Batteries for small-scale robotics

Minshen Zhu* and Oliver G. Schmidt*

The advent of small-scale robots holds immense potential for revolutionizing various industries, particularly in the domains of surgery and operations within confined spaces that are currently inaccessible to conventional tools. However, their tethered nature and dependence on external power sources impede their progress. To surmount these challenges, the integration of batteries into these diminutive robots emerges as a promising solution. This article explores the integration of batteries in small-scale robots, focusing on "hard" and "soft" approaches. The challenges of integrating rigid batteries into microrobots are discussed. Various battery materials suitable for microfabrication are explored, along with creating three-dimensional structures to optimize performance within limited space. The "soft" integration emphasizes the need for flexible and deformable battery technologies that seamlessly integrate with soft robotic systems. Challenges related to flexibility, stretchability, and biocompatibility are addressed. The concept of distributed and mobile energy units, where smaller batteries assemble into a larger power bank, is proposed for scalability and adaptability. Extracting energy from the environment, inspired by fuel cells, reduces reliance on traditional batteries. This article offers valuable insights into battery integration for small-scale robots, propelling advancements in autonomous and versatile systems. By overcoming current limitations, integrated batteries will unlock the full potential of small-scale robots across various industries.

Toward untethered small-scale robots

Advancements in robotics are radically redefining the concept of robots and revolutionizing their role in real life. The stereotypical image of a rigid, sizable robot is gradually giving way to a new breed of miniaturized robots tiny enough to extend their influence from traditional manufacturing into domains such as health care[1–3] and agriculture.[4–6] Such small-scale robots embrace diverse miniaturized devices, ranging from centimeters to micrometers. As portrayed in **Figure 1**a, in a robot, the control component is a circuit with a microcontroller, the energy supply comes from a battery or an energy harvester (e.g., photovoltaic cell), input and output are realized by antennas and sensors, and actuators allow for movement and operation. The incorporation of all these functions constitutes an intelligent robot capable of operating autonomously, sensing its environment and responding to it. Two distinct strategic approaches have been explored to develop small-scale robots.[7] The first approach follows a top-down methodology, beginning with a range of miniaturized components such as tiny microcontrollers, sensors, and batteries, to ensure functional versatility, which are then integrated into a compact form.[8–13] Alternatively, the bottom-up strategy starts with single-function components of minimal size and enhances their capabilities through the gradual addition of new parts. For example, intelligence was incorporated into a swimming microrobot[14] by monolithic integration of sensors and complementary metal oxide semiconductor (CMOS).[15] At the micro- and nanoscales, this approach delves into cutting-edge nanotechnologies to achieve sufficient intelligence, which includes mobility and locomotion,[16,17] adaptability and flexibility,[18,19] reconfigurability and programmability,[20–22] multifunctionality and multimaterials,[23,24] wireless power transfer and communication,[14,25] as well as data processing and computing.[15,26]

In addition to these essential functions, the cornerstone of intelligence lies in autonomous operation. The initial step involves endowing the small-scale robot with motion autonomy by integrating artificial legs or compliance that can react to surroundings or be managed by the microcontroller.[27] Microcontroller-driven motion concurrently entails achieving control autonomy, which requires small-scale robots to carry their own control and feedback systems.[28] Power autonomy is the foundational enabler of autonomous operation. In the realm of small-scale robots, the motion is often curtailed by tethers, which can be either physical connections to a power

Minshen Zhu, Research Center for Materials, Architectures and Integration of Nanomembranes, Technische Universität Chemnitz, Chemnitz, Germany; Material Systems for Nanoelectronics, Technische Universität Chemnitz, Chemnitz, Germany; minshen.zhu@main.tu-chemnitz.de
Oliver G. Schmidt, Research Center for Materials, Architectures and Integration of Nanomembranes, Technische Universität Chemnitz, Chemnitz, Germany; Material Systems for Nanoelectronics, Technische Universität Chemnitz, Chemnitz, Germany; oliver.schmidt@main.tu-chemnitz.de
*Corresponding author
doi:10.1557/s43577-023-00651-z

