Adaptive Morphology

A Design Principle for Multimodal and Multifunctional Robots

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Morphology plays an important role in behavioral and locomotion strategies of living and artificial systems. There is biological evidence that adaptive morphological changes can not only extend dynamic performances by reducing tradeoffs during locomotion but also provide new functionalities. In this article, we show that adaptive morphology is an emerging design principle in robotics that benefits from a new generation of soft, variable-stiffness, and functional materials and structures. When moving within a given environment or when transitioning between different substrates, adaptive morphology allows accommodation of opposing dynamic requirements (e.g., maneuverability, stability, efficiency, and speed). Adaptive morphology is also a viable solution to endow robots with additional functionalities, such as transportability, protection, and variable gearing. We identify important research and technological questions, such as variable-stiffness structures, in silico design tools, and adaptive control systems to fully leverage adaptive morphology in robotic systems.

Soft Technologies for Adaptive Morphology

Soft technologies have recently emerged at the frontier of materials science and robotics [1]. Thanks to their intrinsic compliance, soft technologies are shifting the design paradigm toward a mechanical intelligence that, in synergy with cognition, is leading to artificial systems with an unprecedented level of adaptability [2]. Therefore, soft technologies that, just a decade ago, were considered niche research are now rapidly becoming widespread in our daily lives, spanning different scales and applications [1], [3]–[5].

Intrinsic compliance, i.e., the capability of undergoing large deformations without failure, also offers the possibility of adaptively changing morphology

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to enable new behaviors or functionalities. Morphology deals with the form of things and their composition, and it greatly influences the behavior and performance of both living organisms and robots [6]. Because different environments and functions require specific and tailored morphologies, many animal species have evolved morphable bodies to extend their operational range. Some animals can adapt their morphologies to facilitate locomotion in different substrates [7], to limit biomechanical tradeoffs [8], and to enable additional functionalities, for example, protection [9]. Adaptive morphology allows living organisms to overcome the boundaries imposed by fixed body shapes. Therefore, it is not surprising that a great deal of research effort has been devoted to the development of highly reconfigurable artificial systems with adaptive morphologies. Traditionally, adaptive morphology has been explored using self-reconfigurable robots—modular systems that rearrange their relative position in space and connect together [10]. Modular robots of different shapes, controlled by dedicated planners, provide a glimpse of the potential offered by adaptive morphology [11]–[13]. However, due to their intrinsic mechanical complexity, rigid components, and limited scalability, modular robots have been mostly used as proof of concept.

Leveraging soft technologies and new manufacturing processes, adaptive morphology can be a powerful design principle for engineers who want to increase the flexibility, efficiency, and adaptability of robotic systems. Morphing structures have the potential to pave the way for a new class of intelligent machines: mobile robots that accommodate critical but conflicting locomotion requirements, multifunctional robots that reconfigure their shape on the fly, soft wearable robots, and more. In this article, we highlight benefits and challenges of adaptive morphology with the help of examples in the field of locomotion and functionalization of animals and robots.

Adaptive Morphology in Locomotion

During locomotion, animals use their muscles to generate forces that are transferred to their environments through appendages with highly specialized morphologies. The morphology and material properties of a locomotion system are strongly dependent on the environment and define the way animals move, and, therefore, their dynamics (e.g., locomotion gaits and agility), energy efficiency, and control strategy [14]. Many animals exploit adaptive morphology to extend their dynamic envelope, to reduce tradeoffs (e.g., velocity versus maneuverability), and to transition between multiple substrates. Nature is constantly inspiring the design of artificial locomotion systems [15], [16]. Therefore, fundamental knowledge and design paradigms can be elucidated and applied for the development of more robust and versatile mobile robots by understanding the role of adaptive morphology in animal locomotion.

Adaptive Morphology in a Single Locomotion Mode

When an animal's operational space is restricted to a single substrate, morphing appendages are beneficial for extending locomotion capabilities by reducing tradeoffs. A classic example is a bird's wing, which can be quickly morphed to obtain different dynamics, extending the flight envelope of the animal [8], [17], [18], i.e., optimal performances with limited tradeoffs over a wide variety of radically different flight conditions. A bird's wing can be morphed for different flight modes because it is composed of an articulated skeleton controlled by muscles and covered with feathers that can overlap [17]. Birds exploit fully deployed wings to maximize wingspan and surface with a beneficial effect on lift and energetic efficiency at low speed, e.g., during soaring, or to increase maneuverability for tight turns. Wing adaptation for low speed is further enhanced by an increased airfoil camber induced by modifications of the feather curvature, driven by dedicated tendons [17]. However, when high speed is required, wings can be quickly retracted and swept back and feathers flattened to reduce drag. Partially folded wings are used during aggressive flights, for example, to perform escaping or hunting maneuvers. Birds exploit folded wings also to fly in very cluttered environments and traverse gaps barely larger than their bodies [19]. Wing morphing is also exploited in flapping flight by birds [20] and bats [21]. During a wingbeat cycle, the wing is fully extended in downstroke and folded in upstroke to reduce the energetic costs produced by drag and inertia. Adaptive morphology is also used by terrestrial species. For example, the Mount Lyell salamander (*Hydromantes platycephalus*) [22] and several species of leaf-roller caterpillar [23] morph their body into a wheel to rapidly escape predators instead of walking.

A bird wing can be morphed for different flight modes because it is composed of an articulated skeleton controlled by muscles and covered with feathers that can overlap.

