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Soft Mobile Robots: a Review of Soft Robotic Locomotion Modes

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Abstract

Purpose of Review Soft robotics enables unprecedented capabilities for mobile robots that could not be previously achieved using rigid mechanisms. This article serves as a reference for researchers working in soft robotic locomotion, provides classifications and trends in this field, and looks ahead to make recommendations for future developments.

Recent Findings Soft robotic locomotion tends to be heavily bioinspired. Consequently, we provide a taxonomy of soft robotic locomotion according to locomotion mode, including crawling, flying, swimming, legged locomotion, jumping, and alternative locomotion techniques. For each locomotion mode, we investigate fundamental aspects including actuation type, speed, locomotion gaits, control type, and power autonomy to present an accurate snapshot of soft robotic locomotion research. During the investigation, we focus primarily on the robotics literature from 2016 to 2021, while including some of the seminal work from previous years.

Summary In this article, we provide a comprehensive overview of recent soft robotic locomotion research including a broad overview of soft robotic research in several aspects, such as locomotion applications, flexible substrates, and compliant mechanisms, as part of the larger domain of soft robotic locomotion. We also discuss the research trend recent years in this area, possible future research focus, and application of soft locomotion research in human-robot interaction occasions.

Keywords Soft robotics · Locomotion · Mobile robots

Introduction

Biology provides ample evidence that compliance is a critical factor for improved efficiency, stability, and maneuverability in locomotion. From a physical viewpoint, elasticity, as opposed to rigidity, can improve locomotion in multiple ways. First, a soft body can accumulate energy first, and dissipate it at a much slower rate than a rigid body when making contact with the environment. Second, due to its deformable nature, there is a lower chance of damage to an elastic body or the environment that it physically and consistently interacts with. Third, due to passive shape-changing compliance accommodating external forces, a soft body can conform to its medium (such as water or air) to increase its locomotion efficiency. These additional capabilities and biological examples inspire roboticists to introduce elasticity in mobile robot bodies to improve the speed and efficiency of robot locomotion.

Initially, researchers added discrete springs and suspensions to existing rigid mechanisms to incorporate compliance. In 1995, Pratt et al. presented the serial elastic actuator (SEA), comprising linear springs and a linear motion stage [1], which provide both position and force feedback control. Later, Baxter, SAPHARI, and other well-known humanoid robotic platforms adopted SEA joints [2, 3]. Similarly, Collins et al. demonstrated the advantages of a passive walking gait for bipedal robots with regards to compliance [4]. Later, in the early 2000s, researchers started incorporating new materials and mechanisms with various actuation methods to create novel mobile soft robots instead of rigid components, since rigid components continued to be cumbersome even with additional discrete compliance.

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This paper classifies these advances in two categories: deformable mechanisms, (e.g., for origami-inspired folding structures); and soft materials, such as silicone rubber, hydrogels, stretchable fabrics. These brand-new robots have the significant benefits of being lightweight, low-cost, and compliant, compared to traditional rigid robots. However, several fundamental problems still remain. First, many actuation methods of soft robots suffer from low energy density, small displacement, low bandwidth, slow dynamics, and nonlinearity. As a result, these robots are generally slower than the application requirements. Second, the gait regulations of their locomotion are more complicated than for rigid robots, because the elasticity and the fabrication bias of their bodies create many more uncertainties in their response, and modeling their motions and embedding local sensors to measure their kinematic shape changes are challenging.

To describe the state of the art in soft robot locomotion, this paper focuses on the past 5 years of academic research publications. The outline is as follows: Each section covers the main categories of robots according to a distinct locomotion mechanism, mostly inspired by biological examples: crawling, flying, swimming, legged locomotion, and other alternative methods. The factors we examine are actuation, speed, modeling, and control of each locomotion type. From engaging with this paper, readers will gain a clear overview of the current state of the field of soft robot locomotion. The final section synthesizes these factors to conclude with open research areas and anticipated future trends.

Crawling

In nature, creatures with compliant bodies such as inchworms, starfishes, and snakes utilize crawling as a common locomotion pattern, which provides inspiration for soft mobile robots. Soft legs or deformable rolling mechanisms increase the compliance of their locomotion. Most crawling locomotion approaches in soft mobile robots are friction based. The crawling mobile robots usually have a simplified structure to avoid lifting their limbs or parts of their body against gravity. In this section, we introduce recent research on crawling locomotion gaits in soft mobile robots as shown in Fig. 1. We list some basic information of these research in Table 1.

Robots and Performance

Creatures that perform crawling locomotion, like caterpillars, starfishes, and snakes, have soft and stretchable bodies used both for propulsion and physical compliance under environmental contact forces. Some bio-inspired soft crawling robots mimic the soft body for compliance, and they are usually built with soft and stretchable materials like silicone rubber.

Caterpillar-inspired soft crawling robots use peristaltic locomotion to propel themselves. Similar to caterpillar, these robots consist of one or multiple soft actuators [9, 10] sometimes with modular design for better reconfiguration [11], performing a wave of radial contraction and radial elongation along the body to propel the robot. The actuators are most commonly fluidic [12], cable-driven [13], magnetic [14–16], smart-material-driven [17–25], and dielectric elastomer actuator (DEA) based [6, 26–28]. Locomotion of these robots is coupled with the elongation or bending of each actuator. At the same time, friction limits the each contact point along the body from moving backward so that the actuators can generate net positive propulsion. In some research, methods are taken to increase the friction to improve the crawling performance, to modify the friction to get versatile locomotion [29], and even crawling vertically on a wall was demonstrated [30, 31].

The majority of actuators used for caterpillar inspired peristaltic crawling soft robots are fluidic. The robots are designed to crawl horizontally on a rigid plane [39], water surface [62], vertically on a wall [36], along a rod [38, 43, 56] or enclosure space such as within a tube [40, 58, 66]. For example, Connolly et al. designed fiber reinforced actuators and connected them serially to form a crawling robot [67]. They also built a finite element model to predict the response of the actuators under different fiber angles. To increase the peristaltic crawling ability, Rafsanjani et al. designed a kirigami skin mimicking the anisotropic friction properties of snakes [8]. Liu et al. utilize a similar skin design surrounding a penumatic actuator [34]. When actuating the pneumatic actuator, the kirigami scales pop-up and penetrate the surface, improving the anchoring ability and stopping the module from moving backward. Most of the fluidic crawling robots utilize traditional valves to manipuate the actuators while Rothemund et al. developed a crawling robot with a soft, bistable custom valve [37].

Another actuation strategy for peristaltic crawling robots utilizes cables or tendons along the length, typically actuated by electrical motors. Umedachi et al. designed a cable-driven caterpillar-inspired robot with soft links [65]. By changing the frequency of gait, the authors were able to vary the speed and mode of locomotion.

On a similar track, shape memory alloy (SMA) actuators can be used to drive the legs of a caterpillar inspired robot. For example, Goldberg et al. connected six SMA coil actuators in series to mimic the limbs of caterpillars [17] with discrete elastic rod formulation, which is a finite element method by splitting soft body into discrete elastic rods for modeling, to analyze its locomotion. SMA can

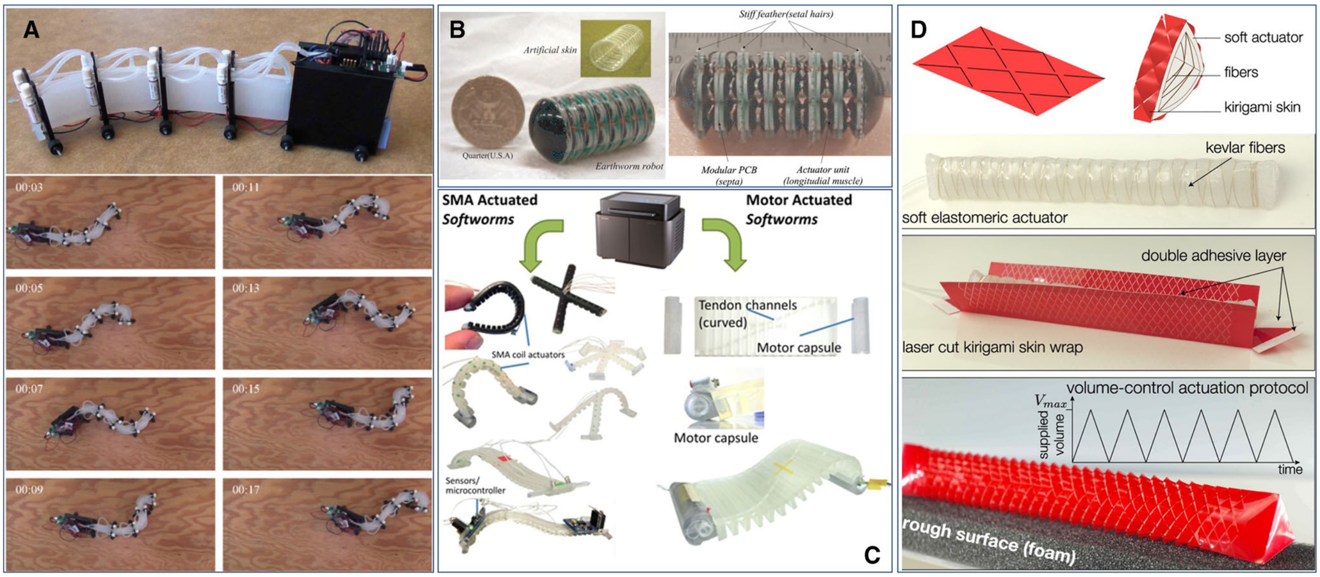

Fig. 1 (A) A fluidic soft robotic snake (From [5], © IOP Publishing. Reproduced with permission. All rights reserved). (B) A soft earthworm robot with DEA (From [6], © IOP Publishing. Reproduced with permission. All rights reserved). (C) Soft robotic worms actuated by SMA and motors (From [7], © IOP Publishing. Reproduced with permission. All rights reserved). (D) Kirigami skins make a simple soft actuator crawl (From [8], © Science Robotics. Reproduced with permission. All rights reserved)

also be used to deform the crawling robot body. Umedachi et al. designed and fabricated a caterpillar inspired soft robot with SMA coils embedded in the main body made with soft materials [7, 22]. By actuating SMA coils in certain gait, the robot is able to perform caterpillar crawling locomotion.

Another direction is to build caterpillar or worm-inspired robots with unstretchable materials or structures. Manwell et al. built a cable-driven worm-like crawling robot [45]. The cable-driven mechanism is wrapped inside of an elastic braided mesh. Onal et al. built an inchworm robot using SMA coils to manipulate the origami main body [44]. Shin et al. introduced a peristaltic crawling flexible robot [48]. The main body consist of a hygroscopically responsive film, which quickly swells and shrinks in lengthwise direction in response to a change of humidity, thus the robot can be actuated to crawl. Kanada et al. present a caterpillar inspired robot with a novel flexible grooved tube and gear mechanism [60].

Starfish-inspired soft crawling robots locomote by elongating and shrinking back their limbs. They also make use of 1D anisotropic friction, which makes the friction lower in forward direction and higher in backward direction. This prevents the robot from moving back when elongating and shrinking the limbs, ensuring that it keeps moving forward [33]. Stokes et al. designed a four-limb soft pneumatic starfish inspired crawling robot with an average speed of 0.0172 body length per second, and a mobile base station was designed to increase its mobility and provide air supply [49] for the pneumatic actuators. Tolley et al. designed an untethered crawling robot operating with a starfish like gait [32]. With a tough custom composite soft material combining silicone with higher elastic modulus, and hollow glass micro sphere or polyaramid fabric, so that the robot is resilient to adverse environment including exposure to flames, and being run over by an automobile.

Dielectric elastomer actuator (DEA) is also considered as a possible actuating strategy for crawling robots. It is a class of electroactive polymers that deform under electric field based on electrostatic forces, allowing them to be used as soft actuators. Digumarti et al. used DEAs to build a planar, soft crawling robot [63]. The robot consists of four pieces of DEA membrane bonded to a rigid ring frame and a smaller central disk which is free to move, each of the DEA membrane can be actuated and expand separately. By actuating them in certain sequence to create a starfish like gait, the robot is able to move on a planar surface. Li et al. designed a DEA actuated insect-sized resilient crawling robot [42]. The robot is resilient to adverse environments including compression under 30,000 times its own weight and collision with a rigid surface at up to 30 m/s. The robot can climb a slope of 30 degrees with a maximum speed of 160 mm/s.

Mao et al. designed an SMA actuated robot [51]. With SMA coil actuator, the limbs are manipulated to perform starfish locomotion. Calisti et al. designed and fabricated an octopus inspired cable-driven soft crawling robot with a similar locomotion gait [57, 68].

Table 1 Taxonomy of recent soft robotic crawling locomotion research

Research	Actuation	Speed	Power autonomy	Control	Locomotion gait
Resilientbot [32]	Pneumatic	0.5 mm/s	Untethered	Open loop	Ambulatory
Shepherd2011 [33]	Pneumatic	/	Tethered	Open loop	ambulatory
Duggan2019 [9]	Pneumatic	0.28 mm/s	Untethered	Open loop	Inchworm
Kirigami [34]	Pneumatic	33.33 mm/s	Tethered	Open loop	Inchworm
Das2020 [12]	Pneumatic	26.2 mm/s	Tethered	Open loop	Inchworm
Wu2018 [35]	Pneumatic	9.85 mm/s	Tethered	Close loop	Inchworm
Zou2018 [11]	Pneumatic	5.14 mm/s	Tethered	Open loop	Inchworm
Tang2018 [30]	Pneumatic	4.77 mm/s	Tethered	Open loop	Inchworm
Qin2019 [36]	Pneumatic	16.29 mm/s 0.12 BL/s	Tethered	Open loop	Inchworm
Booth2018 [29]	Pneumatic	25 mm/s	Tethered	Open loop	Inchworm
Rothemund2018 [37]	Pneumatic	1.4 mm/s	Tethered	Open loop	Inchworm
Kim2019 [10]	Pneumatic	/	Tethered	Open loop	Inchworm
Singh2019 [38]	Pneumatic	4.2 mm/s	Tethered	Open loop	Inchworm
Xie2018 [39]	Pneumatic	6.67 mm/s	Tethered	Close loop	Inchworm
Rafsanjani2018 [8]	Pneumatic	/	Tethered	Open loop	Inchworm
Ito2019 [40]	Pneumatic	17.5 mm/s	Tethered	Open loop	Inchworm
Luo2018 [41]	Pneumatic	/	Tethered	Open loop	Inchworm
Henke2017 [26]	DEA	0.83 mm/s	Tethered	Open loop	Inchworm
Li2019 [42]	DEA	161 mm/s 4 BL/s	Untethered	Open loop	Inchworm
Guo2020 [28]	DEA	0.005 mm/s	Tethered	Open loop	Inchworm
Jung2007 [6]	DEA	2.5 mm/s	Tethered	Open loop	Inchworm
Gu2018 [31]	DEA	88.46 mm/s 1.04 BL/s	Tethered	Open loop	Inchworm
Goldberg2019 [17]	SMA	10 mm/s	Untethered	Open loop	Inchworm
Huang2018 [18]	SMA	74 mm/s	Tethered	Open loop	Inchworm
Trimmer2012 [21]	SMA	0.5 mm/s	Tethered	Open loop	Inchworm
Seok2012 [23]	SMA	5.25 mm/s	Untethered	ILC	Inchworm
Menciassi2004 [24]	SMA	0.22 mm/s	Tethered	Open loop	Inchworm
Yuk2011 [25]	SMA	0.21 mm/s	Tethered	Open loop	Inchworm
Umedachi2018 [43]	SMA	4 mm/s	Tethered	Open loop	Inchworm
Umedachi2018 [43]	SMA	4 mm/s	Tethered	Open loop	Inchworm
Onal2012 [44]	SMA	0.31 mm/s	Untethered	Open loop	Inchworm
Umedachi2016 [7]	Cable-driven	112 mm/s 0.56 BL/s	Tethered	Open loop	Inchworm
Manwell2018 [45]	Cable-driven	1.43 mm/s	Tethered	Open loop	Inchworm
Ta2018 [46]	Motor	17.5 mm/s	Tethered	Open loop	Inchworm
Horchler2015 [47]	Motor	4.3 mm/s	Tethered	Open loop	Inchworm
Umedachi2019 [13]	Motor	/	Tethered	Model based PD	Inchworm
Shin2018 [48]	Hygroscopical	6 mm/s 0.24 BL/s	Untethered	Open loop	Inchworm
Electromag- worm [14]	Electromagnetic Electromagnetic	/ /	Tethered & Untethered	Open loop	Inchworm
Joyee2019 [15]	Magnetic	26.2 mm/s	Tethered	Open loop	Inchworm
Hybrid Starfish [49]	Pneumatic	1.8 mm/s 0.02 BL/s	Tethered	Open loop	Starfish