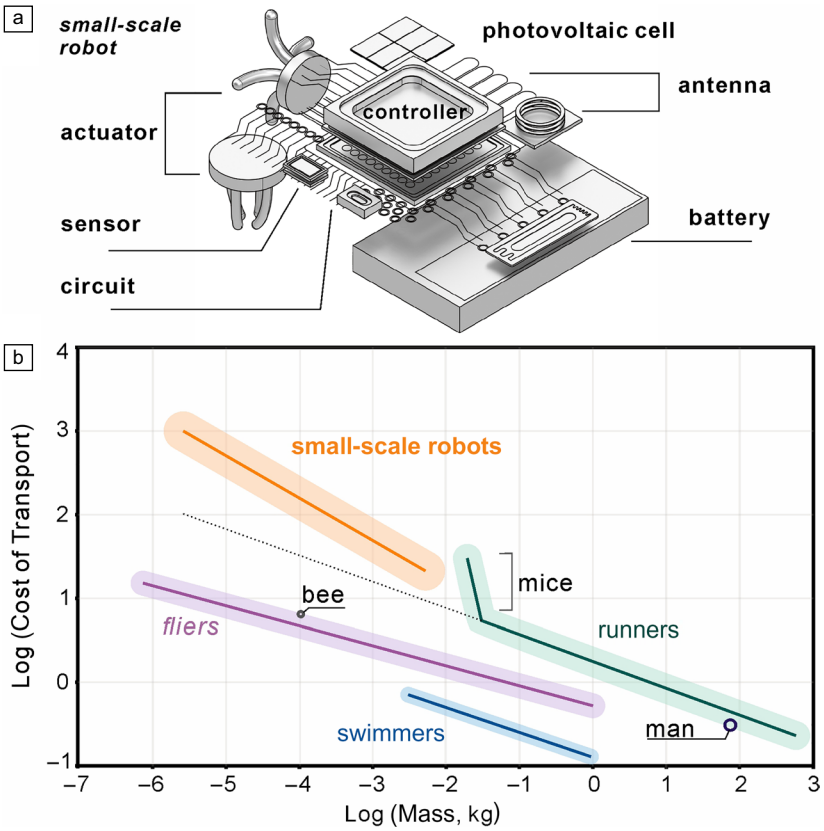


Figure 1. Small-scale robots and their cost of transport. (a) Schematic of a small-scale robot with actuators, electric circuits containing a microcontroller, a battery with a power management circuit, and energy harvesters such as photovoltaic cells and coils for magnetic induction charging. (b) Cost of transport of small-scale robots (runners and fliers), runners, swimmers, and fliers plotted against their body mass. Small-scale swimmers are not included because they are often driven by chemical fuels or external fields like magnetic fields.[30,31]

source or wireless links to a designated field such as magnetic fields, acoustic fields, electric fields, chemical feeds, and light.

Although large-scale robots can readily employ standard-sized batteries such as cylindrical, prismatic, and pouch cells to eliminate the need for tethers, integrating small-scale batteries capable of powering the intricate electronics within small-scale robots poses a significant challenge.[29] Before delving into strategies for enhancing energy density in tiny batteries, it is essential to overview the energy requirements for achieving untethered autonomous operation. Determining a precise energy requirement for the integrable battery is challenging due to varying levels of intelligence and autonomy. However, introducing the notion of cost of transport from biological systems can offer a way to depict this energy requirement. To travel a certain distance at a given speed ($v = dx/dt$), any entity needs a power input ($P = dE/dt$). The ratio P/v is dE/dx, describing the energy consumption to achieve a displacement of unit distance. Dividing P/v by the body mass (m) of the entity introduces a dimensionless indicator for any system, called cost of transport ($= P/mv$).[30] Figure 1b plots the minimum costs of transport of biological systems and small-scale robots; each category roughly falls into a separate group that can be described by a single line. For biological systems, energy efficiency, the ratio of the input power and output power diverted to motion, largely determines the cost of transport. Evidently, if small-scale robots aspire to attain the equivalent intelligence and functionality of a biological system like a bee, their cost of transport exceeds that of the natural counterpart by over tenfold, implying a substantially greater demand for power/energy input. This significant power demand is a driving factor behind the current tethered design of many small-scale robots, underscoring the formidable challenge in developing integrable batteries capable of realizing complete autonomous operation. The collective energy efficiency of small-scale robots is determined by the efficiencies of their actuators and electronics, which typically is 0.1 and 0.5, respectively.[31] In this case, the achievable operational energy is limited to 5% from the integrable battery. Although improving both actuator and electronic efficiency is the most straightforward way to unleash the full potential of small-scale robots in the untethered form, it is important to explore ways for batteries to increase the energy density and identify opportunities to bring batteries closer to the objective of empowering micro/nanorobots to operate independently. As challenges associated with battery materials persist across various scales,[32] the primary objective of this article is to elucidate the strategies for realizing integrable small-scale batteries and the unique material requirements associated with them.