Engineers have been inspired to develop drones with extended flight envelopes by morphing wings [24], [25]. In small drones, passively morphing wings have been demonstrated to increase robustness against wind gusts [26]. Such wings are composed of a flexible carbon fiber skeleton covered with a stretchable latex membrane [Figure 1(c)]. The wings dynamically adapt to the airflow thanks to a tuned aeroelastic washout of their compliant structure. In response to turbulences, the membrane extends and the frame twists to maintain an almost constant lift. Nonflapping and actively morphing wings have been investigated in a series of drones developed by Grant et al. [27]. Inspired by gulls, the drones have shoulder and elbow joints that control the wing's dihedral [Figure 1(a)] and swept [Figure 1(b)] angles. The wing is composed of a multijoint carbon fiber frame that is covered with an inextensible membrane and actuated through

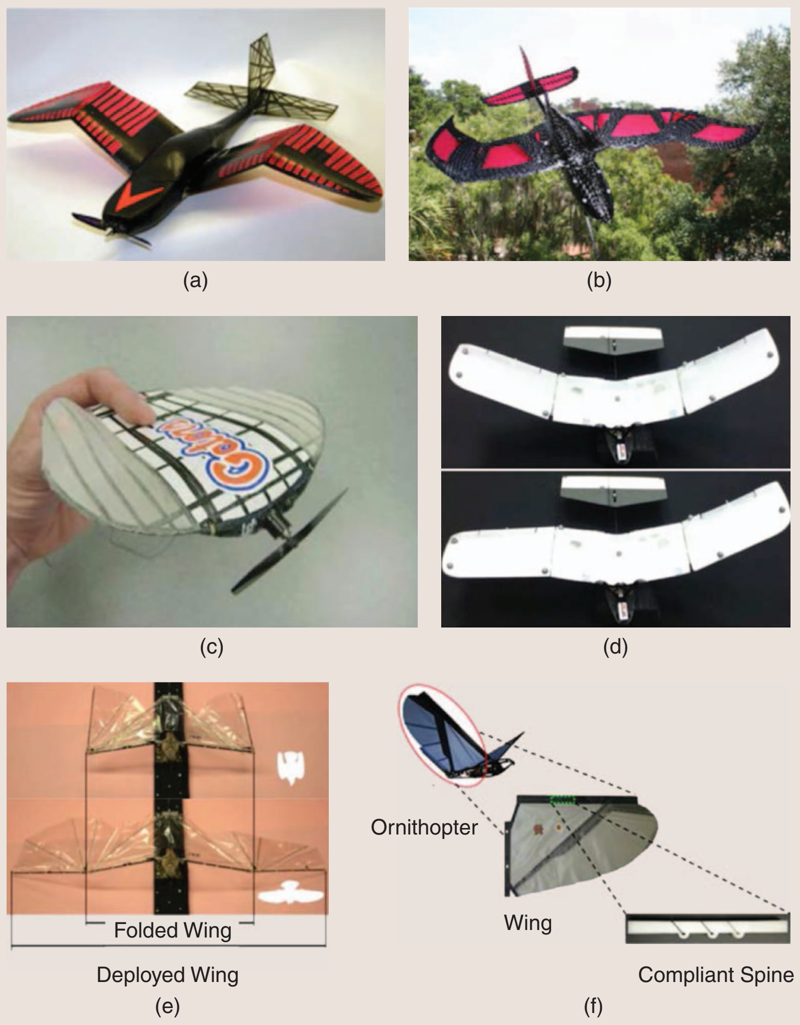

Figure 1. Examples of drones with morphing wings. (a) and (b) Gull-inspired drones with controllable dihedral and swept angles [27]. (c) Flexible wings for small drones [26]. (d) Articulated wing for flight control [28]. (e) Flapping wings with articulated elbow joint [29]. (f) Flapping wing with flexible leading edge [30]. (Photo courtesy of IHOP Publishing.)

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servomotors. Simulation of the flight dynamics demonstrated that morphing is beneficial to endow a single platform with conflicting performances such as improved steep descent, better crosswind resistance, and reduction of turning radius, therefore limiting the tradeoffs that would arise from a fixed wing morphology. Paranjape et al. [28] proposed an articulated wing with a movable dihedral angle to control flight path and heading angles in a tailless drone inspired by birds [Figure 1(d)]. Each wing is composed of a fixed section and a movable section actuated by a dedicated servomotor. Using closed-loop control algorithms, the drone has demonstrated successful landing maneuvers on a human hand. Similar to birds [20] and bats [21], morphing wings improve the energetic efficiency of flapping robots by exploiting passive unfolding driven by centrifugal acceleration [29] or by asymmetric bending [30]. In the former, the wing has an articulated skeleton with a foldable elbow joint that is alternatively retracted and folded during flapping [Figure 1(e)]. In the latter, the leading edge includes a contact-aided compliant spine. In the upstroke, the leading edge of the wings bends to minimize drag, while in the downstroke the system locks holding the leading edge in a straight position [Figure 1(f)].

Similarly, adaptive morphology of the entire body or locomotor structure has also been used in terrestrial robots. For example, Whegs are a series of high-mobility terrestrial robots with legged wheels developed according to principles taken from insect locomotion [15]. Whegs have undergone several design iterations aimed at improving the negotiation of uneven terrains through passive morphing. For instance, similar to cockroaches [31], the latest versions are equipped with a passive body flexion joint to bend the front half of the body down to avoid high centering during climbing [32]. Inspired by Whegs, Kim et al. [33] developed a robot equipped with passively morphing wheels that combines the advantage of both circular and legged wheels [Figure 2(a)]. On flat surfaces, the wheels have a circular shape but can passively morph in whegs to negotiate obstacles. These morphing wheels reduce tradeoffs caused by a change in the substrates and are well suited to obstacle negotiation on uneven terrains while maintaining efficiency and speed on flat terrains. She et al. [34] proposed a similar concept with three-dimensional (3-D)-printed wheels that can actively transform into legged wheels. With the same goal as the previous robots, Quattroped [35] is equipped with four wheels that can morph into legs in uneven terrains. Yet another robot inspired by cockroaches is RHex [36], which easily and efficiently negotiates rough terrains through six continuously rotating compliant legs. RHex has undergone multiple series of design iterations, some of which embed morphing appendages to increase adaptability. For example, Sprawl-Hex [37] and a sprawl tuned autonomous robot (STAR) [38] [Figure 2(b)] are six-legged robots with a variable sprawl angle that combines the advantages of both vertical and in-plane locomotion. At low sprawl angles, the robots' stability and velocity are comparable to a similar wheeled robot, but, at higher sprawl angles, they have better grip and can overcome higher obstacles. Also, at small sprawl angles, the flattened body of the robot can move through narrow gaps. Galloway et al. [39] implemented a RHex robot with legs that adapt their stiffness when morphed to run effectively over a broad range of terrains. Inspired by caterpillars [23], GoQBot [40] is a robot that morphs before rolling. Combining a silicone soft body with shape-memory alloy (SMA) actuators, the long and slender robot can be morphed into a wheel and propelled using a ballistic rolling behavior [Figure 2(c)].

