Locomotion of Miniature Soft Robots

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Abstract

Miniature soft robots are mobile devices, which are made of smart materials that can be actuated by external stimuli to realize their desired functionalities. Here we highlight the key advancements and challenges of the locomotion producible by miniature soft robots in micro- to centimeter length scales. It is highly desirable to endow these small machines with dexterous locomotive gaits because this enables them to easily access highly confined and enclosed spaces via a non-invasive manner. If miniature soft robots are able to capitalize this unique ability, they will have the potential to transform a vast range of applications, including but not limited to, minimally invasive medical treatments, lab-on-chip applications, and search-and-rescue missions. We have categorized the gaits of miniature soft robots into terrestrial, aquatic and aerial locomotion. Except for the centimeter-scale robots that can perform aerial locomotion, our discussions are centered around soft robots that are in the micro- to millimeter length scales. Under each category of locomotion, we have also discussed prospective methods and strategies that can improve their gait performances. We envision that this report will be able to provide critical analyses and discussions to inspire future strategies in making miniature soft robots significantly more agile.

1 Introduction

Miniature robots can be defined as mobile devices that are in the micro- to centimeter length scales.[1-4] A unique feature of these machines is that they are able to take advantage of their size and mobility to non-invasively access highly confined and enclosed spaces.[1, 3, 5] By exploiting this special ability, miniature robots have the potential to revolutionize medical applications such as targeted drug delivery[6-8] and minimally invasive surgery.[5, 9, 10] These small-scale devices can also enable a broad range of manipulation tasks that are critical for fundamental studies in materials science and biology,[4, 11-13] as well as for lab-on-chip applications.[11, 12, 14, 15] They can also be deployed as prospective aerial vehicles that can significantly enhance the efficiency of search-and-rescue missions,[16-18] perform dangerous operations in hazardous environments,[18] and function as miniature nodes in sensor networks.[18]

Because miniature robots are expected to operate in various types of environments, it is essential for them to possess effective locomotive gaits to navigate well in such terrains.[19, 20] This will be especially true if the robots have to negotiate across highly unstructured environments such as within the human body or at disaster sites.[5, 10, 21, 22] Of the miniature robots, the soft robots are significantly more promising than their rigid counterparts in developing dexterous gaits because their degrees-of-freedom and adaptability are considerably higher.[23-25] By having the ability to generate a series of time-varying shapes, miniature soft robots have shown to be able to perform various types of locomotion, which allow them to negotiate across complicated obstacles in their environments.[19, 26] In addition to using such locomotion for navigation purposes, these gaits could also be beneficial for studying the locomotion of various small organisms.[4, 13]

In this report, we review the locomotion producible by miniature soft robots. The scope of this report is therefore different from reviews and commentaries that focus on the actuation,[3] applications,[2, 21] or design[27] of miniature soft robots. It is also significantly different from reviews that focus on the applications of miniature robots,[1, 10, 11] and others that review the general principles[24, 28-35] or locomotion[34, 36, 37] of macro-scale soft robots. To facilitate our discussion, here we categorize the locomotion of the miniature soft robots into terrestrial, aquatic and aerial locomotion (Fig. 1). Under each category, we will highlight their key advancements, as well as their open challenges and future outlook. Except for the aerial robots that are in the centimeter-scale, our discussions will focus on soft robots that are in the micro/millimeter length scales. It is noteworthy that the discussions in this report will be restricted to synthetic materials. For miniature bio-robots based on natural materials, interested readers may refer to other reviews on biomolecular, biohybrid actuation, or microorganism-driven systems.[38-43]

The report is organized as follows: section 2 provides a brief discussion about the general actuation principles of miniature soft robots. This is followed by sections 3, 4 and 5 in which we discuss the advancements of miniature soft robots in their terrestrial, aquatic and aerial locomotion, respectively. We also provide a short discussion on miniature soft robots that are able to navigate across multiple environments in section 6. Finally, sections 7 and 8 will provide additional discussions and conclude this report, respectively.

2 General Actuation Principles

Miniature soft robots are in general constructed by smart materials, which can be actuated via various external stimuli such as heat, light, force/torque/pressure, chemicals, and electrical and magnetic fields.[2, 3] Based on the selected actuation method, a corresponding miniature soft robot can be programmed to generate a series of time-varying shapes, which can enable its desired gaits.[23, 44] Using such working principles, miniature soft robots have shown to be able to walk,[45, 46] roll,[47-49] crawl,[50, 51] jump,[52, 53] swim[13, 23, 44, 54] and fly.[4, 18, 22, 55]

Since miniature soft robots produce their time-varying shapes through deformation, it is favorable to construct them via materials with low elastic moduli, such as polymers, gels and papers.[24, 32, 34] By having low elastic moduli, the soft robots can easily produce large deformations once they are subjected to their respective stimuli. To realize the desired deformations of the robots, these smart materials have to be patterned such that a spatially varying stress can be induced on their bodies once the external stimulus is applied. As an example, a magnetically actuated, miniature soft robot can be programmed with a specified magnetization profile across its body.[19, 23, 56] Once the profile is programmed, the robot will be able to experience a distribution of magnetic torques and forces along its body when subjected to an external magnetic field. These magnetic torques and forces will in turn induce a spatially varying stress on the robot, allowing it to deform into the desired shape. By temporally changing the actuating magnetic field, the magnetic soft robot will thus be able to generate a series of time-varying shapes accordingly. Likewise, similar principles can be applied to miniature soft robots that are actuated by heat,[57] light,[44, 50] chemicals,[53, 58] force/torque/pressure[4, 18, 55] and electrical fields,[22, 59-61] such that they can be programmed to realize their desired locomotion. In order to have a well-rounded discussion, we will also include the locomotion of miniature robots that have rigid bodies but are actuated by soft actuators such as shape memory alloys (SMAs).

As the focus of this report is on locomotion of miniature soft robots, here we will only briefly introduce the actuation principles of these machines so as to facilitate our discussions in the subsequent sections. While the description in this section is brief, it is evident that the design, fabrication and control of smart materials are critical for miniature soft robots to realize their desired locomotion. The reader may refer to the extensive reviews by Hines et al.[3] and Sitti et al.[1] to have a more in-depth discussion on the actuation methods of small-scale, soft robots.

3 Terrestrial Locomotion

To enable terrestrial locomotion, miniature soft robots have to generate appropriate time-varying shapes such that they can interact effectively with the ground and control the induced frictional and reaction forces from it. It is critical to equip micro/millimeter-scale soft robots with dexterous terrestrial locomotion because these devices are expected to negotiate across various obstacles when they are deployed for their targeted biomedical[1, 3] or lab-on-chip applications.[11, 12] In this section, we highlight the key advancements, challenges and opportunities of micro/millimeter-scale soft robots that can execute terrestrial locomotion.

3.1 Key advances

Over the last decade, miniature soft robots have developed numerous terrestrial locomotion to navigate across various unstructured terrains.[19, 48, 50] To facilitate our discussions, we shall classify the exhibited terrestrial locomotion of miniature soft robots into the following categories: walking, crawling, rolling and jumping.

3.1.1 Walking

Walking is a robust terrestrial locomotion, which allows organisms with legs to conquer unstructured lands. This type of locomotion is generally modelled as an inverted pendulum at which its speed is dependent on gravity and leg length.[62-64] By adopting the walking locomotion, miniature soft robots have the potential to negotiate across various obstacles in their land environments.

To realize the walking gait, it is critical to generate effective leg trajectories for the miniature soft robots. A feasible method to determine such trajectories is to use hardware neural network systems as demonstrated by the millimeter-scale, hexapod robot of Uchikoba et al.[65, 66] This robot has three legs on both sides of its body. On each side, the legs are connected via a one-degree-of-freedom mechanical linkage that can be actuated by SMAs. The SMAs are controlled via Joule heating and the amount of heat energy supplied to them is regulated by the output waveforms of the neural network systems. When the SMAs are heated, they will undergo martensitic to austenitic phase transition and shrink. Conversely, the two-way shape memory effect of the SMAs will allow them to extend when they are cooled. By functioning as soft artificial muscles, the SMAs can control the legs of the robot to enable the walking locomotion (0.44 mm/s or 0.16 body lengths per second).[65, 66] While the robot is able to generate feasible walking gaits, it has limited dexterity because the motions of the legs are coupled at each side of the body.

In order to enhance the walking dexterity, another miniature quadruped robot uses four SMAs, which have two-way shape memory effects, to independently control each of its legs. Each SMA is connected to its corresponding leg via a four-bar linkage.[67] When the SMAs undergo extension and contraction, they can control the motions of their corresponding leg. By coordinating the trajectory of the legs, the robot is able to execute its walking locomotion at a mean speed of 0.41 mm/s (0.06 body lengths per second).[68] Because each leg can be controlled independently, different walking patterns can be attained by specifying different sequences of the leg's phases, allowing the robot to display high dexterity.[67] The rigid bodies of the SMA-driven robots, however, have made them less adaptive compared to other miniature robots that have soft bodies.[34] Furthermore, as it is difficult to incorporate on-board power sources for millimeter-scale robots to enable Joule heating, the SMA-driven walking robots have to be tethered to fixed power sources via electrical wires.

In view of these challenges, Xu et al. have created a millimeter-scale, soft robot that can be controlled wirelessly via magnetic fields (Fig. 2A).[45] The walking robot is constructed by first embedding magnetized microparticles into liquid resins, which are curable by ultraviolet (UV) light exposure. During the fabrication process, external magnetic fields are applied so that the embedded particles can be rotated into their desired orientation before selected regions of the resin are polymerized by the UV light. By sequentially repeating this polymerization process, the desired magnetization profile and shape of the miniature robot can eventually be obtained. There are two types of discrete magnetization for the soft robot's legs.[45] Each type has four legs, two on each side of the body in an alternate configuration. Based on the given magnetization profile, the soft legs will be able to rotate under the influence of a rotating magnetic field and there is a constant phase difference between the two types of legs. When the rotating legs strike the ground, a net propulsion will be generated for the walking robot, allowing it to advance forward (average velocity of 0.42 mm/s or 0.09 body length per second under a magnetic field of 7 mT rotating at 1 Hz). Because the deformed robot has a net magnetic moment that tends to align with the external magnetic field, this walking robot can be steered by specifying the direction of the field. Using this steering mechanism, the robot is able to navigate across a U-shaped channel (Fig. 2B).[45] In theory, this robot can also decouple its rotations and translations,[23, 69] and this can be a significant advantage for navigating in constrained areas.[45] While the miniature soft robot of Xu et al. has demonstrated high dexterity, it is not the fastest walking robot available.

It will be advantageous to develop walking gaits that can achieve high speeds as this can enable the miniature robots to execute their tasks more efficiently.[70-73] In this regard, Vogtmann et al. have developed a hexapedal millimeter-scale robot that can use its magnetically actuated soft legs to walk at high speeds of 22.1 mm/s (5.5 body lengths per second).[46] This robot has a configuration that allows it to respond to rotating magnetic fields of high frequencies (21.5 Hz), thereby enabling it to walk very quickly. While the hexapedal millirobot of Vogtmann et al. can walk at high speeds, it is designed to only move forward and thus it cannot be steered to follow a specified path.[46] In the future, it will be desirable to create miniature soft robots that can walk quickly but yet remain steerable.

3.1.2 Crawling

Crawling can be defined as a type of locomotion whereby soft robots undergo body deformations so that the anchored points can induce effective frictional forces from the surroundings to generate net propulsion.[64] Having the ability to crawl is advantageous as caterpillars, earthworms and snails have used such gaits to move through narrow spaces, cracks or tunnels.[74, 75] To date, miniature soft robots have demonstrated various crawling gaits such as the two-anchor, undulatory and peristaltic crawling methods.