Table 1 (continued)

Research	Actuation	Speed	Power autonomy	Control	Locomotion gait
Lee2020 [50]	Cable-driven	/	Untethered	Open loop	Starfish
Mao2013 [51]	SMA	/	Tethered	Open loop	Starfish
Snake [52]	Pneumatic	40 mm/s	Tethered	Open loop	Snake
Onal2013 [5]	Pneumatic	19 mm/s	Untethered	Open loop	Snake
Jia2020 [53]	Pneumatic	/	Tethered	Bayesian	Snake
Branyan2018 [54]	Pneumatic	2.2 mm/s	Tethered	Open loop	Snake
3Dsnake [55]	Pneumatic	131.6 mm/s	Tethered	Open loop	Snake
Liao2020 [56]	Pneumatic	30.85 mm/s 0.19 BL/s	Tethered	Open loop	Snake climbing
Calisti2011 [57]	Cable-driven	3.99 mm/s	Tethered	Open loop	Octopus
Verma2018 [58]	Pneumatic	4 mm/s	Tethered	Open loop	Custom
Rieffel2018 [59]	Vibration Motor	150 mm/s 1.15 BL/s	Tethered	Learning Algorithm	Custom
Kanada2019 [60]	Motor	20 mm/s	Untethered	Open loop	Custom
Usevitch2020 [61]	Motor	60 mm/s 0.04 BL/s	Untethered	PID	Custom
Yamada2018 [62]	Motor	1000 mm/s	Untethered	Open loop	Custom
Digumarti2018 [63]	DEA	12 mm/s	Tethered	Open loop	Custom
Wang2019 [64]	Pneumatic	60 mm/s	Tethered	Open loop	Custom
Umedachi2019 [65]	Cable-driven	20 mm/s	Tethered	Open loop	Custom

Snake-inspired soft crawling robots take advantage of a continuously deformable slender body that undulates. The forward locomotion for these crawling robots generated by the iconic serpentine locomotion of snakes, which is represented by a traveling sinusoidal wave in body curvature. Snakes are able to perform such efficient crawling locomotion without limb motions because of anisotropic friction property of the of the scales on their skin. The anisotropic friction property provides lower friction along the body, and higher friction in normal direction of the body axis. The traveling curvature wave uses this property, pushing off the high-friction direction and propelling the robot forwards. The anisotropic friction is generated either with passive rolling wheels or materials with different friction coefficients in different directions [5, 46]. Luo et al. provided a mathematical model for snake-like crawling robot [52]. Existing soft snake inspired crawling robot utilizes multiple actuators [54] or modular design. Soft modular actuators are connected in series with rigid or soft links. Qin et al. designed and fabricated a modular pneumatic soft snake robot with three degrees of freedom in each module [55], so that the robot is able to perform not only the classical serpentine locomotion but also sidewinding locomotion which needs to raise the body of the robot in an approximately helical manner.

Crawling robots with alternative locomotion also make up an important part in soft crawling robot research area. Wang et al. developed a pneumatic robot with novel locomotion [64]. By flipping forward and backward like a piece of self-foldable paper in different pattern, the robot is able to move in different directions. With close-loop control, the robot is able to follow desired trajectories.

Some crawling soft robots utilize flexible (but not stretchable) materials or structures. Although these robots are less deformable as compared with the robots using stretchable soft materials, these flexible robots can achieve more accurate control with relatively higher energy efficiency. For example, tensegrity structures, a structural principle usually composed of both isolated compressive struts and a network of elastic tendons with a specific configuration of nodes, can achieve flexible actuation or global response using cable or soft materials, and such structures have been used in flexible crawling robots [50, 69]. Mirletz et al. built a simulation for a cable-driven tensegrity crawling robot [70]. They build a central pattern generator (CPG) controller for this multi degree of freedom (DoF) robot. Rieffel et al. designed a resilient soft tensegrity robot with machine learning algorithm to discover more efficient gaits from experimental data [59]. Usevitch et al. present a truss robot similar to tensegrity robots with inflated fabric tubes as the beams [61], with a modular design and morphing options.

Modeling, Simulation, and Control

There are several models for crawling locomotion. Robots inspired by caterpillars usually have simple structures composed of one or multiple fluidic elastomer actuators. Low fidelity models based on EulerBernoulli beam theory are used to describe this locomotion [9]. Daltorio et al. present a simulation for crawling robot in a pipe with radially symmetric Coulomb friction contact and characterize ways to reduce slip-related losses to increase energy efficiency [71].

For more complicated crawling locomotion, for example, the snake crawling locomotion, researchers build more complex dynamical models to describe the complex shape and motion of the body [52]. Finite element method (FEM) is used in modeling and in simulation [72, 73]. Another demonstrated approach is to use a particle-based simulation framework and a powerful GPU to realize real-time simulation and control of many nodes that interact using numerical rules and dynamic equations [74]. Using central pattern generators (CPG) to describe and control certain crawling locomotion gaits has also been demonstrated for caterpillar and tensegrity robots [75, 76].

Most of the soft crawling robot utilize open loop control, while some are model based. For example, for a flexible crawling robot fabricated with a continuous mesh, a custom structural analysis based modeling approach is presented in [77], and a model based open-loop control is implemented to increase energy efficiency.

Only few robots utilize feedback [13], or use a learning method [59]. Wu et al. developed a differential drive pneumatic crawling robot [35] and use neural networks to train the turning ability to create a mathematical map among friction, deflection angle, and inflation time, then build a closed-loop motion controller for linear and turning movement.

Flying

Flight is one of the most complex forms of locomotion, which includes hovering, taking off, and landing, each involving many complex movements. Birds are an important source of biological inspiration for the development of aerial vehicles as they can rapidly change shape to transition from efficient cruise to aggressive maneuvering and precision descents even in complex environments. Research has been done looking at birds and mimicking their wings, body shape, and musculoskeletal mechanisms to create higher efficiency flying robots [78, 79]. One prominent subset involves adding flexibility of wings to enable high performance flight. Adaptive morphology of the wings can improve energy efficiency and robustness to aerodynamic disturbances [80–82].

Biologically inspired flying robots, as shown in Fig. 2, can exhibit impressive flight characteristic. In recent years, with the development of materials science and technology such as soft artificial muscles and flexible lightweight materials has renewed the interest in development of biologically inspired flying robots. In particular, soft robotics has offered unique solutions for developing bird-like robots with lightweight flexible design, increased flight maneuverability, and complex flight locomotion capabilities. Combining novel soft robotics technologies with traditional aerial robotic engineering approaches can increase functional capabilities and flight performance. In Table 2, we list some basic information of biologically inspired flying robots.

This section provides an overview of flight locomotion with flapping and morphing wing structures.

Flapping wing robots can have both high maneuverability [85] and the ability to glide for low energy flying. On the other hand, wing morphing is a promising capability for the development of bird-like aircraft. Morphing mechanisms not only improve aerodynamic performance for maneuverability, but can also provide roll control with asymmetric deformation of the wings, replacing conventional control surfaces.

Flight Systems with Flapping Wings

Flapping wing design is promising for a variety of applications because of their flexible maneuverability and efficient aerodynamics.

In flapping wing flight, drag and lift forces are partially controlled by the movement of the wing itself. Nevertheless, generating a flapping wing mechanism is challenging, since the motion requires a relatively complex transmission system, and the wings have to move in complex patterns at a high frequency.

Many flapping wing aerial vehicle (FWAV) designs use a single electrical motor to flap both wings, which limits performance. Independent wing control provides a greater flight envelope through the ability of wing motions to achieve a desired wing shape and associated aerodynamic forces [92]. For example, an insect-inspired free-flying robotic platform [87] is controlled through its two pairs of independently flapping mechanisms. This robot can fly like an insect, controlling all three axes of rotation.

The “Bat Bot” mimics the morphological properties of bats, with highly-stretchable silicone-based wing membranes stretched over an articulated morphing skeletal structure [86]. In order to reduce complexity and increase reliability, the actuation system, consisting of soft materi-

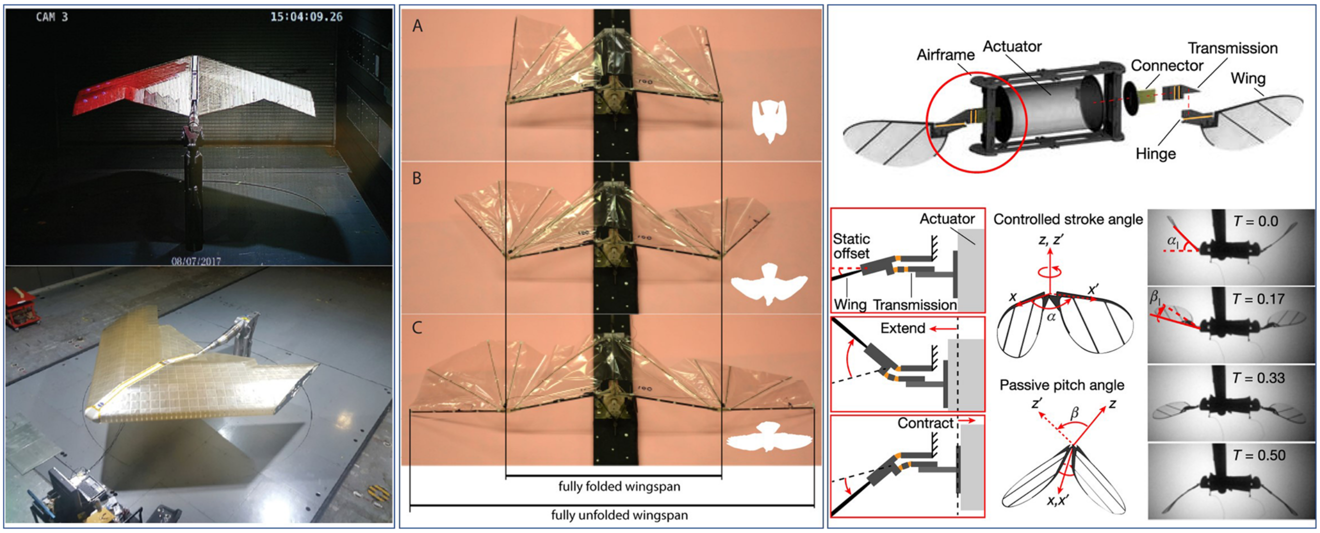

Fig. 2 Left: A elastic morphing wing design increase aerodynamic efficiency and improve roll control authority (from [83], © IOP Publishing. Reproduced with permission. All rights reserved). Middle: A passive morphing wing capable of improving energy efficiency and robustness to aerodynamic disturbances (From [80], © IOP Publishing. Reproduced with permission. All rights reserved). Right: The first microrobot powered by soft actuators to achieve controlled flight. It can crash into walls, fall onto the floor without being damaged r

Table 2 Taxonomy of recent flying soft robotic locomotion research

Research	Actuation	Speed & lift force	Power autonomy	Control	Mass	Flight type
Bat Bot [86]	DC motor	5.6 m/s	Untethered	Closed loop	93 g	Flapping wing
Tailless MAV [87]	DC motor	7 m/s	Untethered	Semi closed loop	28.2 g	Flapping wing
Tailed MAV [85]	Motor	8 m/s	Untethered	Open loop	26 g	Flapping wing
Bee^{+} [88]	Twinned Unimorph	1.40 mN	Tethered	Closed loop	0.095 g	Flapping wing
Microrobot [84]	DEA	0.81-0.88 mN	Tethered	Closed loop	0.16 g	Flapping wing
MAV [89]	EM driven	8.10 mN	Tethered	Open loop	0.07 g	Flapping wing
MAV [90]	DC motor	39 mN	Tethered	Open loop	3.3 g	Flapping wing
MAV [91]	Piezoelectric	/	Tethered	Open loop	0.142 g	Flapping wing
Robo Raven[92]	Servo	6.7 m/s	Untethered	Closed loop	290 g	Flapping wing
MAV [93]	Piezoelectric	/	Tethered	Closed loop	0.19 g	Flapping wing
Multimodal [94]	Bimorph actuator	/	Tethered	Closed loop	0.074 g	Flapping wing
Multimodal [95]	Piezoelectric	2.5 m/s	Tethered	Open loop	0.175 g	Flapping wing
PigeonBot [96]	Motor	11.7 m/s	Untethered	Semi closed loop	280 g	Fixed wing
LisHawk [97]	Motor	8 m/s	Untethered	Open loop	284 g	Fixed wing
Morphing Wing [98]	Servo	/	Untethered	Open loop	/	Fixed wing
Morphing Wing [83]	Servo	/	Untethered	Open loop	/	Fixed wing
Multimodal [99]	Self-Deployable Origami	/	Untethered	Open loop	35 g	Glider
Multimodal [100]	Fluidic	11.2 m/s	Untethered	Open loop	/	Fins and arms

als, should be embedded in the structure, as demonstrated by a recent flapping-wing robot that uses elastic mechanisms that offer enough thrust and control authority to make stable transitions between aggressive flight modes [85].

Insect-scale flying robots are more agile and can generate powerful lift forces with four wings, but this is only possible for lightweight actuators and transmissions. For example, the latest design of "Bee^{+}" with four flapping wings uses twinned unimorph actuators that weigh only 28 mg. The result is a flying robot capable of perching, landing, following a path, and avoiding obstacles [88]. Not surprisingly, the lightest wireless robot to fly is an insect-sized laser-powered flapping wing flying robot [93]. This robot is only 190 mg and has no need for a tether for power and control signals. It uses a tiny on-board circuit that converts the laser energy into enough electrical power to operate its wings.

To improve flapping frequency and aerodynamic efficiency, novel artificial muscle actuation methods have been applied to FWAV. For example, [84] presents the first micro robot actuated by soft artificial muscles, allowing it to crash into walls and fall onto the floor without being damaged. This flying robot is driven by multi-layered dielectric elastomer actuators (DEAs) that weigh 100 mg each and have a resonance frequency of 500 Hz.

Flight Systems with Morphing Wings and Tails

Birds sweep the main wing forward and fan the tail outward to produce considerable lift and drag during slow and aggressive flight to increase maneuverability. Morphing is a promising enabling technology for design of bird-like aircraft. In recent research, a pigeon-inspired drone can bend, extend and simply change the shape of its wings in a biomimetic manner. A biohybrid wing skeletal structure was 3D-printed out of nylon. This pigeon-inspired drone can move its wings like real birds and can make tight turns in smaller spaces [96].

In addition, twist morphing can increase the lift coefficient, and replace conventional control surfaces. Another work was a modular assembled wing that performs continuous span-wise twist deformation [98] with a wing design that can change shape and increase the efficiency of aircraft flight. The wing is made of hundreds of small identical pieces that contain both rigid and flexible components. The main advantage of this morphing structure is it leads to a lighter, and much more energy-efficient wing than those with conventional designs. Additionally, elastic shape morphing design increase aerodynamic efficiency and improve roll control authority [83].

Morphing tails also play an important role in achieving faster turns. Birds change the shape of their tails as well as their wings in order to maneuver quickly, fly slowly, and reduce their air resistance when flying fast. An avian-inspired drone has been developed with feathered wings and tail that give it unprecedented flight agility [97]. The body has a skeleton constructed out of 0.3 mm fiber glass sheet and covered with an airtight and tear-resistant membrane, combining a low mass, flexibility, and sufficient stiffness to absorb aerodynamic loads when the feathers are slightly overlapped.

Multi-modal Locomotion Systems

Most flying robots are unable to perform locomotion modes besides flight. This contrasts with flying animals, which can combine flight with swimming or walking or both. Wings' adaptive morphology allows the robot to modify the shape of its body in order to increase its efficiency during multi-modal locomotion. New design of the "RoboFly" which allows for wing-driven ground and air-water interfacial locomotion, improving the versatility of the robot. The transmission mechanism is constructed from kinematic chains of rigid links and flexure joints [94]. A hybrid, aerial-aquatic microrobot [95] was developed that capable of flying and swimming. The wing-flapping motion is generated by a four-bar linkage that acts as lever arm to amplify the small displacement of the piezoelectric flight muscle. Passive and elastic flexure hinge used at the base of the wing. It is able to transition between air and water, propel itself back out of water, and safely land. The robot flaps its wings at 220 to 300 Hz in air and 9 to 13 Hz in water. An aquatic aerial vehicle [100] was developed that is capable of aerial and aquatic locomotion, which uses a reconfigurable wing to dive into the water from flight using soft morphing fins and arms, made of silicone and controlled by pneumatic actuation.