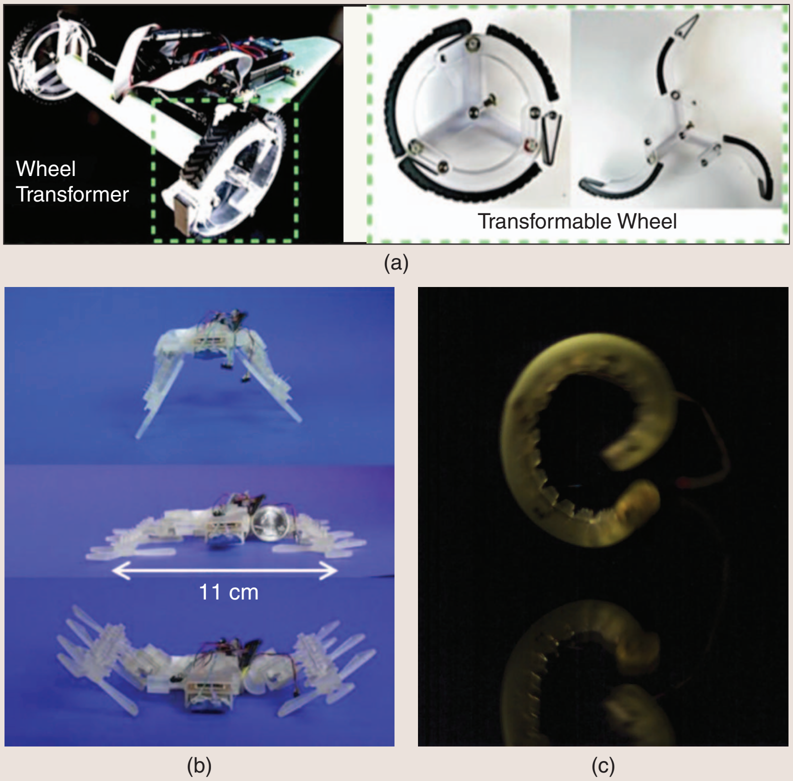

Figure 2. Examples of terrestrial robots with morphing structures. (a) A robot equipped with circular wheels that can morph in whegs to negotiate obstacles [33]. (b) A robot with controllable sprawl angle to combine the benefit of vertical and in-plane locomotion [38]. (c) A GoQBot during rolling locomotion [40].

Adaptive Morphology in Multimodal Locomotion

Several organisms operate with high efficiency across different substrates. Due to variations in physical parameters, different environments often put conflicting selection pressure on the morphology of the locomotion appendages. Therefore, it is not surprising that multimodal species evolved morphing appendages to facilitate the transition between environments. For multimodal animals, adaptive morphology compensates for environmental variability to reduce tradeoffs that would derive from a highly optimized but fixed morphology. A good example of the benefits of adaptive morphology is given by terrestrial or aquatic species with aerial competences. Terrestrial and aquatic movements require a streamlined body to enhance traveling through cluttered terrains [41] and reduce drag during swimming [42], [43]. In contrast, flight requires large lift-generating surfaces to support the animal's weight [17]. Therefore, several multimodal aerial species resort to morphing structures, which are folded during terrestrial or aquatic locomotion to occupy small spaces and can be deployed during flight to maximize support.

For instance, arboreal animals often utilize a deployable membrane, the patagium, to enable aerial locomotion. Frogs belonging to the genus *Rhecophorus* have enlarged hands and feet with strong webbing that is deployed when the frog leaps through the air. Experiments with living animals and models show that deployed webbed feet improve traveling distance and maneuverability during gliding [44]. Mammalian gliders utilize a larger and more effective patagium spanning between the forelimbs and hind limbs [45]. For example, in the flying lizards of the genus *Draco*, the patagium is supported by elongated ribs controlled by a complex muscular system [46], [47]. Decoupling the large patagium from the limbs seems to be a clever solution to prevent hindering of terrestrial locomotion [48]. Among arboreal animals equipped with patagia, bats achieve remarkable flight competences [49] while also displaying various degrees of

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terrestrial locomotion. Although most bats move awkwardly on the ground, the vampire bat *Desmodus rotundus* is an extremely agile crawler and runner and is also very agile in flight [50], [51]. Biologists speculate that this multimodal capability probably evolved to enable the blood-sucking animal to quickly sneak up on prey from the ground.

Flying snakes belonging to the genus *Chrysopelea* are arboreal animals that climb on trees and glide down for hunting. Instead of deployable membranes, flying snakes exploit a peculiar morphological adaptation for aerial locomotion. After reaching the outermost branches, they initiate gliding with their classical undulatory locomotion coupled with a morphed body capable of enhancing lift. Flying snakes morph the circular section of their body into a triangular shape by flattening their ribs [52]. This morphing behavior ensures significantly more lift than the circular body section used during terrestrial locomotion [7].

Animals that operate in air and water benefit from adaptive morphology too. In flight, wings must be slender and have low wing loading for efficient flight. In water, however, short wings with high wing loading are better to cope with increased density and viscosity. Aquatic birds belonging to the family of Alcids meet these conflicting requirements by using morphing wings that partially fold and sweep back during underwater locomotion to reduce the induced drag and increase the lift-to-drag ratio [43]. During their diving maneuver, gannets plunge into the water from up to 30 m high [53]. They sweep back their wings in an effort to maximize water penetration and minimize injury risks [54].