Inspired by inchworms, miniature soft robots can execute two-anchor crawling by sequentially elongating and shortening their body between two anchor points.[37, 76] Based on the body motion, the two anchors can induce a large propulsive frictional force from the ground to translate the robot forward.[37, 75, 76] The two-anchor crawling is an effective locomotion for maneuvering across complex terrains such as inclined slopes and curved surfaces.[50, 75, 77] However, it is non-trivial to execute this locomotion because crawling robots are especially sensitive to surface forces such as adhesion and drag from its surroundings.[27] Without proper control, these surface forces can make the robots move in random trajectories.[78] A feasible method to control the translational direction of two-anchor crawling is to place the crawling robots on substrates that have asymmetric surface topographies including ratchet bases and diffraction gratings. By using this method, the robots will be able to generate differential frictional forces on their two anchors and move forward.[50, 58, 60, 78] A limitation of this method, however, is that it can only make the robots translate along the direction specified by the substrate and thus this is highly restrictive.[50]

In contrast to pre-setting asymmetric surface topographies on the substrate, it will be better to create robust soft robots that can generate anisotropic friction regardless of the surface they crawl on.[76, 79] A possible method to adopt such strategies is to allow the robots to produce asymmetrical deformation along their bodies when they are executing the two-anchor crawling locomotion.[76, 79, 80] This can be realized by imparting different properties and features along the characteristic length of the soft robot.[52, 61, 81] To facilitate untethered crawling via electrochemical actuation, Gupta et al. adopt this two-anchor crawling strategy and incorporate three forms of asymmetry along the robot, which is made of a polypyrrole (PPy) conducting film (Fig. 2C).[61] During the synthesis process, morphological asymmetry is introduced to the robot whereby one surface is made rougher by undergoing preferential ion exchange. Subsequently, polarization asymmetry takes place when the robot is placed between two graphite electrodes and a voltage is applied across to generate a potential difference across the robot. Based on the effects of morphological and polarization asymmetry, the negative polarized end is reduced at which it swells and bends upwards. Conversely, an inverse effect is observed at the positive polarized end as it undergoes oxidation. Lastly, the positive polarized end is overoxidized to be made stiffer with lower electroactivity. As a result, the robot's stiffness asymmetry produces the necessary bending at the non-overoxidized end to crawl forward upon switching the electrode polarity every 5 s.[61] Although implementing asymmetrical deformations can specify the translational direction of miniature soft robots, most of these works demonstrate crawling in one direction and it cannot allow them to navigate planar paths.[52, 61, 81]

To allow steering for two-anchor crawling, Ge et al. have constructed a robot based on a dye-doped liquid crystal elastomer (LCE) that can respond to near-infrared radiation (NIR).[77] This

LCE body is prepared with crosslinked uniaxial LC monodomains on one side while its opposite side is crosslinked with LC polydomains. To enable crawling, the monodomain side is faced downwards and an upward fold acts as the robot's head (front end). Upon NIR irradiation on the robot, the dye induces a photothermal effect that results in a contraction within the LC monodomain layer after conversion from the nematic to isotropic state. When NIR light is scanned from the tail (back end) to the head of the robot, the robot body will curl downwards due to asymmetrical contractions while the tail will shift forward. After the NIR light is removed, the body will elongate while the tail remains anchored. As friction is lower at the head than at the tail at this juncture, the head of the robot will be pushed forward and create a net displacement. Similarly, steering can be achieved by scanning NIR light along one edge of the robot body from the tail to head, leading to asymmetric in-plane contractions in the width direction. Based on this actuation method, the robot is able to U-turn, crawl on incline surfaces of 15º and move at speeds of 2 cm/min.[77]

Inspired by caterpillars, miniature soft robots can generate traveling waves down their bodies to adopt undulations to crawl through narrow spaces.[19, 82] A notable attribute of undulatory crawling is that it can be bi-directional, allowing the soft robots to easily reverse their crawling direction without making U-turns. This attribute will be especially useful when the robots are navigating across convoluted tunnels with limited spaces.[83, 84] Undulatory crawling enables the robots to generate net thrusts through exploiting the differential frictional forces induced by the substrate or enclosed tunnels. Using such gaits, a miniature soft robot of 3.7 mm length is able to crawl through a glass tunnel of rectangular cross-sections (0.645 mm x 2.55 mm) at high speeds close to 15 mm/s (approximately 4 body lengths per second) (Fig. 2D). By programming this robot with a single-wavelength, harmonic magnetization profile, it is able to execute undulatory crawling when a rotating magnetic field is applied.[19] In recent studies, it is found that a magnetic soft robot is able to enhance its undulatory crawling performance on underwater surfaces if its body is constructed by a temperature-responsive hydrogel (poly(N-isopropylacrylamide), PNIPAm). Because the hydrogel body can induce osmotic shrinking when exposed to NIR irradiation, this soft robot can actively reduce its size and crawl through tubes with widths smaller than its original body.[26] This is an enticing ability as it can potentially enable the robots to overcome a broader range of obstacles.

Peristaltic crawling is another feasible approach for miniature soft robots to negotiate across narrow tunnels.[51] Similar to earthworms, miniature soft robots can propel themselves via peristaltic crawling by generating a back-propagating traveling wave of radial contraction and axial elongation.[37, 75] Sun et al. have created a miniature soft robot that can perform bi-directional peristaltic crawling to navigate across a capillary tube that has an inner diameter of 1.2 mm (Fig. 2E).[51] This robot has a photoresponsive hydrogel body that is embedded with gold nanoparticles (AuNPs) and titanate nanosheets (TiNSs). The inclusion of cofacially orientated TiNSs with dense negative charges, endows the hydrogel body with large anisotropic electrostatic repulsion in its interior. By modulating the temperature of the poly(N-isopropylacrylamide) hydrogel body, the robot can reversibly dehydrate and rehydrate to regulate its inner electrostatic repulsive force. The robot can be actuated via light because its embedded AuNPs can serve as photothermal converters. To enable peristaltic crawling, a laser that can output 445 nm wavelength of light is scanned across the robot's body. When these irradiated regions are heated beyond their lower critical solution temperature (LCST), they will become thinner and elongate against the scanning direction, reducing their contact and thus friction with the capillary walls. Meanwhile, the shape of the unirradiated regions remains the same and they will act as anchors for the robot. When the laser is removed, the heated regions will cool below the LCST, allowing the robot to recover its original shape and generate a net displacement. By repeatedly scanning the robot with the laser, the robot can perform peristaltic crawling against the scanning direction.[51] In addition, NIR response is demonstrated by replacing AuNPs with gold nanorods, at which the 5 mm length robot can extend 130% its length within 3 s upon NIR irradiation.

3.1.3 Rolling

In nature, rolling is an effective locomotion that allows insects to quickly escape from danger.[82, 85, 86] For instance, the larva of *Pleurotya ruralis* can anchor its tail to the ground and rapidly curl up into a wheel-shape to roll away from predators. The exhibited rolling speed is notable because it can be 40-fold quicker than the normal crawling speed of the larva.[82] Due to the unique advantages of rolling, this locomotion has also been adopted by various miniature soft robots.[47-49]

To enable rolling, miniature soft robots can morph their shapes to shift their center of mass. In the morphed configurations, the normal force induced by the ground to the robots will have an effective moment arm from the robots' center of mass. As a result, the normal force will be able to induce a rigid-body torque on the robots, leading them to rotate continuously and the induced friction from the ground will propel them forward under no-slip conditions. Yamada et al. first adopted this principle by making a ring-shaped, millimeter-scale soft robot via LCEs that contain azobenzene.[47] By introducing azobenzene functionalities, the robot can undergo trans-cis photoisomerization via photothermal effects when it is irradiated with UV light. This induces liquid crystal-isotropic phase transition that generates a contraction on the robot's surface. In contrast, the robot's surface will expand when it is irradiated by visible light due to the reverse phase transition through cis-trans isomerization. Hence, when UV and visible light are irradiated respectively on the robot's bottom and top sides, the deformed robot can shift its center of mass and roll towards the light source (Fig. 2F).[47] While the robot of Yamada et al. can roll successfully, its achievable speed is relatively low (approximately 0.2 mm/s).

As demonstrated by Hu et al., miniature soft robots can also realize the rolling locomotion by rotating them with magnetic torques after they have transformed into wheel-like shapes.[19] By having a shape that favors rolling, the magnetic millimeter-scale robot of Hu et al. can roll on smooth and rough surfaces under no-slip conditions. When it is rolling on smooth, level surfaces, it can reach a mean speed of 22 mm/s under a rotating field of 4 Hz (Fig. 2G). Using similar rolling principles, miniature soft robots have also demonstrated that they can roll up inclined slopes or stairs.[26, 48] For instance, Wie et al. have created a light-actuated, miniature soft robot that can roll up a 15° inclined surface.[48] This robot is created with azobenzene functionalized LCE film and it can transform from a flat configuration to spiral ribbons when irradiated by UV light (300-450 nm wavelength). To realize this shape change, the robot's body is programmed with twisted nematic configuration where the orientations of the molecules are directed to rotate 90^{o} throughout its body thickness. When the robot is irradiated by UV light, it will undergo trans-cis isomerization, inducing a loss in the programmed molecular order. The loss in molecular order will generate compressive and tensile strains that are parallel and perpendicular to the nematic director, respectively. This will in turn lead to shear strain gradients that form across the robot's film thickness, enabling it to deform into spiral ribbons. When the top of the robot is irradiated, greater twists will occur at its upper surface compared to the shadowed parts. As a result, photostrains that are generated rapidly lead to a net twisting moment for photomotility that enables the rolling locomotion.[48]

It is possible to steer the miniature soft robots when they are rolling. This is an advantageous feature as it allows the robots to track complex paths. A popular approach to steer magnetic robots is via controlling the directions of the rotating magnetic fields.[19, 26] As the net magnetic moment of the robots will tend to align with the applied magnetic field, these robots can be steered to follow various pathways while executing their rolling locomotion.[19, 26] In addition, light-actuated, miniature soft robots can also be made steerable when kirigami patterns are introduced to sheets of liquid crystal polymer networks.[49] For instance, the kirigami-based rolling robot of Cheng et al. is designed with photoinduced petals that can bend and tilt the robot to initiate sequential locomotion upon irradiation by light of 470 nm wavelength. To steer the robot, selective irradiation can allow one side of the petals to generate larger strains and cause the robot to roll towards the other side (Fig. 2H). Using such steering methods, this kirigami-based robot can precisely track “S” or “P”-shaped trajectories on a 2D surface.[49] Although rolling can allow miniature soft robots to navigate across terrains at high speeds, this mode of locomotion is unable to overcome large obstacles and gaps.

3.1.4 Jumping

Jumping enables miniature robots to overcome obstacles and gaps that exceed their characteristic length. In general, miniature soft robots can realize this locomotion by first storing up elastic energy in their bodies and subsequently rapidly releasing this energy such that they can impart sufficient impact force to the ground and launch themselves up.[53]

To jump across large obstacles and gaps, it is critical for miniature soft robots to jump high. In 2011, Churaman et al. presented an 8 mg millimeter-scale jumper that can jump over 32 cm. While this robot can achieve an impressive jumping height, it has to be manually compressed and released to execute this locomotion.[87] In contrast, a humidity driven soft robot can jump without manual intervention and it can achieve jumping heights that are 10,000-fold larger than its film thickness (Fig. 2I).[52] This robot’s body is made of carbon nitride polymer films with high toughness, fabricated through vapor deposition polymerization (VDP) of guanidinium carbonate. The acquired robot is asymmetric along the thickness direction of the films because the growth side during VDP is found to be structurally less ordered and greater chemical defects can be found with a larger number of unreacted amino groups. As a result, water desorption and adsorption mostly take place at the growth side of the robot and generates differential strains across the film thickness during actuation. To make the robot jump, LED light is shone upon it such that desorption of water can be generated, enabling the robot to curl towards the growth side. Due to the friction between the robot and the substrate, the robot will not jump immediately when it deforms. Instead, it will continue to deform until it has accumulated sufficient elastic potential energy to overcome the friction. At this juncture, the robot will release its stored elastic energy and impart an impulsive force to the ground and jump up. As the robot is tough and flexible, it can perform multiple jumps without compromising its performance.[52]

In addition to performing high jumps, it will be interesting if the robots can control their jumping direction and range as this will allow them to be more robust. Directional jumping has been displayed by a magnetically actuated robot that is 3.7 mm long.[19] To initiate the jump, a magnetic field is applied to make the robot curl up into a wheel-like shape such that it can store elastic potential energy. Subsequently, the direction of the magnetic field is changed quickly, resulting in the soft robot to rotate and induce a shape change, such that its momentum can be increased before hitting the ground and jumping over the obstacles.[19] Because the robot's net magnetic moment will always tend to align with the applied magnetic field, it is possible to control the direction of the magnetic field to approximate the robot's jumping direction. While it remains a great challenge to accurately control its initial jumping velocities, the robot of Hu et al. is able to overcome various obstacles, and it can achieve jumping heights and range of approximately 5 mm and 8.8 mm, respectively.[19]

3.2 Challenges and opportunities

While miniature soft robots have made significant advancements on their terrestrial locomotion, their mobility on land can still be enhanced. For instance, although magnetic miniature soft robots are able to execute their walking locomotion well, some of their leg trajectories are still inherently coupled because it is difficult to make the actuating magnetic fields become spatially variant across their bodies.[45, 69, 88-91] The constraint on the robots' leg motions has unnecessarily restricted their robustness and it remains a great challenge to wirelessly control each of the robots' soft legs independently. The coupling effects can potentially be mitigated by increasing the degrees-of-freedom of the robots and controlling their soft legs with a combination of actuation methods such as light, magnetic, chemical, electrical, humidity or thermal actuation. For example, to allow the robots to respond to both light and magnetic stimuli, their soft legs can potentially be made by bilayer actuators.[90, 92, 93] Specifically, one of the layers can be made to respond to external magnetic fields by endowing them with a desired magnetization profile. On the other hand, the other layer can be made to respond to light stimuli by constructing them with liquid crystal polymer films.[92] An advantage of the light-actuated layers is that they can be programmed to respond to selective spectrums of wavelengths,[94-96] and this can potentially further reduce the coupling between the leg trajectories. By increasing the degrees-of-freedom of the soft walking robots, their robustness can potentially be enhanced significantly in the future.