Swimming

While humans may not be able to access the depths of oceans, many underwater animals make it their home. Driven by the need to access and work deep underwater, researchers have begun to develop robots, modeled after the impressive creatures dwelling in the deep. Many of these creatures are soft bodied and soft robotics is a natural avenue to match their performance and efficiency.

The actuation of swimming generates hydrodynamic forces, which can be very similar to flying. These similarities include undulation and lift-induced motion, however, differences between water and air allow swimming robots to use drag-induced motion and a form of jet-propulsion. Soft materials are widely used to create and manipulate these capabilities.

Many swimming robots are designed using soft materials to avoid water leakage caused by bad seals between complex rigid mechanisms or to reduce either the density or weight of the robot to enable natural buoyancy in water in a smaller body size. Hereby, we separate the swimming soft robots into five major categories according to actuation types. For disambiguation purposes, we further distinguish the utilities with locomotion gaits in the following paragraphs. We list some basic information of these research in Table 3.

Shape Memory Alloys Actuated Systems

Shape memory alloys (SMAs) have been used for a wide variety of applications in robotics. When these materials are subjected to an appropriate thermo-mechanical process, they have the ability to return to their original trained shape. SMAs are usually available in the form of wires, pipes, springs or ribbons, which allow them to perform as low-volume actuators in limited space. In robotics, SMAs represent a very interesting alternative that offers very high force per mass or volume despite being relatively inefficient compare to traditional drives such as the electric or hydraulic motors [103].

In this section, we present several swimming robot applications actuated by SMA. Diverse in locomotion type or gait, these applications can be divided to three categories [104]: actuated fins, curvature waves, jet propulsion.

The first class falls into the biomimetic design of underwater animals that propel themselves using fins or limbs, harnessing a similar principle described for flapping-wing flying. A typical example is the manta ray, which uses extended pectoral fins to drive themselves. In 2009, Wang et al. presented the design of a micro biomimetic manta ray robot fish actuated by SMA wires, and verified that SMA wire was a feasible actuator for swimming locomotion [114].

Alternatively, some animals tend to involve their entire bodies to generate curvature waves to propel themselves underwater. This is called swimming by undulation. Scientists replicating this motion in robotics, design streamlined bodies for robots performing a periodic reciprocating motion to achieve underwater propulsion. Two examples are SMA driven soft robots inspired by eels [110] and lampreys [115], which have promising prospects for investigation of tight spaces and complex environments.

Another popular locomotion strategy is jet propulsion in water, a method used by many soft-bodied animals such as octopus and jellyfish. Based on sequential ingestion and expulsion of discrete masses of water, these creatures gradually move their bodies forward. A pioneering soft robotic jellyfish with jet propulsion was first introduced in 2011 [116]. To execute the inflation/ejection routine, this robot used SMAs to actuate a silicone umbrella-shaped body. More recent research in 2016 demonstrated that SMAs could be used to to compress a silicone chamber, such that a squid-like robot could implement a jet propulsion locomotion strategy [113].

Ionic Polymer Metal Composite Actuated Systems

Ionic polymer metal composites (IPMCs) are electroactive polymers with application in biomedical devices and soft robotics. IPMCs consist of an ion-exchange membrane (also referred to as a polyelectrolyte) and electrode layers on opposing sides of the ion-exchange membrane [153]. When an electric field is generated between the electrodes, the ions in the membrane congregate on one side or the other, causing the entire structure to bend. Within such an architecture, IPMCs have several promising properties, allowing for small volume, light weight, low voltage actuation without the need for bearings and sliding parts.

Due to their ionic nature of operation, IMPCs work best in a wet environment and hence, researchers have applied these actuators to soft swimming robots. Example implementations include the manta-like self-lifting gait robot [122], a tiny tadpole-like robot using undulation for in-body exploration [123], a fish-like robot with IPMC driven polyvinyl chloride films to drag and propel itself [125], and a jellyfish inspired robot involving IPMC to achieve jet propulsion [124]. These applications are faithful reproductions to their corresponding creature models.

Dielectric Elastomer Actuated Systems

A common design of DEAs is to sandwich a soft insulating elastomer layer between two compliant electrodes. When a voltage is applied between the electrodes, the arising electric field causes a decrease in thickness and increase in area of the elastomer layer [154, 155]. These actuators have been deployed on various swimming robots with useful properties, such as inherent compliance, being able to store and recuperate energy, featuring high power-to-weight ratio and high energy density compared to human skeletal muscle materials [156].

Although it should be admitted that the appearance for manta ray inspired swimming robots are pretty similar, this locomotion mode can be achieved using multiple actuation methods.

SMA actuated morphing ray propulsor moves by bending the embedded SMA wires, thereby flapping the silicone wings to achieve lifting locomotion. In contrast, in Fig. 3, the DEA actuation involves a sandwiching architecture to obtain periodic reciprocating motion and thus actuating a base joint on the fin.

While IPMC actuators use a similar configuration of electrodes and soft layers as the DEA, the former exploits

Table 3 Taxonomy of recent soft robotic swimming locomotion research

Research	Actuation	Speed	Power autonomy	Control	Locomotion gait
Fish [105]	FEA	150 mm/s (0.44 BL/s)	Untethered	Open loop	Undulation
Multimodal locomotor [106]	FEA	31.5 mm/s (0.9 BL/s)	Tethered	Semi closed loop	Lift
Fish fins [107]	FEA	329 mm/s	Unethered	Open loop	Undulation
Frog [108]	FEA	100 mm/s	Unethered	Open loop	Drag
Manta [109]	SMA	45 mm/s (0.26 BL/s)	Untethered	Open loop	Lift
Manta [110]	SMA	8 mm/s	Tethered	Open loop	Undulation
Micro fish [111]	SMA	112 mm/s	Tethered	Open loop	Drag
Tuna [112]	SMA	x	Tethered	Open loop	Undulation
Squid [113]	SMA	x	Tethered	Open loop	Jet Propulsion
Manta [114]	SMA	57 mm/s	Untethered	Open loop	Lift
Lamprey [115]	SMA	x	Tethered	Semi closed loop	Undulation
Jellyfish [116]	SMA	x	Tethered	Open loop	Jet Propulsion
Fish [117]	DEA	80 mm/s (0.69 BL/s)	Untethered	Open loop	Undulation
Jellyfish [118]	DEA	x	Untethered	Open loop	Jet Propulsion
Sea snail-fish [101]	DEA	51.9 mm/s (0.45 BL/s)	Untethered	Open loop	Lift
Biohybrid microswimmer [119]	DEA	1.9 mm/s (0.009 BL/s)	Untethered	Open loop	Undulation
Fish [120]	DEA	37.2 mm/s (0.25 BL/s)	Tethered	Open loop	Jet Propulsion
Ray [121]	EAP	0.005 mm/s	Tethered	Open loop	Undulation
Manta [122]	IMPC	0.74 mm/s (0.067 BL/s)	Untethered	Open loop	Lift
Tadpole [123]	IMPC	23.6 mm/s	Untethered	Open loop	Undulation
Jellyfish [124]	IMPC	0.77 mm/s	Untethered	Open loop	Jet Propulsion
Micro fish [125]	IMPC	24 mm/s	Untethered	Open loop	Drag
Micro fish [126]	ICPF	5.21 mm/s	Tethered	Open loop	Drag
Turtle [127]	SSC	22.5 mm/s	Untethered	Open loop	Lift
Turtle [128]	SSC	11.5 mm/s	Untethered	Open loop	Lift
Beetle [129]	Servo	59.07 mm/s	Untethered	Open loop	Drag
Octopus [130]	Servo	3.8 mm/s (0.19 BL/s)	Tethered	Open loop	Drag
Spine [131]	Servo	135 mm/s	Tethered	Open loop	Undulation
Tensigrity Fish [132]	Servo	294 mm/s (0.7 BL/s)	Untethered	Open loop	Undulation
Fish [133]	Servo	847.5 mm/s (2.5 BL/s)	Untethered	Open loop	Undulation
Octopus [134]	DC motor	3600 mm/s (10 BL/s)	Untethered	Open loop	Undulation
Long-fin [135]	DC motor	105.8 mm/s (0.23 BL/s)	Untethered	Open loop	Jet Propulsion
Manta [136]	DC motor	3 mm/s (0.25 BL/s)	Untethered	Open loop	Lift
Invertebrate [137]	DC motor	x	Untethered	Open loop	Jet Propulsion
Jellyfish [138]	DC motor	116 mm/s	Tethered	Open loop	Jet Propulsion
Hair [139]	DC motor	x	Tethered	Open loop	Drag
Vortex [140]	DC motor	40 mm/s	Tethered	Open loop	Jet Propulsion
Tuna [141]	Pneumatic	510 mm/s (2 BL/s)	Untethered	Open loop	Undulation
Manta [142]	Pneumatic	100 mm/s	Untethered	Open loop	Lift
Fish [143]	Pneumatic	120 mm/s	Untethered	Open loop	Undulation
Squid [100]	Pneumatic	11200 mm/s (43.9 BL/s)	Untethered	Open loop	Jet Propulsion
Fish [144]	Hydraulic	800 mm/s	Untethered	Open loop	Undulation
Eel [145]	Fluidic	28.8 mm/s (0.12 BL/s)	Untethered	PWM signal gear pump	Undulation

Table 3 (continued)

Research	Actuation	Speed	Power autonomy	Control	Locomotion gait
Magnetic sheet [146]	Magnetic	x	Untethered	Vision-based	Undulation
Cruciform [147]	Magnetic	10 mm/s	Untethered	Vision-based	Lift
Nano swimmers [148]	Magnetic	0.01491 mm/s	Untethered	Frequency	Undulation
Jellyfish [149]	Hydrogen	x	Tethered	Open loop	Jet Propulsion
Phototactic [150]	Hydrogel	0.305 mm/s (1.15 BL/s)	Tethered	Open loop	Undulation
Whiligig beetle [151]	Pneumatic	200 mm/s	Untethered	Open loop	Drag
Microswimmers [152]	Flagella	0.0102 mm/s	Untethered	Magnetic field	Drag

chemical ion transport to induce bending while the latter utilizes physical electrostatic attraction between compliant electrodes. As claimed in [101, 117], DEA actuators offer more promise for swimming robots to deal with severe conditions. As an example application, referring to the deep sea snail-fish characteristics, researchers developed an untethered soft robot to explore the deep sea environment in the Mariana trench, with its DEA fabricated flapping fins.

DEAs are also used on swimming robots with undulatory or jet propulsion gaits. In their investigation to effectively integrate DEAs in swimming robots, Shintake et al. utilized laminated silicone layers to ensure that the high-voltage electrodes remained insulated while guaranteeing actuation performance [120]. The researchers developed a robot fish and a robot jellyfish, which used undulation and jet propulsion respectively, to verify their approach. In 2018, scientists from UCSD introduced a ribbon robot composed of DEAs, inspired by the transparent eel larvae, leptocephali [119]. This robot used chambers filled with electrolytes and the surrounding sea water to function as the two electrodes that actuated the DEA core. The robot was capable for a maximum forward speed of 1.9 millimeters per second and a Froude efficiency of 52%. The Froude efficiency is the propulsive efficiency defined as the ratio of power output to energy input. Some jellyfish can have a Froude efficiency around 10% so this system is highly efficient.

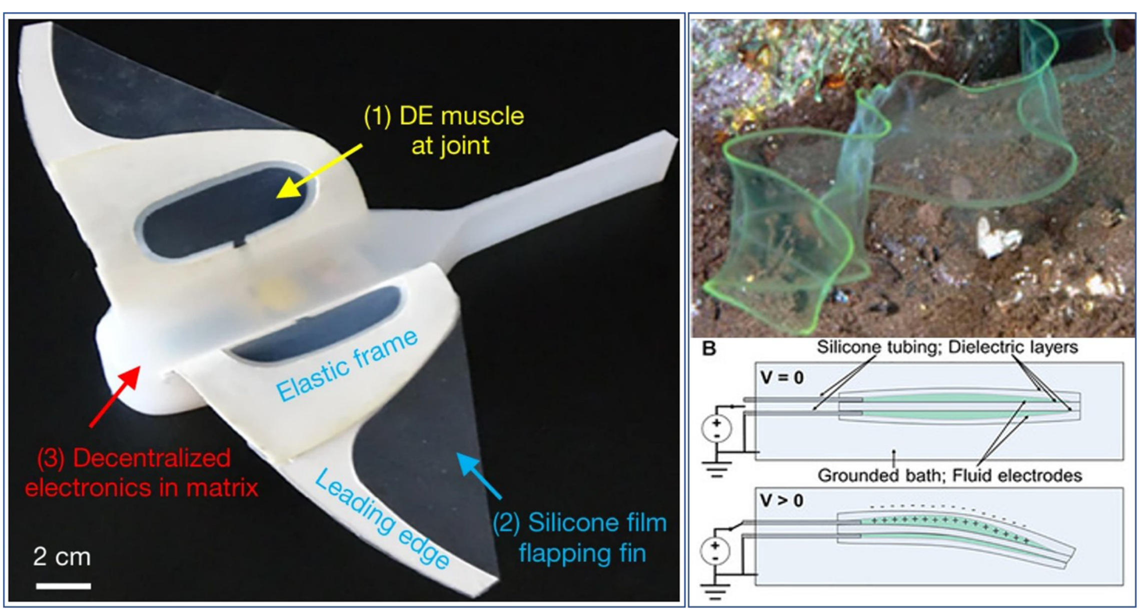

Fig. 3 Left: A self powered fish robot in deep sea (reprinted by permission from Springer Nature: From [101]). Right: A translucent soft swimming robot driven by fluid electrode DEA (reprinted by permission from Science Robotics: From [102])

Fluidic Elastomer Actuated Systems

Fluidic elastomer actuators (FEAs) are composed of low durometer rubber and driven by relatively low-pressure fluid, which can either by pneumatic or hydraulic [105]. In practice, their reliable performance enables these actuators to seek a role in industrial applications, such as soft grippers for robot arms. It is rather straightforward to point out the pros and cons of fluidically actuated swimming robots: they sacrifice volume for valves and tubes, to exchange for powerful propulsive forces. Indeed, there is significant improvement for average locomotion performance of pneumatic system, compared with other soft actuators we mentioned above.

Scientists have proposed a micro sized pneumatically driven underwater soft robot with multiple locomotion modes in 2020 [106]. The authors were inspired by earthworm and cephalopod locomotion, and the robot can perform both crawling and jumping-gliding gaits in the water to propel itself. Another example use of pneumatic FEAs is a frog-inspired swimming robot [108], which uses the actuators in a pair of kicking legs. They can actuate together to achieve a speed of 7.5 cm/s, or asymetrically in order to achieve a turning rate of 15°/s.

However, the most typical implementation of FEAs, allying with the best performance, was on soft fish robots using undulatory locomotion strategies. An investigation of the dorsal/anal fins of fish suggested that the fin area could be modulated actively when accelerating [107]. To verify their hypothesis, scientists used an array of FEAs to mimic the dorsal/anal inclinator and erector/depressor muscles of fish, which allowed the soft fins to be erected or folded within 0.3 s. Such a rapid response and powerful strength could only be achieved by the valve and tube systems, driven by pressurized fluids running inside.

Legged Locomotion

Compliance is useful in locomotion. Cars use inflatable wheels with suspension, while animal legs are made up of soft muscles, tendons, and cartilage. Inspired by nature, researchers make a connection to the spring-mass model for legged robots [157] and original Raibert controller [158], which requires a spring (or compliant element), to create the core hopping frequency. Since the stiffness of the spring directly effects the period of on-ground time, compliance is a core piece of the Raibert hopper. Equally important is the ability to represent complex locomotion patterns, which rely on compliance, as simple spring based models [159]. Implications can be extended to generating non-holomonic motion of a quadruped robot [160] or humanoid robots [161] with controllers relying on simple spring/compliance templates.

