

System-Engineered Miniaturized Robots: From Structure to Intelligence

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The development of small machines, once envisioned by Feynman decades ago, has stimulated significant research in materials science, robotics, and computer science. Over the past years, the field of miniaturized robotics has rapidly expanded with many research groups contributing to the numerous challenges inherent to this field. Smart materials have played a particularly important role as they have imparted miniaturized robots with new functionalities and distinct capabilities. However, despite all efforts and many available soft materials and innovative technologies, a fully autonomous system-engineered miniaturized robot (SEMR) of any practical relevance has not been developed yet. In this review, the foundation of SEMRs is discussed and six main areas (structure, motion, sensing, actuation, energy, and intelligence) which require particular efforts to push the frontiers of SEMRs further are identified. During the past decade, miniaturized robotic research has mainly relied on simplicity in design, and fabrication. A careful examination of current SEMRs that are physically, mechanically, and electrically engineered shows that they fall short in many ways concerning miniaturization, full-scale integration, and self-sufficiency. Some of these issues have been identified in this review. Some are inevitably yet to be explored, thus, allowing to set the stage for the next generation of intelligent, and autonomously operating SEMRs.

modern mechanical systems in the 20th century, eventually leading to the term “robot” coined by Karel Capek in 1921. Since then, humans have been racing to create autonomous, self-propelling synthetic life. In 2012, the International Organization for Standardization (ISO: 8373:2012) defined the robot as “an actuated mechanism programmable in two or more axes with a degree of autonomy moving within its environment to perform intended tasks.” Alternatively, according to the Oxford English Dictionary, “a robot is a machine that is programmable and capable of carrying out a complex series of actions automatically.” In consonance to these definitions, a system can be termed a robot if capable of motion via actuators and control units (e.g., on-board electronics) that give awareness. Finally, robots should follow a set of preprogrammed instructions to conduct tasks, and if robots move without a tether, they can be termed “motile robotic systems.”


Traditional robots are physically, mechanically, and electrically engineered

1. Introduction to the Field: Coming from the Top and Going Down

Nature’s adaptability to create autonomous organisms capable of surviving in a dynamically changing and challenging environment has inspired humans to create mechanical counterparts. One of the first instances of a mechanical device built to conduct a monotonous task occurred around 3000 B.C, which was an Egyptian water clock that used human figurines to strike the hour bells. Inventions like these have paved the path to the creation of

with rigid and bulky links that allow them to conduct tasks within structured environments. However, as the sizes of robots shrink, significant new challenges in system engineering and integration occur.^[1–6] Also, new physical principles come into force and control the behavior and motion of the robotic system.^[6–8] As the systems become smaller, the relative forces that act on the system change dramatically, and the robots experience an increase in friction and adhesion. At the same time, weight and inertia gradually become irrelevant.^[6–8] Changes in fluid mechanics and stochastic motion challenge fundamental engineering

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notions of how mechanical elements move and interact. These physical effects form a crucial factor in designing and operating robots on a small scale.

The inspiration for such small machines was first envisioned in a famous lecture by Feynman, “There is plenty of room at the bottom,” in 1959, which marked the start of the microsystems era and triggered the rapid development of micro- and nanoengineering.^[9] Since then, advances in microscale engineering fueled the demand of tiny integrated systems for applications in inter- and transdisciplinary fields. Science fiction movies like *Fantastic Voyage* (1966) and *Inner Space* (1987) envisioned tiny carrier vehicles for autonomous operation inside the human body. By now, micromachined structures can indeed access enclosed small spaces in vivo.^[10] Miniaturized robots are often designed and built for tasks that are monotonous or even dangerous for people, including routine manufacturing^[11] and space exploration.^[12]

However, despite all efforts, it has remained elusive to create any useful system-engineered robot on the submillimeter scale. The true challenge resides in the monolithic integration of multiple heterogeneous microcomponents into a flexible or even soft 3D robotic shell. To this end, nature is doing a far better job. Natural autonomous organisms come in various shapes and sizes that range from insects at millimeter scale to the single cell of the size of a few micrometers.^[13] Cells are capable of motion, sensing by mechanical interactions, efficient processing of information, and having a rapid activation response, all of which are enclosed in a dynamic, adaptable body. The cell provides a blueprint to create synthetic life forms at the microscale (**Figure 1a**).^[14–17] Synthetic life in the form of a system-engineered miniaturized robot (SEMR) should therefore include an engine for locomotion, a sensor array for sensation, integrated electronic components for information processing, actuators for conducting tasks, and an energy source to power the system.^[18,19] Ideally, all these elements should be assembled into a flexible or soft architecture (**Figure 1b**).

The field of robotics has been inspired to a large extent by nature to design and develop SEMRs of all shapes and sizes. The term “miniaturized robot” has many implications based

on the robot size, the precision with which the robot can operate, or on the ability and flexibility to handle objects of various shapes and dimensions. Different research communities have different views that depend on the application and the robotic skills, which are essential for successfully implementing a particular task. Generally, SEMRs deal with smaller-than-conventional robotic systems, the sizes of which vary from decimeters to micrometers. Ideally, the essential components of a robotic system should be fully integrated and embedded into a soft and flexible structure and allow for locomotion, sensing, and functional operation at the same time.

Bacteria, algae, neutrophils, trypanosomes, or organisms, such as flies, mosquitoes, and shrimp, provide a rich source of inspiration to create robust synthetic life. However, embedding different components at the small scale comes with significant challenges, and monolithically integrated SEMRs hardly exist. Entirely soft systems often need a tethered connection for power supply, whereas bulky on-board components such as batteries, microprocessors, and electronic components are used in untethered systems. SEMRs may contain functional elements, such as actuators, sensors, electronic components, and on-board energy. The functional components allow SEMRs to conduct specific tasks, such as microsurgery, cargo transport, or recon. However, with miniaturization of the robot’s size, it is also clear that robots lose the ability of on-board intelligence and become limited in functionalities (see **Figure 2**).

Centimeter-scale robotic systems are assembled using off-the-shelf components (actuators, sensors, and surface-mounted devices).^[20–22] The first centimeter-scale miniaturized robotic systems using off-the-shelf motors and gears (typically used in watches) were integrated with on-board capacitive energy to power sensing and reactive control.^[23] In the past decade, off-the-shelf assembly techniques have become powerful tools to create several unique aerial robotic systems^[24–26] such as the RoboBee.^[26] The miniaturized robotic bee has a wingspan of ≈ 3 cm and integrates off-the-shelf piezoelectric bimorph actuators and efficient solar cells. The RoboBee could take flight due to low mass and high output power of the solar cell. Materials science has created novel polymeric and gel actuators that

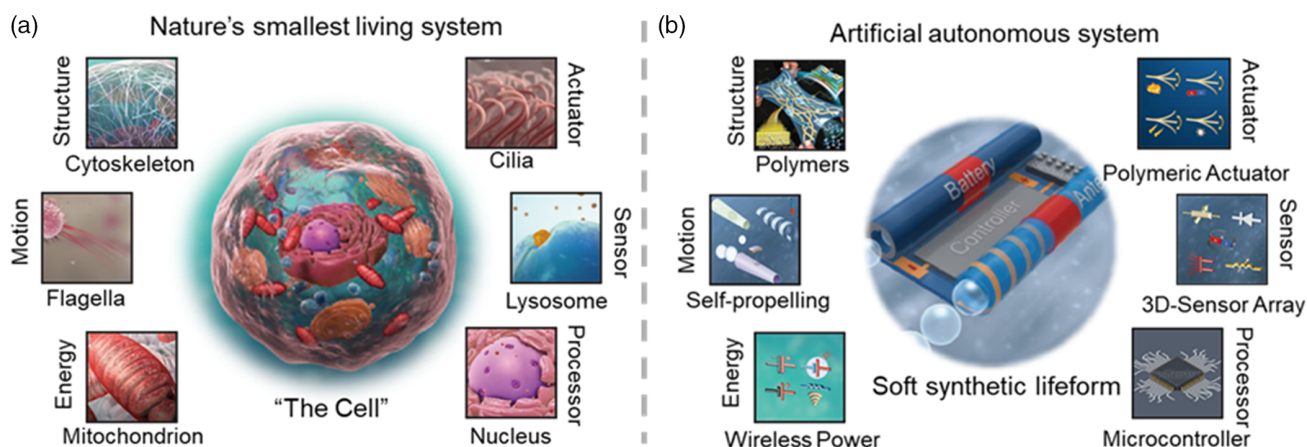


Figure 1. Nature-inspired robotics. a) The cell, nature’s smallest living system (Adapted with permission.^[286] Copyright 2015, Nucleus Medical Media Inc.), and the various organelles. b) An artificial autonomous system form (Adapted with permission.^[18] Copyright 2011, The Royal Society of Chemistry), and the various synthetic organelles.

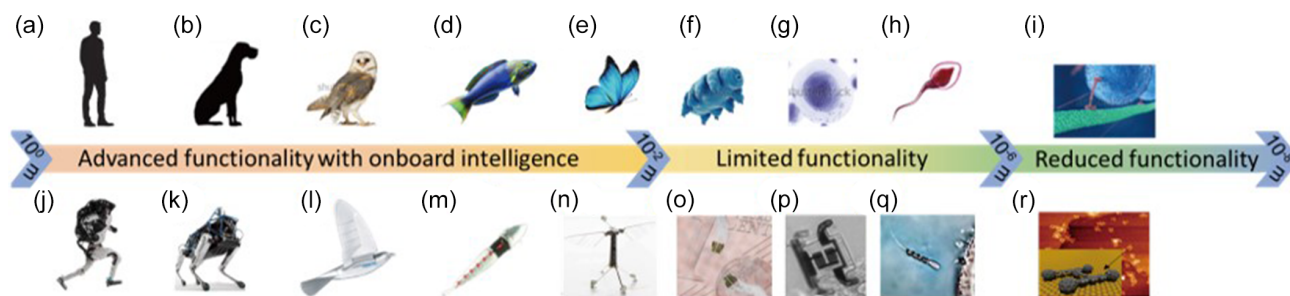


Figure 2. Nature's autonomous organisms, and their synthetic counterparts at different size scales. As the size is reduced, the functionality and complexity of the system reduces, too. a–i) Adapted with permission.^[289] Copyright 2021, shutterstock.com. m) Adapted with permission.^[290] Copyright 2014, Mary Ann Liebert, Inc. n) Adapted with permission.^[24] Copyright 2019, Springer Nature. o) Adapted with permission.^[39] Copyright 2020, Springer Nature. p) Adapted with permission.^[40] Copyright 2020, Springer Nature. q) Adapted with permission.^[58] Copyright 2016, American Chemical Society. r) Adapted with permission.^[291] Copyright 2005, PhysOrg.com.

respond to stimuli like electricity, heat, or light.^[27–29] Actuators such as ionic–polymer metal composites,^[30] ionic gels,^[31,32] shape memory polymers,^[33,34] and liquid crystal polymers^[35,36] have led to soft and robust SEMRs.^[37–40] The assembly of soft materials with simple structures makes the SEMR demonstrated in the study by Wu et al.^[37] exceptionally robust. The SEMR was able to withstand a load of 1 million times its own body weight and continued to walk at speeds up to 8.7 cm s^{-1} .