Although walking miniature robots can achieve a speed of 5.5 body lengths per second,[46] these soft devices are still far slower than their biological counterparts, e.g., desert ants can walk at speeds up to 40 body lengths per second.[97] A plausible explanation why miniature soft robots are unable to maximize their walking speed is because their compliant legs are unable to be actuated at high frequencies. In the future, this may potentially be mitigated if the robot legs can be made with stiffer materials that have lower viscoelasticity as this can improve their dynamic actuation performances.[98] The legs, however, should not be made too stiff that they cannot produce sufficient deformations to realize the walking locomotion.

The crawling locomotion generally has a high cost of transport because the robots suffer a great amount of energy losses from frictional slips. Due to these slips, miniature soft robots are unable to maximize their crawling speed, and their soft bodies are also subjected to potential damages.[50, 83] To address this limitation, Kandhari et al. demonstrate the use of force sensing resistors and flexible stretch sensors to reduce forward slips. Using the feedback signals from these sensors, closed-loop controls can be implemented for the robot to reduce frictional slips.[99] However, this strategy is demonstrated at the larger scale and utilizes tethered sensors. Nonetheless, with the development of flexible pressure and strain sensors that can operate wirelessly, miniature soft robots may eventually adopt similar principles to enhance their crawling performances.[100-103] In particular, to avoid using on-board batteries for these wireless sensors, a promising method is to let these sensors adopt near-field-communication strategies, which allows data transmission and power transfer to be accomplished wirelessly.[100, 101] This can be seen from a liquid-metal system composed mainly of a strain sensor to measure normal and tensile strains, and an antenna coil to receive radio frequency power and transmit data wirelessly.[100] While it is possible to endow these soft sensors with sub-millimeter thickness, they are often presented at the centimeter-scale. In the future, if they can be further miniaturized, they will show promise in their integration with miniature soft robots for closed-loop controls.

Although miniature soft robots can roll at speeds of 22 mm/s,[19] they are still far slower than their counterparts in nature, e.g., the *Pleurotya ruralis* can roll at a speed of 39 cm/s.[82] To enhance the speed of miniature soft robots that roll by shifting their center of mass, materials with lower viscoelasticity can be selected for these robots such that they can generate their time-varying shapes faster.[98] In comparison, soft robots that roll after adopting wheel-like shapes, are able to achieve much higher speeds. However, as these robots do not assume a perfect circular shape, they have gaps between their open ends.[19, 26] As these gaps can potentially cause the robots to jump unexpectedly when they are rolling at high speeds, it is difficult to control the robots in such situations.[19] A potential solution to this challenge will be to allow the robots to assume a perfect wheel-shape before they roll. This will eliminate the gaps between their open ends, potentially allowing the robots to be more controllable when they are rolling at high speeds.[104] In addition, rolling miniature robots can potentially enhance their terrain adaptivity by making their soft bodies assume wheel-like structures that have multiple spokes, otherwise known as Whegs in macro-scale robotics.[105-107] As demonstrated by their macro-scale counterparts, rolling robots with Whegs are much more adaptable, and they can overcome small obstacles and have a lower probability to collide with them.[105-107]

While light and magnetic actuation have been used widely for controlling miniature soft robots wirelessly, the locomotion of light-actuated soft robots is generally slower than their magnetic counterparts. This can be attributed to the loss of light intensity due to scattering over a certain distance or these robots may have weak photothermal or photochemical responses.[108-112] In the future, the locomotion speed of light-actuated soft robots can potentially be improved if enhanced light sensitive materials with faster response times can be introduced, or optimization of specific light intensity and irradiation duration can be incorporated.

Miniature soft robots can perform directional jumping, but it is difficult to precisely control the magnitude and direction of their initial jumping velocities.[19] This remains a great challenge because existing theoretical models are unable to fully describe the physics of the jumping mechanism, making it difficult to determine the necessary actuating signals to accurately control such parameters.[19, 87] In the future, it will be interesting to investigate whether machine learning techniques, such as deep learning algorithms,[113, 114] can be employed to overcome this limitation. By training the weights of the neural networks with experimental data, it may be possible to develop numerical models that can accurately predict the jumping characteristics of miniature soft robots, allowing such locomotion to be more deterministic.[113-115]

Although miniature soft robots have demonstrated various types of terrestrial locomotion, their climbing locomotion is relatively underdeveloped, and more research will be required before these soft devices can climb effectively. It will be advantageous to have the ability to climb because this can allow miniature soft robots to move against gravity and navigate on vertical surfaces or ceilings. To realize this mode of locomotion, it will be ideal to make the climbing robots light-weight and allow them to possess a dependable grasping mechanism that can support their weight.[116] While Rogóż et al. have demonstrated preliminary work on miniature soft robots that can climb, constant lubrication of synthetic mucus (glycerin) is required for the robot to control the adhesion between itself and the surface to execute this locomotion.[117] As a result, such methods are neither sustainable nor applicable for the robots to implement in unstructured terrains. In contrast, reversible adhesives such as gecko-fibers or gallium adhesive can potentially be used in the future to overcome this challenge.[118-121] A critical advantage of these adhesives is they can exhibit highly switchable adhesive properties across a wide range of materials.[121-123] In their high-adhesion state, they can help the robot to stick to surfaces and support their weight. Conversely, these adhesives can switch to a low-adhesion state to release the robots and allow them to move with ease. By exploiting such reversible and switchable adhesives, miniature soft robots will have the potential to climb across a wide range of surfaces and enhance their land mobility.

By advancing the terrestrial locomotion of miniature soft robots, these machines can become much more dexterous and efficient in executing their targeted biomedical or lab-on-chip applications.

4 Aquatic Locomotion

Miniature robots, which are in the micro- to millimeter length scales, have the potential to create a paradigm shift for targeted drug delivery and minimally invasive surgery as they can non-invasively access highly confined and enclosed spaces.[1, 3, 124] Likewise, these devices can also enable critical manipulation tasks, which are essential for a wide range of lab-on-chip applications.[11, 12, 125] An important criterion to realize the aforementioned applications is to equip these small robots with effective swimming gaits so that they can navigate through various types of aqueous media.[19, 20, 124] As a result, scientists and engineers have created a broad range of miniature robots that are able to mimic the aquatic locomotion of various small organisms.[13, 126, 127]

Because miniature soft robots have much higher degrees-of-freedom in comparison to their traditional rigid counterparts, they can generate far more complicated swimming gaits that can potentially be much more efficient.[24, 128-130] Due to this critical advantage, there is a rising trend in using miniature soft robots to enable aquatic locomotion. In this section, we highlight the key advancements, challenges and opportunities for micro/millimeter-scale soft robots that are able to propel themselves in or on aqueous media.

4.1 Key advances

Due to scaling laws, micro/millimeter-scale robots generally have to operate in low Reynolds number regimes whereby their inertial forces are negligible compared to the external viscous forces induced by their liquid environments.[124, 131-134] Under such conditions, many miniature robots have obeyed the scallop theorem and adopted non-reciprocal swimming gaits in order to generate net propulsion.[54, 131-133] In general, non-reciprocal gaits can be defined as a sequence of shape changes that are not identical when reversed. Over the last decade, numerous non-reciprocal gaits have been proven feasible for miniature soft robots to swim in or on aqueous media.

Undulatory swimming is a popular, non-reciprocal gait for miniature soft robots to swim in low Reynolds number regimes.[19, 54, 135-137] By making the robots generate travelling waves along their bodies, the soft robots are able to produce effective undulations that result in net propulsion.[126, 132, 138-140] The Taylor swimming sheet is a classical, hypothetical device that can produce such bio-inspired undulations.[132] While it is enticing to mimic such locomotion, scientists and engineers can only construct such a complicated swimmer after 63 years of its theoretical inception.[54] To create the Taylor swimming sheet, Diller et al. endow their miniature soft robots with harmonic magnetization profiles.[54] Based on such profiles, the soft robots are able to deform and produce effective travelling waves along their bodies when a rotating magnetic field is applied (Fig. 3A). The generated undulation allows the robots to swim within the fluid bulk and on an air-fluid interface. The robots swim quickly and they can also be controlled well with this gait.[54] For example, a Taylor swimming sheet of 5.9 mm in length can swim up to 17 body lengths per second on the water surface, and it can be commanded to follow complex, planar trajectories. If two of such swimmers have different net magnetic moments, they can even be controlled to follow independent trajectories on an air-water interface under a global magnetic field.[54] This is an attractive feature as it represents the first step towards creating a swarm of independent miniature swimmers, which can potentially collaborate with one another.

In addition to the Taylor swimming sheets, Lum et al. have also created a magnetic, millimeter-scale robot that can undulate and swim like a biological sperm (Fig. 3B).[23] As it is difficult to deduce the required magnetization profile and actuating magnetic field of such a complicated robot, they have developed a universal computational method that allows computers to automatically generate these parameters.[23] The effectiveness of this method is evident as it is able to output the necessary parameters for constructing and controlling such a convoluted soft robot. This universal computational method therefore represents a significant advancement for magnetic swimmers as it can potentially inspire a wide range of miniature soft robots that have complicated swimming gaits.[23] The constructed sperm-like robot is able to swim on an air-water interface at 11 mm/s and it can also be controlled to follow planar trajectories.[23] While undulating soft robots have great potential to navigate well in liquid environments, they have yet to swim in 3D-trajectories.

Inspired by the swimming locomotion of *E. Coli*, scientists and engineers have developed various miniature soft robots that can use helical flagella to propel themselves in aqueous media.[20, 56, 57, 135] For example, Mourran et al. present a helical microrobot that can swim via a series of rapid swelling and deswelling.[57] As the robot is made of a temperature responsive hydrogel (PNIPAm) embedded with gold nanorods, the robot undergoes torsion and bending via photothermal heating when irradiated by NIR light (wavelength of 808 nm), causing the helix to unwind. A significant advantage of using light actuation is that it can raise the temperature of the microrobot by approximately 20°C within milliseconds, allowing it to unwind quicker than if it were to rely on other stimuli such as pH or ionic strength.[57] Furthermore, as small robots can cool down easily,[3] this microrobot can return to its original shape within 8 ms after the actuating light is switched off.[57] By toggling the actuating light signals, the helical robot's swelling and deswelling rate can thus be controlled to produce a non-reciprocal swimming locomotion. Although the achieved swimming speed of this robot is comparable to biological *E. Coli* (25 μm/s)[141], it requires the constraints of the walls to translate along a straight line. Without such constraints, the robot will simply rotate and produce no propulsion.[57]

Huang et al. have also created millimeter-scale soft robots that are able to swim via helical flagellar propulsion (Fig. 3C).[20] The reported robots are made up of layers of hydrogel embedded with magnetic nanoparticles. By patterning the distribution and alignment of the nanoparticles during polymerization, the robots are able to self-fold and create the desired helical flagella when they are exposed to near infrared heating. Using the helical flagella, the robots can be magnetically actuated to rotate and produce corkscrew motions that generate net propulsion.[20] In recent developments, it is found that the performance of the robot can be further enhanced if its body is replaced with hydrogels that can deform accordingly with respect to different concentrations of sucrose.[56] Because such a robot can be programmed to adopt lower drag morphologies when the sucrose concentration is increased, its step-out frequency can be increased to follow rotating magnetic fields of higher frequencies in such situations. By exploiting this attribute, the robot can be controlled to maintain its velocity when it ventures into regions of stronger sucrose concentration that have higher viscosity.[56] In the future, it will be desirable to expand on such concepts and create adaptive miniature soft robots, which can better respond to other stimuli in their liquid environments.