"Hard" integration

"Hard" integration, including technologies such as wire bonding and on-chip monolithic integration, stands as the most direct and uncomplicated strategy for incorporating batteries into small-scale robotics. In this case, batteries are developed independently and then readily utilized in the construction of robotics. Within this framework, the capacity of a battery is fundamentally dictated by its electrode materials, making them a pivotal factor in the quest for materials capable of storing substantial amounts of charge. As a device, the energy density of a battery is also influenced by other integral elements: current collectors, serving the anode and cathode, respectively, to guide the flow of electrons to external circuits, and an electrolyte, functioning as a medium with ion mobility while simultaneously hindering electron movement.

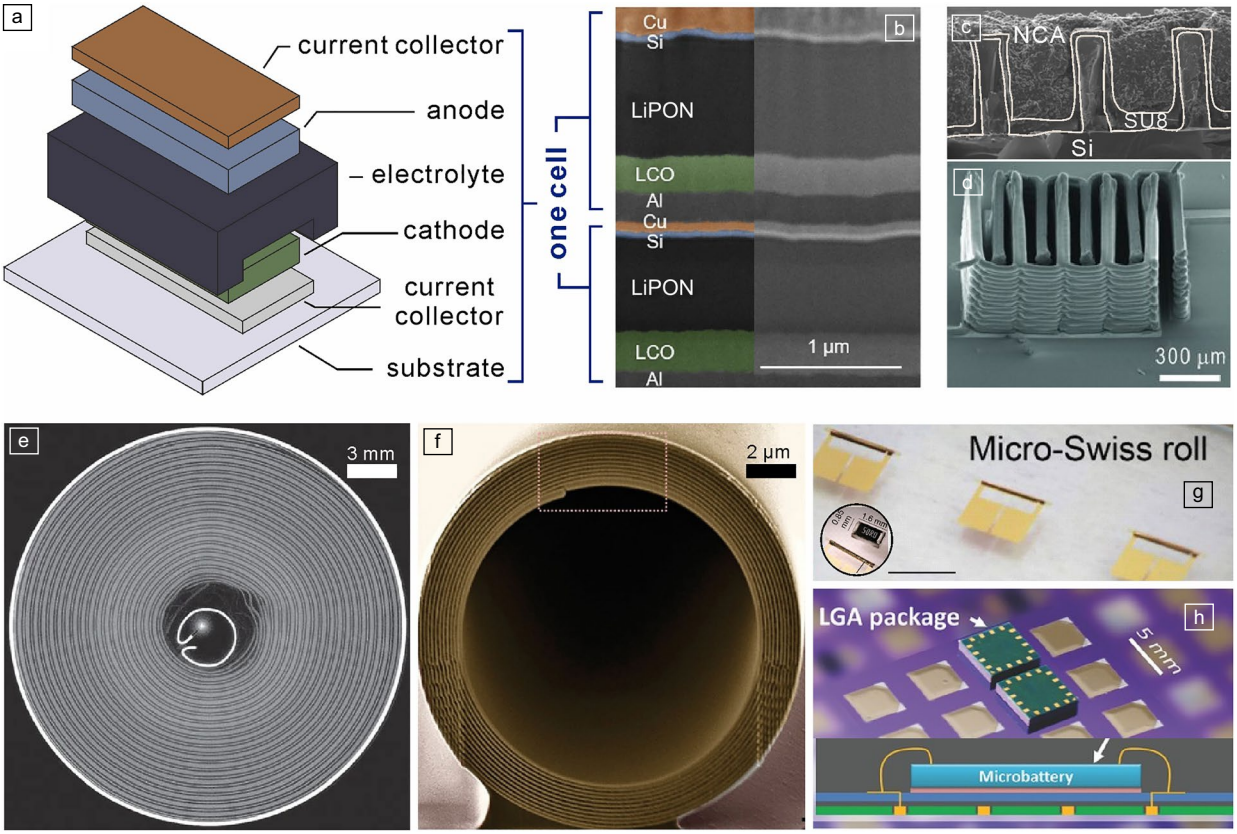


Figure 2. Development of "hard" batteries. (a) Schematic of the basic structure of a battery on a "hard" substrate. Scanning electron microscopy (SEM) image of (b) a stacked battery with two cells. (c) A battery using micropillar arrays. (d) A 3D printed battery with plane-arranged electrodes. (e) Reconstructed image of an 18650 cell imaged by x-ray computed tomography. (f) SEM image of a micro-Swiss-roll layer stack. (g) An array of micro-Swiss rolls with gold thin film and polymeric origami stack. Inset compares the micro-Swiss roll to a surface-mounted device. Scale bar = 3 mm. (h) Package of a cell and its connection to the chip. LGA, land grid array. (b–h) Adapted with permission from Reference 51. © 2023 Springer Nature. Reference 56. © 2018 Elsevier. Reference 57. © 2013 Wiley-VCH. Reference 61. © 2015 Springer Nature. Reference 62. © 2020 Wiley-VCH. Reference 66. © 2022 Wiley-VCH. Reference 70. © 2015 Wiley-VCH.

Liquid electrolytes are extensively used due to their high ionic conduction. It is imperative to ensure robust packaging to prevent electrolyte leakage and safeguard battery components against external impacts. Integrating all these components into miniaturized robots poses a significant challenge. Therefore, compact batteries such as coin cells and pouch cells are often used for centimeter-scale robots.[9–11] Down to the millimeter scale, the solution for onboard batteries lies in on-chip thin-film batteries.[13] The battery components are deposited as a stack of solid films (**Figure 2**a). It is different from conventional batteries, where electrodes are composed of microparticles mixed with additives, immersed in a liquid electrolyte to minimize diffusion distance, which enables the electrode coating exceeding 100 µm in thickness. In contrast, thin-film electrode materials are usually only a few micrometers thick. However, recent developments in the electrodeposition of cathode materials have demonstrated the feasibility of creating ultrathick and densely packed electrodes at centimeter scales.