As the size of SEMRs approaches the subcentimeter scale, the off-the-shelf assembly technique becomes impractical because the envisioned size of the entire robotic system is smaller than the size of the individual components. At the millimeter scale and below, microelectromechanical systems (MEMS) therefore become dominant. MEMS technology can build microelectronic components, microactuators, miniaturized mechanical motors, and sensors,^[19] which are core elements to create SEMRs. To enable the SEMR to move, sense, think, and act, researchers have proposed the use of microfabrication to create insect-like SEMRs that integrate sensing, actuation, and control units.^[41–43] Such MEMS-based SEMRs were demonstrated in 1987.^[44] Since then, the primary focus of millimeter-sized SEMRs was the development of microactuation mechanisms. For instance, researchers designed a network-integrated circuit miniaturized robot, capable of locomotion via articulated legs, that integrated MEMS with small-sized rotary-type actuators operating six legs to realize an ant-like switching behavior. The system also integrated a driving waveform generator and a complementary metal–oxide–semiconductor (CMOS) open-loop controller.^[45] One of the challenges in designing capable SEMRs is the limited power budget, as existing propulsion methods require significant power, and the energy-storage systems (ESSs) are extremely difficult to downscale into the submillimeter range.^[46] Alternatively, SEMRs may use wireless energy delivery routes to power on-board functional components, for instance, inductive coupling,^[39,47,48] solar cells,^[26,40] and vibrational fields.^[49] Real-time feedback and remote control are further challenges in regulating the interactions of the SEMRs with their working environment. Overcoming these challenges is central to achieve smart, safe, and precise operation.^[1–6]

The great success of microfabrication in the 1990s has enabled precise patterning of a wide range of materials, leading to further miniaturization of functional components, paving the way to the

realm of multifunctional submillimeter SEMRs. At such scales, motion poses a critical challenge to the robots as the microscopic forces such as surface tension, friction, and adhesion start to dominate. However, the development and implementation of powerful propulsion mechanisms,^[50,51] such as electrostatic,^[51–53] magnetic,^[54–62] and optical actuation,^[63–67] as well as those relying on chemical energy taken from the environment^[39,67–69] and biological microorganisms and cells,^[70–73] have enabled SEMRs to overcome the microscopic forces and move efficiently. Due to the propulsion capability, even very simple SEMRs are already of great interest for biomedical applications. The first demonstration of such a simple SEMR as a potential medical tool was a magnetically actuated helical screw.^[61] Prominent simple SEMRs at submillimeter and micrometer scale are micromachined rolled-up^[74–76] or template-assisted^[77–79] tubular microengines. These tubular micromotors can conduct targeted microsurgery,^[80,81] and the surface of these tubular microengines can be easily functionalized for biosensing^[82–86] and active drug delivery.^[87–90] Though simple SEMRs show great potential for many applications, these systems are still very rudimentary without electrical energy or microelectronic units on-board, thus making these systems motile but not true SEMRs. A significant step forward was recently taken, when a microscopic SEMR used a flexible polymeric platform to integrate twin microtubular jet engines, electronic components, and a robotic arm.^[39] The polymeric platform provided sufficient space to integrate an on-board inductive coil, enabling convenient energy transfer to drive the electronic components wirelessly. To develop small machines once envisioned by Feynman many decades ago, more research is required in materials science, biology, neuroscience, robotics, and computer science.

Here, we summarize the development, recent progress, and challenges in creating SEMRs that are under a decimeter small, motile, include flexible components, and preferably show at least a couple of other essential functionalities such as sensing, actuation, on-board energy supply, and intelligence. This Review does not focus on simple micromotors like catalytic microparticles, magnetically driven microstructures, or rudimentary “two-component” biohybrid single-cell systems, as these do not show the complexity required by a truly robotic system, yet. Instead, we refer the interested reader to recent literature, where such microsystems have been comprehensively reviewed, especially concerning their applications in biomedical fields.^[3,91]

2. Building Blocks of a Soft Miniaturized Robotic System

SEMRs require unique features and unconventional processing techniques to structure and fabricate them based on soft materials.^[4,5,92,93] SEMRs are designed to eventually conduct complex functions, for example, swimming, walking, grabbing, and flying. For swimming SEMRs, ambitious biomedical tasks have been envisioned in the human body such as cancer screening, targeted drug delivery, neuron stimulation, biopsy, and biosensing.^[3,94–99] To control and conduct such delicate operations, an SEMR should be capable of deterministic locomotion and accommodate on-board wired/wireless units for on-demand exchange of power and information.^[1,18,19] Moreover, dynamically operating actuators and sensors must be installed. Building blocks made of rigid components like metal wires, glass optical fibers, and electric motors have already been used for decades in macroscale robots.^[100–103] However, the development of SEMRs has changed the technological scenery and calls for the development of functional components on, in, and with soft and flexible materials.

2.1. Soft and Flexible Structure

The soft, flexible, and deformable body structure of animals helps them to adapt and move in constantly changing complex environments. The polymorphic adaptability and dynamic reconfigurability of these structures enable animals to hide and hunt through small spaces. Soft structures conform to surfaces distributing stress over a larger volume, in this way efficiently reducing impact force. It goes without saying that such strategies are appealing to design and construct soft artificial robotic systems, too.^[104–106] The goal is to design robots with bio-inspired capabilities that permit adaptive and flexible interactions with unpredictable environments.^[107,108] Especially in the biomedical sector, soft SEMRs with material stiffness similar to the body and tissue^[106,107] can overcome the constraints of their rigid counterparts, putting forth various new application scenarios in theranostics and healthcare.^[106,109–111] SEMRs should have the following capabilities.

2.1.1. Polymorphic Adaptability

The ability of biological organisms to transform morphology, shape, and, to a certain extent, size has inspired robotics at all scales using soft and flexible material. The multigait soft robot,^[112] for instance, demonstrates the capability of successfully passing through a gap narrower than the robot itself by pneumatically squeezing through the small opening. In another case, a polydimethylsiloxane (PDMS)-based pneumatic balloon actuator (PBA) driven by pneumatic pressure was used as a surgical tool for retinal pigment epithelium (RPE) sheet transplantations.^[113] The PDMS film loaded with the RPE was pneumatically rolled into a small cylinder that could be inserted through a narrow needle operating in the eyeball.

2.1.2. Dynamic Reconfigurability

The abundant choice in materials, together with ample design freedom in geometry and size, continuously pushes the limits

of polymorphic adaptability and adds new functionality and usability to the robots and actuators.^[114–116] As a result, dynamic adaptability and reconfigurability form the key prerequisite for on-demand competition and prompt handling of dedicated soft robotic tasks. For instance, soft micromanipulators made of thermal-responsive material such as poly (*N*-isopropylacrylamide-*co*-acrylic acid) (pNIPAM-AAc), 2-hydroxyethyl methacrylate (PHEMA), and poly (ethylene glycol) acrylate (PEGDA)^[9,39,117–120] have utilized shape reconfiguration to function as gentle grabbers for tissue biopsy.

2.1.3. Continuous Motion

The ability to integrate hinges, fixtures, and friction-mitigation mechanisms to form a finite number of joints with multiple degrees of freedom enabled the motion of complex rigid robots.^[37,121–123] This structural complexity poses a challenge to further miniaturize SEMRs. In contrast, actuation based on deformable materials enables and greatly facilitates continuous joint-less motion. Compactness, compliance, and deformability become crucial in selecting materials to build SEMRs. Elastomers and polymeric materials are a good choice as their Young's moduli are similar to that of biological tissues. Good examples are polyester ($E = 60$ kPa) and polymethyl methacrylate (PMMA) composites ($E = 170$ kPa).^[124–126] These features and requirements become essential in designing soft, safe, and smart SEMRs.

2.2. Locomotion

In nature, biological organisms move through a variety of ecosystems.^[127–130] The locomotion modes of biological organisms are classified based on their environmental interaction. These interactions lead to four major types of locomotion: aquatic (locomotion through water), terrestrial (on the ground or on other surface), fossorial or subterranean (locomotion underground), and aerial (locomotion through the air). Moreover, the evolution and natural selection of biological organisms have led to innovative and complex adaptation of locomotion modes that exploit the use of microscopic forces such as surface tension, friction, and adhesion. These adaptations of biological systems have given rise to locomotion through multiple media, leading to aquatic surface locomotion (at air/water interface), aqua-terrain locomotion (at land/water interface), and arboreal locomotion (at air/land interface or tree dwelling). As the robots become smaller and smaller, the balance of physical effects changes dramatically. In nature, the downscaling of organisms leads to propulsion principles of small animals with capabilities inaccessible at the large scale.^[130–132] For instance, the water strider insect supports its weight on water using surface tension rather than buoyancy.^[133] The study of such biological systems has inspired artificial locomotion of SEMRs.

Among the many locomotion modes available in nature, the field of SEMRs has mainly explored locomotion in three different environments, namely, aquatic locomotion, terrestrial locomotion, and aerial locomotion. To move through different environments, SEMRs should efficiently use their actuation mechanisms, similar to microscopic biological organisms.

The past decades have seen tremendous developments in micro-scale actuation systems capable of precise, stable, and robust locomotion control with minimum energy consumption.^[27–36] These systems can walk,^[134–137] roll,^[138] swim,^[139–143] glide,^[55] and jump^[55,143,144] through different environments similar to their biological counterparts.

2.2.1. Aquatic

SEMRs in liquid environments are prime candidates for bioengineering, drug delivery, and other theranostic applications such as cancer treatment^[3,70,91] and assisted reproduction technologies.^[71] When constructing aquatic SEMRs, the micro-propulsion units are critical for achieving motility. The locomotion through aqueous solutions can be achieved by three main propulsion mechanisms^[1,49,50]: chemical,^[39,67–69,145–148] physical,^[39–47,51–66,149,150] and biohybrid.^[71–74,151] To achieve force-free swimming, the propulsion mechanisms have to provide a propulsive force that balances the viscous drag imposed by the low-Reynolds number ($Re < 10$) environment.^[152–155]

Undulation-based swimming is the most common mechanism used by animals such as golden fish, batoid fish, and jellyfish. These living organisms generate propulsion force by traveling waves with an elastic tail or body driven by an oscillating head.^[156] Microactuation in aquatic SEMRs has been demonstrated using on-board actuators, such as shape memory alloys,^[157] hydraulic actuators,^[158] dielectric elastomers,^[159,160] hydrogels,^[161] and liquid crystal elastomers,^[162] which could be actuated by light,^[161–165] heat,^[9] or magnetic field,^[166,167] allowing on-demand locomotion direction control. The jellyfish-like SEMR^[168] was equipped with multiple functionalities in moderate-Reynolds number environment ($Re \approx 7$) (as shown in **Figure 3a**). An external oscillating magnetic field coupled to magnetic composite elastomer lappets allows the jellyfish-like SEMR to produce controlled fluidic flows around its body. It mimics well the motion of a jellyfish (see **Figure 3a**), thus making this particular robotic platform an important scientific object to study the behavior of Ephyra. Magnetic actuators offer accurate control over posture, speed, and direction by simply changing the frequency, strength, and direction of the field. Even multidegree freedom in speed and direction has been demonstrated by designing actuator geometries that respond differently to the magnetic field applied in a specific direction^[169] (**Figure 3b**).