Bio-inspired ciliary motion is another popular, non-reciprocal swimming gait that has been widely adopted by various miniature soft robots.[23, 44, 142, 143] It is desirable to mimic such a gait because ciliated organisms such as *paramecia* and *opalina* are among the fastest micro-swimmers in nature, i.e., in terms of their absolute swimming speed.[143-145] In general, cilia are arrays of short, hair-like appendages that are attached to the surface of ciliated organisms.[27, 145] To propel the small organisms, each individual cilium will continuously beat with two intrinsically non-reciprocal strokes: the power stroke and the recovery stroke. When the beating of cilia becomes coordinated, metachronal waves emerge to create a strong propulsion for the ciliated organism.[27, 144] Although it is attractive to create miniature soft robots that can mimic ciliary swimming, it remains a great challenge to fully replicate such complex motions.[27]

In 2016, Palagi et al. presented one of the most successful miniature soft robots that can mimic ciliary swimming.[44] While this liquid crystal elastomer (LCE) robot does not have an array of artificial cilia that can continuously beat with the power and recovery strokes, it can undergo deformations that mimic the metachronal waves generated by ciliated organisms (Fig. 3D). Despite having a simple, homogeneous nematic alignment along its longitudinal axis, a critical advantage of this cylindrical robot is that it can produce such complicated deformations when exposed to spatiotemporal, structured light (532 nm wavelength).[44] This is possible because the deformation of the robot can be localized upon illumination by the periodic light pattern.[44] Using its ciliary swimming gait, this 1.23 mm robot is able to achieve a swimming speed of up to 2.8 μm/s in a viscous glycerol-water solution.[44] While this soft robot is able to generate metachronal waves at a frequency of 2 Hz, it can potentially swim faster if its LCE body can have a higher mechanical bandwidth or be made to produce larger deformations.[44] Moving along a similar direction, Kim et al. used 3D laser lithography to fabricate a swimming robot that has artificial cilia attached to it.[142] To actuate the cilia via magnetic fields, thin layers of nickel and titanium are sputtered onto them. When the actuating magnetic fields are applied, each individual cilium of this 220 μm robot is able to generate a non-reciprocal beating motion, allowing the robot to swim at a maximum speed of 1.55 body lengths per second.[142] However, the artificial cilia beat in synchrony and do not produce metachronal waves like their biological counterparts, and this causes the robot to be unable to maximize their propulsion.[146] Furthermore, although each individual cilium in the robot is able to create a non-reciprocal motion, they are significantly different from the power and recovery strokes exhibited by a biological cilium. To date, only the artificial cilium of Lum et al. have been able to closely mimic the power and recovery strokes of a biological cilium.[23] However, as this artificial cilium is fixed to the ground, it functions more like a pump than a swimmer.

In addition to the non-reciprocal gaits, researchers have also identified other possible methods to propel miniature soft robots. For instance, Qiu et al. develop a millimeter-scale robot that can be magnetically actuated to deform and produce a reciprocal, scallop-like gait to swim in shear-thickening or shear-thinning fluids.[134] This is possible because unlike Newtonian environments, the viscosity of these non-Newtonian fluids will change when the fluids are subjected to different shear stresses or shear rates.[147, 148] The demonstration of Qiu et al. is therefore critical as it shows that non-reciprocal gaits are not the only feasible modes of locomotion for small-scale robots to effectively propel themselves in aqueous media.[134] Instead, miniature soft robots can alternatively swim with reciprocal gaits via exploiting the unique rheological properties of non-Newtonian fluids.[134] Since the human body contains various biological fluids that are non-Newtonian (e.g., blood[149, 150] and mucus[151-153]), reciprocal swimming gaits are indeed potential modes of aquatic locomotion for miniature soft robots to execute their biomedical applications. However, note that when the robots are swimming in non-Newtonian fluid, their speeds are expected to be different than when they are swimming in Newtonian fluids, but such effects are currently difficult to be modelled and predicted.[147]

It is also possible for miniature soft robots to use reciprocal, pulsatile gaits to propel themselves in Newtonian fluids.[13, 19, 154] Pulsatile gaits allow the robots to generate net propulsion via periodically ingesting and discharging fluids to produce impulsive thrusts.[138] A series of magnetic jellyfish-like robots, which are in the millimeter scale, have been created to adopt such swimming gaits.[13, 19, 154] By using the pulsatile gaits, these robots are able to achieve high velocities in water (2.7 to 18.1 body lengths per second), which substantially increase their Reynolds number (39 to 421) such that they can harness sufficient inertial effects to propel themselves.[19] An advantage of these jellyfish-like robots is that they can be highly dexterous when they are swimming on the air-water interface and within the fluid bulk. In particular, the robots can follow 3D trajectories when they are swimming within the fluid bulk.[13, 19] In recent developments, the magnetic jellyfish-like robots, spanning 5.6 mm in diameter, are also able to take advantage of their flow vortices such that they can transport microobjects, burrow and mix fluids while executing their pulsatile gaits (Fig. 3E).[13] While millimeter-scale miniature soft robots demonstrate high agility and diverse functionalities with the pulsatile gaits, it will be challenging to implement this type of locomotion for micrometer-scale robots that have negligible inertia effects.

Similar to insects, miniature soft robots can also adopt locomotion like jumping and meniscus-climbing to move along air-fluid interfaces.[19, 155-157] Jumping is a highly dexterous locomotion for maneuvering on water surfaces, as insects use such methods to catch prey or evade predators.[156] However, adopting such a locomotion is not an easy task for small-scale robots. Unlike jumping on land, the force cannot be so large that it makes the robots penetrate through the water surface. At the same time, the robots would have to control their force output to exert sufficient impulsive impact onto the surface to lift-off.[158, 159] Inspired by a water springtail, Hu et al. create a millimeter-scale robot that can overcome this challenge and successfully jump on water surfaces.[155] The robot is made of a strip of Kapton polyimide held in a curved position with a manually engaged latch (Fig. 4A). When the spring is unlatched via heat, the released elastic energy will make its free ends strike the water surface and launch the robot up (Fig. 4B).[155] As the robot is coated with Teflon, its hydrophobic surfaces can easily detach from the water surface during jumping. Although the robot can jump up to 10 cm, it remains a great challenge to control its angle of departure and landing position.[155]

Meniscus-climbing is an energy efficient method for insects to overcome frictionless barriers and transit from liquid to solid terrains.[155, 157, 158, 160, 161] A 5 mm robot is designed to climb the meniscus by exploiting capillary effects.[157] The bi-gel structure robot is synthesized with different densities of ruthenium on each side. This resulted in uneven swelling via the ruthenium-catalyzed, Belousov-Zhabotinsky reaction. The curved body deforms the free surface of the liquid to create positive menisci that results in capillary attraction with the like positive meniscus at the edge of the air-fluid interface.[162, 163] The robot climbs the meniscus at a speed of 0.3 body lengths per second.[157] Alternatively, Hu et al. have created a 3.7 mm magnetic robot that can ascend the water meniscus by increasing its buoyancy (Fig. 4C).[19] When external magnetic fields are applied, this hydrophobic, soft robot can increase its bending curvature to displace higher volumes of fluids and thereby increase buoyancy. While it is difficult to precisely land the robot at its targeted position laterally along the meniscus, the robot of Hu et al. is able to use this locomotion to effectively transit from the water surface to land.[19]

4.2 Challenges and opportunities

It remains a great challenge to develop miniature soft robots which can fully replicate the complex swimming locomotion of ciliated organisms, i.e., creating an array of artificial cilia that can replicate the power and recovery strokes of a biological cilium, and coordinate with one another to produce metachronal waves.[27] Although Gu et al. have recently presented centimeter-scale, magnetic cilia that can mimic the beating motions of ciliated organisms, they have yet to scale down their size to micro/millimeter length scales.[164] Furthermore, as these devices can only create such motions when they are fixed to the ground, they function more like pumps than swimmers. It is desirable to create biomimetic ciliated robots at small scales because they can potentially swim very quickly with this gait as demonstrated by their biological counterparts.[143, 144, 165]

Although jumping and meniscus-climbing are effective locomotion for miniature soft robots to maneuver on air-fluid interfaces, they are unable to position the robots accurately.[155] In the future, it might be interesting to explore other bio-inspired gaits such as the rowing locomotion demonstrated by the water striders.[155] As shown by existing centimeter-scale robots which are inspired by the water striders (Fig. 4D),[155, 166-169] rowing is a potential mode of locomotion that can accurately position the robots on the water surface. Scaling down the size of the rowing robots to millimeter scales can potentially be realized in the future by making their rigid actuators and mechanisms soft. Furthermore, it will be crucial to make the robot surface hydrophobic as this can help them acquire sufficient surface tension to stay afloat on the water surface in order to maneuver with the rowing locomotion.[170, 171]

Developing effective gaits for miniature soft robots to transit from fluid surfaces to the fluid bulk will be another great challenge.[19] This is a challenging task because it is very difficult for miniature robots to break the surface tension of the fluid, especially if they are on air-water interfaces.[19, 172, 173] While the 3.7 mm soft robot of Hu et al. is able to accomplish this task with an applied magnetic torque, the motions generated by the robot are neither predictable nor are they repeatable.[19] In the future, it will be good to further analyze and improve on such gaits so that the robots can transit from the fluid surface to the fluid bulk in a smoother and more controlled way. The transition from fluid bulk to its surface, however, will be much easier. This is especially true for hydrophobic robots as their interfacial energy becomes lower when they transit from the robot-water interface to full robot-air interface.[19]

While miniature soft robots are able to execute a broad range of swimming gaits, most of these aquatic locomotions are evaluated within Newtonian fluids such as water.[20, 23, 54] As evidenced by the work of Qiu et al., the properties of the non-Newtonian fluids should not be ignored as they can greatly influence the robots' swimming performances.[134] Therefore, it will be essential to further characterize the swimming performances of miniature soft robots in non-Newtonian, biological fluids such as blood, tears and mucus, before these devices can be practical for their targeted biomedical applications.[147, 148] Furthermore, it also remains a great challenge to identify and select the optimal gait for the soft robots to swim in a specified aqueous medium because it can be difficult to predict their dynamics accurately. This is especially true if these robots are placed in non-Newtonian fluids.[174-177] In the future, simulations and optimization methods can potentially be used to numerically identify the optimal swimming gaits of the robots such that they can swim efficiently in a specified aqueous medium. To evaluate the swimming performances of the robots accurately, numerical solvers such as the computational fluid dynamics and finite element analysis can also be integrated into such simulations. Identifying the optimal swimming gaits for the robots will be critical and beneficial as it can enable the robots to maximize their speed and agility in their aqueous media.

5 Aerial Locomotion

It is of great significance to develop miniature robots that can fly. As these devices can easily access highly confined spaces, they have the potential to significantly enhance the efficiency of search-and-rescue missions.[16] Furthermore, these aerial robots could also be deployed for dangerous operations in hazardous environments, and they can hypothetically also function as miniature nodes in sensor networks.[18] In this section, our discussion will focus on the smallest class of aerial robots, which have wingspans that are smaller than 10 cm, because these machines will be the ideal candidates for the aforementioned applications.