In this section, we will present recent researches of legged robots with compliance. We list some basic information of these research in Table 4.

Inspired by RHex [163] and similar passively balanced running robots [164–166], Sprawl robot uses a multi material manufacturing process to introduce dampening and spring effects into legged locomotion. This is an advancement over using regular mechanical coiled springs in the traditional Raibert hopper. These robots, similar to a dead fish, can balance passively, without internal or external feedback, demonstrating the utility of mechanical compliance as a means to reduce computational complexity.

Mechanically finding the right material for desired compliance characteristic is a challenge. Based on preliminary simulation results, [167] proposed an actively controlled slider mechanism to control leg stiffness of an RHex-like robot. They go over the weaknesses and strengths of Nitinol, fiber glass, aluminum, and industrial plastic with an eye towards achieving a desired compliance bandwidth. Easily plugging in different materials to change the passive dynamics of the vehicle would make it robust for usage in different ground environments (mud, grass, smooth surfaces).

Using low gear-ratio drive trains, low inertia legs and high torque density electric motors can not only introduce efficient locomotion but it can also create a realistic fully autonomous robot [168]. In the field of soft robotics, [169] avoids high inertia legs (as compared to body inertia) by being directly inspired by arthropods. The authors do not directly address the importance of low leg inertia but focus on a desire for overall lightweight robot design.

Artificial muscle based on dielectric elastomers can be made as well. The MERbot [170] demonstrates sensing, axial extension, bending and multi degree of freedom actuation. Each leg has a spring and a dielectric layer attached to it, allowing for a two degree of freedom curved motion pattern.

Leg mechanisms have advanced from industrial spring-like solutions to flexible materials with lower elastic modulus to introduce compliance. As shown in Fig. 4, the authors introduce a soft-bodied robot with much lower Young's modulus than its predecessors [162], demonstrating one of the first examples of legged locomotion using soft materials. The mechanism's actuation was powered by pneumatics, using asymmetrical cavities to induce bending when pressurized. The untethered successor [171] is entirely autonomous by carrying the miniature air compressors, battery, valves, and controller. Tendons can also be used to drive entirely soft legs such as in [174], where the

Table 4 Taxonomy of recent soft robotic legged locomotion research

Research	Actuation	Speed	Power autonomy	Control	Number of legs
MERbot [170]	MERs	136 mm/s	Tethered	Open loop	6
iSprawl [166]	Cable-driven	230 mm/s (15 BL/s)	Untethered	Open loop	6
Fully Soft Quadrupedal [162]	Pneumatic	26 mm/s (0.2 BL/s)	Tethered	Open loop	4
Fully Soft Quadrupedal [171]	Pneumatic	5 mm/s	Untethered	Open loop	4
6-legged robotic platform [172]	Pneumatic	11.1 mm/s	Untethered	MIND	6
Arthrobots [169]	Pneumatic	/	Tethered	Open loop	6, 8
Quadrupedal [173]	Tendon-driven	5 mm/s	Untethered	Open loop	4
3-legged [174]	Tendon-driven	10.17 mm/s	Untethered	Open loop	3
Insects [175]	DEAs	18 mm/s	Untethered	FSM	3
Flexible magnetic [176]	Magnetic	3.38 mm/s (0.78 BL/s)	Untethered	Open loop	8
Continuum Limb [177]	PMAs	/	Tethered	Open loop	4
PoseiDRONE [178]	Three bars	7.964 BL/s	Tethered	Open loop	4

authors used 3D printing techniques to create complex geometries that improve the ability of the legs to withstand out-of-plane loading. In addition, the authors used the same techniques to easily reroute the tendons through the legs to create different foot trajectories with a single actuator morphology.

A similar robot body architecture but with more rigid components was introduced in [177], making the system more capable. This robot can crawl and perform basic movements like getting into a standing posture. It diverges from the theme of passive dynamics by driving the continuum legs with motion planning which verifies that center of mass of the rigid robot follows a desired path. Another design where researches use pneumatic, continuum legs with a rigid body is demonstrated in [172]. In this work, each leg has multiple independent degrees of freedom, giving them superior individual flexibility, but resulting in large power consumption. The large rigid body also allows for a full array of sensors and communication/control infrastructure.

An interesting design gets rid of the pneumatic tethers and source but keep the benefits of high power-to-weight ratio by using “pre-charged” pneumatics in [173]. The pre-pressurized silicone chamber translates the simple motion of tendons into a complex output motion. The prototype quadrupedal soft robot can walk untethered, combining the safety of pneumatic actuators with the precision of servo motors.

Jumping

In nature, jumping is an effective locomotion strategy widely used by animals in cluttered environments or in rough terrain. This locomotion method offers animals the ability to catch prey or escape from predators as well as cross over obstacles. Many different animals at different scales such as frogs, locusts, and kangaroos successfully use jumping for locomotion [179]. Reproducing such a locomotion mode would enable a robot to overcome obstacles several times larger than its body. Jumping locomotion is generally achieved in robots based on a quick release of potential energy [180] to generate propulsion and translate it into an initial momentum against gravity. Jumping strategies offer great benefits such that a robot can be operated under a low average energy consumption.

Jumping was initially realized and studied with robots in traditional rigid mechanical structures like multi-bar linkages associated with elastic elements driven by motors, or other similar traditional actuators. However, weight is always a primary factor which always influences performance. Saving weight by reducing the characteristic size scale affects robots’ ability to store energy. Continuing research mostly focuses on ways to reduce total mass by optimizing the mechanical structures, increase energy density, and increase energy efficiency. To solve these issues, researchers have used different strategies with different trade-offs.

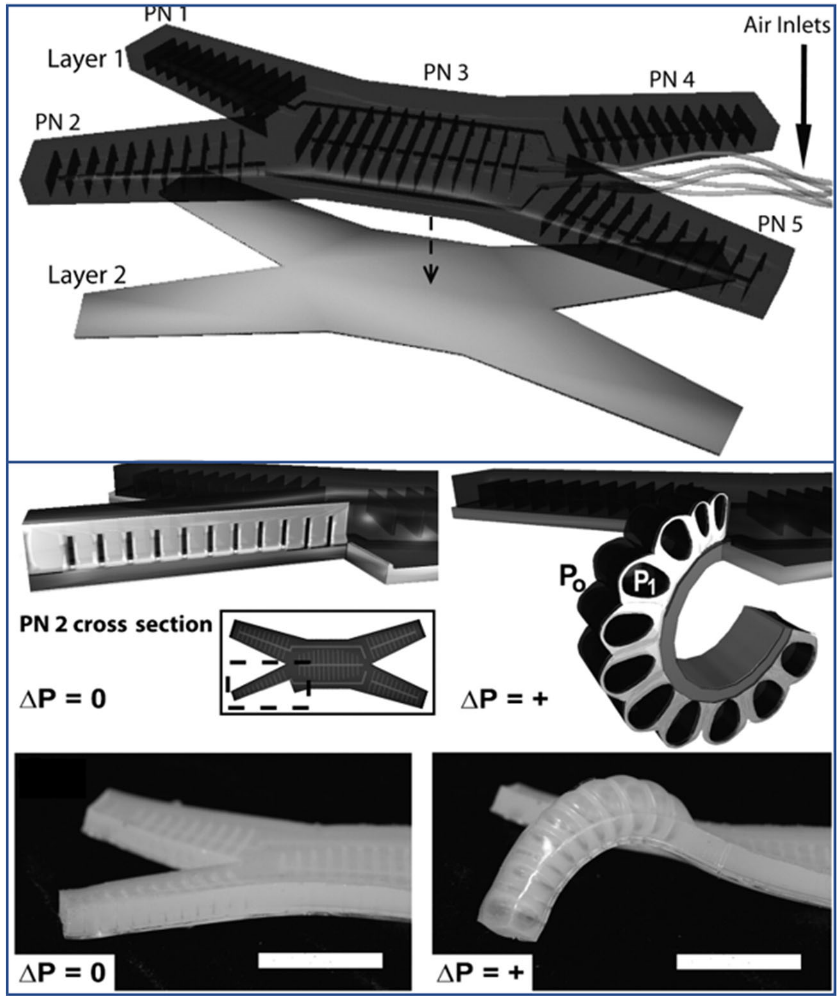

Fig. 4 Schematic representation of the soft pneumatic actuation architecture called pneu-net (PN) and the fully soft robot. (From [162], with permission from PNAS)

As studies of soft materials and soft robotics progressed, jump locomotion developed rapidly on semi-soft or even completely soft robots, due to their being lightweight, high compliance, safer, more adaptable, and more resilient than their rigid counterparts. Nevertheless, the complex fabrication and assembly process and the difficulty of interfacing of soft and rigid components are all bottlenecks for the development of jumping soft robots [181].

In this section, we will present recent researches of soft or semi-soft jumping robots as shown in Fig. 5. We list some basic information of these research in Table 5.

Inspired by animals ranging from small-scale insects to large-scale mammals, researchers utilize various actuation strategies for different jumping mechanisms. Based on the body elasticity of the robot, in this section, we classify jumping robots in three types: rigid, semi-soft, and soft.

Jumping Robots with a Rigid Body and Discrete Elastic Elements

Although many jumping robots are built completely with rigid bodies, elastic elements and mechanisms are employed to store energy which provide mechanical advantages during the energy saving phase [184].

Locust-Inspired

Locusts are an example of an animal that is capable of significant jumps, making them a major source of inspiration for jumping robots. The jumping mechanism of locusts has been studied in [185–188], where they have been found to store energy in preparation for jumps in the mechanical structures of their legs [189].

A series of robots, the EPFL jumpers were designed, where jumping locomotion is driven by a micro DC motor

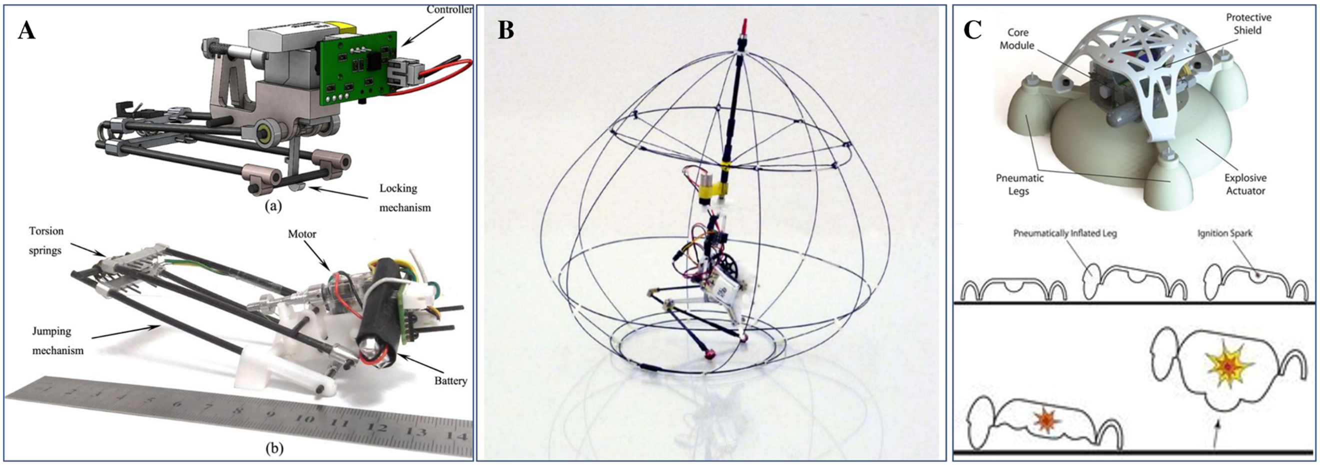

Fig. 5 (A) A locust inspired jumping robot (From [182], © IOP Publishing. Reproduced with permission. All rights reserved). (B) Jumping robot by a research group from EPFL (From [183], © IOP Publishing. Reproduced with permission. All rights reserved). (C) Prototype of a 3D printed soft robot jumper powered by combustion and tilted by surrounding pneumatic legs (From [181], © Science Robotics. Reproduced with permission. All rights reserved)

which turns an eccentric cam to store energy to two steel springs [183, 190–192]. To jump, the springs release their energy into a four-bar linkage leg structure. In a novel spherical design in [183], a micro motor and a cage made of carbon rods are combined to achieve the up-righting and steering of the robot. This version (EPFL jumper v3) weighs 14.33 g, half of which is the cage. It can jump up to 111 cm at a take-off angle of 75° without the cage (62 cm with the cage). The jump height-to-mass ratio for the spherical design is 4.17 cm/gr while jump height-to-body size ratio is 3.4. Additional mechanisms can improve the controllability of the robot at the expense of jumping capability.

EPFL jumper has the ability to adjust its jumping height, jumping distance and take-off angle by altering the angle between components of its inner jumping mechanism. In addition, with the cage and setting the center of mass in the lower part of the body, the robot can always recover passively and orient itself after each jump, which allow the robot to perform repeated jumps without supervision [183, 191].

A locust-inspired miniature jumping robot TAUB can achieve jumping and gliding by mimicking the locust's energy storage structures [182, 195, 207]. Carbon fiber rods of equal length are designed to mimic femur and tibia for each leg of the robot. Torsional springs are utilized as the elastic elements to store energy and link the two carbon rods on each leg to mimic the semi-lunar process (SLP). A geared electric motor with a tendon-like wire connected to the leg is designed to mimic the extensor muscle. An aluminum latch mechanism inspired by the locking mechanism of the locust is designed to overcome the releasing speed issues of the geared motor. This mechanism performs much better in the energy storage than the previously mentioned cam mechanisms, while performing the same during energy release, leading to an improved jumping height of 3.35 m and a jumping distance of 1.37 m. This comes out to a jumping height-to-mass ratio is 14.57 cm/gr and a jumping height-to-body length ratio is 25.8. However, it has the drawback in that the loading and releasing takes much longer in the TAUB mechanism than in the cam mechanism.

Galago-Inspired

The galago (bush baby) is a species famous for its phenomenal jumping capability. The recorded vertical jumping height of a 250-g galago can reach over 2.25 m [208]. The vastus muscle-tendon systems of the galago provide most of the power for jumping and the peak power output implies complex aponeurotic system which work as a substantial power amplifier [209].

In [196, 197, 210–212], a galago-inspired jumping robot "Salto" using power modulation as the jumping mechanism was designed and studied. Power modulation has been investigated in animals like salamanders [213] and mantis shrimps [214] but not explicitly studied on robots until recent years. This mechanism is capable of varying mechanical advantage (defined as the ratio between the reaction force at the foot and the force generated by actuators) while preserving the benefits of a series-elastic actuator. It can reduce the motor power density required for a powerful jump. Researches indicate that any robot with a limb driven by series elastic actuator with a non-linear mechanical advantage should have the potential to achieve higher power modulation ratios than a non-specialized

Table 5 Taxonomy of recent soft robotic jumping locomotion research

Research	Actuation	Speed	Power autonomy	Control	Rigidity	Height
Miniature [190]	Motor	/	Untethered	Open-loop	Discrete spring	1400 mm
Self-Recovery Miniature [183, 191]	Motor	/	Untethered	feedback	Discrete spring	62 mm
Jumping Gliding [193]	Motor	/	Untethered	Open-loop	Discrete spring	1700 mm
Jumping Gliding [194]	Motor	6000 mm/s avg	Untethered	Open-loop	Discrete spring	3000 mm
Locust [195]	Motor	/	Untethered	Open-loop	Discrete spring	3100 mm
Locust [182]	Motor	/	Untethered	Open-loop	Discrete spring	3350 mm
Salto [196]	Motor: power Modulation	/	Untethered	PID	Discrete spring	1008 mm
Salto-1p [197]	Motor: power Modulation	/	Untethered	Model-based	Discrete spring	900 mm
Direct Drive [198]	Motor	1450 mm/s (bound) 800 mm/s (pronk)	Untethered	Close-loop	Discrete spring	480 mm
Omnidirectional Jumper [199]	Motor	/	Untethered	Feedback	Discrete spring	1130 mm
Data-Driven [200]	SEA		Untethered	Feedback Data-Driven	Discrete spring	60 mm
Rolling Jumper [201]	Spring steel Elastic strip	1200 mm/s	Untethered	Feedback	Discrete spring	590 mm
Origami Hopper [202]	Cable-driven	1.5 BL/s	Tethered	PID	Flexible semi-soft	/
SMA Circular [203]	SMA	26 mm/s (crawl)	Tethered	Open-loop	Soft-material	80 mm
Roly-poly [204]	Combustion	/	Untethered	Open-loop	Soft-material	200 mm
Shell Snapping [205]	Isochoric Snapping	/	Tethered	Volume control	soft-material	42.9 mm
Ultrarobust Insect [206]	Elastic Structure	20 BL/s	Tethered	pwm control	Soft-material	1.5 mm
Gradient Top [181]	Combustion	/	Untethered	Open-loop	Soft-material	760 mm

series elastic actuator. In [196, 210], the metric of vertical jumping agility is proposed to express and analyse jumping performance more clearly. This agility is indicated as vertical jump height per second based on the maximum average vertical velocity of the jumping system that can be achieved during repeated jumping, and limited to the power-to-weight ratio of the system. Considering the constraints and arrangement of links, the mechanical advantage of Salto is created by a optimized single DOF eight-bar revolute linkage. The series-elastic actuator includes a torsional latex spring designed for an SEA snake [215] that took advantage of the energy storage capability of latex and a geared brushless motor to drive the linkage. Before a jump, Salto maintains a a low mechanical advantage state to store energy. During the jump, Salto adjusts to a high mechanical advantage state to rapidly transfer the stored energy and generate a large upward acceleration. Salto can jump 0.9 m high with a vertical jumping agility of 1.36 m/s, equivalent to 78% of the galago's agility, which is also the highest record of a vertical jumping robot.