Self-propulsion using chemical locomotion has become indispensable for miniaturized robots when swimming through aqueous solution (such as H_2O/H_2O_2 or acidic pH solutions). This type of locomotion often relies on catalytic reactions that generate gas bubbles. The recoil of these gas bubbles drives the tiny robot forward.^[18,74,75,145–148] Chemically propelled engines have undergone several developments concerning propulsion fuels and locomotion control.^[167,170–172] In these self-propelled chemical systems, the integration of on-board energy can be used to power other useful functions. Recently, a chemically self-propelling microjet twin engine was used as a flexible microsystem capable of controlled motion and actuation by wireless power transfer (WPT)^[39] (see **Figure 4a**).

Another way to achieve locomotion is via an electrical field through liquid environments. This propulsion mechanism consists of a diffuse electrical layer that is surrounded by a liquid. When an electrical field is applied between the electrical layer and the surrounding fluid, hydrodynamic pressure is created by the motion of ions in the field's direction.^[173] Such propulsion units could be beneficial especially when used in conjunction with other activation methods. The SEMRs relying on this method exploit a large surface area-to-volume ratio to increase propulsion power. An electronically integrated, mass-manufactured, microscopic robot using such a propulsion mechanism was recently demonstrated.^[40] The robotic system in **Figure 4b** integrates surface electrochemical actuators (SEAs) with on-board silicon photovoltaics (PVs) on a soft polymer platform. The surface oxidation of the platinum causes a sequential swelling of the SEA, allowing locomotion control of the robot. These SEMRs reach speeds up to $30 \mu\text{m s}^{-1}$ at a power consumption of 10 nW provided by on-board PVs illuminated by an external 1 mW laser.

2.2.2. Terrestrial

The forces acting on the system change as the robot starts to move on land. The influence of friction due to electrostatic attraction is dramatically increased.^[174] The most common locomotion modes on terrestrial surfaces at the small scale are crawling, rolling, and push/pull motion induced by an external physical field.^[175] To achieve motility, the SEMRs integrate piezoelectric materials,^[176–178] magnetic particles,^[178–180] or electroactive polymers^[42,52,53,181,182] as actuator components. The external field gradient generates the force for the motion. The SEMRs start to move when the applied external physical force overcomes the static sliding friction.^[174]

One way to achieve such motion is by developing a micropillar array that acts as the legs or feet of SEMRs, as shown in **Figure 5a,b**.^[37,121] These micropillar arrays lift the body from the ground, leading to smaller friction. This principle offers the SEMR higher degrees of locomotion freedom, lower power consumption, and an enhanced obstacle-crossing ability, thus allowing the system to adapt well in complex terrain. An external magnetic field deforms and aligns the SEMR feet into the magnetic field direction. This deformation generates the required pulling force to overcome friction, thus generating motion of the robot. Once the motion of SEMR is triggered, the applied force balances the kinetic friction and lets the system move with a uniform velocity. Such robotic platforms can integrate on-board electronics to control locomotion and sense the surrounding environment. The systems can conduct simple tasks such as cargo delivery and surveillance. More complex tasks would require electrical digital signal processing, and a magnetic field could well pose a roadblock on the way to achieve that.

A caterpillar-inspired robot driven by shape memory alloys is shown in **Figure 6a**.^[136] These systems were capable of integrating radio-controlled units and batteries that make them fully untethered and autonomous. The walking mechanisms of arthropods are still exemplary for designing soft robots.^[183–185] These animals maintain extreme robustness while showing

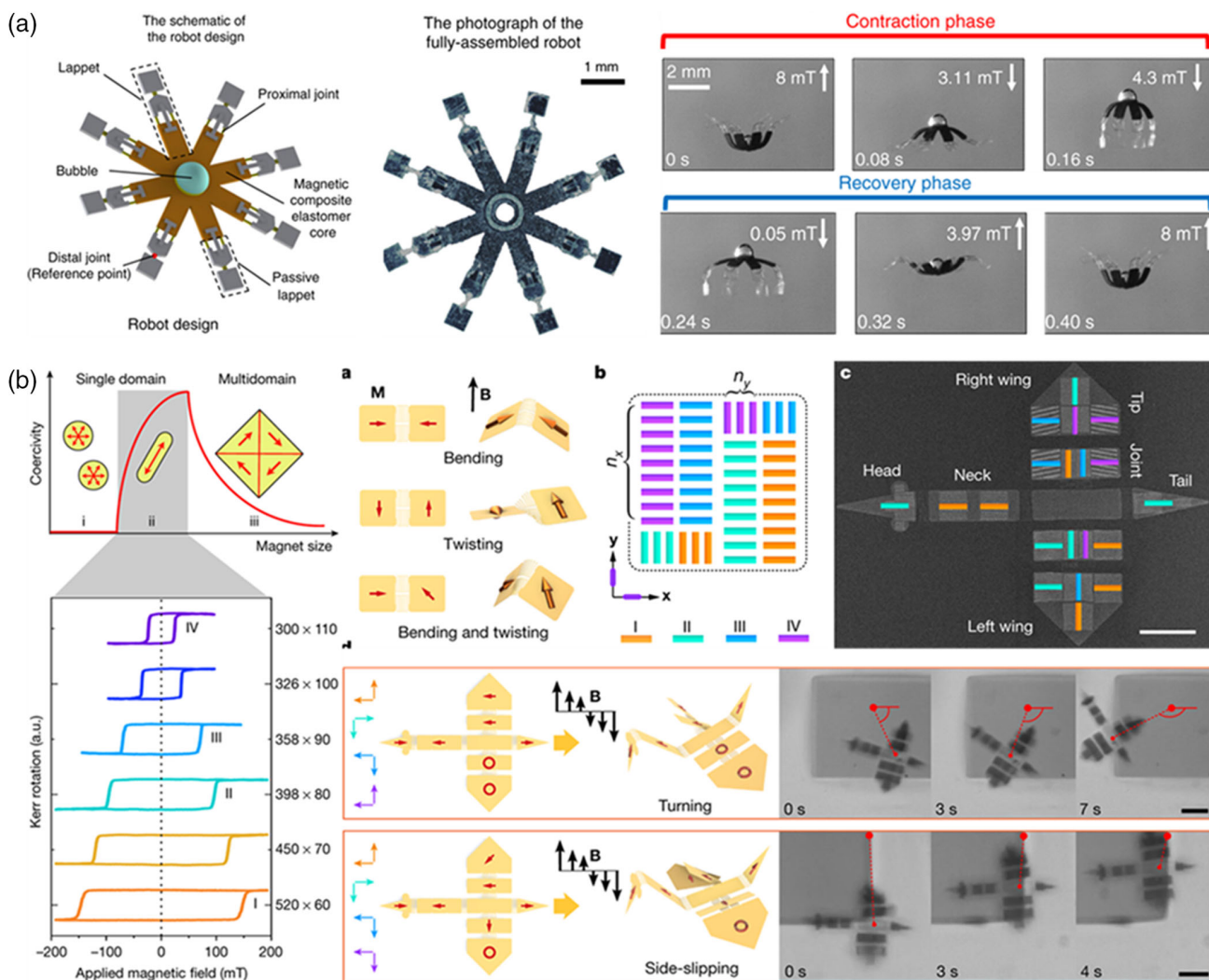


Figure 3. Soft aquatic miniaturized robots. a) Multifunctional soft jellyfish-like swimming robot. Schematic (top) and photograph (bottom) of fully assembled robot. Adapted with permission.^[168] Copyright 2019, Springer Nature. b) Schematic diagram of the magnetic states found in magnets with increasing size: i, superparamagnetic; ii, stable single domain at room temperature; and iii, multidomain state. The red arrows indicate possible magnetization directions. The red trace schematically illustrates the size dependence of the coercivity of the magnets. Nanomagnets in region ii (the shaded area) are implemented in this work (top left). Magneto-optical Kerr effect hysteresis loops of single-domain nanomagnets with the same volume but with six different aspect ratios. The lateral dimensions are indicated to the right of the vertical axis in nanometer. The coercive fields of the type I–IV nanomagnets are $B_{c(I)} \approx 140$ mT, $B_{c(II)} \approx 90$ mT, $B_{c(III)} \approx 70$ mT, and $B_{c(IV)} \approx 30$ mT (bottom left). Nanomagnetic-encoded shape-morphing micromachines conducting “flapping,” “hovering,” “turning,” and “side slipping” in liquid. Adapted with permission.^[169] Copyright 2019, Springer Nature.

high-frequency rapid cyclic locomotion.^[186,187] Biologically inspired, two anchor crawling locomotion can be used to move on surfaces.^[37] This kind of motion is achieved by creating low and high inertial forces. The change in forces is generated by a periodic lengthening and shortening of the robot’s body. The rapid contraction–extension cycles allow for a more efficient forward direction motion, as shown in Figure 5a and 6b. Such crawling-based movement can be implemented in SEMRs by the use of electroactive material. Controlled chemical reactions are an alternative approach to induce electronics-free motion of soft machines. An example of such a chemical reaction-based SEMR^[188] is a crawling hydrogel driven by a chemical self-oscillating response.

2.2.3. Aerial

Some of the aerial locomotion modes are the highest power-consuming ones, as the robotic system needs to lift its body weight and propel itself forward against gravity.^[189] The aerodynamic flapping and rotating wing design of insects form inspiration for flying SEMRs. The motion of aerial SEMRs includes gliding and soaring. For gliding-based locomotion, the mechanical systems are designed with an aerodynamic body, allowing them to stay aloft and glide efficiently through air without an engine. Gliding is an efficient way to move the SEMRs through air without the requirement of a power supply, as shown in Figure 7a.^[56] The volant SEMR uses a self-folding and shape-changing origami

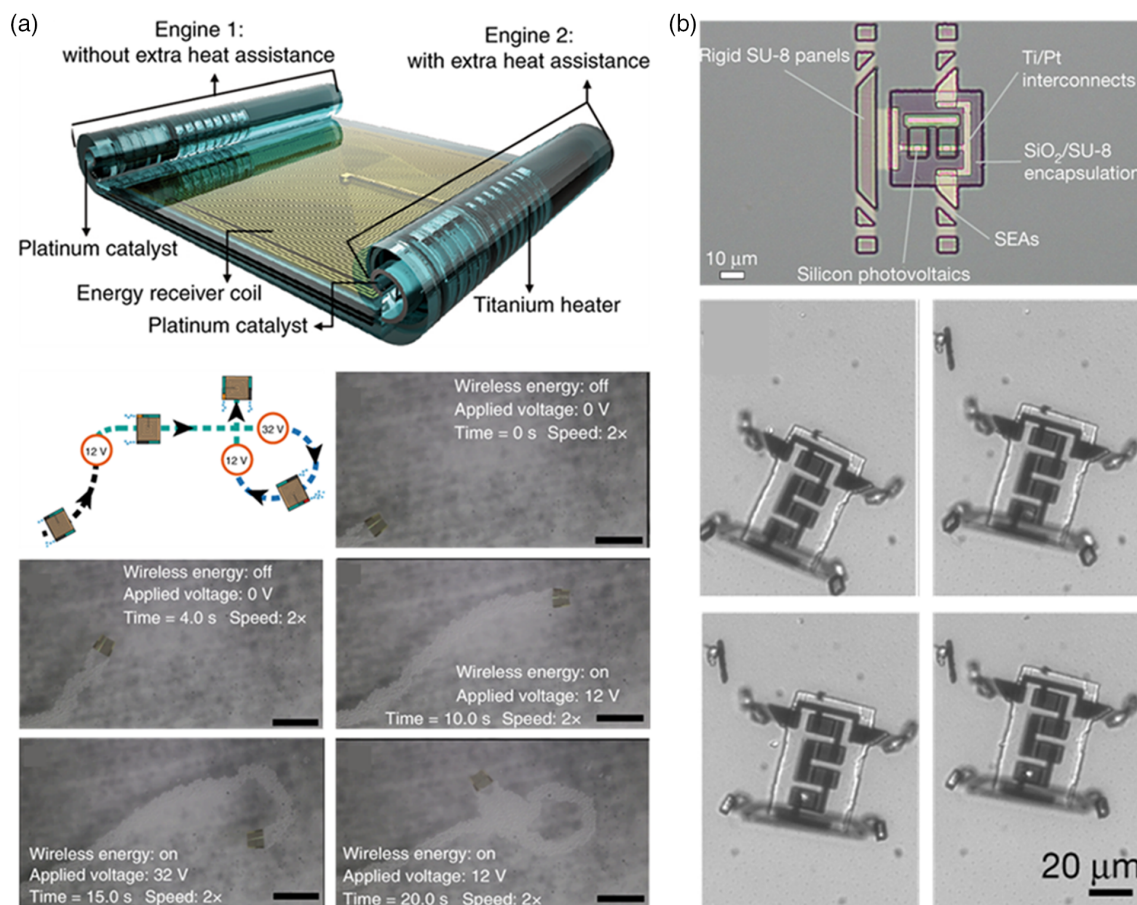


Figure 4. System-engineered miniaturized electronic robots moving in aqueous solution. a) Flexible twin jet-propelled microbot controlled by wireless power. Adapted with permission.^[39] Copyright 2020, Springer Nature. b) Laser-powered robot walking under water. Adapted with permission.^[40] Copyright 2020, Springer Nature.