Small-scale aerial robots are operating in much lower Reynolds number regimes than their macro-scale counterparts.[178] As a result, the inertia effects of small-scale aerial robots are dominated by their viscous effects.[178, 179] Due to this phenomenon, fixed-wing flights become impractical as their lift-to-drag ratio will be too low at this length scale.[179] Rotary-wing flights are also unsuitable for miniature robots that are smaller than 10 cm because their rigid transmission mechanisms, such as gears, will produce too much friction under such conditions.[179] In contrast, flapping-wing flights generated by soft robots will be the most promising aerial locomotion at small-scale because they allow the robots to exhibit very high agility via hovering.[4] To realize this mode of locomotion, the robots will have to continuously flap their soft wings such that vortices can be created to generate lift.[179]

Because flapping-wing robots realize their gaits via deformation, their bodies are generally designed to be compliant mechanisms that have a specified stiffness profile. Once the actuators apply forces/torques/pressure onto the robots, the robots' body will deform and act as a soft linkage mechanism that will allow their wings to undergo a prescribed trajectory. An advantage of having a flexible body is that they can store and convert elastic potential energy into kinetic energy, and this will help to reduce the energy cost during flight.[180] Furthermore, as compliant mechanisms generate their motions via deformations, they allow soft robots to eliminate dry friction when their wings are flapping. This has proven to be a highly favorable attribute for small-scale aerial locomotion.[179]

5.1 Key advances

The first lift-off by flapping-wing robots signifies one of the key advancements for small-scale aerial locomotion.[55] Specifically, Wood has adopted the mechanical morphology of Dipteran insects in 2008 to construct such a soft robot with a wingspan of 3 cm.[55] This robot has an airframe, piezoelectric actuator, compliant mechanism, and airfoils that correspond to the insects' exoskeleton, flight muscle, thorax transmission, and wings (Fig. 5A(i)). The airfoils/wings of the robot are connected to a piezoelectric actuator via the compliant mechanism, and the compliant mechanism will deform whenever the piezoelectric actuator exerts a force/pressure on it. By having a prescribed stiffness profile, the actuator can make the compliant mechanism generate a series of time-varying shapes, which allows the robot to produce a wing trajectory similar to that of its biological counterparts. By realizing this wing trajectory, the 60 mg soft robot is shown to be able to generate sufficient thrust for lift-off (Fig. 5A(ii)).[55]

While the reported aerial robot by Wood is able to lift-off, both of its wings are coupled via a single actuator.[55] As a result, this robot has limited degrees-of-freedom, and thus it can neither hover nor control its flight directions. To increase the degrees-of-freedom of flapping-wing robots, the robots reported by Arabagi et al.[181] and Ma et al.[4] use one actuator to control each of their wings (Fig. 5B-C). By decoupling the wings, these robots are able to control their roll, pitch, and yaw torques independently. This is a significant step towards making the flights of flapping-wing robots controllable. Indeed, together with a visual feedback system, the 80 mg robot reported by Ma et al. can be successfully controlled to hover and maneuver laterally (Fig.

5C).[4] The displayed agility is therefore impressive as it can mirror that of biological insect flight.

As visual feedback systems constrain the workspace of flapping-wing robots, Ristroph and Childress explore the feasibility of creating an aerial robot that can hover stably via open-loop control.[182] By exploiting the phenomenon in which vertical, oscillating airflow can make cone-shaped bodies hover,[183] Ristroph and Childress present a 2.1 g jellyfish-like robot that is able to assume a cone-shaped configuration when its soft wings are flapping (Fig. 5D).[182] Using such a method, this robot is shown to be able to hover or maneuver successfully without feedback. However, as the ascending, maneuvering and hovering modes of this jellyfish-like robot require different structural configurations, such passive control methods will not allow the aerial robots to accomplish all three modes of flights with one design.[182]

To realize untethered aerial locomotion, it is essential for the flapping-wing robots to carry on-board power sources. However, due to scaling laws, it remains a great challenge to create centimeter-scale batteries that can support long continuous flights for these soft robots. Since available small batteries can only achieve power densities that range between 75-100 W/kg,[179] they are insufficient to power flapping-wing robots which require 0.25-15 kW/kg of power densities to fly.[55, 184] Hence, existing miniature aerial robots have to be tethered to external energy sources.[4, 55, 184-187]

In view of the limitations in power, Graule et al. attach electrostatic adhesive patches to their flapping-wing robot so that it can conserve energy via perching on flat surfaces (Fig. 5E).[18] The adhesive patches are compliant, and they are made of thin polymer layers which are embedded with interdigitated copper electrodes. A critical advantage of these adhesive pads is that they consume little energy (three orders of magnitude less than sustained flight), but yet they can produce sufficient adhesion for the 100 mg soft robot to perch onto a wide range of biological and synthetic overhangs.[18] Similar to birds or bats that will perch onto branches to rest,[188, 189] the flapping-wing robot can extend its overall flight time by conserving energy via this perching mechanism. Heading towards a similar direction, Jafferis et al. integrate six solar cells into their soft, aerial robot so that it can harvest light energy from the environment.[17] Under strong light conditions (approximately 3 suns light intensity), the solar cells will be able to provide approximately 150 mW of power to the 259 mg soft robot such that it can achieve untethered flights in a sustainable way (Fig. 5F).[17] While the solar cells are able to mitigate the power constraints of flapping-wing robots, sufficient power can only be harvested when the robots are operating in controlled environments that can output intense light energy.

It is appealing to make the actuators of the aerial robots soft because this will permit these devices to better conform, adapt, and negotiate across cluttered spaces.[22] Moving towards this objective, Chen et al. have created a flapping-wing robot of weight 155 mg by replacing the traditional, rigid piezoelectric actuators with soft dielectric elastomer actuators (DEAs) (Fig. 5G).[22] These soft DEAs are constructed by several layers of carbon nanotube electrodes and silicone elastomers, and they are connected to the wings via a compliant mechanism. By applying a time-varying electric field to the DEAs, these actuators will enable the compliant mechanism to generate a prescribed trajectory for the wings, allowing the robot to lift-off, hover and maneuver laterally.[22] By having a soft actuator, this flapping-wing robot is able to minimize impact resulting from collision with obstacles or other aerial robots (Fig. 5H). For instance, it is able to continue flying even after having multiple collisions with the surroundings. This unique advantage will allow the flapping-wing robot to increase its chances to survive and successfully accomplish its missions in cluttered environments. However, this robot still has a rigid frame, and it will be desirable to make flapping-wing robots entirely soft in the future so that they can further enhance their abilities to navigate in cluttered spaces. Furthermore, as the DEAs operate at high voltages (1.3 kV),[22] this may hinder the robot's ability to realize untethered flights. Nonetheless, there have been ongoing efforts to reduce the voltage requirements of DEAs by increasing their dielectric constants or reducing their thickness.[190-194] In the future, if DEAs are able to operate with substantially lower voltage, they will be beneficial for miniature soft robots to perform aerial locomotion.

5.2 Challenges and opportunities

While significant advancements have been made for miniature aerial robots, it remains a great challenge to provide sufficient on-board power for these machines to perform untethered, long continuous flights. As demonstrated by Jafferis et al.,[17] embedding light energy harvesters into the robots can be a promising and viable solution to resolve this limitation. It might also be interesting to embed flapping-wing robots with energy harvesters that exploit other ubiquitous power sources in the environment, such as wind energy. Miniaturization of wind energy harvesters, perhaps through the use of piezoelectric microcantilevers[195] or triboelectric nanogenerators[196], may help to achieve this purpose at small-scale. In addition to harvesting energy, these devices may also function as air flow sensors for environmental monitoring purposes.[195]

The on-board power limitations of flapping-wing robots may alternatively be addressed via enhancing their energy efficiency. Recently, soft robots have shown to be able to significantly increase their energy efficiency with distributed power sources that resemble the circulatory systems in animals instead of relying solely on traditional batteries.[197] The benefit of this proposed strategy can be observed from a soft robotic fish that can increase its working duration threefold after the addition of a synthetic vascular system, which stores electrochemical energy in hydraulic fluids distributed throughout its body.[197] Hence, if such strategies can be miniaturized and integrated to flapping-wing robots, their flight durations may potentially be prolonged.

Flapping-wing robots can potentially also increase their energy efficiencies by optimizing their flight trajectories and wing designs. At present, the power densities of existing flapping-wing robots are far less efficient than insects. Specifically, insects will only require a body-mass-specific power density of 29-40 W/kg to maintain continuous flight,[198, 199] while flapping-wing robots would require 0.25-15 kW/kg to accomplish the same task.[55, 184] A plausible explanation of why flapping-wing robots have low flight efficiencies is because these machines are mimicking the wing design and flight trajectories of organisms that are either much smaller or larger than themselves. Hence, while such imitations are feasible to make the flapping-wing robots fly, they are not necessarily optimal. To enhance flight efficiencies, it might be worth investigating if numerical optimization methods can be used to identify the optimal wing design and flight trajectories of flapping-wing robots. By having an optimal configuration, flapping-wing robots can potentially fly much more efficiently. While such a computational approach has not been applied for designing and controlling flapping-wing robots, these methods have proven to be able to surpass the barriers of human intuition, and create miniature soft robots[23] and flexural devices[200-202] that have unprecedented performances.

Autonomous control of miniature aerial robots is another great challenge in this research area.[16, 179] To control the robots autonomously, it will be essential to provide real-time position and orientation feedback to stabilize their flights. It will also be necessary for the robots to have additional sensors that can help them map out their surroundings. Although global visual feedback systems are able to provide the robots with such sensory information, these systems are only workable within a small workspace.[4, 17] In the future, it will be worthwhile investigating if onboard sensors such as miniaturized gyroscopes[203] and visual sensors[204, 205] can be integrated into the flapping-wing robots. If such integration can be done successfully without over compromising the robots' flight performances, it will be a significant step towards enabling autonomous control for miniature aerial robots.[179]

In the future, if flapping-wing robots are able to sustain untethered, long continuous flights autonomously, they will become invaluable for search-and-rescue missions, dangerous operations in hazardous environments, as well as for sensor networks.

6 Locomotion Across Multiple Environments

When miniature soft robots have to negotiate across highly unstructured environments such as within the human body or at disaster sites, it will be advantageous if they can transit reversibly across multiple environments.[19, 206] To address this critical challenge, Hu et al. have created an amphibious, millimeter-scale soft robot that can swim, meniscus-climb, crawl, roll and jump (Fig.s 2D and 6A-B).[19] To realize multimodal locomotion, the soft robot of Hu et al. is programmed with a single-wavelength harmonic magnetization profile. Based on this prescribed profile, the robot can be actuated by external magnetic fields to generate various types of time-varying shapes and execute the aforementioned modes of locomotion. By switching its locomotive gaits, this magnetic robot is able to navigate across liquid–solid environments smoothly and overcome various obstacles in its surroundings.[19] For instance, when the robot is immersed in the fluid bulk, it can swim up to the air-fluid interface via a pulsatile gait. On the air-fluid interface, the robot can either increase its buoyancy to climb the fluid meniscus or perform undulatory swimming to maneuver. When it reaches the juncture between land and fluid, this hydrophobic robot can use a rolling locomotion to peel itself off the fluid surface and land on the solid terrain. Upon landing, the robot can also choose to either roll quickly across the landscape or perform two-anchor crawling to position itself accurately. If necessary, the robot can also jump across barriers or execute undulatory crawling to go through confined, narrow tunnels.[19] Due to the exhibited dexterity, the soft robot of Hu et al. is able to navigate across a stomach phantom easily (Fig. 1D), demonstrating a significant advancement towards deploying small-scale robots for biomedical applications.[19] Heading towards a similar goal, Du et al. have created another millimeter-scale soft robot that can be magnetically actuated to perform undulatory crawling, rolling and swimming via a helical flagellum (Fig. 6C).[26] A critical advantage of this robot is that its hydrogel body can be shrunk upon NIR irradiation, allowing the robot to crawl through tunnels that are smaller than its undeformed body.[26] Although the robot of Du et al. can theoretically perform terrestrial and aquatic locomotion, it does not demonstrate the required locomotive strategy to transit between these two environments.

Search-and-rescue missions can potentially be much more efficient if miniature aerial robots are equipped with swimming abilities.[207] As a result, Chen et al. have reported a centimeter-scale robot soft that can use its flapping-wing mechanism to fly, swim, and transit between air and water.[207] This aerial-aquatic robot is programmed with a desired stiffness profile and it can be actuated by piezoelectric actuators to realize its wing trajectories. By controlling the frequency of its wing trajectories, the robot of Chen et al. can be made to hover stably in air and swim in water with a reciprocal gait (2 cm/s) (Fig. 6D-E).[207] The transition between water and air, however, can be very challenging as the robot has to overcome the high surface tension at the air-water interface.[207] To accomplish this goal, the robot is integrated with lightweight electrolytic plates and a sparker. Using the electrolytic plates, the robot can decompose its surrounding waters into hydrogen and oxygen, accumulate these gases in a chamber to increase its buoyancy and eventually protrude its wings out of the water surface (Fig. 6F). In such a configuration, the robot can then ignite the sparker to allow the chamber gases to explode and be rapidly ejected such that the robot can generate sufficient thrust to overcome the surface tension of the fluid and transit from water to air.[207] However, it is difficult to control the amount of thrust generated by such explosive mechanisms. As a result, the speed of the robot becomes so high that the robot is unable to immediately resume controllable flight after lift-off from the water surface.[207] In the future, it will be beneficial to improve such explosive mechanisms such that the aerial-aquatic robots can be more controllable when they transit from water to air.