Controllability and Multi-modal Locomotion

To improve the controllability and jumping performance of miniature robots, researchers have added more components to provide robots with additional functionalities or even extra locomotion modes. In later research [197, 212], enhanced Salto-1P expands its functionality to include yaw control, roll control, and precise repetitive jumping. This was done using 2 propellers and an inertial tail. Researchers introduced a deadbeat foot placement hopping controller, which uses a third order Taylor series approximation of the dynamic model. It is able to adjust the velocity and direction rapidly while controlling the take-off velocity in a single jump.

Adding a glide wing to a jumping robot is a useful strategy, allowing it to improve its performance and adjust its direction on the fly. The EPFL jumpers [192, 216] also added extra wings and tails to help improve the controllability while sacrificing the jumping performance. In [193, 194], a bat-inspired robot MultiMo-Bat was proposed. The authors divided up its locomotion into four phases: energy storage, jump, coast, and glide. A research group in CMU developed a robot [194], which is 115.6 g and consists of 2 four-bar leg structures, each with 2 DOF and fixed at the shoulder joints. The wings are made of soft elastic materials, which allow the wings to change shape and facilitate membrane collapse to help reduce the influence on jumping performance. The internal mechanism and main power springs are supported by four-bar legs that are responsible for energy storage. Kinetics and mechanical designs can be quite complex when combining multiple locomotion methods. To solve that, researchers make use of components sharing, which leads to robots that preserve over 80% of the independent jumping performance with nearly 70% of robots mass are shared components for both jumping and gliding modes. The robot can jump up to 305 cm with an horizontal distance of 232 cm. When the leg is compressed, elastic energy will be stored for jumping, the wing membranes are collapsed as well to reduce the drag during liftoff. When the leg is extended, the wing membranes are also extended. The integration of the the wing and legs not only helps stabilize the robot, but can also improve performance.

In [201], jumping is combined with rolling locomotion in a compact robot. Jumping while rolling has the advantages of varying the jumping height and width and not influencing the movement speed, which requires an instantaneous force generation mechanism. Besides the two-wheel drive mechanism, the jumping mechanism consists of an aluminum frame with a movable joint with motors and an elastic strip made of spring steel which generates the instantaneous force based on snap-through buckling. Its jumps were an average of 5.9 cm high while rolling at a steady speed of 1.2 m/s, giving it the ability to traverse obstacles that would otherwise be impassible. In [199], an omnidirectional jumper capable of steering, self-righting, and adjusting take-off angle with only two motors is introduced. Similar to the Multimo-Bat, this strategy works to minimize the actuators and additional mass, resulting in a total of only 64.4 g. The jumping mechanism is based on [217] with a four-bar linkage and torsional springs, and is implemented by a modified active triggering mechanism using one motor with a rhombus-shaped four-bar linkage and latex bands as elastic components. The robot is able to jump in all directions with a maximum height of 113 cm and distance of 170 cm.

Control of these highly compliant robots is always a challenge. The authors of [200] proposed a new bang-bang control approach based completely on data. They convert the motion planning to a discrete-timing problem and utilize the features of the discrete parameterization to plan directed aperiodic jumping motions. This can avoid the need for complex dynamic modeling and offline calculations, basing all commands on data from previous jumping trials.

Direct-Drive Actuation

In contrast to previously introduced robots, in [198] a new direct-drive (DD) legged robot is introduced for jumping. A DD system makes use of the fact that the torque generating capability of the robot's motor is used without the friction from belts or gears. [218]. It has numerous benefits like: no backlash, back-drivable, high torsional stiffness, lower weight and cost, high precision, low compliance, and high reliability. The downside is they require high-torque, low speed motors. The robot Minitaur is compared with other two DD robots, Delta Hopper and Penn Jerboa. Minitaur is a quadruped robot with 8 DD actuators, each leg has 2 DOF and able to to move in the longitudinal plane. An IMU is attached to measure the orientation and the angular velocity of the robot body and an STM32 micro-controller is used to gather sensory information and send out commands to the motors. The motors are also equipped with encoders to measure motor rotation angles so that Minitaur can be controlled through a pulse width modulation (PWM) or even position control. Minitaur can jump twice per second with a greater power density but half the vertical jumping agility of the galago.

Jumping Robots with a Semi-soft Body

Some jumping robots use materials that are flexible but not stretchable, which we classify here as having semi-soft bodies. In [202], a laptop-sized paper origami jumping robot is proposed. The robot is based on reconfigurable expanding bistable origami (REBO) that when fully extended flattens into a circle and forms a cone [219]. The cone is formed as a stack of concentric rings with different radii while each ring is extendable and flatten individually, which gives the mechanism the ability to form a range of 3D shapes. The robot consists of 3 main parts: the REBO linear spring with a tendon, a force sensor, and the control components. The REBO spring is a double-layered REBO mechanism with different design parameters which store elastic energy for the jumping robot. The spring is connected with a tendon and it is driven by the cable through holes laced on the spring and a pulley mounted on an electric motor.

The force sensor is attached to the compliant 3D printed toe and is mounted at the bottom of the REBO spring. It is used to detect the exact moment when the hopper contacts the ground when falling or leaves the ground when jumping, so that the controller can switch between compressing and releasing the spring. For vertical hopping, the hopper is controlled through PD feedback by 3 DC motors with encoders. When the robot comes in contact with the ground, the REBO spring is released to generate a vertical jumping force. When lifting off, the spring is compressed by the motor to store energy for the next jump. For fore-aft hopping, two control strategies are used during experiments. The open-loop control can adjust the direction for the robot and change the speed qualitatively, while the Raibert-style [220] closed-loop control can regulate the speed and resist perturbation.

Jumping Robots with a Soft Body

Robots made of completely soft materials can be more compliant and lighter. Since jumping performance is largely related to the weight of the robots and the energy density. Driven by various power sources including magnetic fields, chemical reactions, electrical voltage, and pressurized air, soft robots have been studied in multiple approaches for jumping.

Chemical Power

In [204], an untethered and combustion-actuated soft robot in roly-poly toy geometry is presented. The bottom semi-spherical body with a combustion chamber is made of silicone cast in 3D printed molds. The silicone body is used to shelter the fuel tanks and the spark igniter. The upper body is covered with an upside-down lightweight bowl to protect the inner components during jumping where a camera is attached to monitor the robot locomotion from its own point of view. This roly-poly structure enables the robot to reorientate itself after each jump as the rotation center is always above the center of gravity, giving it the potential for repetitive jumping. The power source is a mixture of nitrous oxide, propane and butane whose energy density is much higher than electrical batteries.

With 2.1 kg in weight and 18 cm in diameter, the robot can jump up to 0.2 m with an energy efficiency over 0.4%. And the take-off velocity can also be controlled by adjusting the gas ratio and flow rate of the flammable gas. However, due to gas storage limits, the total operation time of the robot is no longer than 2 minutes, which is not suitable for realistic applications in real environments. In [181], another soft robot driven by combustion is studied. This robot is manufactured by multi-material 3D printing techniques with a modular design and the separation of actuators and power source. The body is composed of two nested hemispheroids. The top hemisphere is designed with layers of increasing stiffness, creating a smooth transition between the soft bodies and rigid components to enhance performance. The bottom hemisphere has a small depression for pumping mixed gas. Three pneumatic legs with the same hemi-ellipsoid design are attached to the robot's body to control the jumping direction. The main control module is a rigid part with circuit board, power source, battery, air compressor, and solenoid valves. covered with a protective shield. The robot injects 40 ml of butane and 120 ml of oxygen into the ignition chamber, which expands during ignition to cause the robot to jump.

Electrical Power

Electricity is a common power source to provide jumping energy as well. In [206], a film-based insect-scaled robot made in curved piezoelectric polyvinylidene difluoride (PVDF) unimorph structure is proposed. The active layer of the structure is a 0.018-mm-thick PVDF laminated to a 0.025-mm PET tape attached with a 0.025-mm layer of silicone rubber. The size of the robot is 3×1.5 cm total with a curved body and a folded leg-like structure. Two electrodes with wires are attached to the top layer to provide alternating current from an external power source. The current causes the PVDF layer to extend and contract through the piezoelectric effect, changing the shape of the body.

This body shape is able to mimic animal locomotion based on a pattern by oscillating the center of mass of the robot which lifts its body off the ground and move forward. The maximum speed the 10-mm-long prototype can reach 20 body lengths-per-second under 850 Hz AC, making it the fastest insect-scale mobile robot.

Fluid Power

Using fluid properties to drive a soft robot is another interesting way to perform jumping locomotion. In [205], a soft jumping robot made of fluidic soft actuators which overcomes the limitation of slow actuation speed is explained. It uses a bistable elastomeric dome that, after a certain deformation is reached, will suddenly snap into a convex shape. To trigger this motion, the robot utilizes a second dome above it, which serves as a pressure chamber. When the pressure inside the cavity reaches a certain threshold, the lower membrane will snap downwards, causing the robot to jump. This allows a slow increase in flow-rate to trigger an abrupt motion of the robot.

The original design with a soft rubber outer cap can jump up to 42.9 mm, but by analyzing through a simplified mass-spring model and adjusting the parameters of of the domes, the authors were able to create a version that could reach 283 mm. Moreover, this method proves that the jumping height can be decoupled from the size of the robot which broadens the path for larger soft jumping robots with other light-weight components.

Shape Memory Alloy Actuated

In [203], a deformable circular soft robot is presented. The outer shell of the robot is made of rubber while the inner surface is connected with multiple SMA coils which are used as elastic components to deform the robot and store energy for locomotion. This robot uses 8 SMA actuators for crawling or 9 for jumping. During jumping, appropriate SMA actuators contract to store the energy and then rapidly release to generate a force and lift the robot off the ground. The robot weighs 3 g with a radius of 40 mm. It can jump up to 80 mm and crawl at a maximum velocity of 26 mm/s.

Alternative Locomotion

In addition to the major research directions in soft robotic locomotion, Some researchers developed soft robots with alternative locomotion techniques by modifying bio-inspired locomotion approaches, or creating novel locomotion methods without obvious inspiration from nature. In Table 6, we list some basic information of these research.

Preston et al. demonstrated a soft pneumatic oscillator to trigger pneumatic actuators at a certain frequency. By actuating the six actuators around a ring in sequence, soft rolling locomotion is generated [221].

Sun et al. developed a salamander inspired continuum mobile robot. Like salamanders in nature, the main body is flexible and deformable made of a cable-driven origami mechanism, while wheels are used as to generate thrust, which demonstrate agile locomotion in narrow and unstructured environments [222].

A similar direction is deformable wheels. Researchers utilize origami structures and motors [223], SMA [224], temperature sensitive liquid crystal elastomers (LCEs) [225], or springs [226] to fabricate active or passive deformable wheels, which are able to modify the radius or shape of the wheel in order to adapt to different application requirements like lowering the robot to travel beneath an obstacle or climbing up stairs.

Discussion

This article provides a comprehensive reference guide for researchers working in soft mobile robots and soft robotic locomotion systems. We provide a broad overview of soft robotic research in locomotion applications, encompassing discrete elastic elements, flexible substrates, compliant mechanisms, and fully deformable materials as part of the larger domain of soft robotic locomotion.

We classify the domain in different mostly bioinspired locomotion modes in each section. Figure 6 shows the distribution of research on soft locomotion recent years. Not surprisingly, a large body of research focuses on crawling and—to a lesser degree—swimming locomotion modes, since these happen to be the most approachable areas with a lot of model animals to be inspired from. However, we do notice an increasing number of contributions from other areas such as flying and jumping, where some unique properties of body elasticity and lightweight materials are harnessed for greater performance. According to our review references in this article, there have been about the same number of research papers in flying locomotion (at different levels of elasticity) in the past 3 years as compared to swimming locomotion papers since bioinspired flapping wings and bird-like robot with flexible wings enable high

Table 6 Taxonomy of recent soft robotic alternative locomotion research

Research	Actuation	Speed	Power autonomy	Control	Locomotion gait
Soft Ring [221]	Pneumatic	0.034 BL/s	Untethered	Open loop	Ring Oscillator
Salamanderbot [222]	Cable driven	303.1 mm/s (2.05 BL/s)	Tethered	Semi closed loop	Salamander inspired
Oriwheel [223]	Cable driven	/	Untethered	Open loop	Deformable Wheel
Oriwheel [224]	SMA	120 mm/s	Untethered	Open loop	Deformable Wheel
LCEwheel [225]	LCE	/	Untethered	Open loop	Morphing
Morphing Wheel [226]	Motor	1280 mm/s	Untethered	Open loop	Passive Spoke

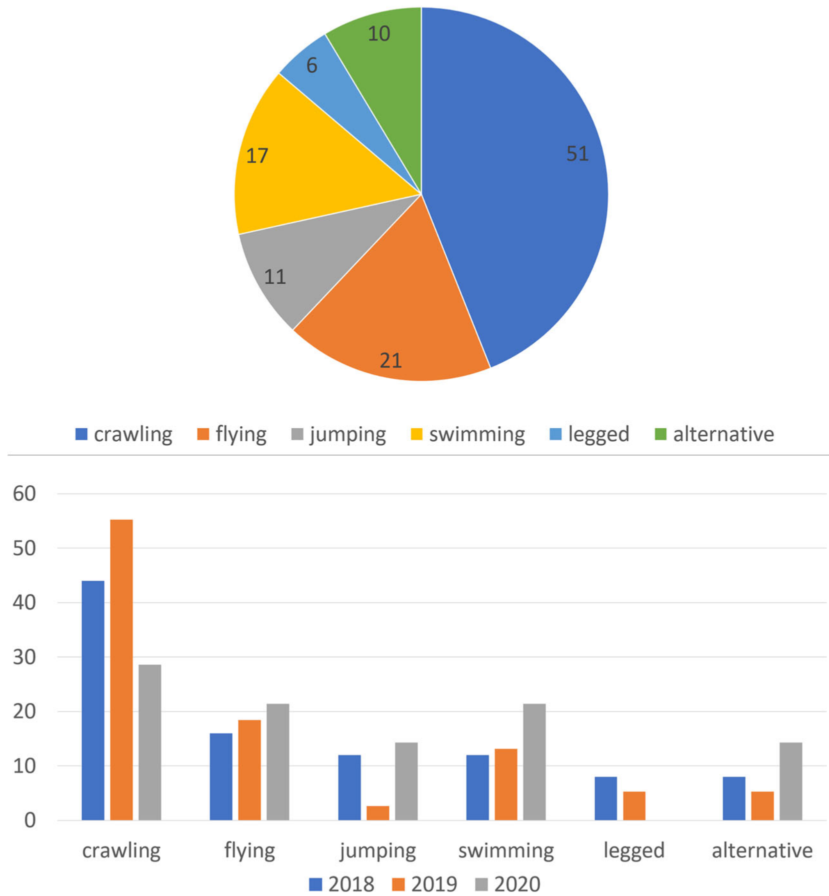

Fig. 6 Top: Distribution of research articles on soft locomotion from year 2018 to 2020. Bottom: Percentage of research articles in different locomotion each year. Here, we include data gathered from the following journals: Soft Robotics, Science Robotics; and the following conferences: ICRA, IROS, RoboSoft

performance flight and increasing flight maneuverability, which makes it an interesting research area. We also note some non-bioinspired approaches offering alternative locomotion modes that focus on the engineering utility of elasticity and not necessarily starting with inspiration from a model animal.