“exoskeleton,” enclosing a permanent magnet to efficiently glide up to a distance of 112 cm through air. External magnetic fields were used to achieve locomotion direction control.

Active flight locomotion methods such as soaring rely on the aerodynamics of flapping at 30–1000 Hz and rotating wings similar to that of flies, bees, and moths. The rapid flapping motion generates a leading-edge vortex that creates the necessary lift to propel the SEMRs into air. In 2008, the first biologically inspired flapping-wing-based insect-robot was introduced.^[190] This SEMR integrates two carbon fiber-enhanced polyester wings that offer stable and robust motion. Flapping SEMRs have undergone many iterations, leading to the current untethered solar-powered RoboBee,^[24] as shown in Figure 7b. These flying SEMRs also mark a milestone in robotic systems operating in more than one environment (as shown in Figure 7b–d), bringing them closer to multipurpose applications, which are less dependent on a specific setting.

2.3. On-Board Sensing

Robots need extensive information about their environment to operate effectively. On-board sensors enable the SEMRs to

understand and respond to their environment. SEMRs need different sensing elements to become aware of displacement, strain, force, acceleration, chemicals, gas, flow, temperature, and humidity.^[7,19] The most common sensing methods for SEMRs are based on capacitive, piezoresistive, piezoelectric, and optical signals. Depending on the static and dynamic conditions, the sensing units should possess high linear/nonlinear sensitivity, nanoscale-to-picoscale resolution, wide dynamic range, bandwidth, low noise, low power consumption, and compatibility with the surrounding environment.

Sensor systems allow proprioception of robotic hardware, as shown in Figure 8a. However, SEMRs are currently actuated with open-loop control without sensor feedback, which is mainly due to the deformable characteristic of the soft body. Soft sensors have been the main focus of research in the fields of electronic skin and soft robotics providing feedback signals for controlling the robots.^[191–198] As conventional rigid sensor technologies can hardly be used, soft and shapeable substrates are taken as a platform to design and fabricate appropriate interfaces and sensors^[199–203] (see Figure 8b). The call for miniaturization has further complicated physical implementation of functional sensing units. Still, soft, and stretchable sensors have been enabled by embedding nanostructures into the material, such

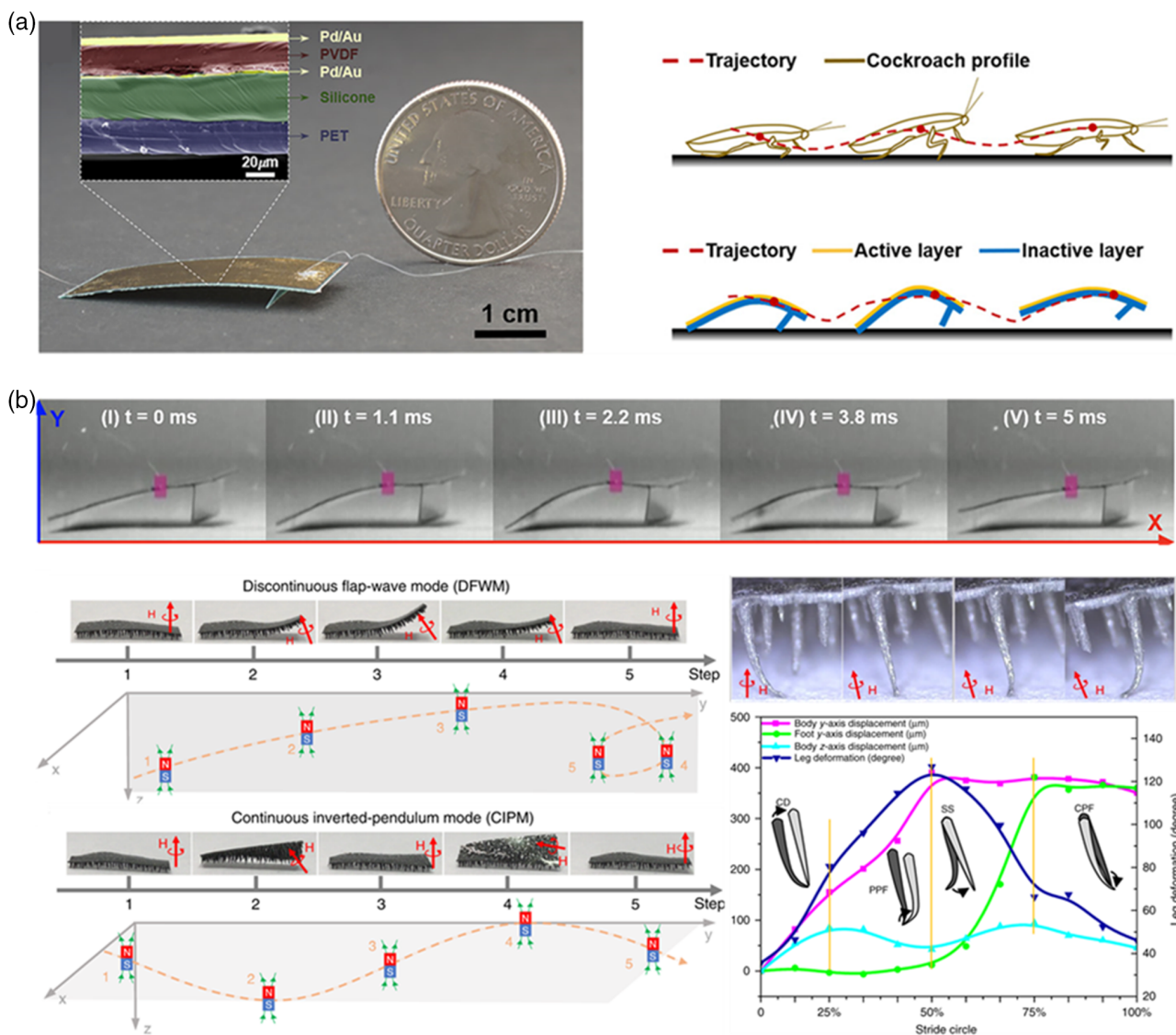


Figure 5. Soft land-dwelling miniaturized robots use legs. a) Insect-scale fast-moving soft robot. (top left) Optical photo of robot and scanning electron microscope (SEM) image of different layers of materials. (top right) Comparison of the wavelike running paths showing the movements of the centre of mass of a cockroach and the robot. (bottom) Series of optical images recording the movements of the robot in one driving cycle. Adapted with permission.^[37] Copyright 2019, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. b) Discontinuous flap-wave and continuous inverted-pendulum locomotion mode of multilegged magnetic soft robot. Adapted with permission.^[21] Copyright 2018, Springer Nature.

as nanowires, nanoparticles, and nanotubes,^[198,200,202] and using conventional sensing techniques like resistive and capacitive methods^[200–203] (see Figure 8c,d).

One strategy to obtain ultracompact sensors is to fabricate the sensing elements onto a shapeable soft platform. The shapable nature of the platform allows to self-assemble the sensing units into compact 3D geometries by micro-origami techniques.^[204] This enables the sensor to decode 3D vector fields^[205] or measure and sense biological and chemical samples in small quantities.^[206,207] “Swiss-roll” 3D architectures are interesting candidates for satisfying the sensing demands of SEMRs as the “swiss-roll” can serve as a microchannel that allows sampling

of materials which pass through freely.^[208] By integrating electrodes on the inner walls of such channels, the radial mapping of optical^[209] and electric fields has been realized,^[210] leading to highly sensitive detectors that have already been applied for spectroscopy of biological liquid and single cells.^[208–210]

“Swiss-roll” 3D architectures with a stimuli-responsive function based on volume expansion are particularly well suited as sensory-actuators. For instance, the strain induced during hydrogen absorption and desorption reduces the diameter of a “swiss-roll,” as demonstrated in the study by Xu et al.^[211] Wide-angle optical sensing and signal detection are unique