It is highly beneficial to create miniature soft robots that can negotiate across multiple environments, especially those that have to operate in unstructured environments. However, research in this area is still relatively new with only a few preliminary works and thus many aspects of such robots can potentially still be enhanced. For instance, although the robots can perform various modes of locomotion, each mode is not necessarily optimal and can be improved in the future. In addition, it may be possible to endow more modes of locomotion into these robots so that their overall agility can be further augmented to maximize their efficiencies. In particular, it will be highly desirable to endow amphibious, millimeter-scale soft robots with an effective climbing locomotion as this can potentially allow them to overcome a wider range of obstacles in their environments. Furthermore, while the soft robot of Hu et al. can generate multiple modes of locomotion, its surface properties are not optimized to allow smooth transition between different environments.[19] For example, while the robot's hydrophobic surfaces may help it to stay afloat on the air-fluid interface, such surface properties make it difficult for the robot to overcome the high surface tension of the interface during the transition from the surface into the fluid bulk.[19] To facilitate the transition between such environments, it will be interesting to investigate the feasibility of constructing miniature soft robots with materials, which can actively switch their wettability upon command in the future.[208-210] It will also be interesting to explore the creation of a miniature soft robot that can eventually execute terrestrial, aquatic and aerial locomotion.

7 Discussion

Although miniature soft robots are able to execute numerous modes of locomotion, their agility can potentially still be enhanced significantly. A potential limitation of these robots is that their material properties are fixed once they have been programmed, e.g., their magnetization profiles. As a result, existing miniature soft robots can only achieve a fixed range of time-varying shapes when subjected to external stimuli, and this may have severely restricted their overall dexterity. In the future, it might be worth investigating if miniature robots can be constructed by novel soft actuators that can reprogram their material properties upon demand. Examples of such soft actuators include, but are not limited to, LCEs that can reconfigure their patterns of azomerocyanine and hydroxyazopyridinium dyes with acid treatments[95] and membranes with cobalt nanomagnets that can reprogram their magnetization profiles with short magnetic field pulses.[211, 212] Using such reprogrammable materials, miniature soft robots will have the potential to enhance their robustness considerably. Alternatively, miniature soft robots can also further enhance their dexterity if they can be built by modular parts, which can be actively reassembled. As demonstrated by Miyashita et al., modularization is a low-cost, simple and rapid strategy for small-scale robots to enhance their robustness via active reconfiguration of their morphology.[213] While such concepts have only been demonstrated by rigid small-scale robots,[213-217] miniature soft robots can potentially also benefit from these strategies in the future. Furthermore, if each of these modules can be programmed to respond to different types of actuation, the dexterity of miniature soft robots can be further enhanced. By using such reprogramming or reconfiguring strategies, miniature soft robots can potentially generate a more diverse range of time-varying shapes and adopt gaits that are far more dexterous and robust. These strategies will be especially useful for micro/millimeter-scale soft robots that have to navigate across multiple environments.

There are generally two main strategies for steering miniature soft robots. The first strategy is to allow the robots to produce asymmetrical deformation between both sides of their bodies such that each side can induce different magnitudes of propulsive force to make the robots turn.[49, 77] Although this is a feasible steering strategy, it will generally couple the robots' rotational and translational motions, and this may restrict their abilities to maneuver in tight spaces. The second method is only applicable for miniature soft robots that can be magnetically actuated. By exploiting the phenomenon in which the robots' net magnetic moment will tend to align with the external magnetic field, the orientation of the robots can be specified via controlling the direction of the applied field.[13, 19, 45] While this steering strategy is able to decouple the magnetic robots' rotations and translations, the generated magnetic torques to rotate the soft robots into their desired orientation may be weak when the robots have a small net magnetic moment.[13, 23, 45] A potential solution to mitigate this limitation is to attach a rigid magnetic component to the robots such that their net magnetic moment can be strengthened.[23]

The structural design of miniature soft robots determines their stiffness profile, and thus it has great influence on the robots' deformation characteristics. As a result, regardless of the actuation methods, it will be beneficial to exploit the structural design of miniature soft robots to further enhance their locomotion capabilities. While the centimeter-scale aerial robots have extensively exploited such concepts in enabling their flying locomotion,[4, 55] the geometrical designs of the smaller-scale terrestrial and aquatic robots have remained relatively simpler. In the future, it will be interesting to optimize the structural designs of micro/millimeter-scale soft robots as this is a promising method to augment their dexterity.

There is an emerging trend to use soft robotic systems as experimental platforms to investigate the locomotion of organisms.[218] A significant advantage of these systems is that they can precisely specify the control parameters in the experiments, allowing scientists to conduct their biomechanics investigations in a more rigorous and deterministic manner.[218-222] An example of such robotic systems is shown by the flapping wing robot of Wood that is able to mirror the flight of the Diptera insects.[4] Due to its resemblance to the insects, this robot has the potential to be deployed as an effective experimental platform for investigating the flight mechanics of its biological counterpart.[4] Likewise, the millimeter-scale, jellyfish-like robots of Ren et al. can potentially accomplish a similar task. By having similar soft-bodied locomotion and geometries as its biological counterpart, this soft robot can potentially be used to study the kinematics and behaviors of jellyfish ephyrae through a controlled environment.[13] To facilitate more of such studies in the future, it will be imperative to expand the locomotion abilities of miniature soft robots so that they can conduct a broader range of biomechanics investigations.

While a variety of locomotion modes have been developed for miniature soft robots, scientists and engineers have yet to successfully extend such concepts to maneuver a swarm of such devices. It will be highly advantageous to implement swarm control because the efficiencies of miniature soft robots can potentially be increased considerably when they can cooperate with one another.[1, 90, 223-229] As an example, a swarm of micro/millimeter-scale soft robots will have much better performances in targeted drug delivery than a single robot as a team of them will be able to deliver a much larger quantity of drugs to the targeted location.[90, 227, 228] The key challenges of implementing swarm control for centimeter-scale aerial robots are to enable them to fly autonomously as well as to integrate on-board sensors that can allow the robots to communicate with one another. If these challenges can be resolved, it may be possible to adopt swarm control algorithms on the flapping-wing robots so that they can collaborate as a team.[230] For the micro/millimeter-scale soft robots, their key challenge in enabling swarm control is to make their external stimuli spatially variant across multiple robots.[69, 90, 91, 231] Because the external stimuli are generally uniform across the entire environment in current set-ups, all the robots within the environment will produce similar motions when subjected to such stimuli and thus they cannot be controlled independently.[227, 231] Although independent control of two soft aquatic robots have been achieved by Zhang and Diller,[137] such concepts have not been extended to controlling a larger number of robots independently. In the future, it might be interesting to investigate if a combination of actuation methods may help to control a swarm of micro/millimeter-scale soft robots such that they can produce independent locomotion and function as a team.[90]

The selection procedure of the actuation method is critical for micro/millimeter-scale soft robots to realize their targeted applications. Actuation by magnetic fields have great potential to be deployed across a wide range of biomedical and lab-on-chip applications because their actuating fields can easily and harmlessly penetrate through most biological and synthetic materials.[1, 10] Light-based actuation such as longer wavelength NIR lights also have the potential to control the locomotion of miniature soft robots during medical applications. However, the penetration depth for such stimuli are typically limited to 1-2 cm underneath the skin,[90] making them more suitable for lab-on-chip applications where transparent media or open environments are feasible.[11] Likewise, (electro)chemically-actuated miniature soft robots are attractive in controlled, chemically-active environments typically found in lab-on-chip applications.[11, 53, 61, 157, 221] For miniature soft robots to further enhance their dexterity and adaptability in their targeted applications, more in-depth research on finding the optimal combination of actuation methods will be necessary.

While miniature soft robots have yet to be deployed for their targeted medical applications, those that can be magnetically actuated and tracked by ultrasound images have shown great promise.[19] In recent advancements, these robots have sufficient dexterity to navigate well in an unstructured, *ex vivo* biological phantom.[19] The locomotion of the soft robot can be executed and tracked well when the robot is enclosed by the phantom surroundings because the actuating magnetic fields and ultrasound imaging system have minimal interference with one another.[19] Furthermore, since the actuating magnetic fields can safely penetrate through most biological tissues and the soft robot can be made bio-compatible,[19] this demonstration signifies a substantial advancement towards using miniature soft robotic technologies for medical applications. We envision that with further advancements, miniature soft robots may eventually create paradigm shifts for treatments like minimally invasive surgery and targeted drug delivery.

8 Conclusion

This report reviews the key advances in the locomotion of miniature soft robots, which are made of smart materials that can be actuated by external stimuli. A significant advantage of these soft machines is that they have considerably higher degrees-of-freedom and adaptability than their rigid counterparts, and thus they have much greater potential to attain dexterous gaits. To have a more systematic discussion, we have organized the gaits of the robots into various categories such as terrestrial, aquatic, and aerial locomotion. Except for the aerial robots that are in the centimeter-scale, the focus of our discussions is on soft robots that are in the micro/millimeter length scales. We have discussed the critical challenges in each category of locomotion and also offered plausible methods that can potentially enhance the gait performances of the robots. Examples of such methods include novel implementations to exploit the unique properties of soft materials and actuators, and the usage of numerical optimization methods and machine learning algorithms. It will be highly desirable to equip miniature soft robots with dexterous gaits because this can empower them to easily and non-invasively access highly confined and enclosed spaces. By leveraging on this unique ability, miniature soft robots will have the potential to create a paradigm shift across a broad range of applications pertaining to medicine, materials science, biology, sensor networks, and search-and-rescue missions. In conclusion, this report aims to provide critical analyses and discussions, which can inspire scientists and engineers to develop miniature soft robots with augmented dexterity.

Authors' Note

The sequence of the first four authors is arranged in alphabetical order of their last name.

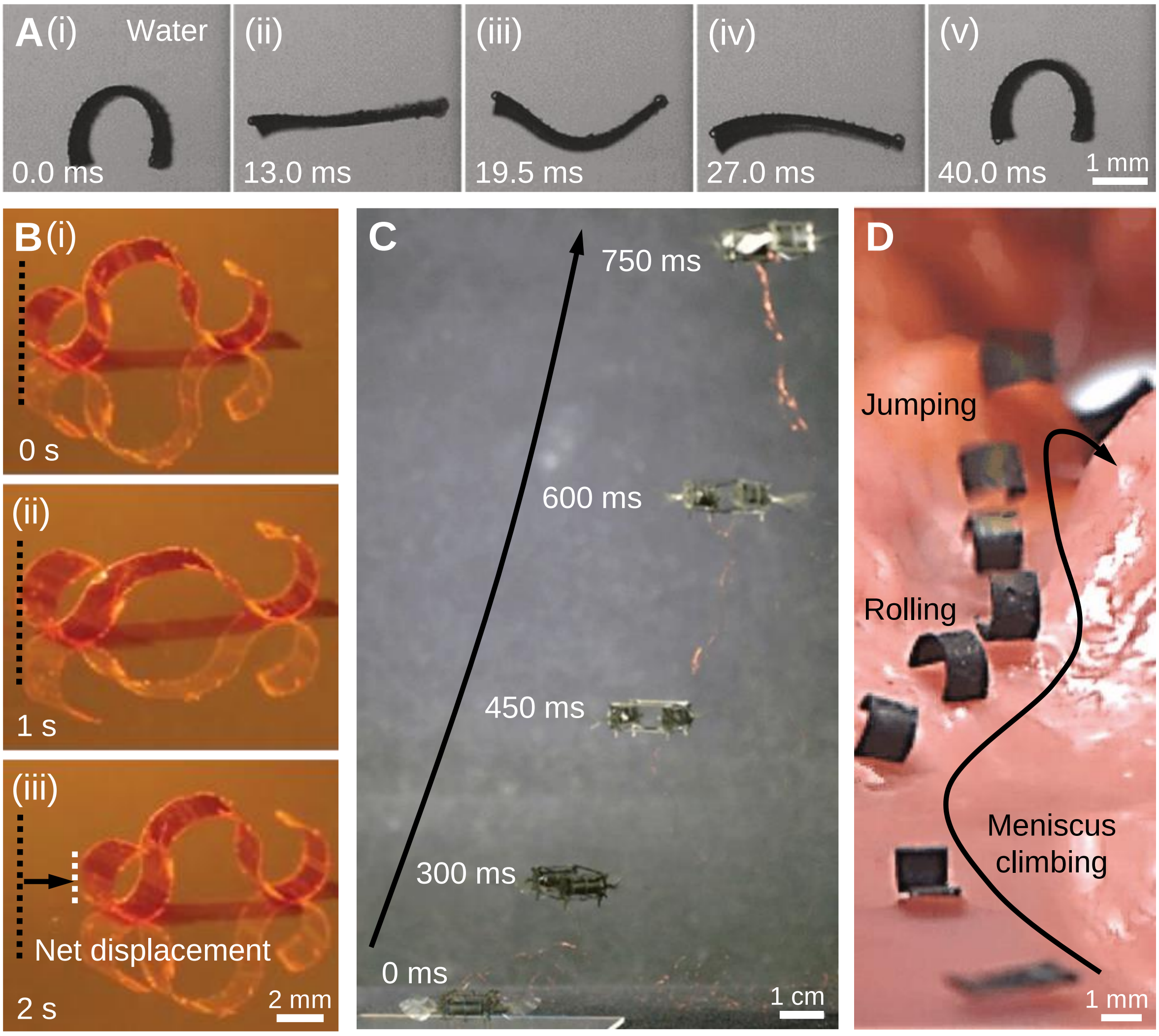

Fig. 1. Locomotion of miniature soft robots in different environments. (A) A magnetic soft robot that is swimming in the fluid bulk via a pulsatile gait.[19] (B) A light-driven soft robot that is executing two-anchor crawling.[50] (C) The lift-off and flight of an aerial robot that is actuated by soft dielectric elastomer actuators.[22] (D) Multiple locomotive gaits performed by a miniature soft robot that can negotiate across liquid-solid environments.[19]