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These multimodal capabilities are attracting the attention of roboticists attempting to develop more flexible and adaptable machines [48], [55], [56]. For example, some multimodal robots exploit morphing appendages to facilitate the transition between substrates. Foldable wings can be added to jumping robots to enable gliding. Kovač et al. [57] developed the jump glider illustrated in Figure 3(a). During the ballistic jump motion, the wings are first folded to reduce drag and afterward are deployed in midair to stabilize attitude and glide. In this case, the wings' adaptive morphology was not seen as offering improved performance but adding complexity and weight to the robot. Woodward and Sitti [58] proposed a jump-gliding robot in which the wings are integrated into the legs [Figure 3(b)]. After the jump, the two four-bar leg structures stretch membranes and turn parallel to the ground, behaving like a wing. Due to the additional membranes, the maximum jumping height is decreased by 20%, but the horizontal traveled distance is increased.

The Morphing Micro Air–Land Vehicle (MMALV) [59] and the Deployable Air–Land Exploration Robot (DALER) [60] [Figure 3(c)] are two drones with powered aerial and terrestrial locomotion. MMALV has the morphology of an airplane with two additional whegs for terrestrial locomotion. The robot is equipped with a fanlike foldable wing that is retracted on the ground to avoid hampering locomotion in cluttered environments. The wing has a carbon fiber skeleton covered with a foldable nylon fabric and is actuated with servomotors. DALER has the morphology of a flying wing but has a more integrated design whereby the extremities of the wings, the wingerons, are recruited for both flight control and terrestrial locomotion. The adaptive morphology of the wing is further exploited compared to MMALV. In addition to a reduced wingspan for improving mobility in cluttered terrestrial substrates, folded wings move the wingerons closer to the center of mass of the robot, maximizing their grip on the ground, and consequently increase the speed and reduce the cost of transport (COT). As illustrated in Figure 3(d), the COT of terrestrial locomotion when the wings are folded (green line) is much lower than the COT for open wings (red dashed line), especially at high speeds. The foldable wing allows reduction in the tradeoffs that a fixed morphology optimized for flight would impose on terrestrial locomotion.

Wings with adaptive morphology have also been explored for hybrid aerial/aquatic locomotion. Lock et al. numerically [61] and experientially [62] investigated a morphing wing for the future development of a flapping wing aquatic drone. During swimming, the swept angle of the wing is increased and the area reduced to minimize induced drag. Adaptive morphology has been exploited by the amphibious robot AmphiHex [63]. The robot is equipped with six legs that can be transformed into flippers [Figure 3(e)]. On the ground, the legs have a curved shape, like RHex [36]. However, the legs can be flattened, assuming the shape of flippers for maneuvering under water. The legs are composed of multiple interconnected segments and driven by cables for morphing.

Functionality Through Adaptive Morphology

Living and artificial systems also exploit adaptive morphology to add functionality. Because the function of a system is often directly encoded in its shape and structure, adaptive morphology is a promising solution for designing multifunctional devices. For example, the research field of programmable matter is concerned with the theory, design, and manufacturing of systems that reconfigure assuming different morphological configurations or functionalities starting from minimal sets of constitutive elements. Physical implementations of programmable matter are based on a bottom-up approach, starting from building blocks, which can reversibly assemble or disassemble into 3-D objects. Rigid modular robots capable of packaging into a lattice structure and reconfiguring using self-manipulation or mutual displacement have been investigated for a long time, and the theoretical background for more advanced implementations has been settled [10]. Gilpin et al. developed the robot Pebbles [64], cubic centimeter robots that connect and detach using electropermanent magnets and share energy and information. Starting from a lattice of Pebbles, the distributed system can assume the desired morphology by detaching unnecessary robots. Rubenstein et al. [65] developed a swarm of a thousand robots capable of self-assembling in complex two-dimensional (2-D) shapes. Each individual of the swarm is a miniature and low-cost robot called *Kilobot*. They are equipped with vibration motors controlling locomotion and infrared sensors for local communication. Using a decentralized algorithm, each individual of the swarm coordinates its movements to create the shape and potentially the function as defined by the user. Cheung et al. [66] presented a technique for the self-assembly of one-dimensional strings of permanently connected modules. The strings can assume different 2-D or 3-D configurations by wrapping or folding. Self-assembly of permanently connected modules is a promising assembly technique because it has a superior range of achievable morphologies compared to other assembly techniques and it simplifies the modules' design so as not to require complex docking mechanisms.

Smart matter based on rigid modules has two main drawbacks, a resolution limited by the size of the building blocks and a lack of controllable stiffness. Germann et al. [67] proposed to replace rigid building blocks with self-foldable strings of soft cells. The cells are made of soft silicone rings, can assume varying levels of softness, and can connect together using magnets. Because the folding behavior of the chains of soft cells is mediated by their softness, variable-stiffness building blocks increase the morphological diversity of the resulting structures for a given size and type of cells.