Soft robotic locomotion offers greater compliance, safety, and adaptability. These aspects are used to offer unique capabilities in multiple locomotion modes in the literature. While most of the existing research remains tethered and using open-loop control with pressure-driven fluidic actuation, there is an increasing number of research activities that challenge these more traditional approaches. Researchers explore (1) new closed-loop control methods that rely on a new generation of proprioceptive sensors; (2) new actuation methods that range from motor-driven systems, smart materials, and chemical means; and (3) achieving power autonomy for truly tetherless operation, which will help us take soft mobile robots outside the labs and in the complex environments they are built to traverse.

Despite these promising advances, we notice that the vast majority of existing soft robots remain weaker and slower than their rigid counterparts. We believe the next decade of soft robotics research should focus on more dynamic capabilities that rival and surpass existing systems. Similarly, we recommend that soft locomotion systems should be investigated outside the crawling and swimming domains where gravity is not a big challenge and focus more on different locomotion modes and applications where greater value can be provided in the field.

Finally, harnessing the inherent safety and adaptability of their soft bodies, we see a significant research area for soft robotic locomotion systems in human environments. In future workplaces and other applications where humans and robots physically interact, human-soft robot teams may enable new ways to perform tasks more effectively and efficiently than current approaches. We anticipate intuitive interfaces can be explored for soft mobile robots or other soft bodied technologies to be commonly incorporated in everyday use cases and work collaboratively with users.

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Declarations

Conflict of Interest Cagdas Onal has the following patents planned, issued, or pending: US Patent App. 16/541,414, US Patent 10,551,923, US Patent 10,478,975, US Patent 10,456,316, US Patent App. 16/176,138, US Patent 9,857,245, US Patent 9,686,867. Dr. Onal also reports stock or stock options for Ubiros Inc. and is the co-founder of Ubiros Inc. The other authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Disclaimer Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

References

1. Pratt GA, Williamson MM. Series elastic actuators. In: Proceedings 1995 IEEE/RSJ international conference on intelligent robots and systems, human robot interaction and cooperative robots. IEEE; 1995. p. 399–406.
2. Ju Z, Yang C, Li Z, Cheng L, Ma H. Teleoperation of humanoid baxter robot using haptic feedback. In: 2014 international conference on multisensor fusion and information integration for intelligent systems (MFI). IEEE; 2014. p. 1–6.
3. Gaz C, Cognetti M, Oliva A, Giordano PR, De Luca A. Dynamic identification of the franka emika panda robot with retrieval of feasible parameters using penalty-based optimization. IEEE Robot Autom Lett. 2019;4(4):4147–4154.
4. Collins S, Ruina A, Tedrake R, Wisse M. Efficient bipedal robots based on passive-dynamic walkers. Science. 2005;307(5712):1082–1085.
5. Onal C, Rus D. Autonomous undulatory serpentine locomotion utilizing body dynamics of a fluidic soft robot. Bioinspir Biomim. 2013;8(2):026003.
6. Jung K, Koo JC, Lee Y, Choi HR, et al. Artificial annelid robot driven by soft actuators. Bioinspir Biomim. 2007;2(2):S42.
7. Umedachi T, Vikas V, Trimmer B. Softworms: the design and control of non-pneumatic, 3d-printed, deformable robots. Bioinspir Biomim. 2016;11(2):025001.
8. Rafsanjani A, Zhang Y, Liu B, Rubinstein SM, Bertoldi K. Kirigami skins make a simple soft actuator crawl. Sci Robot. 2018;3(15).
9. Duggan T, Horowitz L, Ulug A, Baker E, Petersen K. Inchworm-inspired locomotion in untethered soft robots. In: 2019 2nd IEEE international conference on soft robotics (RoboSoft). IEEE; 2019. p. 200–205.
10. Kim W, Byun J, Kim J-K, Choi W-Y, Jakobsen K, Jakobsen J, Lee D-Y, Cho K-J. Bioinspired dual-morphing stretchable origami. Sci Robot. 2019;4(36).
11. Zou J, Lin Y, Ji C, Yang H. A reconfigurable omnidirectional soft robot based on caterpillar locomotion. Soft Robot. 2018;5(2):164–174.
12. Das R, Babu SPM, Palagi S, Mazzolai B. Soft robotic locomotion by peristaltic waves in granular media. In: 2020 3rd IEEE international conference on soft robotics (RoboSoft). IEEE; 2020. p. 223–228.
13. Umedachi T, Shimizu M, Kawahara Y. Caterpillar-inspired crawling robot using both compression and bending deformations. IEEE Robot Autom Lett. 2019;4(2):670–676.
14. Nemitz MP, Mihaylov P, Barraclough TW, Ross D, Stokes AA. Using voice coils to actuate modular soft robots: wormbot, an example. Soft Robot. 2016;3(4):198–204.
15. Joyee EB, Pan Y. A fully three-dimensional printed inchworm-inspired soft robot with magnetic actuation. Soft Robot. 2019;6(3):333–345.
16. Pham LN, Abbott JJ. A soft robot to navigate the lumens of the body using undulatory locomotion generated by a rotating magnetic dipole field. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 1783–1788.
17. Goldberg NN, Huang X, Majidi C, Novelia A, O'Reilly OM, Paley DA, Scott WL. On planar discrete elastic rod models for the locomotion of soft robots. Soft Robot. 2019;6(5):595–610.
18. Huang X, Kumar K, Jawed MK, Nasab AM, Ye Z, Shan W, Majidi C. Chasing biomimetic locomotion speeds: creating untethered soft robots with shape memory alloy actuators. Sci Robot. 2018;3(25).
19. Huang X, Kumar K, Jawed MK, Ye Z, Majidi C. Soft electrically actuated quadruped (seaq)—integrating a flex circuit board and elastomeric limbs for versatile mobility. IEEE Robot Autom Lett. 2019;4(3):2415–2422.
20. Trimmer B, Takesian AE, Sweet BM, Rogers CB, Hake DC, Rogers DJ. Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots. In: 7th international symposium on technology and the mine problem. Mine Warfare Association Monterey, CA; 2006. p. 1–10.
21. Trimmer B, Lin H-T, Baryshyan A, Leisk GG, Kaplan DL. Towards a biomorphic soft robot, design constraints and solutions. In: 2012 4th IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics (BioRob). IEEE; 2012. p. 599–605.
22. Umedachi T, Vikas V, Trimmer B. Highly deformable 3-d printed soft robot generating inching and crawling locomotions with variable friction legs. In: 2013 IEEE/RSJ international conference on intelligent robots and systems. IEEE; 2013. p. 4590–4595.
23. Seok S, Onal C, Cho K-J, Wood RJ, Rus D, Kim S. Meshworm: a peristaltic soft robot with antagonistic nickel titanium coil actuators. IEEE/ASME Trans Mechatron. 2012;18(5):1485–1497.
24. Menciassi A, Gorini S, Pernorio G, Weiting L, Valvo F, Dario P. Design, fabrication and performances of a biomimetic robotic earthworm. In: 2004 IEEE international conference on robotics and biomimetics. IEEE; 2004. p. 274–278.
25. Yuk H, Kim D, Lee H, Jo S, Shin JH. Shape memory alloy-based small crawling robots inspired by c. elegans. Bioinspir Biomim. 2011;6(4):046002.
26. Henke E-FM, Schlatter S, Anderson IA. Soft dielectric elastomer oscillators driving bioinspired robots. Soft Robot. 2017;4(4):353–366.
27. Zhao J, Zhang J, McCoul D, Hao Z, Wang S, Wang X, Huang B, Sun L. Soft and fast hopping–running robot with speed of six times its body length per second. Soft Robot. 2019;6(6):713–721.
28. Guo J, Xiang C, Conn A, Rossiter J. All-soft skin-like structures for robotic locomotion and transportation. Soft Robot. 2020;7(3):309–320.
29. Booth JW, Shah D, Case JC, White EL, Yuen MC, Cyr-Choiniere O, Kramer-Bottiglio R. OmniSkins: robotic skins that turn inanimate objects into multifunctional robots. Sci Robot. 2018;3(22).
30. Tang Y, Zhang Q, Lin G, Yin J. Switchable adhesion actuator for amphibious climbing soft robot. Soft Robot. 2018;5(5):592–600.
31. Gu G, Zou J, Zhao R, Zhao X, Zhu X. Soft wall-climbing robots. Sci Robot. 2018;3(25).
32. Tolley M, Shepherd RF, Mosadegh B, Galloway KC, Wehner M, Karpelson M, Wood RJ, Whitesides GM. A resilient, untethered soft robot. Soft Robot. 2014;1(3):213–223.

33. Shepherd RF, Ilievski F, Choi W, Morin SA, Stokes AA, Mazzeo AD, Chen X, Wang M, Whitesides GM. Multigait soft robot. Proc Natl Acad Sci. 2011;108(51):20400–20403.
34. Liu B, Ozkan-Aydin Y, Goldman DI, Hammond FL. Kirigami skin improves soft earthworm robot anchoring and locomotion under cohesive soil. In: 2019 2nd IEEE international conference on soft robotics (RoboSoft). IEEE; 2019. p. 828–833.
35. Wu P, Jiangbei W, Yanqiong F. The structure, design, and closed-loop motion control of a differential drive soft robot. Soft Robot. 2018;5(1):71–80.
36. Qin L, Liang X, Huang H, Chui CK, Yeow RC-H, Zhu J. A versatile soft crawling robot with rapid locomotion. Soft Robot. 2019;6(4):455–467.
37. Rothemund P, Ainla A, Belding L, Preston DJ, Kurihara S, Suo Z, Whitesides GM. A soft, bistable valve for autonomous control of soft actuators. Sci Robot. 2018;3(16).
38. Singh G, Patiballa S, Zhang X, Krishnan G. A pipe-climbing soft robot. In: 2019 international conference on robotics and automation (ICRA). IEEE; 2019. p. 8450–8456.
39. Xie R, Su M, Zhang Y, Li M, Zhu H, Guan Y. Pisrob: A pneumatic soft robot for locomoting like an inchworm. In: 2018 IEEE international conference on robotics and automation (ICRA). IEEE; 2018. p. 3448–3453.
40. Ito F, Kawaguchi T, Kamata M, Yamada Y, Nakamura T. Proposal of a peristaltic motion type duct cleaning robot for traveling in a flexible pipe. In: 2019 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2019. p. 6614–6621.
41. Luo Y, Zhao N, Kim KJ, Yi J, Shen Y. Inchworm locomotion mechanism inspired self-deformable capsule-like robot, design, modeling, and experimental validation. In: 2018 IEEE international conference on robotics and automation (ICRA). IEEE; 2018. p. 6800–6805.
42. Li T, Zou Z, Mao G, Yang X, Liang Y, Li C, Qu S, Suo Z, Yang W. Agile and resilient insect-scale robot. Soft Robot. 2019;6(1):133–141.
43. Umedachi T, Kawahara Y. Caterpillar-inspired crawling robot on a stick using active-release and passive-grip elastic legs. In: 2018 IEEE international conference on soft robotics (RoboSoft). IEEE; 2018. p. 461–466.
44. Onal C, Wood RJ, Rus D. An origami-inspired approach to worm robots. IEEE/ASME Trans Mechatron. 2012;18(2):430–438.
45. Manwell T, Guo B, Back J, Liu H. Bioinspired setae for soft worm robot locomotion. In: 2018 IEEE international conference on soft robotics (RoboSoft). IEEE; 2018. p. 54–59.
46. Ta TD, Umedachi T, Kawahara Y. Design of frictional 2d-anisotropy surface for wriggle locomotion of printable soft-bodied robots. In: 2018 IEEE international conference on robotics and automation (ICRA). IEEE; 2018. p. 6779–6785.
47. Horchler AD, Kandhari A, Daltorio KA, Moses KC, Ryan JC, Stultz KA, Kanu EN, Andersen KB, Kershaw JA, Bachmann R, et al. Peristaltic locomotion of a modular mesh-based worm robot: precision, compliance, and friction. Soft Robot. 2015;2(4):135–145.
48. Shin B, Ha J, Lee M, Park K, Park GH, Choi TH, Cho K-J, Kim H-Y. Hygrobot: A self-locomotive ratcheted actuator powered by environmental humidity. Sci Robot. 2018;3(14).
49. Stokes AA, Shepherd RF, Morin SA, Ilievski F, Whitesides GM. A hybrid combining hard and soft robots. Soft Robot. 2014;1(1):70–74.
50. Lee H, Jang Y, Choe JK, Lee S, Song H, Lee JP, Lone N, Kim J. 3D-printed programmable tensegrity for soft robotics. Sci Robot. 2020;5(45).
51. Mao S, Dong E, Zhang S, Xu M, Yang J. A new soft bionic starfish robot with multi-gaits. In: 2013 IEEE/ASME international conference on advanced intelligent mechatronics. IEEE; 2013. p. 1312–1317.
52. Luo M, Agheli M, Onal C. Theoretical modeling and experimental analysis of a pressure-operated soft robotic snake. Soft Robot. 2014;1(2):136–146.
53. Jia Y, Ma S. A bayesian-based controller for snake robot locomotion in unstructured environments. In: 2020 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2020. p. 7752–7757.
54. Branyan C, Menğüç Y. Soft snake robots: investigating the effects of gait parameters on locomotion in complex terrains. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 1–9.
55. Qin Y, Wan Z, Sun Y, Skorina EH, Luo M, Onal C. Design, fabrication and experimental analysis of a 3-d soft robotic snake. In: 2018 IEEE international conference on soft robotics (RoboSoft). IEEE; 2018. p. 77–82.
56. Liao B, Zang H, Chen M, Wang Y, Lang X, Zhu N, Yang Z, Yi Y. Soft rod-climbing robot inspired by winding locomotion of snake. Soft Robot. 2020.
57. Calisti M, Giorelli M, Levy G, Mazzolai B, Hochner B, Laschi C, Dario P. An octopus-bioinspired solution to movement and manipulation for soft robots. 2011, Vol. 6.
58. Verma MS, Ainla A, Yang D, Harburg D, Whitesides GM. A soft tube-climbing robot. Soft Robot. 2018;5(2):133–137.
59. Rieffel J, Mouret J-B. Adaptive and resilient soft tensegrity robots. Soft Robot. 2018;5(3):318–329.
60. Kanada A, Giardina F, Howison T, Mashimo T, Iida F. Reachability improvement of a climbing robot based on large deformations induced by tri-tube soft actuators. Soft Robot. 2019;6(4):483–494.
61. Usevitch NS, Hammond ZM, Schwager M, Okamura AM, Hawkes EW, Follmer S. An untethered isoperimetric soft robot. Sci Robot. 2020;5(40).
62. Yamada Y, Nakamura T. Blade-type crawler capable of running on the surface of water as bio-inspired by a basilisk lizard. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 1–9.
63. Digumarti KM, Cao C, Guo J, Conn AT, Rossiter J. Multi-directional crawling robot with soft actuators and electroadhesive grippers. In: 2018 IEEE international conference on soft robotics (RoboSoft). IEEE; 2018. p. 303–308.
64. Wang J, Fei Y, Liu Z. Fifobots: Foldable soft robots for flipping locomotion. Soft Robot. 2019;6(4):532–559.
65. Umedachi T, Shimizu M, Kawahara Y. Actuation frequency-dependent automatic behavioral switching on caterpillar-inspired crawling robot. In: 2019 2nd IEEE international conference on soft robotics (RoboSoft). IEEE; 2019. p. 167–171.
66. Zhang B, Fan Y, Yang P, Cao T, Liao H. Worm-like soft robot for complicated tubular environments. Soft Robot. 2019;6(3):399–413.
67. Connolly F, Polygerinos P, Walsh CJ, Bertoldi K. Mechanical programming of soft actuators by varying fiber angle. Soft Robot. 2015;2(1):26–32.
68. Calisti M, Giorelli M, Laschi C. A locomotion strategy for an octopus-bioinspired robot. In: Conference on biomimetic and biohybrid systems. Springer; 2012. p. 337–338.
69. Cera BM, Thompson AA, Agogino AM. Energy-efficient locomotion strategies and performance benchmarks using point mass tensegrity dynamics. In: 2019 IEEE/RSJ international conference on intelligent robots and systems (IROS); 2019.
70. Mirletz BT, Bhandal P, Adams RD, Agogino AK, Quinn R, SunSpiral V. Goal-directed cpg-based control for tensegrity