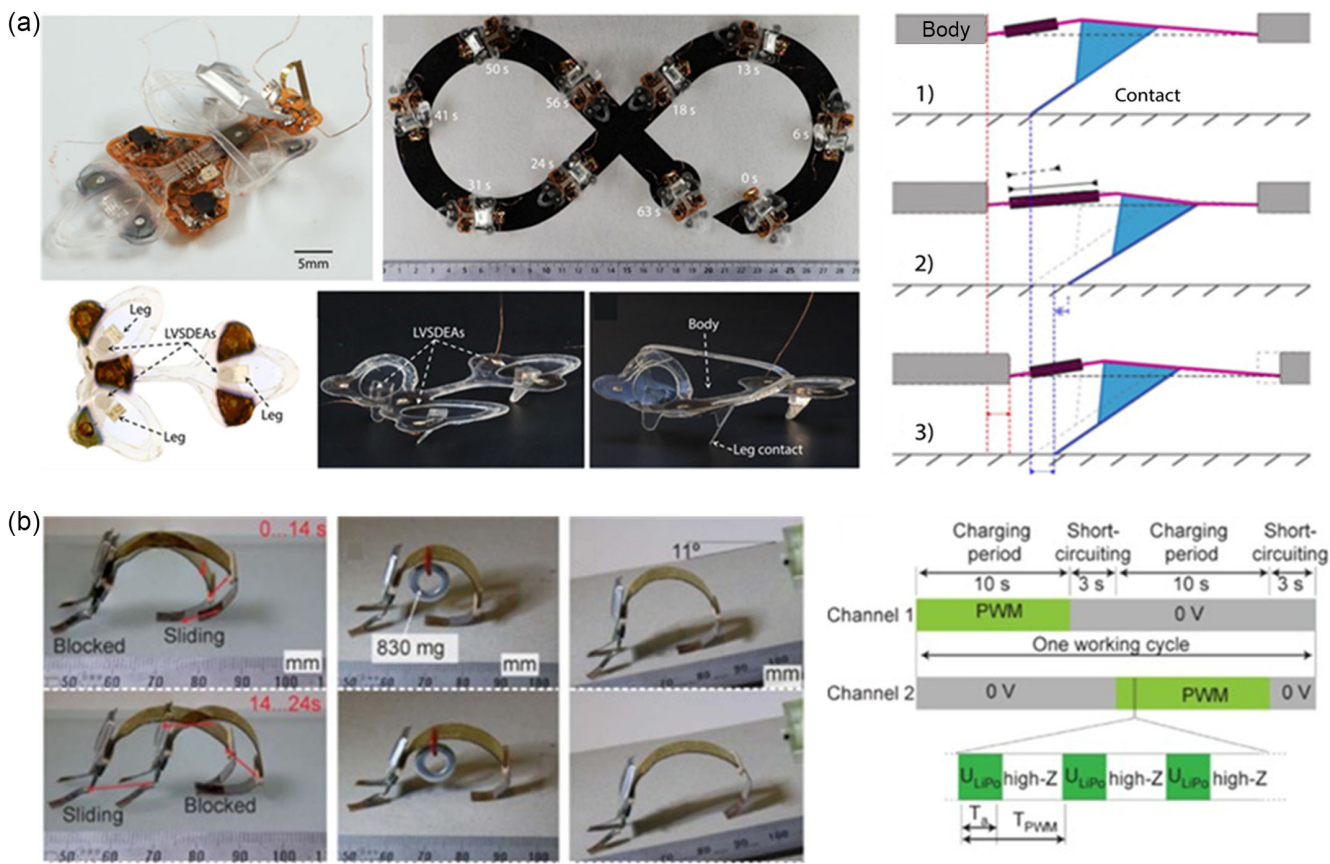


Figure 6. Soft land-dwelling miniaturized electronic robots. a) Photo of an autonomous untethered robot driven by three low-voltage stacked dielectric elastomer actuators (LVSDEAs) carrying control and power elements, with a total mass of 970 mg. (top left) Snapshots of the untethered dielectric elastomer actuators (DEA) insect autonomously navigating along the path and automatically stopping at the end of the path. Ruler scale is in centimetres. The total elapsed time is 63 s (top right). (bottom) Soft robot using three LVSDEAs to operate three independent legs based on asymmetrical friction drive. (bottom right) Top view: Photo of flat (as-fabricated) DEAnsect robot. (bottom middle) Side-view photo of flat DEAnsect robot. (bottom left) Side view of deformed DEAnsect with the body held in bent shape using tape. The load capacity of the deformed DEAnsect is increased by the enhanced stiffness. The DEAnsect is fully mobile in both flat and deformed configurations. (right) Simplified schematics of robot leg-body motion. When the LVSDEA expands, the leg is pushed forward. When the LVSDEA contracts, the leg remains nearly static due to directional friction, and the robot body moves forward. Adapted with permission.^[38] Copyright 2019, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. b) Locomotion of a squirming robot compared with an inchworm (left) and control waveform for one working cycle of the robot (right). Adapted with permission.^[136] Copyright 2014, Wiley-VCH GmbH.

advantages of self-assembled 3D structures.^[212] 3D cylindrical infrared photodetectors provide an efficient route for light coupling, demonstrate enhanced responsivity, and are able to sense the direction, intensity, and angular divergence of the incident light^[212,213] (see Figure 8e,f).

2.4. On-Board Actuation

Deformable actuators are essential building blocks for SEMRs. For instance, the McKibben actuator developed in the early days uses air compression and control units that boast a high strength-to-weight ratio.^[214,215] The demand for such actuators in soft and rigid robots at the small scale has triggered rapid development in materials science to produce many new actuation mechanisms that respond to a variety of stimuli, for example, light, heat,

electrical, and magnetic fields.^[27–36,157–167,216–218] A wide range of polymer materials can be used for small-scale actuation. They can be classified into three main categories: magnetic, thermal, and electroactive polymer actuators. Magnetic micro-/nanoparticles can be embedded in the material^[219] or magnetic thin films can be coated on various polymer materials^[220] for actuation with remote magnetic field gradients. Such a soft magnetic polymer actuation concept has significant potential for complex, dynamic, and remote SEMR actuation. Shape memory polymers and other temperature-sensitive polymers can be heated locally using photothermal or electrical Joule heating methods to create actuation.^[39,218] The materials for the development of soft actuators can be categorized into PDMS or related elastomers, hydrogels, photoresponsive polymers, and ionic polymers.^[27–36,157–167,216–218]

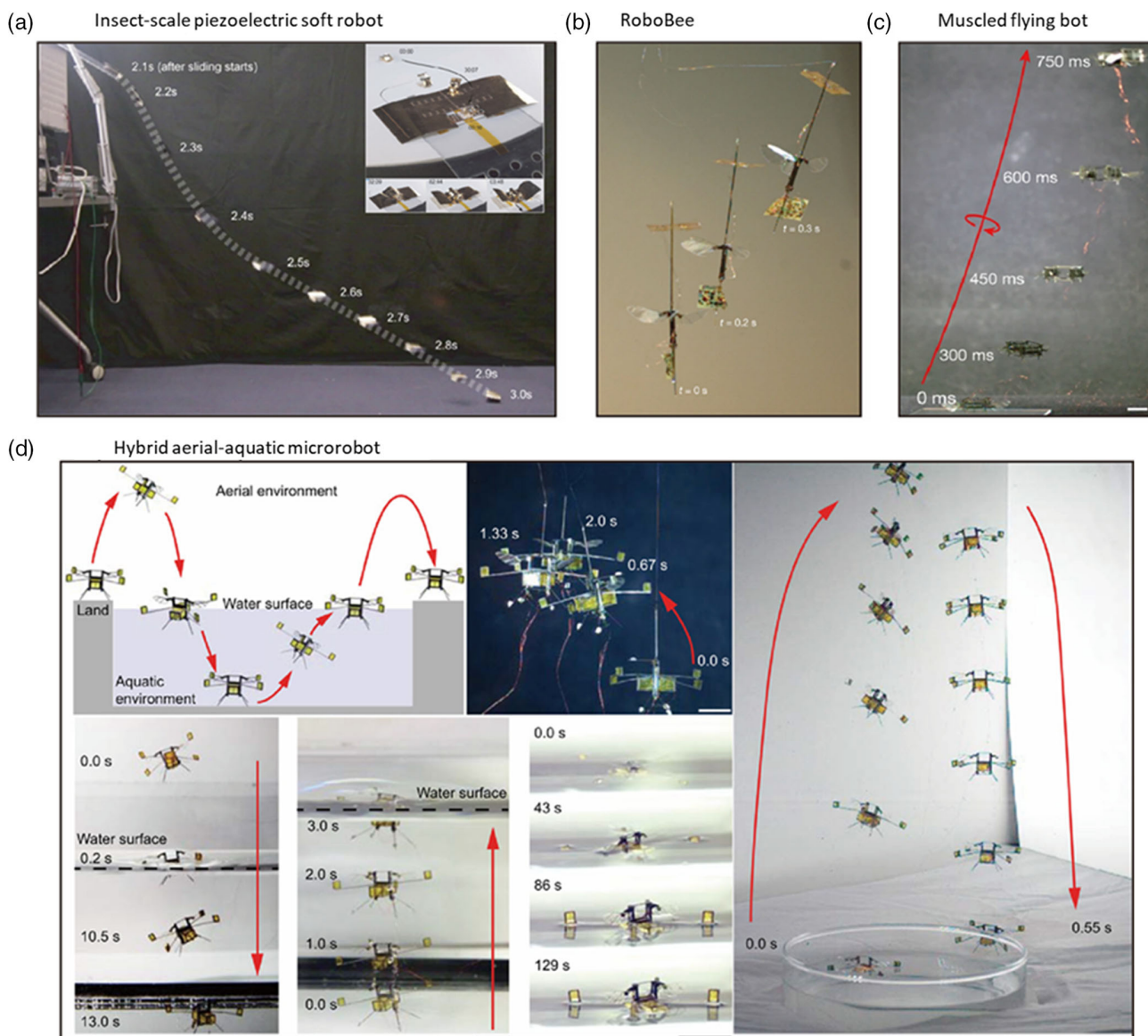


Figure 7. Volant miniaturized robots. a) Origami walk bot with gliding capability. Adapted with permission.^[56] Copyright 2017, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. b) X-wing RoboBee performing sustained untethered flight. Adapted with permission.^[24] Copyright 2019, Springer Nature. c) Composite images of a 16 s-controlled hovering flight that is demonstrated by a 660 mg robot driven by four DEAs. Adapted with permission.^[25] Copyright 2019, Springer Nature. d) Demonstration of aerial–aquatic locomotion. Adapted with permission.^[287] Copyright 2017, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science.

2.4.1. PDMS-Based Actuators

In the past decade, research efforts have focused on tailoring miniaturized soft actuators for efficient microscale actuation. By now, nanoscale accuracy is possible by pneumatically actuated elastomers using proper control mechanisms.^[221] The combination of PDMS-based microfluidic structures and electrochemical effects, such as electrolysis, stands out to be efficient in soft activation.^[222,223] The pneumatic force, resulting from gas bubble inflation, has been directly exploited to induce actuation response by an increase in volume of the confinement chambers.^[222–224] The volumetric actuation technique can be

used by any other volume-changing material or device such as microspheres made of magnetically responsive elastomer/nanoparticle composites.^[225,226] As demonstrated in a series of reports,^[226–228] quick-release actuation can be achieved by the hybridization of elastomeric structures with silicon-based rigid MEMS. The PDMS portion of the actuators functioned as a rubber string causing jumping action of the SEMRs.^[228]

2.4.2. Hydrogel-Based Actuators

Hydrogels have attracted great interest in the field of soft robotics as biomimetic and programmable actuator structures.^[229]