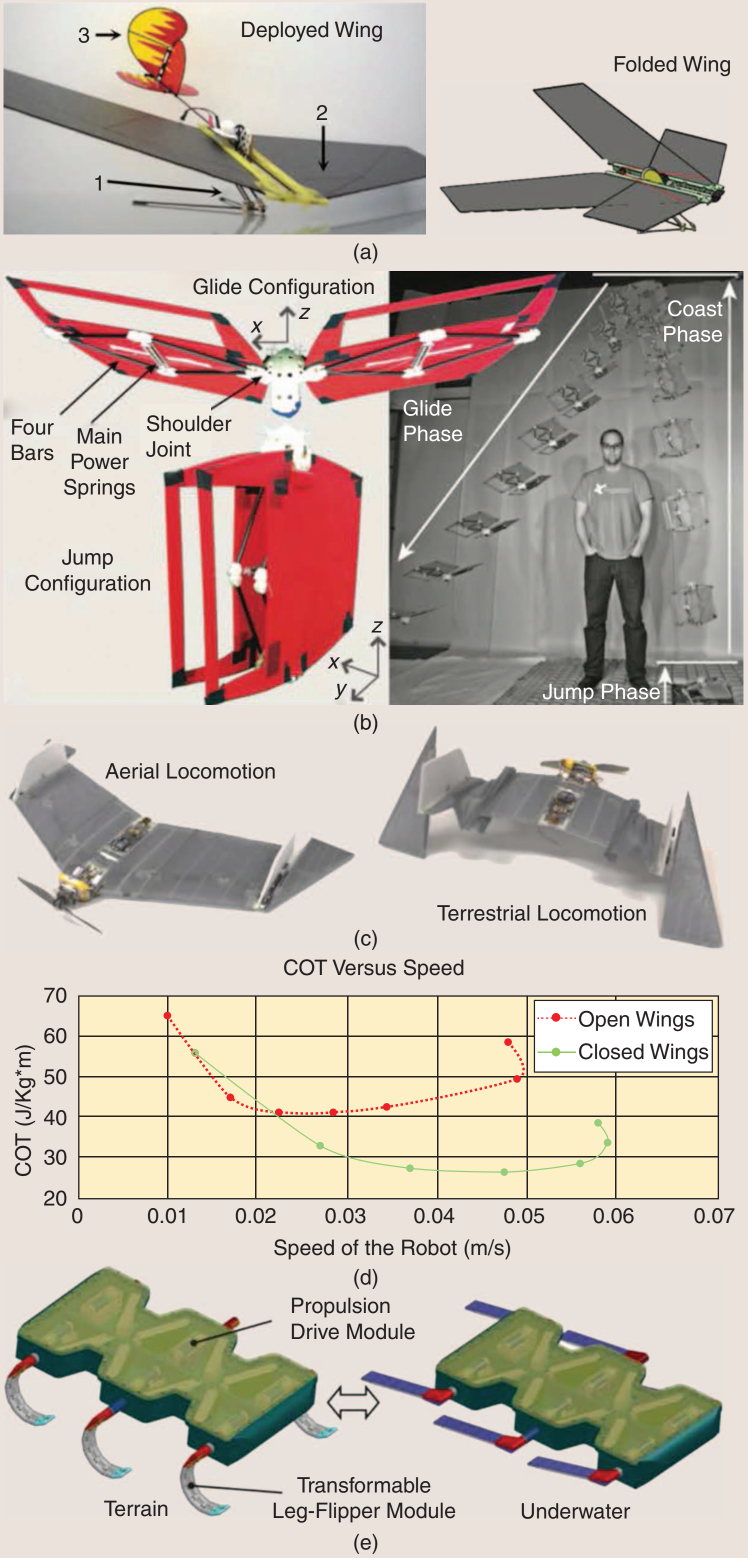
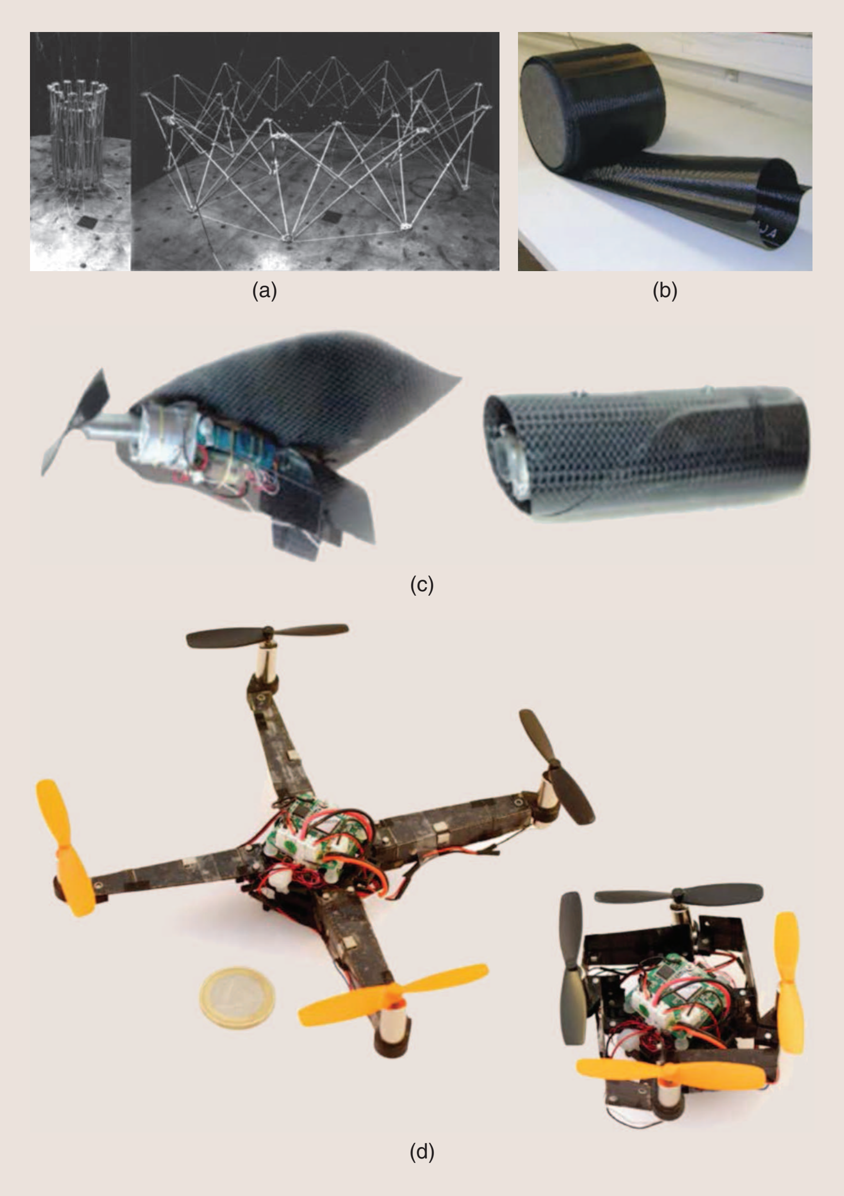


Figure 3. Examples of morphing multimodal robots. (a) A jump-gliding robot composed of (1) a jumping mechanism, (2) a foldable wing for gliding, and (3) a tail for aerial control [57]. (b) A MultiMo-Bat with wings integrated in the legs [58]. (c) A DALER, capable of flying and crawling on the ground. (d) Using adaptive morphology, the DALER can maximize speed and efficiency during terrestrial locomotion [60]. (e) The AmphiHex, an amphibious robot with morphing legs [63].