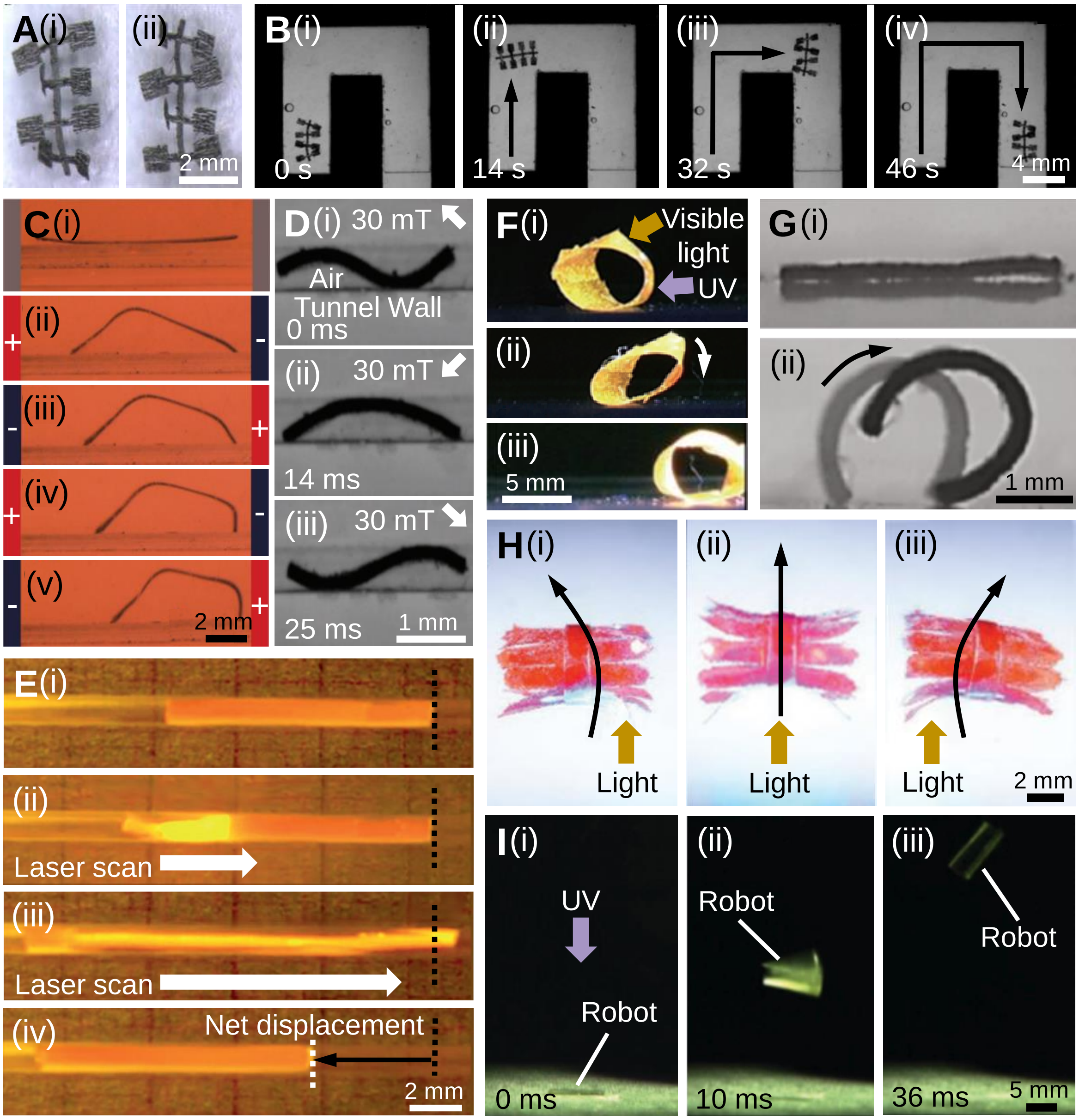
A(i)
(ii)
2 mm
B(i)
0 s
(ii)
14 s
(iii)
32 s
(iv)
46 s
4 mm
C(i)
(ii)
(iii)
(iv)
(v)
2 mm
D(i) 30 mT
Air
Tunnel Wall
0 ms
(ii) 30 mT
14 ms
(iii) 30 mT
25 ms
1 mm
E(i)
(ii)
Laser scan
(iii)
Laser scan
(iv)
Net displacement
2 mm
F(i)
Visible light
UV
(ii)
(iii)
5 mm
G(i)
(ii)
1 mm
H(i)
Light
(ii)
Light
(iii)
Light
2 mm
I(i)
UV
Robot
0 ms
(ii)
Robot
10 ms
(iii)
Robot
36 ms
5 mm

Fig. 2. Miniature soft robots with terrestrial locomotion. (A-B) A walking millimeter-scale soft robot, which can be steered across a 2D U-shaped microchannel.[45] (C) Two-anchor crawling of a PPy conducting film actuated under an electric field.[61] The red, blue and gray areas represent the positive electrode, negative electrode, and zero potential electrode, respectively. (D) A magnetic miniature soft robot that performs undulatory crawling.[19] (E) Peristaltic crawling of a TiNS/AuNP hydrogel in a capillary (1.2 mm inner diameter) by scanning a laser that outputs 445 nm wavelength of light.[51] (F) Photoinduced rolling of a ring of LCE film. UV and visible light are shone on the robot's top and bottom sides, respectively, to enable the robot to roll towards the light source.[47] (G) A soft magnetic sheet that curls into a wheel-like shape before it executes the rolling locomotion.[19] (H) A robot actuated by light to control its rolling direction.[49] (I) Ultrathin carbon nitride polymer film jumping under the exposure to UV light.[52]

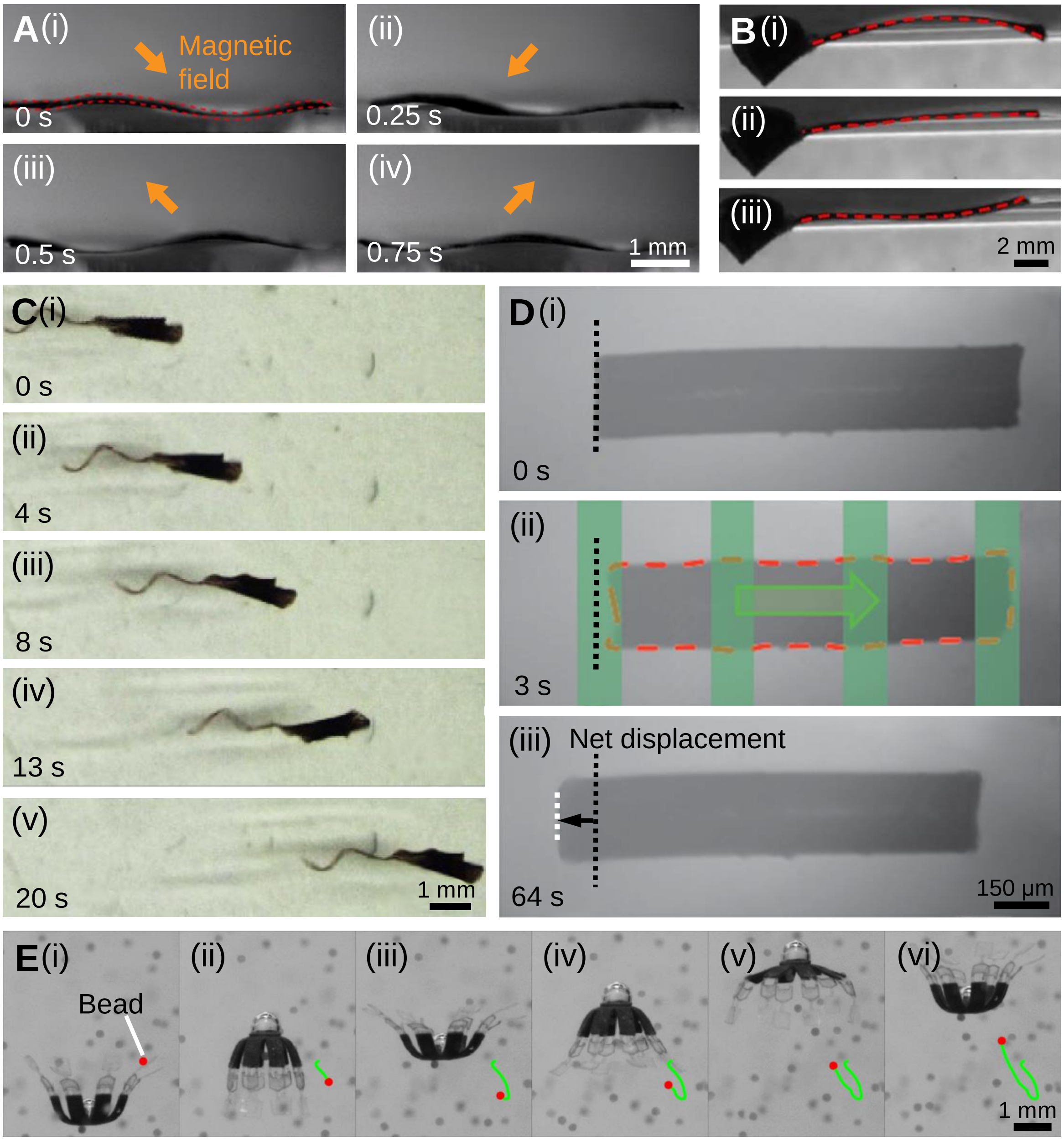
A(i)
Magnetic field
0 s
(ii)
0.25 s
(iii)
0.5 s
(iv)
0.75 s
1 mm
B(i)
(ii)
(iii)
2 mm
C(i)
0 s
(ii)
4 s
(iii)
8 s
(iv)
13 s
(v)
20 s
1 mm
D(i)
0 s
(ii)
3 s
(iii) Net displacement
64 s
150 μm
E(i)
Bead
(ii)
(iii)
(iv)
(v)
(vi)
1 mm

Fig. 3. Miniature soft robots with aquatic locomotion. (A) A Taylor swimming sheet that can generate a travelling wave down its body when it is subjected to a rotating magnetic field.[54] (B) A sperm-like magnetic robot that can perform undulatory swimming at the air-fluid interface.[23] (C) A swimmer with a helical tail driven by a rotating uniform magnetic field.[20] (D) A miniature soft robot that can mimic ciliary swimming. When the robot is irradiated by structured light, it can produce deformations that are similar to the metachronal waves produced by biological cilia. The green overlays and arrows represent the light pattern and travelling direction, respectively.[44] (E) A jellyfish-like robot swimming with pulsatile motion and capturing a neutrally buoyant bead using the fluid flow around its lappets.[13]