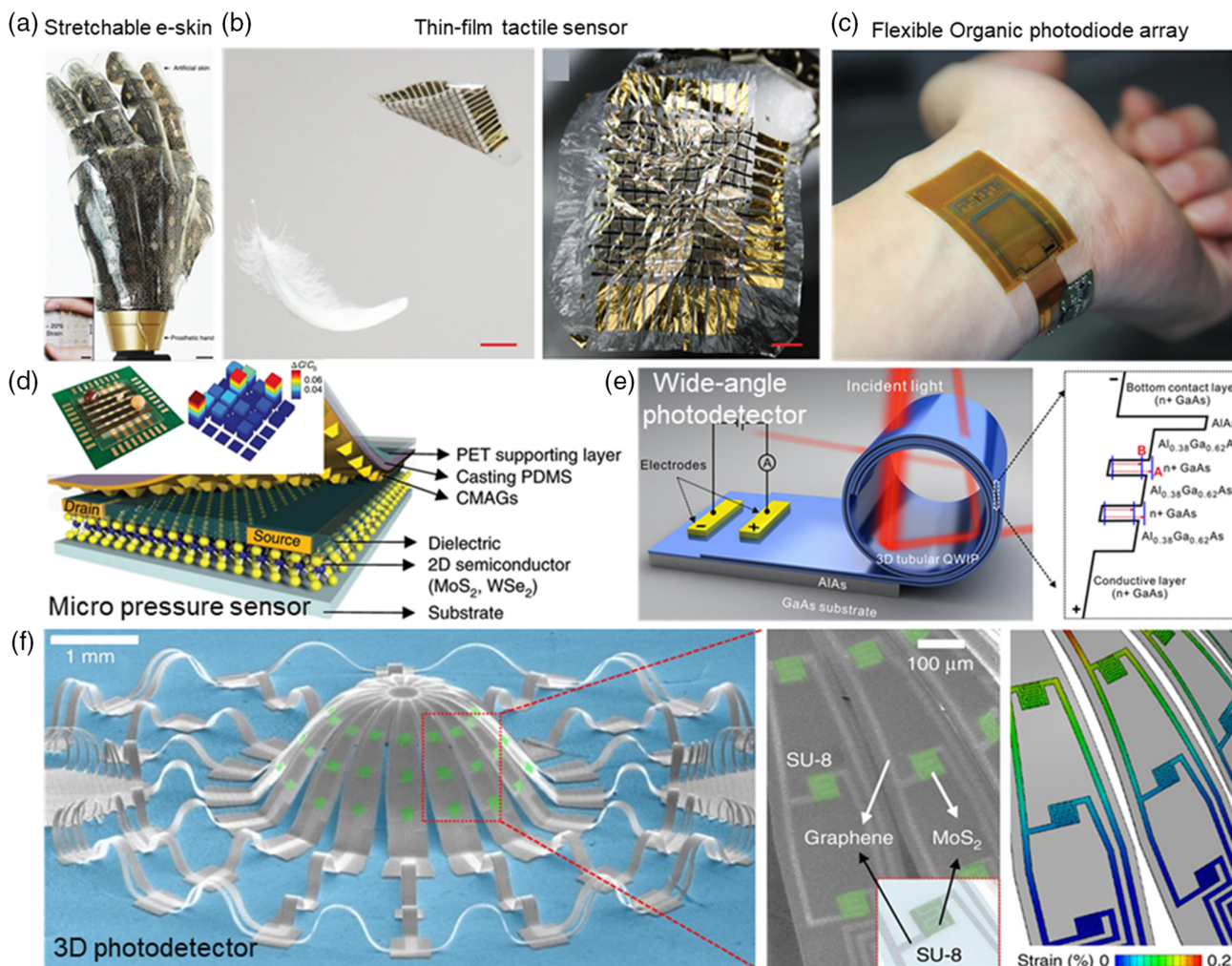


Figure 8. Soft compact sensing for SEMRs. a) Mechanical prosthesis with stretchable electronic skin. Adapted with permission.^[192] Copyright 2014, Springer Nature. b) Schematics and photograph of imperceptible organic electronics equipped with tactile active sensor matrix. Adapted with permission.^[201] Copyright 2013, Springer Nature. c) Low-temperature polycrystalline silicon (LTPS) thin film transistors (TFTs) and near infra-red (NIR) organic photodiode attached to a wrist. Adapted with permission.^[199] Copyright 2020, Springer Nature. d) Flexible conductive micro-structured air gaps (CMAG) capacitor-based pressure sensors for static pressure mapping and real-time wave monitoring of the radial artery. Adapted with permission.^[202] Copyright 2020, Springer Nature. e) Schematic diagram of a 3D microtubular wide-angle infrared photodetector and conduction band diagram. Adapted with permission.^[212] Copyright 2016, The Authors, published by American Association for the Advancement of Science. f) 2D materials in functional 3D architectures. (middle) Array of devices fabricated in parallel on a chip. (right) Colorized SEM image of 3D MoS₂ photodetector consisting of MoS₂ (green), graphene (light gray), and SU-8 (gray) on the hemisphere with 3D interconnects and finite-element analysis results for strain distribution. Inset: Schematic illustration of a single device unit enclosed by the red box in the main image. Adapted with permission.^[213] Copyright 2018, Springer Nature.

Their applications have recently expanded into simple tubular aquabots^[170] and microgrippers,^[230,231] as shown in **Figure 9a**, for intravascular use. To keep pace with further miniaturization, challenges in small-scale patterning and shaping have to be addressed. PNIPAM, a biodegradable thermoresponsive polymer that possesses reversible deformation properties, was used to create temperature-controlled self-folding/unfolding microtubes and microjet engines.^[170,232] Recently, a full polymeric platform was created that bridges two microjet engines and provides the possibility to construct SEMRs with reconfigurable components, such as actuators, by integrating soft stimuli-responsive microarms (Figure 9b).^[39] A PNIPAM layer, Fe/Au layers, and an SU-8

layer form the microarm in these SEMRs. The integration of magnetic material allows for local induction heating to remotely tune the temperature of the PNIPAM area and use the microarms as gripping tools.

2.4.3. Ionic Polymer-Based Actuators

Morphological changes and mechanical motion in ionic polymers that respond to electric fields through the migration of ions are of great interest to SEMRs. In addition to light weight and flexibility, they also offer mechanical robustness.^[216–218,233] Electrically active polymer (EAP) actuators can contract or expand

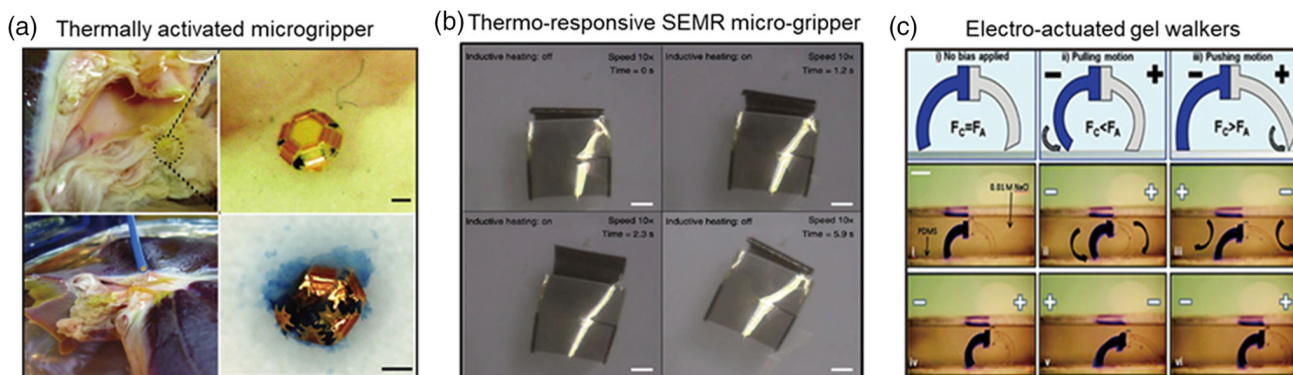


Figure 9. On-board soft actuators. a) Untethered microgrippers on the bile duct opening of the porcine liver. Adapted with permission.^[118] Copyright 2013, Wiley-VCH GmbH. b) Expandable and soft microarm grabber on a soft microrobot controlled by remote but local inductive heating. Microscope images show the microarm opening and closing. Adapted with permission.^[39] Copyright 2020, Springer Nature. c) Electroactuated hydrogel walkers with dual-responsive legs in ionic solution. Adapted with permission.^[188] Copyright 2014, Royal Society of Chemistry.

in response to electric energy and are the most common polymer actuators for SEMRs, as shown in Figure 9c.^[188] EAPs consist of two main subgroups: ionic and electronic EAPs. Ionic EAPs, such as conductive polymers, ionic polymer–metal composites, and ionic gel actuators, involve mobility or diffusion of ions (mass transport), are typically wet, require low driving voltage (1–10 V), and yield large displacements but produce low forces.^[233] Electronic EAPs, such as dielectric elastomers,^[234] electrostrictive polymers,^[235] electro-viscoelastic elastomers,^[236] ferroelectric polymers,^[237] and liquid crystal elastomers,^[238] are typically dry and driven by electric field or Coulomb forces.^[233] Overall, polymer microactuators can operate in salt solutions, blood plasma, urine, and cell culture media,^[239] producing considerable strain and energy density at low voltages, making them attractive for biomedical and soft miniaturized robot applications.

To enable the next generation of SEMRs with active proprioception, they must be integrated with actuators capable of closed-loop feedback control. The dynamic closed-loop feedback control allows the SEMRs to interact with the environment actively. One possible way to achieve functional proprioception is by combining electroactive polymer actuators with reshapeable smart electronic sensors. The on-board sensor signals can be used to attain closed-loop feedback control of the actuators. Demonstration of such a closed-loop feedback control actuator was done by integrating electroactive ionic–polymer with flexible microelectronic strain and magnetic sensors.^[240] The integrated sensors enable active feedback control, compensate for varying operating conditions, and improve positioning by sending the sensor data to an off-board proportional-integral-derivative (PID) controller. Such control allows dynamic interfacing with the environment such as controlled grasping and release of biological tissues.

2.5. On-Board Energy

Many current start-of-the-art SEMRs mentioned in the earlier sections (especially terrestrial and aerial) use tethered power for locomotion and on-board functions. Next-generation

SEMRs would therefore greatly benefit from on-demand on-board energy supply^[18,19] to facilitate their autarkic operation. Thus, future research in the field of SEMRs is directed toward full autonomy and energy self-sufficiency. Harvesting ambient energy to power on-board functionalities becomes a crucial challenge.^[46] As the performance of power sources such as electrochemical batteries scales with volume and they are difficult to integrate at the microscale, SEMRs are commonly driven by off-board energy supplies. However, the development of on-board power-harvesting and storage systems has seen steady growth, leading to the development of novel technologies. Energy can be harvested by WPT, PV, and thermal and mechanical vibrations.

2.5.1. On-Board Energy Storage

Although impressive results have been achieved in the field of energy-storage platforms, the fabrication of high-performance energy-storage units at the microscale remains a challenge.^[46] Microscale ion batteries and supercapacitors are the primary energy-storage devices.^[241–243] One efficient way to miniaturize energy-storage elements is the use of rolled-up nanomembranes. Active layers of batteries or supercapacitors are deposited on prestrained nanomembranes, which in turn are deposited on a sacrificial layer on a substrate surface. Once the sacrificial layer is selectively etched away, the strained layer system (including the energy-storage layers) snaps back and self-assembles into a compact tubular energy-storage device (shown in Figure 10a–c).^[46] The use of large active surfaces for electrochemical reactions, shortened paths for fast ion diffusion, and easy fabrication makes these devices well suited for microdevice applications. Microsupercapacitors and microbatteries serve different roles in SEMRs. Microsupercapacitors are used for mid-term energy-storage requirements with a fast release of energy, whereas microbatteries are suited for long-term energy storage at higher energy densities. A microtubular methanol fuel cell was fabricated with Ru₂O layers coated with Pt nanoparticles (Figure 10b).^[244] These tubular fuel cells have an ultras-small footprint area of $1.5 \times 10^{-4} \text{ cm}^2$ with a high power density of