(a)

(b)

(c)

(d)

Figure 4. Examples of foldable structures: (a) a multijoint solar array [71], (b) a flexible collapsible boom [73], (c) a drone with a foldable wing [75], and (d) an origami foldable quadcopter [79].

Other physical implementations of programmable matter are based on top-down approaches to overcome hardware limitations. Researchers are investigating continuous structures with integrated actuators, sensors, and computational capabilities that can actively morph. An example is foldable programmable matter that consists of a functionalized origami sheet that can fold to assume different shapes [68]. Origami is a promising approach to programmable matter because any specific polyhedron can be approximated with a large enough origami sheet and a tailored crease pattern. The origami sheet is an integrated system composed of rigid fiberglass tiles connected through silicone hinges. Embedded SMA actuators activate the folding pattern of the origami sheet. Given the desired final configuration, the activation sequence and folding directions are computed by shape-specific algorithms. Although many of the aforementioned implementations are concerned with scientific and technological explorations, adaptive morphology has also recently been used to address practical functions, such as transportability, protection, and variable gearing.

Adaptive Morphology for Transportability

Foldable structures that can be easily packaged for transportation are of great interest for space, aeronautical, and civil applications. Such structures may occupy a fraction of their volume when folded, while preserving the conventional load-bearing functionality when deployed. As a first approximation, deployable structures are classified in two families [69], multijoint and continuous deformable systems. Multijoint structures are composed of rigid links connected with movable joints. They fold locally and offer wide freedom in the selection of folding patterns; however, mechanical complexity limits their scalability.

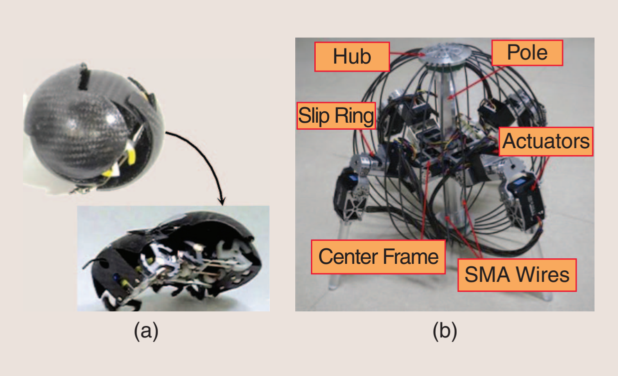
Foldable multijoint structures have been successfully exploited to develop aerospace structures [70], [71] [Figure 4(a)], civil structures, and most of the foldable drones available on the market. Continuous deformable elastic structures have better manufacturability and scalability, but folding is constrained by the strain limit of the material. Continuous foldable structures have been used for aerospace [72], [73] [Figure 4(b)] and civil and medical [74] applications as well as wings. The wing proposed by Jagdale et al. [75] is manufactured using composite materials, and its geometry is tailored to remain stable during flight but to buckle into a smaller package under manual pressure [Figure 4(c)]. The family of continuous foldable structures also comprises inflatable systems, thin-walled membranes that can bear flexural loads after pressurization. Several drone prototypes with inflatable wings have been developed and tested [76], [77]. These wings are composed of a series of longitudinal pressurized tubes approximating the desired wing shape. The resulting bumpy surface can be covered with compliant skin to improve aerodynamic efficiency for Reynolds numbers over 500,000 [77].

In addition to the aforementioned approaches, origami manufacturing is emerging as a viable alternative [78]. Two-dimensional laser micromachining is used to engrave the desired crease pattern on a multilayer material. This manufacturing method allows for implementing complex 3-D folding patterns with a simple, scalable, and affordable process. The authors developed a pocket-sized foldable quadcopter [Figure 4(d)] with origami arms [79]. The arms can be wrapped around a central main frame and, as soon as the propellers start to spin, they autonomously deploy in 0.3 s. The crease pattern is tailored so that the arm locks in a stiff configuration when deployed to ensure good controllability of the drone.

Adaptive Morphology for Protection

Adaptive morphology can also add protection against external threats or collisions. For instance, the pillbug (*Armadillidium vulgare*) rolls into a ball when disturbed. This conglobation behavior is triggered by strong vibrations or pressure and creates an external spherical shell for the protection of the sensitive ventral surface of the animal. Conglobation offers protection against predators and lethal conditions in the external environment and acts as a water conservation mechanism [9]. Inspired by such capabilities, the latest version of Pillbot [80] can assume different morphologies for protection and locomotion [Figure 5(a)]. For protection, the robot rolls up in a spherical, shock-absorbing shell that ensures survival when the robot is hand launched. Once it has safely landed, Pillbot opens and exposes its whegs for locomotion. Similarly, the quadruped walking robot with a spherical shell (QRoSS) [Figure 5(b)] is a morphing robot capable of storing its legs inside a protective spherical cage [81]. The cage protects the robot when thrown to the floor, but after landing, the legs are deployed from the cage and the robot can start its mission. This approach is also exploited by Kovač et al. [82] in a steerable jumping robot. The robot is equipped with a cage that stores and protects the leg of the robot, which is subsequently deployed for jumping.

