphibious robots. As with legged platforms, a fundamental understanding of undulating propulsion over fluidized sediment needs comprehensive experimental analysis and could help inform locomotion policies for littoral zones. Lastly, the lack of large centralized payload capability seems to be an inherent shortcoming of undulating. One solution could be towing a payload behind the robot. Another could be creating systems with a centralized chassis like Pliant Energy's Velox [100].

A consistent disadvantage among most wheeled, legged, and undulating robots presented in the preceding sections is that they are composed of immutable structures with high stiffness, precluding the capability to substantially adapt a propulsive mechanism or body structure for more effective locomotion in a particular environment. Zhong et al. took a step in this direction and showed how a transformable robot limb geometry could be used to enhance performance in water and on land [121]. Zhong et al. also showed that modulating stiffness of a robot's limbs can benefit its locomotion across fluidized sediment [9]. The results of studies such as these, in tandem with studies of terrestrial and aquatic animal locomotor adaptions [22, 30, 116], motivate two pillars to strive for with future amphibious robot designs: (1) endow shape change and (2) devise mechanisms that can switch between soft and rigid states. Soft amphibious robots are well-suited to adapting their shape and stiffness to the environment and therefore represent an untapped reservoir of potential for addressing the multi-faceted challenge of transitions between aquatic and terrestrial locomotion. However, they are not a panacea; as mentioned, soft robots have the prominent disadvantages of low speeds and reduced ability to bear payloads. A promising research avenue is thus developing systems that marry the advantages of soft and rigid materials into a cohesive robotic platform.

3.5 Case Study: Example Propulsive Mechanism for Efficient Amphibious Locomotion

Our group is currently building an amphibious turtle/tortoise-inspired robot with variable stiffness limbs that change between the shape of a flipper and a leg [115, 122]. We drew inspiration from the specialized flipper propulsor of the green sea turtle and the legs of the Galapagos tortoise (Fig. 3.4a). Aside from the propulsors, we noted that sea turtles and tortoises demonstrate similar body plans. In addition to being quadrupedal, they have protective shells occupying a large portion of their bodies. A hybrid robotic platform based on the turtle/tortoise body plan should permit highly efficient movement in both water and on land, moderate speeds and maneuverability in water, as well as stability to negotiate obstacles in the littoral zone. Furthermore, a rigid central shell lends itself to storing control system hardware and a heavy payload.

The limb of the robot is pictured alone in Fig. 3.4b and in the context of a rendered quadruped robot in Fig. 3.4c. The limb consists of an antagonistic pneumatic actuator pair whose strain limiting layers are thermoset polymers that are rigid below 60 °C. Heating up the thermoset polymer past its glass transition temperature softens it, and it is subsequently deformed into a round geometry using the pneumatic actuators. The actuators are held at the inflated state until the material cools, at which point it retains the leg shape. Heating up the material again induces relaxation and it morphs back to the flipper shape.

Placing the morphing limb in a flow tank, we varied its angle of attack and monitored lift and drag forces (inset of Fig. 3.4d shows components). Figure 3.4d illustrates how the airfoil geometry of the flipper markedly increased its glide ratio (ratio of lift to drag forces on an object) in water compared to the leg. Like a traditional airfoil, the peak of the flipper state's glide ratio occurred around an 8° angle of attack. The leg state, on the other hand, resembles a thick hydrofoil, delaying onset of stall to 30° and exhibiting much lower glide ratio [123].

We subjected the limb to compression tests in either its flipper or leg phase (Fig. 3.4e). The leg's circular cross section (and correspondingly increased moment of inertia) enhanced its capability to bear compressive loads relative to the flipper. Consider that the critical buckling load for a beam (leg) under compression is

$$P_{cr} = \frac{\pi^2 EI}{(kL)^2}, \tag{3.3}$$

where E is the elastic modulus of the variable stiffness material, I is the cross-sectional area moment of inertia, k is the length factor (1 for pin boundaries on either side), and L is the unsupported length of the limb. Based on the fact that