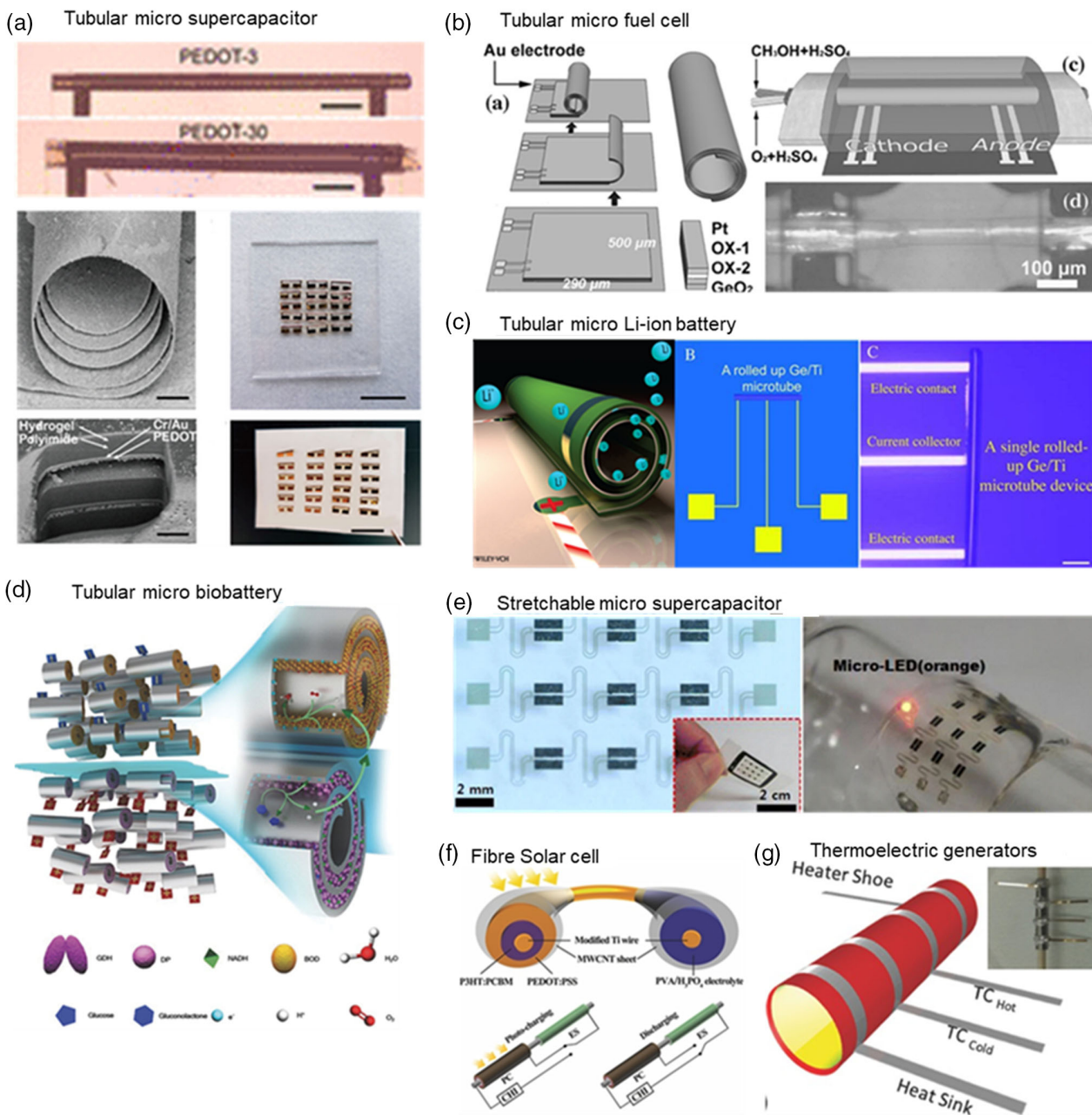


Figure 10. Compact energy systems for soft miniaturized robots. a) Self-assembled tubular microsupercapacitors. (left) SEM image. (right) Array of freestanding supercapacitors on glass and paper. Adapted with permission.^[288] Copyright 2019, American Chemical Society. b) Schematic diagram of a Pt(RuO₂) tubular fuel cell fabricated with the prestrained bilayers of RuO₂ and Pt-cat nano particles deposited on the sacrificial layer (GeO₂). (right bottom) Optical photographic image of a fluidic cell. Adapted with permission.^[244] Copyright 2017, Wiley-VCH GmbH. c) Schematic illustration of a rolled-up lithium-ion microbattery. Adapted with permission. Copyright 2013, Wiley-VCH GmbH. d) Artistic rendering of an enzymatic biobattery. Adapted with permission.^[245] Copyright 2018, Wiley-VCH GmbH. e) Stretchable 2D planar microsupercapacitor array on PDMS substrate without electrolyte. Adapted with permission.^[246] Copyright 2013, American Chemical Society. f) (top) Schematic illustration of an all-solid-state, coaxial, and integrated fiber device. The left and right sections correspond to the photocell and electrical storage parts, respectively. (bottom) Schematic diagram of the circuit during charging. Adapted with permission.^[250] Copyright 2013, Wiley-VCH GmbH. g) Schematic of a self-rolled tube with four contact probes (two for the heater shoe and heat sink and the remaining two for hot and cold thermocouples, respectively). The inset shows the optical image of the rolled tube with four contacts. Adapted with permission.^[252] Copyright 2017, Wiley-VCH GmbH.

257 mW cm⁻². When compared with conventional micrometer-sized methanol fuel cells, the tubular fuel cells show three orders of magnitude increase in performance. Another example

of a tubular electrochemical energy-storage device is a glucose biobattery.^[245] The enzymatic biocatalysts of glucose in a biobattery based on immobilized diaphorase and bilirubin oxidase

enable them to deliver a power density of 3.7 mW cm^{-2} and a stable output power of 0.8 mW cm^{-2} . (Figure 10d). Recently, a stretchable microsupercapacitor array based on all-solid-state materials was demonstrated.^[246] As shown in Figure 10e, the microsupercapacitor array adopted two strategic design concepts of long and narrow serpentine interconnections in a mechanical neutral plane. The spray-coated carbon nanotubes (CNTs) as electrodes and the ionic liquid-based triblock copolymer electrolyte enable the microsupercapacitors to show capacitances of $\approx 100 \mu\text{F}$ with a stable performance under stretching and compression of over 30% of the original length. Microenergy-storage devices are crucial to achieve full autonomous and energy-self-sufficient SEMRs. However, critical challenges remain: the miniaturization of ESSs limits the effective area/volume available for 3D energy storage causing an overall capacity decay. The charge leakage commonly encountered due to the short channels in current microscale ESSs has to be addressed.

2.5.2. On-Board Energy Harvesting

Electrical power can be supplied wirelessly to overcome the limitations of ESSs. Energy can be scavenged from the SEMR operational environment. For example, incident light,^[247] temperature gradients,^[248] and mechanical vibrations^[249] in the environment can be harvested to create electrical energy on-board of the SEMRs. In recent years, macroscale energy-harvesting systems have delivered impressive results, achieving about 1% conversion efficiency in a solid-state, coaxial, and self-powered energy fiber (Figure 10f).^[250] A thermoelectric generator using rolled-up microtubes was also demonstrated

(Figure 10g).^[251,252] The rolled-up tubes in these thermoelectric generators are of lightweight and occupy an ultrasmall area when compared with planar devices. The tubular thermoelectric generator can separate hot and cold ends along the tube axis and can maintain temperature gradients. Although the amount of harvested energy is small, the tubular generators could be used to power sensor systems and simple on-board electronics.

WPT: Monolithically integrated on-board microcoils with a diameter $< 1 \text{ mm}$ have been used to harvest electromagnetic energy wirelessly by inductive coupling. A transmitting coil drives these systems at a matched resonant frequency using radio frequency (RF) power transfer.^[39] The use of inductively coupled coils with an efficiency of 40% has enabled the transfer of tens of watt power over distances of several meters.^[253] However, short-distance applications of WPT technologies started only in the past 8 years.^[254] Using a receiver coil in the range of several mm and a high-Q transmitting circuit, several milliwatts of power could be delivered to drive electrostatic actuators.^[255] Only recently, the WPT technology was miniaturized to submillimeter to power a flexible microsystem capable of controlled motion and actuation (Figure 11a).^[39] The on-board, 55-winding “zero-pitch” receiver coil has a series inductance of $1.39 \mu\text{H}$ and was able to receive wireless power with a maximum efficiency of 40%. The received energy was used to locally heat the catalytic engines, resulting in active remote steering control. The on-board energy was also used to power miniaturized electronic devices such as an infrared light-emitting diode.

Optical Power Transfer (OPT): OPT uses PV cells to gather light radiation from ambient light or focused laser beams and converts it into electrical energy. The use of a 1 mW laser beam focused onto on-board PV cells to power electronically integrated,

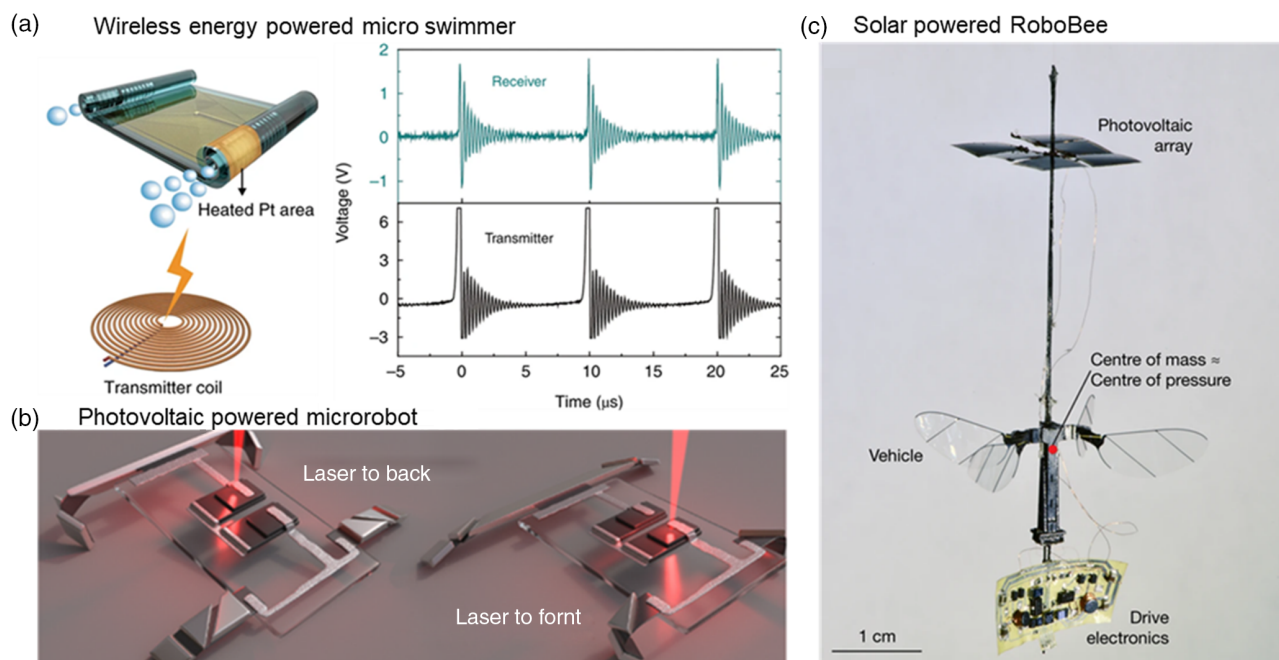


Figure 11. SEMRs powered by on-board energy. a) Schematic of a wirelessly controlled twin jet-powered microelectronic robot. Adapted with permission.^[39] Copyright 2020, Springer Nature. b) Schematic illustration of the laser-powered microscopic robot. Adapted with permission.^[40] Copyright 2020, Springer Nature. c) Untethered flapping-wing microscale aerial vehicle integrating solar cells for energy harvesting. Adapted with permission.^[25] Copyright 2019, Springer Nature.

mass-manufactured SEMRs was recently demonstrated.^[40] The fabrication of the SEMR combined a p-type wafer with standard doping, lithography, and metallization processes to create on-board circuitry of the robot. The on-board circuit consists of two PV cells $10\ \mu\text{m} \times 20\ \mu\text{m}$ in size (Figure 11b). The cells were illuminated by laser pulse at 785 nm with an intensity of $1\ \text{mW}\ \mu\text{m}^{-2}$ and generated an open voltage of 0.7 V and a short current of $2.5\ \mu\text{A}$. This on-board power was able to drive voltage-controllable electrochemical actuators at low 200 μV consuming only 10 nW. Another example is a 9.2 mm-wide and 60 mm-long cylindrical in-pipe inspection SEMR, that integrates 63 amorphous silicon PV cells connected in series at its back end.^[256] Laser light with a power of 1 mW at 532 nm was focused on the robot to generate 101 V and 88 μA electrical power. The generated energy was used to power on-board voltage-stabilizing circuits to drive a MEMS electrostatic actuator. However, laser light is of limited use for autonomous applications in the human body or other vulnerable biological organisms.