[33] It is worth noting that although these advances showcase the potential for thicker electrodes, achieving significant thickness increases can be highly challenging from a technological standpoint, primarily due to the mechanical constraints associated with applying thick films onto confined footprints, especially at millimeter or even smaller scales. Moreover, the time required to fully charge an electrode increases proportionally to the square of its thickness, imposing kinetic limitations.[34,35] Creating a fast charge transfer pathway by controlling the crystal orientation for thick electrodes is necessary.[36–38] Furthermore, the ion mobility within solid-state electrolytes is notably slower than that observed in liquid counterparts.[39] The combined impact of these adjustments leads to a significant reduction in capacity, more than three orders of magnitude decrease when compared to coin cells produced through the conventional methods.[40]

While dismantling these constraints presents a formidable task, new ways to improve capacity are being explored. A strategic approach involves the utilization of the anode-free concept, wherein the deposition of a lithium-metal anode is achieved by charging the cell. The omission of the anode during

cell fabrication not only simplifies the manufacturing process, but also unlocks the complete potential of the cathode material (20-µm $LiCoO_2$), showing a high capacity of 0.89 mAh cm^{-2}.[41] Advances in electrode material deposition processes, such as photonic-assisted annealing[42,43] to improve the crystallinity and cosputtering[44] to introduce new cathode materials can improve the cell performance. In the realm of solid-state electrolytes for thin-film cells, the predominant choice has been lithium phosphorus oxynitride (LiPON), primarily due to challenges in producing thin layers (<10 µm) with conventional ceramic electrolytes derived from particle sintering. However, recent breakthroughs have emerged with micrometer-thick ceramic oxide garnet $Li_7La_3Zr_2O_{12}$ (LLZO) electrolytes. These advancements, achieved through techniques like pulsed laser deposition,[45] radio-frequency magnetron sputtering,[46] atomic layer deposition,[47] and chemical vapor deposition,[48] hold the promise to yield notable improvements, boasting three orders of magnitude higher ionic conductivity compared to LiPON (10^{-3} versus 10^{-6} S cm^{-1}).[49,50]