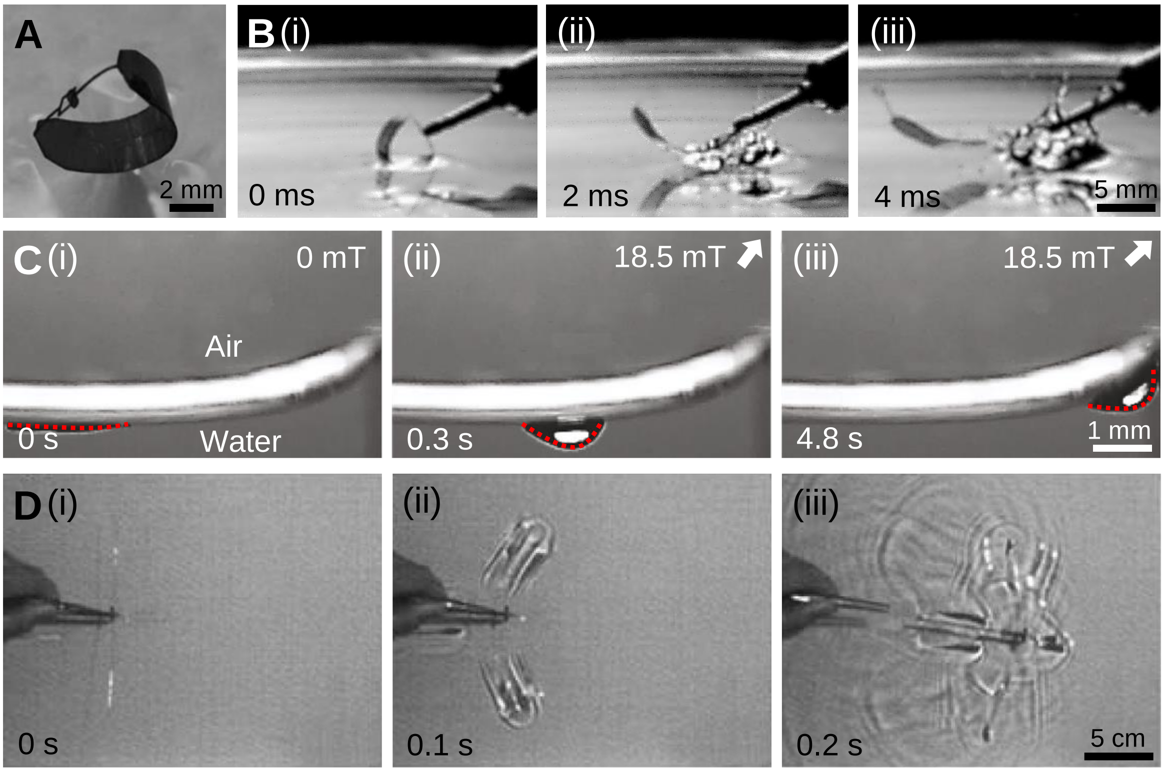

Fig. 4. Small-scale robots that can jump, meniscus-climb and row on the air-fluid interface. (A-B) A robot floating on the water surface that is held in a curved position with a latch. The robot jumps on the water surface by releasing the latch via heat from a soldering iron.[155] (C) A meniscus-climbing robot, outlined by a red dotted line, that deforms to increase its buoyancy and thereby ascend the meniscus.[19] (D) A water strider-inspired robot designed to float and move on the water surface. It is released by hand, and subsequently performs a rowing motion to move on top of the water surface.[155]

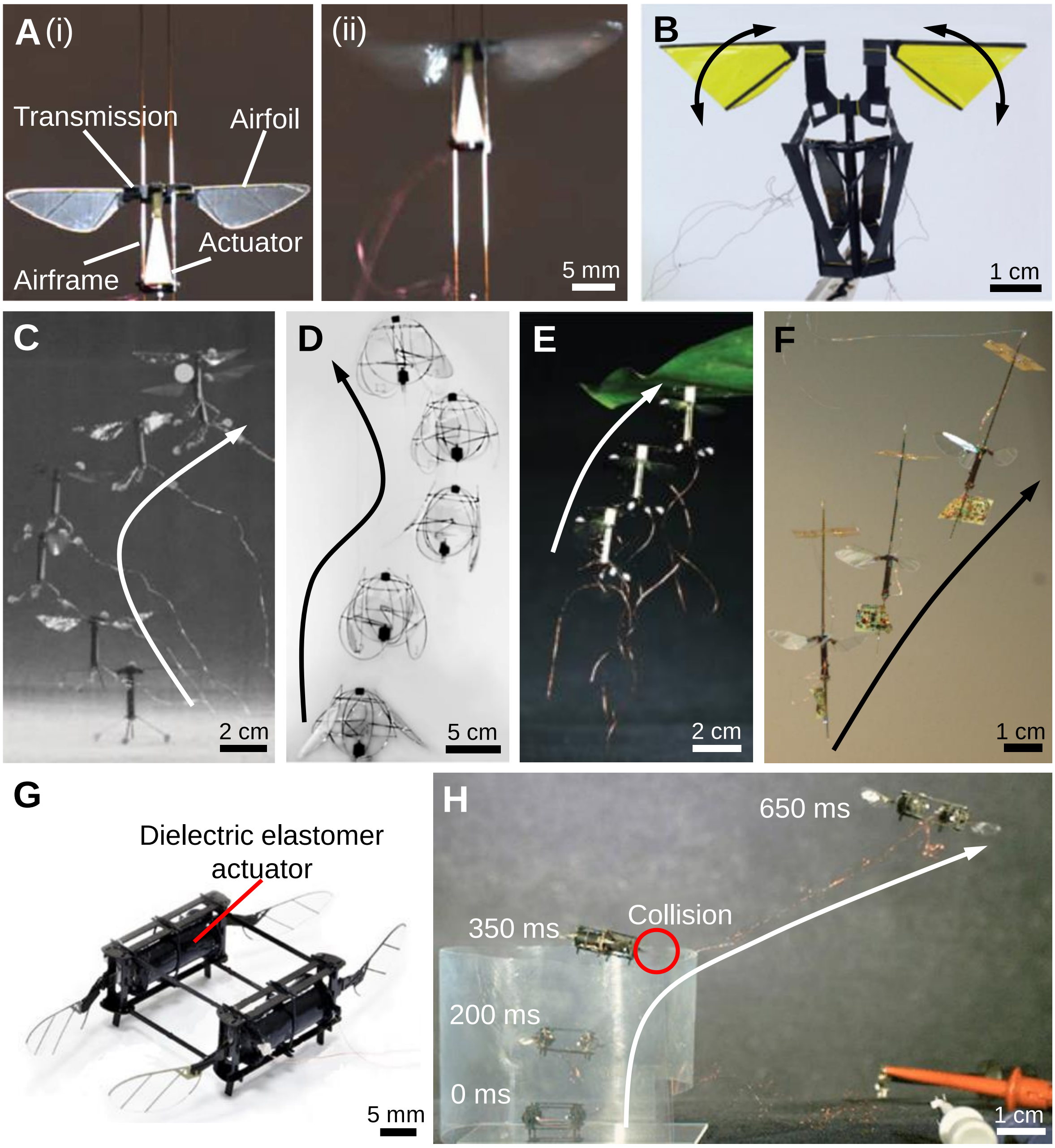
A (i)
Transmission
Airfoil
Actuator
Airframe
(ii)
5 mm
B
1 cm
C
2 cm
D
5 cm
E
2 cm
F
1 cm
G
Dielectric elastomer actuator
5 mm
H
650 ms
350 ms
Collision
200 ms
0 ms
1 cm

Fig. 5. Miniature soft robots with aerial locomotion. (A) Lift-off of a miniature aerial robot that has a soft flapping-wing mechanism.[55] (i) The robot includes four components: airframe, piezoelectric actuator, transmission/compliant mechanism and airfoils. (ii) Vertical take-off of the robot. (B) Flapping-wing robot that uses one actuator to control each wing.[181] (C) Controlled maneuvering and hovering flight of an insect-scale aerial robot.[4] (D) Ascending flight of a jellyfish-like flyer.[182] (E) A miniature aerial robot that perches on a natural leaf with switchable electrostatic adhesion.[18] (F) Untethered flight of an aerial flapping robot powered by six solar panels.[17] (G) The structure of an aerial robot with soft dielectric elastomer actuators.[22] (H) An aerial robot with soft dielectric elastomer actuators flying across cluttered space.[22]

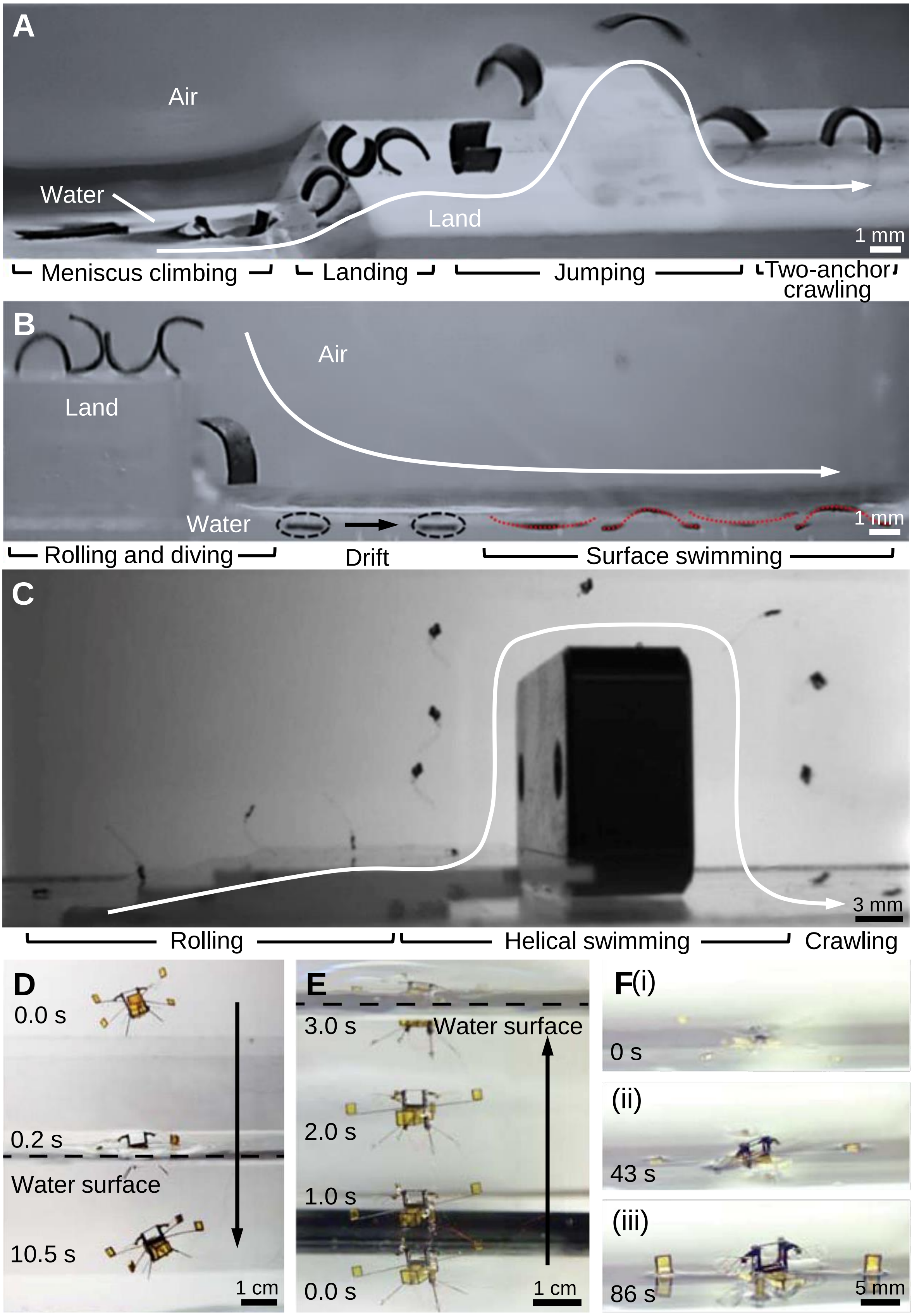
A
Air
Water
Land
1 mm
Meniscus climbing
Landing
Jumping
Two-anchor crawling
B
Land
Air
Water
1 mm
Rolling and diving
Drift
Surface swimming
C
3 mm
Rolling
Helical swimming
Crawling
D
0.0 s
0.2 s
Water surface
10.5 s
1 cm
E
3.0 s
Water surface
2.0 s
1.0 s
0.0 s
1 cm
F(i)
0 s
(ii)
43 s
(iii)
86 s
5 mm

Fig. 6. Miniature soft robots that can navigate across multiple environments. (A) A soft magnetic robot that can navigate across unstructured terrains by climbing up a water meniscus, jumping, and two-anchor crawling.[19] (B) A soft magnetic robot that rolls on land before transiting into water. Thereafter, it swims with undulatory motion on the water surface.[19] (C) A robot that rolls up stairs, swims with helical propulsion over an obstacle, lands and crawls.[26] (D) An aerial-aquatic robot transiting from air to water.[207] (E) An aerial-aquatic robot swimming to the water surface.[207] (F) Emergence of the aerial-aquatic robot from the water surface by trapping gases from electrolysis.[207]

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