Shim et al. [83] developed the Buckliball, an elastic continuum conceived for drug encapsulation and protection during delivery. As proof of concept, they developed a shell patterned with a regular array of voids and ligaments. The latter buckle below a certain internal pressure, leading to a folding behavior (volume reduction up to 54%) of the structure that can be used for drug encapsulation and delivery. Mountcastle et al. [84] reported a biomechanical strategy exploited by wasps to mitigate the effect of collisions on their wings. A flexible joint along the leading edge coupled with a flexion line allows the wing tip to bend in case of collision, reducing wear. In robotics, Stowers and Lentink [29] showed that passively morphing wings can absorb frontal impacts with no damage to the drone. Similarly, in the DALER multimodal drone [60], the wing morphing mechanism relies on tensioning springs that can be used to absorb energy in case of collision, for example, during landing.



(a) (b)

Figure 5. (a) The Pillbot and (b) QRoSS are two robots that can morph into a protective configuration to withstand collisions when dropped [80], [81].

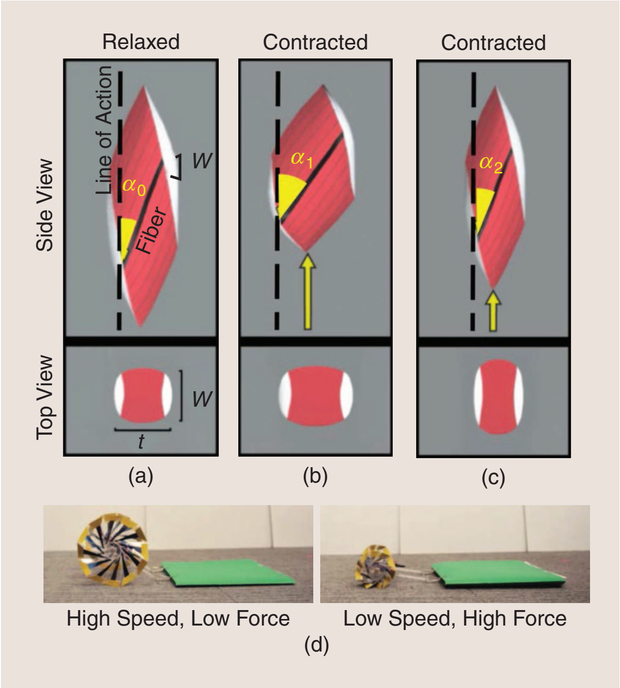
Adaptive Morphology for Variable Transmissions

Transmissions with a variable gear ratio are the typical engineering solution to minimize the tradeoff between force and velocity for actuators with limited power, enabling efficient operation under different dynamic conditions. Usually variable transmissions are cumbersome and complex because they require auxiliary gears, clutches, and actuators. However, animals evolved an elegant and simple variable transmission that is directly integrated in pennate muscles and exploits adaptive morphology.

Pennate muscles [Figure 6(a)] are biological actuators composed of muscle fibers that are obliquely oriented with respect to the line of action of the muscle (pennation angle α_0). The contraction of pennate muscles is the result of fibers both shortening and rotating, the latter being associated with increasing values of the pennation angle [$\alpha_1 > \alpha_0$ and $\alpha_2 > \alpha_0$ in Figure 6(b) and (c), respectively]. High values of fiber rotation increase shortening and velocity during muscle contraction. On the other hand, during rotation, fibers become more oblique, and their load-bearing capability along the line of action of the muscle is decreased. Overall, the amount of rotation defines the tradeoff between fast and strong contractions.

Origami manufacturing is an emerging technology for the development of morphing structures.

Azizi et al. [85] showed that fiber rotation passively adapts to the loading condition on the pennate muscle, favoring either fast contractions or high forces similarly to a variable transmission. The value of fiber rotation self-tunes to different loading conditions through a passive adaptation of muscle morphology. During light lifting [Figure 6(b)], the muscle shortens while it increases its



(a) (b) (c)

High Speed, Low Force

Low Speed, High Force

(d)

Figure 6. (a) A relaxed pennate muscle with thickness (*t*) and width (*W*). The pennation angle (α_0) is identified by the yellow insert. When pennate muscles lift low loads (b), their thickness increases with respect to the relaxed condition (a). This morphing favors the rotation of the fibers, therefore large and fast contractions. Instead, during heavy lifting (c), thickness variation is constrained, and the fibers are maintained more aligned with the load. This morphology increases the bearing capabilities of the muscle at the expense of a reduced contraction velocity. (d) A robot equipped with origami wheels that passively decrease their diameter to efficiently tow heavy loads while not compromising high speed when towing light loads [88].

thickness, leaving the fibers free to rotate. This favors large and rapid contractions of the muscle while exerting low forces. Instead, heavy lifting [Figure 6(c)] constrains thickness variation and therefore the rotation of the fibers, so that they remain better aligned to the load. This favors force generation at the expense of shorter and slower contractions. In summary, pennate muscles passively adapt their morphology by tuning their thickness based on the load to vary gearing and conveniently extend their dynamic envelope to different load conditions. Azizi and Roberts [86] implemented this working principle using an artificial muscle composed of an array of McKibben actuators [87]. The working principle is also applicable to other types of soft actuators that can morph under loading. Felton et al. [88] implemented a continuously variable transmission using a morphing origami wheel [Figure 6(d)]. When the robot has to tow a heavy load, the wheel passively reduces its diameter to amplify the ground reaction force for a given motor torque input. The tradeoff between speed and efficiency is minimized because the robot can tow payloads with high motor efficiency without sacrificing maximum speed when unloaded.

Challenges and Potential Solutions

The living and artificial systems described previously suggest that adaptive morphology is a promising design principle to accommodate conflicting requirements extending the dynamic envelope during locomotion and to develop multifunctional systems. However, the real potential of adaptive morphology is often bounded by the use of conventional design strategies and rigid materials. Currently, morphing systems mostly rely on conventional kinematic chains implemented using a multijoint approach, resulting in bulky and often fragile systems. Soft materials can unleash the true potential of adaptive morphology as demonstrated by a few yet promising and elegant implementations. Clearly, the implementation of morphing per se, and especially one based on soft materials, is calling out for new materials, design strategies, and control algorithms.