In the context of engineering, monolithically stacking more cells on the substrate is a straightforward way. Figure 2b shows a bipolar stack of cells, each consisting of an Al cathode current collector, an amorphous $LiCoO_2$ (LCO) cathode, a LiPON solid electrolyte, a Si anode, and a Cu anode current collector.[51] To ensure the smooth interface between two adjacent cells, Si instead of *operando* deposited Li is used as the anode layer. The anode-free concept is, however, applicable to this bipolar design if the unstable interface induced by the deposition and stripping of lithium metal can be addressed. Although the projection of stacking 10 cells holds the potential to exceed the energy density of cylindrical 18650 cells, several significant challenges persist, including ensuring consistent performance of each deposited cell and maintaining interface stability. Additionally, compatibility issues between the fabrication processes of various functional components are common, where subsequent processes involving high temperatures, etching liquids, and aggressive solvents risk damaging already established cells.

Additionally, advancements in electrode architecture design can scale the battery capacity through the expansion of the electrode surface area while keeping the electrode material film thin. Micropillar arrays, crafted through techniques such as the Bosch process or template methods, exhibit the remarkable ability to enhance surface area by over 20-fold.[34,52–55] However, the area enhancement is subject to physical constraints. Consider tall and thin micropillars, which, though potentially boosting surface area, could be fragile and collapse during cycling, given the repeated expansion and contraction of the electrode material. Similarly, a densely packed array could constrict material thickness on individual pillars, thereby potentially undermining capacity.[40] The micropillar array also forms a container for the electrode particles. An intuitive way involves the direct utilization of a silicon (Si) chip as the anode. The Si substrate, sculpted into micropillars offers an astonishing theoretical capacity exceeding 4000 mAh g^{-1}. To assemble the cell, the Si micropillar needs to be covered by the electrolyte, SU8 soaked with the electrolyte for instance (Figure 2c).[56] The integration of cathode microparticles (lithium nickel cobalt aluminum oxides, NCA) within the Si micropillar interstices forms a cell with an extraordinary capacity, of over 4 mAh cm^{-2}.

Furthermore, applying cutting-edge fabrication techniques, such as additive manufacturing, could provide a means to produce intricate and thicker electrode structures that push the limits of capacity while managing mechanical challenges. Functional inks composed of anode ($Li_4Ti_5O_{12}$, LTO) and cathode ($LiFePO_4$, LFP) are printed into high-aspect-ratio electrodes that are interdigitated on the substrate (Figure 2d).[57] The electrode aspect ratio can be controlled by the number of printed layers. For a 16-layer electrode configuration, the aspect ratio reached 16, attaining a capacity of up to 2 mAh cm^{-2}. The formulation of functional electrode inks is close to conventional approaches for preparing electrode slurries. This similarity allows for the incorporation of a wide range of novel materials into these direct writing technologies.[58] However, the planar arrangement of electrodes does lead to a limitation in the available area for accommodating electrode materials.[59,60] Considering the typical print diameter surpasses 10 µm, creating batteries at a submillimeter scale remains a significant challenge.