spines with many degrees of freedom traversing irregular terrain. Soft Robot. 2015;2(4):165–176.
71. Daltorio KA, Boxerbaum AS, Horchler AD, Shaw KM, Chiel HJ, Quinn R. Efficient worm-like locomotion: slip and control of soft-bodied peristaltic robots. 2013, Vol. 8.
72. Coevoet E, Escande A, Duriez C. Soft robots locomotion and manipulation control using fem simulation and quadratic programming. In: 2019 2nd IEEE international conference on soft robotics (RoboSoft). IEEE; 2019. p. 739–745.
73. Goury O, Duriez C. Fast, generic, and reliable control and simulation of soft robots using model order reduction. IEEE Trans Robot. 2018;34(6):1565–1576.
74. Gasoto R, Macklin M, Liu X, Sun Y, Erleben K, Onal C, Fu J. A validated physical model for real-time simulation of soft robotic snakes. In: 2019 international conference on robotics and automation (ICRA). IEEE; 2019. p. 6272–6279.
75. Schuldt DW, Rife J, Trimmer B. Template for robust soft-body crawling with reflex-triggered gripping. Bioinspir Biomim. 2015;10(1):016018.
76. Ishige M, Umedachi T, Taniguchi T, Kawahara Y. Exploring behaviors of caterpillar-like soft robots with a central pattern generator-based controller and reinforcement learning. Soft Robot. 2019;6(5):579–594.
77. Kandhari A, Daltorio KA. A kinematic model to constrain slip in soft body peristaltic locomotion. In: 2018 IEEE international conference on soft robotics (RoboSoft). IEEE; 2018. p. 309–314.
78. Li D, Zhao S, Da Ronch A, Xiang J, Drofelnik J, Li Y, Zhang L, Wu Y, Kintscher M, Monner HP, et al. A review of modelling and analysis of morphing wings. Prog Aerosp Sci. 2018;100:46–62.
79. Chen C, Zhang T. A review of design and fabrication of the bionic flapping wing micro air vehicles. Micromachines. 2019;10(2):144.
80. Stowers AK, Lentink D. Folding in and out: passive morphing in flapping wings. 2015, Vol. 10.
81. Sareh S, Siddall R, Alhinai T, Kovac M. Bio-inspired soft aerial robots: adaptive morphology for high-performance flight. In: Soft robotics, trends, applications and challenges. Springer; 2017. p. 65–74.
82. Cevdet Ö, Özbek E, Ekici S. A review on applications and effects of morphing wing technology on uavs. Int J Aviat Sci Technol. 2021;1(01):30–40.
83. Cramer N, Cellucci D, Formoso OB, Gregg CE, Jenett B, Kim JH, Lendraitis M, Swei S, Trinh GT, Trinh KV, et al. Elastic shape morphing of ultralight structures by programmable assembly. Smart Mater Struct. 2019;28(5):055006.
84. Chen Y, Zhao H, Mao J, Chirarattananon P, Helbling EF, Hyun N-sP, Clarke DR, Wood RJ. Controlled flight of a microrobot powered by soft artificial muscles. Nature. 2019;575(7782):324–329.
85. Chin Y-W, Kok JM, Zhu Y-Q, Chan W-L, Chahl JS, Khoo BC, Lau G-K. Efficient flapping wing drone arrests high-speed flight using post-stall soaring. Sci Robot. 2020;5(44).
86. Ramezani A, Chung S-J, Hutchinson S. A biomimetic robotic platform to study flight specializations of bats. Sci Robot. 2017 ;2(3).
87. Karásek M, Muijres FT, De Wagter C, Remes BD, de Croon GC. A tailless aerial robotic flapper reveals that flies use torque coupling in rapid banked turns. Science. 2018;361(6407):1089–1094.
88. Yang X, Chen Y, Chang L, Calderón AA, Pérez-Arancibia NO. Bee+: A 95-mg four-winged insect-scale flying robot driven by twinned unimorph actuators. IEEE Robot Autom Lett. 2019;4(4):4270–4277.
89. Bhushan P, Tomlin CJ. Milligram-scale micro aerial vehicle design for low-voltage operation. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 1–9.
90. Li Z, Suntharasantic S, Chirarattananon P. Simplified quasi-steady aeromechanic model for flapping-wing robots with passively rotating hinges. In: 2018 IEEE International Conference on Robotics and Automation (ICRA). IEEE; 2018. p. 6110–6115.
91. Singh A, Libby T, Fuller SB. Rapid inertial reorientation of an aerial insect-sized robot using a piezo-actuated tail. In: 2019 international conference on robotics and automation (ICRA). IEEE; 2019. p. 4154–4160.
92. Gerdes J, Holness A, Perez-Rosado A, Roberts L, Greisinger A, Barnett E, Kempny J, Lingam D, Yeh C-H, Bruck HA, et al. Robo raven: a flapping-wing air vehicle with highly compliant and independently controlled wings. Soft Robot. 2014;1(4):275–288.
93. James J, Iyer V, Chukewad Y, Gollakota S, Fuller SB. Liftoff of a 190 mg laser-powered aerial vehicle: the lightest wireless robot to fly. In: 2018 IEEE international conference on robotics and automation (ICRA). IEEE; 2018. p. 3587–3594.
94. Chukewad YM, Singh AT, James JM, Fuller SB. A new robot fly design that is easier to fabricate and capable of flight and ground locomotion. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 4875–4882.
95. Chen Y, Wang H, Helbling EF, Jafferis NT, Zufferey R, Ong A, Ma K, Gravish N, Chirarattananon P, Kovac M, Wood RJ. A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot. Sci Robot. 2017;2(11).
96. Chang E, Matloff LY, Stowers AK, Lentink D. Soft biohybrid morphing wings with feathers underactuated by wrist and finger motion. Sci Robot. 2020;5(38).
97. Ajanic E, Feroskhan M, Mintchev S, Noca F, Floreano D. Bioinspired wing and tail morphing extends drone flight capabilities. Sci Robot. 2020;5(47).
98. Jenett B, Calisch S, Cellucci D, Cramer N, Gershenfeld N, Swei S, Cheung KC. Digital morphing wing: active wing shaping concept using composite lattice-based cellular structures. Soft Robot. 2017;4(1):33–48.
99. Baek S-M, Yim S, Chae S-H, Lee D-Y, Cho K-J. Ladybird beetle–inspired compliant origami. Sci Robot. 2020;5(41).
100. Hou T, Yang X, Su H, Jiang B, Chen L, Wang T, Liang J. Design and experiments of a squid-like aquatic-aerial vehicle with soft morphing fins and arms. In: 2019 international conference on robotics and automation (ICRA). IEEE; 2019. p. 4681–4687.
101. Li G, Chen X, Zhou F, Liang Y, Xiao Y, Cao X, Zhang Z, Zhang M, Wu B, Yin S, Xu Y, Fan H, Chen Z, Song W, Yang W, Pan B, yi Hou J, Zou W, He S, Yang X, Mao G, Jia Z, Zhou H, Li T, Qu S, Xu Z, Huang Z, Luo Y, Xie T, Gu J, Zhu S, Yang W. Self-powered soft robot in the mariana trench. Nature. 2021;591(7848):66–71.
102. Christianson C, Goldberg NN, Deheyn D, Cai S, Tolley M. Translucent soft robots driven by frameless fluid electrode dielectric elastomer actuators. Sci Robot. 2018;3(17).
103. Kheirikhah MM, Rabiee S, Edalat ME. A review of shape memory alloy actuators in robotics. RoboCup 2010, robot soccer world cup XIV. In: Ruiz-del Solar J, Chown E, and Plöger PG, editors. Berlin: Springer; 2011. p. 206–217.
104. Calisti M, Picardi G, Laschi C. Fundamentals of soft robot locomotion. J R Soc Interf. 2017;14(130):20170101.

105. Marchese AD, Onal C, Rus D. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Robot. 2014;1(1):75–87.
106. Liu Z, Chen B, Liang S, Guan Y, Wen L, Liu J, Wang H, Yu X, Yang K, Liu W, Nie S, Sun W, Xie Z. A 1 mm-thick miniatured mobile soft robot with mechanosensation and multimodal locomotion. IEEE Robot Autom Lett. 2020;5:3291–3298.
107. Wen L, Ren Z, Di Santo V, Hu K, Yuan T, Wang T, Lauder G. Understanding fish linear acceleration using an undulatory biorobotic model with soft fluidic elastomer actuated morphing median fins. Soft Robot. 2018;5:04.
108. Fan J, qi Wang S, Yu Q, Zhu Y. Swimming performance of the frog-inspired soft robot. Soft Robot. 2020.
109. Kim H-S, Lee J-Y, Chu W-S, Ahn S-H. Design and fabrication of soft morphing ray propulsor: undulator and oscillator. Soft Robot. 2017;4(1):49–60.
110. Low KH, Yang J, Pattathil AP, Zhang Y. Initial prototype design and investigation of an undulating body by sma. In: 2006 IEEE international conference on automation science and engineering; 2006. p. 472–477.
111. Wang Z, Hang G, Li J, Wang Y, Xiao K. A micro-robot fish with embedded sma wire actuated flexible biomimetic fin; 2008. p. 354–360. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0924424708001283.
112. Suleman A, Crawford C. Design and testing of a biomimetic tuna using shape memory alloy induced propulsion. Comput Struct. 2008;86:491–499.
113. Jian L, Jianing Z, Zhenlong W. Cfd simulation of effect of vortex ring for squid jet propulsion and expeiments on a bionic jet propulsor. Int J u- e- Serv Sci Technol. 2016;9:211–226.
114. Wang Z, Wang Y, Li J, Hang G. A micro biomimetic manta ray robot fish actuated by sma. In: 2009 IEEE international conference on robotics and biomimetics (ROBIO); 2009. p. 1809–1813.
115. Westphal A, Rulkov N, Ayers J, Brady D, Hunt M. Controlling a lamprey-based robot with an electronic nervous system. Smart Struct Syst. 2011;8:07.
116. Villanueva A, Smith C, Priya S. A biomimetic robotic jellyfish (robojelly) actuated by shape memory alloy composite actuators. Bioinspir Biomim. 2011;6:036004.
117. Li T, Li G, Liang Y, Cheng T, Dai J, Yang X, Liu B, Zeng Z, Huang Z, Luo Y, Xie T, Yang W. Fast-moving soft electronic fish. Sci Adv. 2017;3.
118. Godaba H, Li J, Wang Y, Zhu J. A soft jellyfish robot driven by a dielectric elastomer actuator. IEEE Robot Autom Lett. 2016;1(2):624–631.
119. Christianson C, Goldberg NN, Deheyn D, Cai S, Tolley M. Translucent soft robots driven by frameless fluid electrode dielectric elastomer actuators. Sci Robot. 2018.;3.
120. Shintake J, Shea H, Floreano D. Biomimetic underwater robots based on dielectric elastomer actuators. In: 2016 IEEE/RSJ international conference on intelligent robots and systems (IROS); 2016. p. 4957–4962.
121. Punning A, Anton M, Kruusmaa M, Aabloo A. A biologically inspired ray-like underwater robot with electroactive polymer pectoral fins. In: Proceedings of IEEE/international conference mechatronics and robotic; 2004.
122. Chen Z, Um T, Bart-Smith H. Bio-inspired robotic manta ray powered by ionic polymer–metal composite artificial muscles. Int J Smart Nano Mater. 2012;3:1–13.
123. Jung Jaehoon, Kim Byungkyu, Tak Younghun, Park Jong-Oh. Undulatory tadpole robot (tadrob) using ionic polymer metal composite (ipmc) actuator. In: Proceedings 2003 IEEE/RSJ international conference on intelligent robots and systems (IROS 2003) (Cat No.03CH37453); 2003. p. 2133–2138 vol.3.
124. Najem J, Sarles A, Akle B, Leo D. Biomimetic jellyfish-inspired underwater vehicle actuated by ionic polymer metal composite actuators. Smart Mater Struct. 2012;21:09.
125. Ye Xiufen, Su Yudong, Guo Shuxiang, Wang Liquan. Design and realization of a remote control centimeter-scale robotic fish. In: 2008 IEEE/ASME international conference on advanced intelligent mechatronics; 2008. p. 25–30.
126. Guo Shuxiang, Fukuda T, Asaka K. A new type of fish-like underwater microrobot. IEEE/ASME Trans Mechatron. 2003;8(1):136–141.
127. Kim H, Song S-H, Ahn S-H. A turtle-like swimming robot using a smart soft composite (ssc) structure. Smart Mater Struct. 2012;22:014007.
128. Song S-H, Kim M-S, Rodrigue H, Lee J-Y, Shim J-E, Kim M-C, Chu W-S, Ahn S-H. Turtle mimetic soft robot with two swimming gaits. Bioinspir Biomim. 2016;11:036010.
129. Kwak B, Lee D, Bae J. Efficient drag-based swimming using articulated legs with micro hair arrays inspired by a water beetle. In: 2019 2nd IEEE international conference on soft robotics (RoboSoft). IEEE; 2019. p. 795–800.
130. Sfakiotakis M, Kazakidi A, Pateromichelakis N, Tsakiris DP. Octopus-inspired eight-arm robotic swimming by sculling movements. In: 2013 IEEE international conference on robotics and automation; 2013. p. 5155–5161.
131. Liu B, Hammond FL. Modular platform for the exploration of form-function relationships in soft swimming robots. In: 2020 3rd IEEE international conference on soft robotics (RoboSoft). IEEE; 2020. p. 772–778.
132. Chen B, Jiang H. Swimming performance of a tensegrity robotic fish. Soft Robot. 2019;6(4):520–531.
133. Zhong Y, Du R. Design and implementation of a novel robot fish with active and compliant propulsion mechanism. Robot Sci Syst. 2016.
134. Weymouth G, Subramaniam V, Triantafyllou M. Ultra-fast escape maneuver of an octopus-inspired robot. Bioinspir Biomim. 2015;10(1):016016.
135. Wang Y, Wang R, Wang S, Tan M, Yu J. Underwater bioinspired propulsion: From inspection to manipulation. IEEE Trans Ind Electron. 2020;67:7629–7638.
136. Gao Jun, Bi Shusheng, Xu Yicun, Liu Cong. Development and design of a robotic manta ray featuring flexible pectoral fins. In: 2007 IEEE international conference on robotics and biomimetics (ROBIO); 2007. p. 519–523.
137. Krieg M, Sledge IJ, Mohseni K. Design considerations for an underwater soft-robot inspired from marine invertebrates. Bioinspir Biomim. 2015;10(6):065004.
138. Marut K, Stewart C, Michael T, Villanueva A, Priya S. A jellyfish-inspired jet propulsion robot actuated by an iris mechanism. Smart Mater Struct. 2013;22:094021.
139. Kwak B, Bae J. Design of a robot with biologically-inspired swimming hairs for fast and efficient mobility in aquatic environment. In: 2016 IEEE/RSJ international conference on intelligent robots and systems (IROS); 2016. p. 4970–4975.
140. Giorgio Serchi F, Arienti A, Laschi C. Biomimetic vortex propulsion: Toward the new paradigm of soft unmanned underwater vehicles. IEEE/ASME Trans Mechatron. 2013;18(2):484–493.
141. Zhu J, White C, Wainwright DK, Santo VD, Lauder G, Bart-Smith H. Tuna robotics: a high-frequency experimental platform exploring the performance space of swimming fishes. Sci Robot. 2019;4.
142. Suzumori K, Endo S, Kanda T, Kato N, Suzuki H. A bending pneumatic rubber actuator realizing soft-bodied