Morphing requires materials that can be deformed with a small amount of energy and that undergo large and reversible strains but can also withstand loads. The load-bearing capability is important in several applications: in foldable structures during operation and in locomotion, where high forces are periodically generated during the interaction with the environment. These conflicting requirements make soft materials alone not always a viable solution for implementing adaptive morphology. A first solution to mitigate this challenge consists of the development of variable-stiffness materials that can become soft during morphing and stiff during regular operation. Variable-stiffness structures can be obtained by integrating soft materials (e.g., silicone and natural rubber) with low melting point alloys [89], shape-memory polymers [90], wax [91], electro- and magnetorheological fluids [92], and jamming systems [3], which are capable of changing stiffness under certain stimuli such as temperature, electric or magnetic fields, and pressure. A second solution could be to develop variable-stiffness mechanisms using origami manufacturing. The crease pattern of origami systems can be tailored to easily fold during morphing but also to rigidly lock in the desired configurations during operation [78], [79], [93]. A third solution could be to develop systems with structural instability, namely, the capability of slender elastic structures to undergo large geometric deformations with small material strain and stress [94]. This allows the implementation of morphing structures composed of relatively rigid, load-bearing materials that are capable of reversibly transitioning between radically different shapes. Furthermore, structural instability is scalable because it is mostly correlated to material properties and aspect ratio rather than to absolute length scales. While in the past structural instability has been considered as a source of structural failure, there is now a trend of *Bukliphilia* [94] with an increasing number of devices relying on structural instability for functionalization [75], [83].

Another challenge is the capability of predicting the behavior of a morphing system that results from a highly coupled orchestration of multiple elements, such as material properties, morphology, control algorithms, and environmental interactions. An efficient exploration of such large and highly coupled spaces requires specialized design tools. Finite elements or particle-based [95] simulators for soft materials offer a solution for assessing relatively simple situations, for example, passive morphing driven by interaction with the environment [26]. However, mechanical simulators alone are not enough to overcome the limitations of human intuition in the exploration of more complex morphological transformations. Questions such as how to adapt the morphology to transition between substrates or how to modify controllers and locomotion gaits after morphing need automated design tools. Evolutionary algorithms promise to be a very effective tool for the exploration of interactions among environment, morphology, and behavior. Sims [96] pioneered this field, simulating organisms with different morphologies and behaviors evolved from simple primitive shapes. Cheney et al. [97] extended evolutionary algorithms incorporating soft elements to increase the complexity of the evolved morphologies. Rieffel et al. [98] proposed tools to study the growth of soft robots and therefore the coevolution of body morphology, muscle placement, and firing patterns. Although these in silico tools are not directly optimized for adaptive morphology, they are promising methods. We expect that the capability of exploring this multidimensional design and control space will significantly reduce the development time and provide helpful insights into design choices with minimal tradeoffs and higher adaptability.

In addition, control systems will require plasticity to deal with changes in body morphology and functionality. The aforementioned evolutionary tools can generate controllers offline that can be strategically recalled during operation depending on the substrate of locomotion or required functionality. Another approach is to develop control architectures that can be directly tuned during operation by changing few parameters. Ijspeert et al. [99] showed that central pattern generator (CPG)-based controllers can handle the transition between swimming and crawling by simply adapting the frequency of the CPG oscillators. Yet a different approach relies on controllers that self-adapt to severe morphological changes directly during operations. Bongard et al. [100] developed algorithms to infer robot morphology and subsequently generate appropriate walking gaits. As recently shown by Cully et al. [101], adaptive controllers can compensate for morphological failures in less then two minutes. The proposed algorithm generates an a priori knowledge of the behavior of the robot in case of failure and relies on a trial-and-error algorithm to identify the best controller given the condition of the robot. These adaptive controllers are complementary to adaptive morphology and require further specialization to enhance beneficial synergies.

Future Perspectives

Given the interdependencies among morphology, environment, and behavior, adaptive morphology is an emerging and powerful design principle that can increase flexibility, robustness, and efficiency over a broad range of substrates and functions. When moving within a single substrate, morphing extends the dynamic envelope of locomotion systems. When transitioning between different substrates, morphing appendages limit tradeoffs. Adaptive morphology is also a viable solution to endow robots with additional functions, for example, transportability, protection, or variable gearing.

We believe that a relevant number of robotic applications would benefit from adaptive morphology, and we foresee an exponential development and deployment of morphing devices in the near future. For instance, the increasing demand for multimodal and multifunctional robots for search and rescue, environmental monitoring, and inspection of infrastructure will greatly benefit from the advantages of adaptive morphology. Similarly, the burgeoning field of flying robots is facing a bottleneck caused by limited energetic autonomy. Morphing wings are a promising solution to design efficient drones capable of adapting their flight style and energetic requirements to the required operation. For instance, drones could hover when precise positioning is required and use morphing wings to transition to a more efficient forward flight for cruising over long distances.

A significant scientific challenge will be to understand how to properly design adaptive morphologies with high numbers of degrees of freedom to endow robots with resilience against changes in the environment and task.

Although the use of conventional materials and manufacturing processes is predominant in the state of the art of morphing systems, new findings in the fields of soft materials, origami manufacturing, and elastic instability will definitely catalyze the interest and expectations of engineers looking for more integrated and robust designs. In this context, a significant scientific challenge will be to understand how to properly design adaptive morphologies with high numbers of degrees of freedom to endow robots with resilience against changes in the environment and task. The concept of embodied artificial intelligence provides a strong theoretical background and, together with in silico tools for the coevolution of body and controllers, will strongly contribute to answering this scientific question and will provide engineers with the specific design tools required to fully unleash the potential of adaptive morphology. Finally, the study of adaptive morphology is expected to shed new light in the field of evolutionary biology. Organisms that exploit adaptive morphologies to meet conflicting requirements imposed by multiple modes of locomotion or functions are key to understanding how living organisms have transitioned from different substrates and have developed different behaviors during evolution.

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