All of the previously mentioned on-chip cells were developed under the assumption that the materials inside the cell maintain a rigid structure during the manufacturing process, but in fact, full-sized batteries (cylindrical cells) are fabricated by winding material layers many times, forming a Swiss-roll structure as illustrated in Figure 2e depicting a cross section of a typical cylindrical 18650 cell.[61] The Swiss-roll configuration, comprising numerous thin layers, effectively tackles the mechanical and kinetic constraints associated with thicker electrodes, simultaneously enhancing capacity within a confined footprint. Although larger-scale Swiss rolls can be readily produced using a rolling mandrel, the absence of an analogous tool for micrometer-scale Swiss rolls presents a challenge. The micro-origami technology, also known as one kind of self-assembly process, is able to roll nanometer-thick films through the internal strain of the layered films (e.g., lattice mismatch, different swelling capabilities, etc.) and has shown the capability to produce the micro-Swiss-roll structures as illustrated in Figure 2f.[62] Such micro-origami process is compatible with very well-established inherently planar techniques to create thin-film stacks.[63,64] Hence, in principle, any planar batteries can be shaped into the Swiss-roll configuration. For example, Zn anode and Ag cathode interdigitated on a polymeric layer stack that can roll up upon swelling in water creates a 0.2 mAh cm^{-2} battery with a footprint under 0.1 mm^2.[65] The micro-Swiss-roll also acts as a 3D conductive scaffold to host electrode material particles. The incorporation of MnO_2 nanowire slurry demonstrates a high electrode capacity of up to 3.3 mAh cm^{-2} within 1 mm^2.[66] Moreover, the folding process can be executed without the need for manual or physical connections, thus facilitating parallel assembly (Figure 2g).

Compatibility with planar device fabrication offers substantial potential, but it also entails the necessity to address the identical issues encountered in planar systems. Ensuring the mechanical and chemical stability of thin-film materials under shape morphing introduces an additional layer of complexity that demands careful attention. Moreover, achieving an extended rolling length is pivotal in significantly surpassing the energy density of current miniature batteries. To achieve this, mechanisms like magnetic field correction[67] for guiding the rolling process and preventing misalignment must be developed.

Finally, the "hard" integration necessitates the inclusion of a battery packaging solution. Depending on the operational environment, small-scale robots could encounter water, salt, and microbes, which can damage the battery. For example, unprotected lithium-ion batteries will fail when exposed to water and air. Emerging aqueous batteries offer a viable alternative.[68,69] In either scenario, incorporating insulating layers, such as a land grid array (LGA) package as depicted in Figure 2h is necessary. Like packaging for microelectromechanical systems, battery on a chip will be attached to the package substrate through a secure bonding process, which can involve adhesives or bonding techniques. Wire bonding or flip-chip bonding is then employed to establish the necessary electrical connections between the battery chip and the external leads or terminals for power transfer. To shield the battery from moisture, dust, and other contaminants, a hermetic seal is created. This seal is achieved through methods like welding and soldering. Alternatively, for thin-film batteries, hermetic cells can be directly formed by utilizing current collectors as integral sealing component.[33,71] It is worth noting that it is important to address the challenge of integrating batteries into stacked microsystems, rather than in-plane connections, toward further miniaturization of robots.

"Soft" integration

"Soft" integration of controllers (**Figure 3**a),[72] sensors (Figure 3b),[73] and actuators (Figure 3c)[74] has become achievable through advancements in both soft materials and integration technologies. Soft-bodied designs offer more degrees of freedom compared to rigid robots, as their shape can be dynamically or autonomously adjusted, enabling them to seamlessly adapt to their surroundings.[75–77] Achieving softness can be approached in two ways. One involves using soft functional materials such as conductors, dielectrics, and semiconductors.[78] The other method is more versatile, entailing the fabrication of thin rigid devices on a soft substrate (Figure 3a–c). This, in principle, allows any rigid device to be transferred onto a soft substrate, thereby gaining flexibility.[79,80] As battery materials are largely rigid, achieving flexibility often requires depositing or coating these materials onto a soft film. Similar to the fabrication of soft controllers and sensors, thin-film electrode materials are layered on a plastic substrate (Figure 3d).[81] However, the stack of thin films can restrict flexibility, leading to the design of interdigitated electrodes within the same plane to address this limitation. It is important to note that the mechanical and kinetic restrictions of thin-film cells also apply to such interdigitated batteries. Consequently, thin electrodes must be spread across a large area to attain the sufficient capacity, implying the inefficiency of integrating them into rigid and miniature systems on a chip.[82] On the other hand, the overall thickness could be even controlled under 10 μm,[83] enhancing the battery's flexibility and suggesting potential integration as an additional layer in soft controllers, sensors, or actuators to achieve a distributed and embodied energy supply design.[84,85]