Another way to use OPT is via solar cells. Solar cells are well-understood power sources used to gather sunlight radiation and convert it into an electrical potential. Although the cells have limited power density and low voltage output, MEMS solar cells can be fabricated in arrays to generate tens of volts with μA -level current. Commercial solar cells are usually made from silicon (Si), gallium arsenide (GaAs), and amorphous silicon (a-Si) and perform at an efficiency of 30%,^[257] 29%,^[258] and 10.8%,^[259] respectively. Solar cells were used to create a RoboBee,^[26] including a pair of wings and piezoelectric actuators. The bee spans across a length of 5 cm, weighs 259 mg, and integrates the solar cells at the top and the drive-electronics at the bottom. The on-board electronics helps to boost the generated voltage to 200 V, which is used to drive the on-board actuators that flap the wings at 200 Hz. The RoboBee (Figure 11c) is capable of untethered flight for a period of 1 s.

2.6. Embedded On-Board Intelligence

Real-world applications of SEMRs are likely to be achieved when the system can integrate functionalities such as sensing, actuation, computation, power storage, and communication with on-board processing units. Possible solutions for embedded intelligence are currently under discussion.^[260] One promising way is the development of a processing system as the central control unit using integrated microelectronics. Conventional silicon microelectronics can create small and high-density devices but due to harsh fabrication conditions (e.g., temperature budget up to 1000 °C) is incompatible to the fabrication requirements of soft materials. The quest for embedded soft on-board intelligence for SEMRs could profit from the development of flexible devices, circuits, and systems.^[261–264] However, until recently, flexible processing engines were not powerful enough to run algorithms to achieve practical SEMR tasks. Thus, a new generation of on-chip computational capabilities that allow collection, transition, and processing of data on tiny flexible and soft substrates is highly sought after.^[261]

The challenges associated with building flexible processor units are well known. One strategy is to thin the silicon chip down to a few micrometers and combine conventional silicon-

based CMOS technology with flexible integrated circuits.^[262] However, the above strategy complicates the packaging process leading to reduced flexibility of the processors. Another strategy is to find alternative semiconductive materials to replace silicon by flexible substrates. Recently, a domain-specific processing engine using commercial 0.8 μm metal-oxide thin-film transistor technology integrated 2084 field-effect transistors (FETs) and 1048 resistors over an area of around $5.6\ \text{mm}^2$.^[265] The high-density integration enabled the researchers to directly implement a machine-learning algorithm into the hardware. The $183\ \text{mm}^{-2}$ gate density of the flexible processing engine was used to collect data from several gas sensors, allowing the microsystem to differentiate between various odors. This work shows high integration potential with SEMR technologies and opens up various application scenarios in areas such as mobile healthcare, food technology, and the internet-of-things.^[265–268] Thus far, the limitation in this metal-oxide thin-film transistor process is that only n-type FETs and resistors are available, leading to more complicated layouts than, for instance, required by Si-based CMOS design. Metal-oxide thin-film materials that can provide an alternative to p-type Si would be critical to develop compact flexible on-board electronics to create environmental awareness.^[269,270]

3. Conclusion and Outlook

The integration of soft materials and structures into robotic systems is crucial to increase the adaptability and robustness of these systems in challenging environments. Multidisciplinary research will drive robotic applications into various scenarios that include biomedical services, inspection, search and rescue, and exploration. Crossdisciplinary research in materials science, biology, neuroscience, robotics, and computer science is needed to advance SEMR technologies. Despite all efforts and a plethora of available soft materials and smart technologies, a fully autonomous SEMR of any practical relevance has not been developed yet. A careful examination of currently existing SEMRs shows that they fall short in many ways concerning miniaturization, full-scale integration, and self-sufficiency. To qualify as a true SEMR, the robot must maneuver and conduct given tasks autonomously in an untethered and reliable fashion. Some of these issues have been identified in this Review, and some are inevitably yet to be explored. The aim in the near future would be to produce smarter SEMRs with environmental awareness and the ability to communicate with each other, like, for instance, biological cells.

Currently, there is a big gap between simple microscopic motors and millimeter-sized robotic systems. The former category has very limited functionality,^[271–273] and the latter is too modular to be easily downscaled in size.^[274–277] The two recent examples, which we have discussed in Section 2.5.2, are exciting exceptions in the field. They embed structure and function into a single SEMR by monolithic integration technologies. To create more sophisticated SEMRs, these approaches should be further refined to provide dynamic physicality, awareness, and multifunctionality. However, seamless integration is challenging as design and fabrication processes have to be adapted to novel soft and flexible materials, so that increasingly more components can be integrated and miniaturized into a single heterogeneously embedded

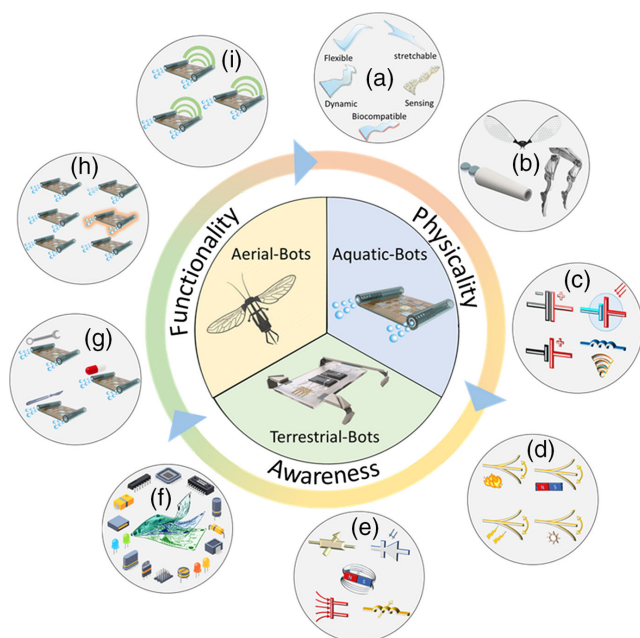


Figure 12. Next-generation SEMR systems need dynamic physicality, awareness, and functionality—all integrated into a compact shell or structure. Aerial-bots: Adapted with permission.^[291] Copyright 2012, Opensource.com. Terrestrial-bots: Adapted with permission.^[40] Copyright 2020, Springer Nature. Next-generation SEMRs should a) achieve dynamic physicality by a flexible, soft, and dynamic body, b) integrate active propulsion units that allow for active locomotion control, c) on-board dynamic energy harvesting and storage, d) on-board actuation components to conduct tasks, e) achieve dynamic awareness by on-board active sensor arrays, and f) embedded on-board intelligence. Integration of all the earlier components would allow the SEMRs to have advanced functionalities such as g) cooperative functional operation, h) single robot control in a swarm, and i) active tracking and communication.

robotic system (for illustrations, see **Figure 12**). However, efforts could be rewarding as millions of SEMRs can be produced in parallel on a single chip so that, once released from the surface, they can finally act autonomously in large swarms, communicating and intelligently completing collaborative tasks.

On the roadmap to achieving these goals, research needs to be focused on addressing and overcoming a few challenges concerning propulsion, sensing, and powering SEMRs. For instance, current state-of-the-art microswimmer systems (MSs) are typically propelled by chemical reactions or remotely actuated by physical fields (such as magnetic, optical or acoustic). A popular way to control and guide the locomotion of MSs is to integrate magnetic materials into the swimmer's microstructure and apply global external magnetic fields.^[278–280] However, a significant drawback is that this technique cannot easily address individual MSs selectively in a swarm. The next generation of aquatic SEMR systems should therefore be equipped with advanced electronics and integrated circuitry to provide complete motion control and tractability at a single SEMR level to conduct several different tasks simultaneously. The propulsion should be biocompatible, and the MSs should be equipped with feedback-controlled flexible sensors and actuators.^[240] The propelling force could

be generated by the production of H₂ and O₂ bubbles (absorbed by the human body) expelled from microelectrochemical engines (μ -ECEs) via on-board electrolysis of water.^[281,282] The water splitting in these μ -ECEs occurs via the oxygen evolution reaction (OER) and the hydrogen evolution reaction (HER) when a potential (> 1.28 V) is applied between the HER and OER electrodes. Locomotion control could be achieved by wireless commands sent to a locomotive integrated circuit to modulate the electrolysis of on-board μ -ECEs.^[281] The MS uses water, a globally available fluid for propulsion, which makes the MS well suited for operation in multiple environments ranging from biofluids to open waters.

Research should be dedicated to equip SEMRs with active proprioception. Dynamic closed-loop feedback control would allow SEMRs to interact with the environment actively. To facilitate proprioception, SEMRs must be able to sense the 3D environment. Thus, research should be focused on developing novel 3D vector sensors^[205] with high spatial resolution and low power consumption. For this purpose, 3D self-assembled micro-origami microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) architectures^[283] could be developed and integrated into SEMRs. The self-assembly process transforms 2D sensor layers into 3D objects, distributing the sensing pixels over the 3D surface. Miniaturized 3D sensor systems such as those incorporating optical,^[212,213] electrical, and magnetic^[205] components would be able to count and track microparticles, supramolecular structures, or DNA that enter the vicinity of the SEMR. Moreover, the 3D architecture would be able to map the 3D environment, providing the SEMR with a sense of its own location and orientation.

Current SEMRs have no energy on-board and lack any continuous feedback-controlled sensing, actuation, data processing, and communication. Only recent developments have demonstrated slightly more advanced SEMRs, which are remotely powered and controlled by inductively coupled wireless energy transfer^[39] and laser illumination.^[40] The next generation of SEMRs should be equipped with tiny ESSs that provide on-demand power and autonomous energy management. For biomedical applications, an ESS must not self-discharge (ideally, it should even self-charge) and has to rely on biocompatible materials entirely. Microenergy-storage devices capable of on-demand power output are expected to unleash the full potential of SEMRs. However, today's smallest bio microenergy-storage devices are larger than 2 mm^[246,284,285] and cannot continuously drive the complex functions of SEMRs. At submillimeter scales, self-assembled "swiss-roll" batteries could solve the demand for micro-ESSs, which can be cleverly integrated into the SEMRs.^[46] All these innovations will pave the way to come closer to the synthetic life once envisioned by Feynman many decades ago.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

autonomous systems, flexible micro-electronics, motile miniaturized-machines, soft shareable materials, system-engineered miniaturized robotics

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