manta swimming robo. In: Proceedings 2007 IEEE international conference on robotics and automation; 2007. p. 4975–4980.
143. Conte J, Modarres-Sadeghi Y, Watts M, Hover F, Triantafyllou M. A fast-starting mechanical fish that accelerates at 40 m s(-2). Bioinspir Biomim. 2010;5(3):035004.
144. Katzschmann RK, Marchese AD, Rus D. Hydraulic autonomous soft robotic fish for 3d swimming. In: Experimental robotics. Springer; 2016. p. 405–420.
145. Feng H, Sun Y, Todd PA, Lee HP. Body wave generation for anguilliform locomotion using a fiber-reinforced soft fluidic elastomer actuator array toward the development of the eel-inspired underwater soft robot. Soft Robot. 2020;7(2):233–250.
146. Zhang J, Diller E. Untethered miniature soft robots: Modeling and design of a millimeter-scale swimming magnetic sheet. Soft Robot. 2018;5(6):761–776.
147. Su M, Xu T, Lai Z, Huang C, Liu J, Wu X. Double-modal locomotion and application of soft cruciform thin-film microrobot. IEEE Robot Autom Lett. 2020;5:806–812.
148. Jang B, Aho A, Nelson BJ, Pané S. Fabrication and locomotion of flexible nanoswimmers. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 6193–6198.
149. Tadesse Y, Villanueva A, Haines C, Novitski D, Baughman R, Priya S. Hydrogen-fuel-powered bell segments of biomimetic jellyfish. Smart Mater Struct. 2012;21.
150. Zhao Y, Xuan C, Qian X, Alsaid Y, Hua M, Jin L, He X. Soft phototactic swimmer based on self-sustained hydrogel oscillator. Sci Robot. 2019;4(33).
151. Jia X, Chen Z, Riedel A, Si T, Hamel WR, Zhang M. Energy-efficient surface propulsion inspired by whirligig beetles. IEEE Trans Robot. 2015;31(6):1432–1443.
152. Alapan Y, Yasa O, Schauer O, Giltinan J, Tabak AF, Sourjik V, Sitti M. Soft erythrocyte-based bacterial microswimmers for cargo delivery. Sci Robot. 2018;3(17).
153. Carrico JD, Hermans T, Kim KJ, Leang K. 3d-printing and machine learning control of soft ionic polymer-metal composite actuators. Sci Rep. 2019;9.
154. Pelrine R, Kornbluh R, Pei Q, Joseph J. High-speed electrically actuated elastomers with strain greater than 100%. Science. 2000;287(5454):836–9.
155. Zhao X, Suo Z. Theory of dielectric elastomers capable of giant deformation of actuation. Phys Rev Lett. 2010;104:178302.
156. Yoo IS, Reitelshöfer S, Landgraf M, Franke J. Artificial muscles, made of dielectric elastomer actuators - a promising solution for inherently compliant future robots. In: Soft robotics; 2015. p. 33–41.
157. Blickhan R. The spring-mass model for running and hopping. J Biomech. 1989;22(11-12):1217–1227.
158. Raibert MH, Brown J, Chepponis M, Koechling J, Hodgins JK. Dynamically stable legged locomotion, MASSACHUSETTS INST OF TECH CAMBRIDGE ARTIFICIAL INTELLIGENCE LAB, Tech Rep. 1989.
159. Holmes P, Full RJ, Koditschek D, Guckenheimer J. The dynamics of legged locomotion: models, analyses, and challenges. SIAM Rev. 2006;48(2):207–304.
160. Zhang G, Ma S, Liang F, Li Y. Quadruped locomotion control based on two bipeds jointly carrying model. In: IEEE/RSJ international conference on intelligent robots and systems (IROS), Madrid, IEEE; 2018. p. 1732–1738.
161. Poulakakis I, Grizzle JW. The spring loaded inverted pendulum as the hybrid zero dynamics of an asymmetric hopper. IEEE Trans Autom Control. 2009;54(8):1779–1793.
162. Shepherd RF, Ilievski F, Choi W, Morin SA, Stokes AA, Mazzeo AD, Chen X, Wang M, Whitesides GM. Multigait soft robot. Proc Natl Acad Sci. 2011;108(51):20400–20403.
163. Saranli U, Buehler M, Koditschek DE. RHex: a simple and highly mobile hexapod robot. Int J Robot Res. 2001;20(7):616–631.
164. Cham JG, Bailey SA, Clark JE, Full RJ, Cutkosky MR. Fast and robust: hexapedal robots via shape deposition manufacturing. Int J Robot Res. 2002;21(10-11):869–882.
165. Allen T, Quinn R, Bachmann R, Ritzmann R. Abstracted biological principles applied with reduced actuation improve mobility of legged vehicles. In: Proceedings 2003 IEEE/RSJ international conference on intelligent robots and systems (IROS 2003) (Cat. No. 03CH37453). Las Vegas: IEEE; 2003. p. 1370–1375.
166. Kim S, Clark JE, Cutkosky MR. iSprawl: design and tuning for high-speed autonomous open-loop running. Int J Robot Res. 2006;25(9):903–912.
167. Galloway KC, Clark JE, Koditschek DE. Design of a tunable stiffness composite leg for dynamic locomotion. In: Volume 7: 33rd mechanisms and robotics conference, parts A and B. San Diego, California, USA, ASMEDC; 2009. p. 215–222.
168. Bledt G, Powell MJ, Katz B, Di Carlo J, Wensing PM, Kim S. MIT Cheetah 3: design and control of a robust, dynamic quadruped robot. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS), Madrid, IEEE; 2018. p. 2245–2252.
169. Nemiroski A, Shevchenko YY, Stokes AA, Unal B, Ainla A, Albert S, Compton G, MacDonald E, Schwab Y, Zellhofer C, Whitesides GM. Arthrobots. Soft Robot. 2017;4(3):183–190.
170. Pei Q, Rosenthal MA, Pelrine R, Stanford S, Kornbluh RD. Multifunctional electroelastomer roll actuators and their application for biomimetic walking robots. In: Smart structures and materials 2003: Electroactive polymer actuators and devices (EAPAD). International Society for Optics and Photonics; 2003. p. 281–290.
171. Tolley M, Shepherd RF, Mosadegh B, Galloway KC, Wehner M, Karpelson M, Wood RJ, Whitesides GM. A resilient, untethered soft robot. Soft Robot. 2014;1(3):213–223.
172. Waynelovich J, Frey T, Baljon A, Salamon P. Versatile and dexterous soft robotic leg system for untethered operations. Soft Robot. 2016;3(2):64–70.
173. Li Y, Chen Y, Ren T, Li Y, hong Choi S. Precharged pneumatic soft actuators and their applications to untethered soft robots. Soft Robot. 2018;5(5):567–575.
174. Barreiros J, O'Brien KW, Hong S, Xiao MF, Yang H-J, Shepherd RF. Configurable tendon routing in a 3D-printed soft actuator for improved locomotion in a multi-legged robot. In: 2019 2nd IEEE international conference on soft robotics (RoboSoft). Seoul, Korea (South). IEEE; 2019. p. 94–101.
175. Ji X, Liu X, Cacucciolo V, Imboden M, Civet Y, Haitami AE, Cantin S, Perriard Y, Shea H. An autonomous untethered fast soft robotic insect driven by low-voltage dielectric elastomer actuators. Sci Robot. 2019;4(37).
176. Xu T, Zhang J, Salehizadeh M, Onaizah O, Diller E. Millimeter-scale flexible robots with programmable three-dimensional magnetization and motions. Sci Robot. 2019;4(29).
177. Godage IS, Nanayakkara T, Caldwell DG. Locomotion with continuum limbs. In: 2012 IEEE/RSJ international conference on intelligent robots and systems. Vilamoura-Algarve, Portugal. IEEE; 2012. p. 293–298.
178. Corucci F, Calisti M, Hauser H, Laschi C. Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot. In: 2015 international conference on advanced robotics (ICAR). Istanbul, Turkey. IEEE; 2015. p. 337–344.
179. Zhang C, Zou W, Ma L, Wang Z. Biologically inspired jumping robots: A comprehensive review. Robot Auton Syst. 2020;124:103362.

180. Mo X, Ge W, Miraglia M, Inglese F, Zhao D, Stefanini C, Romano D. Jumping locomotion strategies: from animals to bioinspired robots. Appl Sci. 2020;10(23):8607.
181. Bartlett NW, Tolley M, Overvelde JT, Weaver JC, Mosadegh B, Bertoldi K, Whitesides GM, Wood RJ. A 3d-printed, functionally graded soft robot powered by combustion. Science. 2015;349(6244):161–165.
182. Zaitsev V, Gvirsman O, Hanan UB, Weiss A, Ayali A, Kosa G. A locust-inspired miniature jumping robot. 2015, Vol. 10.
183. Kovač M, Schlegel M, Zufferey J-C, Floreano D. Steerable miniature jumping robot. Auton Robot. 2010;28(3):295–306.
184. Calisti M, Picardi G, Laschi C. Fundamentals of soft robot locomotion. J R Soc Interf. 2017;14(130):20170101.
185. Heitler W. The locust jump. J Compar Physiol. 1974;89(1):93–104.
186. Heitler W, Burrows M. The locust jump. i. the motor programme. J Exper Biol. 1977;66(1):203–219.
187. Heitler W, Burrows M. The locust jump. ii. neural circuits of the motor programme. J Exper Biol. 1977;66(1):221–241.
188. Heitler W. The locust jump: Iii. structural specializations of the metathoracic tibiae. J Exper Biol. 1977;67(1):29–36.
189. Burrows M, Morris G. The kinematics and neural control of high-speed kicking movements in the locust. J Exper Biol. 2001;204(20):3471–3481.
190. Kovac M, Fuchs M, Guignard A, Zufferey J, Floreano D. A miniature 7g jumping robot. In: 2008 IEEE international conference on robotics and automation; 2008. p. 373–378.
191. Kovač M, Schlegel M, Zufferey J-C, Floreano D. A miniature jumping robot with self-recovery capabilities. In: 2009 IEEE/RSJ international conference on intelligent robots and systems. IEEE; 2009. p. 583–588.
192. Kovac M. Bioinspired jumping locomotion for miniature robotics, Epfl, Tech Rep. 2010.
193. Woodward MA, Sitti M. Design of a miniature integrated multi-modal jumping and gliding robot. In: 2011 IEEE/RSJ international conference on intelligent robots and systems. IEEE; 2011. p. 556–561.
194. Woodward MA, Sitti M. Multimo-bat: a biologically inspired integrated jumping–gliding robot. Int J Robot Res. 2014;33(12):1511–1529.
195. Zaitsev V, Gvirsman O, Ben Hanan U, Weiss A, Ayali A, Kosa G. Locust-inspired miniature jumping robot. In: 2015 IEEE/RSJ international conference on intelligent robots and systems (IROS); 2015. p. 553–558.
196. Haldane DW, Plecnik MM, Yim JK, Fearing RS. Robotic vertical jumping agility via series-elastic power modulation. Sci Robot. 2016;1(1).
197. Yim JK, Fearing RS. Precision jumping limits from flight-phase control in salto-1p. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 2229–2236.
198. Kenneally G, De A, Koditschek DE. Design principles for a family of direct-drive legged robots. IEEE Robot Autom Lett. 2016;1(2):900–907.
199. Yim S, Baek S-M, Jung G-P, Cho K-J. An omnidirectional jumper with expanded movability via steering, self-righting and take-off angle adjustment. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 416–421.
200. Seidel D, Lakatos D, Albu-Schäffer A. Data-driven discrete planning for targeted hopping of compliantly actuated robotic legs. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 2261–2266.
201. Misu K, Yoshii A, Mochiyama H. A compact wheeled robot that can jump while rolling. In: 2018 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2018. p. 7507–7512.
202. Chen W-H, Misra S, Caporale JD, Koditschek DE, Yang S, Sung C. A tendon-driven origami hopper triggered by proprioceptive contact detection. In: 2020 3rd IEEE international conference on soft robotics (RoboSoft). IEEE; 2020. p. 373–380.
203. Sugiyama Y, Hirai S. Crawling and jumping of deformable soft robot. In: 2004 IEEE/RSJ international conference on intelligent robots and systems (IROS)(IEEE Cat No. 04CH37566). IEEE; 2004. p. 3276–3281.
204. Loepfe M, Schumacher CM, Lustenberger UB, Stark WJ. An untethered, jumping roly-poly soft robot driven by combustion. Soft Robot. 2015;2(1):33–41.
205. Gorissen B, Melancon D, Vasios N, Torbati M, Bertoldi K. Inflatable soft jumper inspired by shell snapping. Sci Robot. 2020;5(42).
206. Wu Y, Yim JK, Liang J, Shao Z, Qi M, Zhong J, Luo Z, Yan X, Zhang M, Wang X, et al. Insect-scale fast moving and ultrarobust soft robot. Sci Robot. 2019;4(32).
207. Hanan UB, Weiss A, Zaitsev V. Jumping efficiency of small creatures and its applicability in robotics. Procedia Manuf. 2018;21:243–250.
208. Hall-Crags E. An analysis of the jump of the lesser galago (Galago senegalensis). In: Proceedings of the zoological society of London. Wiley Online Library; 1965. p. 20–29.
209. Aerts P. Vertical jumping in Galago senegalensis: the quest for an obligate mechanical power amplifier. Philos Trans R Soc London Ser B Biol Sci. 1998;353(1375):1607–1620.
210. Haldane DW, Plecnik M, Yim JK, Fearing RS. A power modulating leg mechanism for monopedal hopping. In: 2016 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2016. p. 4757–4764.
211. Plecnik MM, Haldane DW, Yim JK, Fearing RS. Design exploration and kinematic tuning of a power modulating jumping monopod. J Mech Robot. 2017;9(1).
212. Haldane DW, Yim JK, Fearing RS. Repetitive extreme-acceleration (14-g) spatial jumping with salto-1p. In: 2017 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE; 2017. p. 3345–3351.
213. Deban SM, O'Reilly JC, Dicke U, Van Leeuwen JL. Extremely high-power tongue projection in plethodontid salamanders. J Exper Biol. 2007;210(4):655–667.
214. Patek SN, Nowroozi B, Baio J, Caldwell RL, Summers AP. Linkage mechanics and power amplification of the mantis shrimp's strike. J Exper Biol. 2007;210(20):3677–3688.
215. Rollinson D, Ford S, Brown B, Choset H. Design and modeling of a series elastic element for snake robots. In: ASME 2013 dynamic systems and control conference. American Society of Mechanical Engineers Digital Collection; 2013.
216. Kovač M, Fauria O, Zufferey J-C, Floreano D, et al. The locomotion capabilities of the epfl jumpglider: a hybrid jumping and gliding robot. In: 2011 IEEE International Conference on Robotics and Biomimetics. IEEE; 2011. p. 2249–2250.
217. Jung G-P, Casarez CS, Jung S-P, Fearing RS, Cho K-J. An integrated jumping-crawling robot using height-adjustable jumping module. In: 2016 IEEE international conference on robotics and automation (ICRA). IEEE; 2016. p. 4680–4685.
218. Asada H, Youcef-Toumi K. Direct-drive robots: theory and practice. Cambridge: MIT Press; 1987.

219. Yuan H, Pikul J, Sung C. Programmable 3-d surfaces using origami tessellations. In: 7th international meeting on origami in science, mathematics, and education; 2018. p. 893–906.
220. Raibert MH. Legged robots that balance. Cambridge: MIT press; 1986.
221. Preston DJ, Jiang HJ, Sanchez V, Rothemund P, Rawson J, Nemitz MP, Lee W-K, Suo Z, Walsh CJ, Whitesides GM. A soft ring oscillator. Sci Robot. 2019;4(31).
222. Sun Y, Jiang Y, Yang H, Walter L-C, Santoso J, Skorina EH, Onal C. Salamanderbot: A soft-rigid composite continuum mobile robot to traverse complex environments. In: 2020 IEEE international conference on robotics and automation (ICRA). IEEE; 2020. p. 2953–2959.
223. Lee D-Y, Kim S-R, Kim J-S, Park J-J, Cho K-J. Origami wheel transformer: a variable-diameter wheel drive robot using an origami structure. Soft Robot. 2017;4(2):163–180.
224. Lee D-Y, Koh J-S, Kim J-S, Kim S-W, Cho K-J. Deformable-wheel robot based on soft material. Int J Precis Eng Manuf. 2013;14(8):1439–1445.
225. Kotikian A, McMahan C, Davidson EC, Muhammad JM, Weeks RD, Daraio C, Lewis JA. Untethered soft robotic matter with passive control of shape morphing and propulsion. Sci Robot. 2019;4(33).
226. Ryu S, Lee Y, Seo T. Shape-morphing wheel design and analysis for step climbing in high speed locomotion. IEEE Robot Autom Lett. 2020;5(2):1977–1982.