An alternative approach for achieving soft integration is to utilize fibers as substrates. Fibrous batteries offer a significant advantage as they can be shaped to serve as both structural units and actuators.[86,87] However, producing fibrous batteries in lengths beyond a few centimeters presents challenges, often leading to increased resistance and limited electrochemical performance. Remarkably, the phenomenon of decreased polarization resistance followed by stabilization has been observed in the case of two electrode fibers twisted coaxially, attributed to the formation of equivalent circuits within the coaxial fiber configuration as shown in Figure 3e.[88] Intriguingly, this abnormal behavior improves rate performance with extended length. Scalable production of fibrous batteries is viable, as shown in the right panel of Figure 3e, demonstrating a capacity of 25 mAh m^{-1}.

Addressing the challenge of stretchability in batteries intended for use in soft robots, hydrogel electrolytes consisting of aqueous electrolytes offer a promising solution due to their inherent elasticity.[89] To accommodate rigid metal current collectors and electrode materials, a practical approach involves coating electrodes onto a prestretched hydrogel electrolyte and subsequently releasing the strain to achieve the desired stretchability. Alternatively, the engineering of electrode structures can also contribute to stretchability. For instance, adopting a planar wavy layout (Figure 3b) imparts flexibility and stretchability. Employing electrode designs in a Kirigami style also introduces a degree of stretchability (Figure 3f).[90] Both elastic hydrogels and stretchable Kirigami devices can serve as actuators, indicating a potential for distributed energy storage within the actuator.

In fact, the constrained thickness of electrode materials to ensure flexibility and stretchability presents a challenge. To achieve a sufficient capacity for powering intelligent electronic functions, a substantial flat area and extended length are required. Regrettably, this requirement imposes constraints on the feasibility of integrating batteries into soft robots down to micrometers. To circumvent the inherent constraint on electrode material loading, a promising approach is to leverage electrochemically active species in operating fluids, as for actuators in fluids (Figure 3c). Intuitively, fuel cells are inspiration resources. Redox flow batteries in the robot body is another option.[91] Alternatively, storing energy in a solid and high-capacity material such as Zn metal and utilizing common substances in the surrounding environment like dissolved oxygen in biofluids decouple the energy-storage limit from cathode material loading, focusing instead on enhancing the efficiency of redox reactions involving electrochemically