$$I_{circle} = \frac{\pi}{4}\left(r_2^4 - r_1^4\right) \tag{3.4}$$

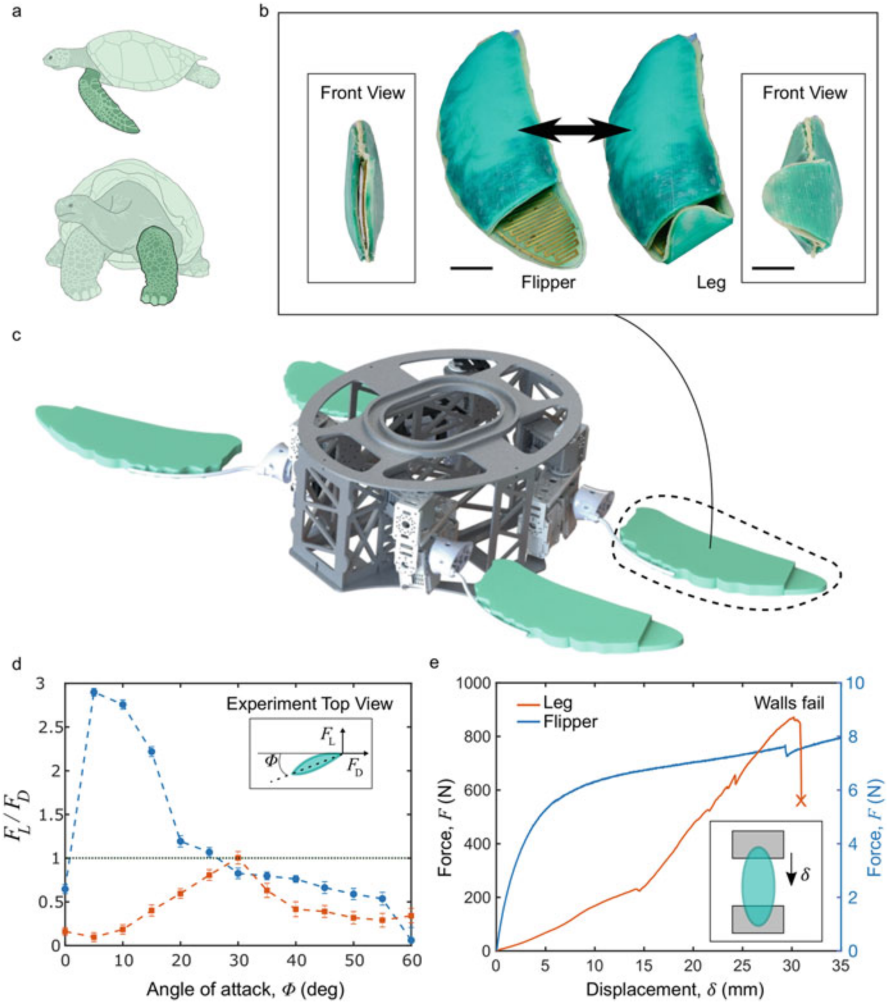

Fig. 3.4 (**a**) Sea turtles and tortoises demonstrate specialized propulsors for aquatic and terrestrial environments, respectively (images adapted from [115]). (**b**) Turtle-inspired limb: morphing between streamlined and load-bearing geometries allows it to perform well in water and serve as a strong leg for land. Scale bar: 40 mm. Inset scale bar: 30 mm (images adapted from [122]). (**c**) Rendering of morphing limbs equipped to quadruped amphibious robot. (**d**) Flow-tank test results at 0.6 m/s water speed. Ratio of lift to drag on the flipper and leg. (**e**) Compress-to-failure test for the flipper and leg

$$I_{rectangle} = \frac{bh^3 - b_1 h_1^3}{12}, \tag{3.5}$$

having as close to a circular cross section as possible enhances the limb's critical Euler buckling load [122].

Moreover, modulating the material's stiffness by heating it past T_g gives us the ability to tune the limb's mechanical response to external forces [115]. This ability may prove useful if bumping into obstacles, or further tuning propulsor performance for a given media [9]. By leveraging on-demand shape and stiffness changes and modulating the gait of the quadruped robot it is attached to, we hypothesize the limb will enable a legged amphibious robot to traverse land and water with high speed, efficiency, maneuverability, and payload capacity.

Beyond our case study, there are myriad soft, responsive, and rigid materials that could be incorporated into a single robot design to facilitate shape change and variable stiffness. Studies should seek to leverage shape change not just of a single propulsor, but of the entire robot body, to improve amphibious locomotion. For instance, changing its body from a fish to a legged quadruped form might grant a robot high speeds in water and on land (Fig. 3.2–soft). We also see work on varying stiffness in amphibious locomotion as a promising domain for future research. Combining variable stiffness materials with wheels, for instance, may enable a robot to selectively distribute its weight over a higher area to easily traverse patches of fluidized sediment; variable stiffness in combination with undulation may allow a robot to passively harness flow of the water to generate productive thrust; toggling between stiff states during the power stroke and compliant states during the retraction stroke can enhance swimming of legged robots; and so on. Lastly, new complementary control strategies must be developed in parallel with hardware that changes shape and stiffness. Controllers must account for an internal representation of the shape and stiffness states of a robot at all times to adapt to underwater currents, terrain grade, and viscosity of substrate, among other factors. For instance, central pattern generators commonly employed to control amphibious robots could be altered with terms that scale amplitude and phase offset as a robot changes shape or stiffness.

3.6 Conclusion

A brief discussion of biological propulsors provided insight into solutions that animals use to transition between aquatic and terrestrial locomotion. Amphibious animals strive to balance performance in various media, which results in mediocre performance. Contrastingly, highly derived species are well-adapted to a specific environment, often at the expense of locomotion in the other. The diversity of aquatic and terrestrial locomotor strategies and body plans invites researchers to combine mechanisms in clever ways to converge on some measure of optimal performance (Fig. 3.1). Our discussion on biology segued into a survey of amphibious robots, which we classify into those that utilize separate or united propulsive mechanisms. Further, we break down amphibious robots into (1) wheeled, (2) legged, (3) undulating, and (4) soft categories. We sort them by analyzing salient aspects of their body plans and locomotion strategies. The advantages and disadvantages of specific robot propulsive mechanism designs from each category highlight areas where future research effort is needed. In particular, it seems that soft, stiffness-changing materials offer significant opportunities to enhance mechanical resilience, hydrodynamic efficiency, and shape-morphing capability of amphibious robots. Our preliminary results toward a turtle/tortoise-inspired quadruped robot with variable stiffness morphing limbs provide a case study of this design philosophy. We believe there is promising future research oriented around amphibious robots that follow a similar design paradigm, one in which shape-morphing, variable-stiffness materials serve to balance the locomotive merits of rigid and soft robots in water and on land.

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