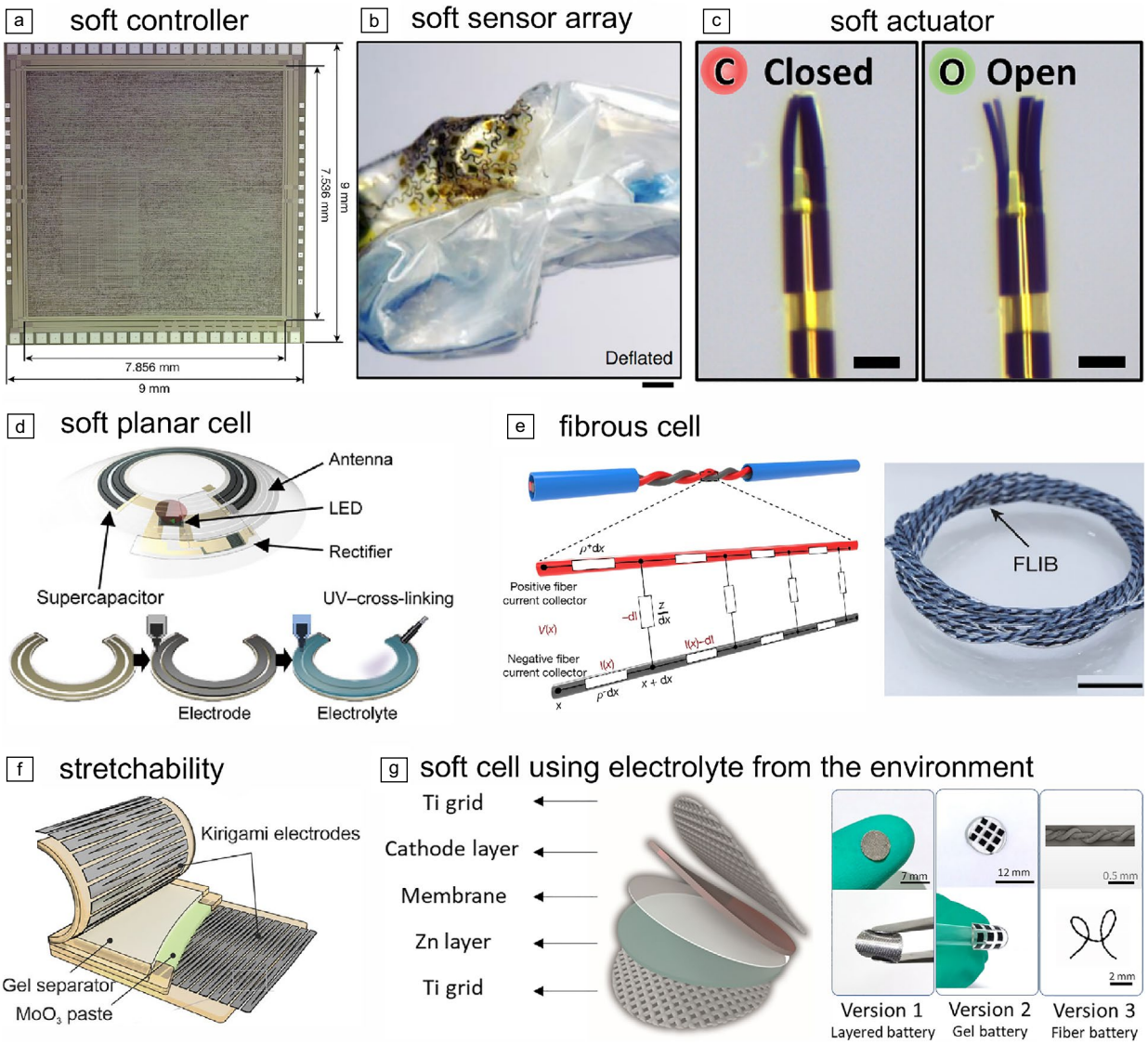


Figure 3. Soft batteries. (a) Micrograph of a soft controller, PlasticARM. Images of (b) soft temperature and strain sensor array (scale bar = 2 mm) and (c) a soft micro-actuator (scale bars = 100 µm). Schematics of (d) planar electrodes interdigitated on a soft substrate and (e) fibrous electrode assembled into a coaxial configuration (image in the right panel, scale bar = 1 cm). LED, light-emitting diode; FLIB, fiber lithium-ion battery. (f) Soft cells using biofluid as electrolyte. (g) Kirigami electrodes enabling stretchability. (a–g) Adapted with permission from Reference 72. © 2021 Springer Nature. Reference 73. © 2020 Springer Nature. Reference 74. © 2021 Wiley-VCH. Reference 81. © 2019 AAAS. Reference 88. © 2021 Springer Nature. Reference 90. © 2022 Wiley-VCH. Reference 92. © 2023 AAAS.

active species, which largely depends on the performance of catalysts. As illustrated in Figure 3g, the cell structure remains consistent with the depiction in Figure 2a. Therefore, the cell can be miniaturized into flexible thin-film cells and fabricated as a fibrous cell (right panel in Figure 3g) for a wide array of applications. The primary distinction lies in the role of the cathode layer, which reduces oxidants such as oxygen during the discharge process.[92] In terms of materials, compatibility to the operation environment emerges as a critical consideration.[93] For instance, employing oxygen dissolved in biofluid with cells necessitates a biocompatible cathode material such as polyimide, along with a Zn anode that does not harm cells.[92] In cases requiring rechargeability, the cathode layer must catalyze the reverse oxidation reaction, such as the oxygen evolution reaction.[94] Employing active substances sourced from the surrounding environment presents a strategy to circumvent the packaging challenge, which could otherwise compound the difficulty of maintaining softness of batteries.

Additionally, the batteries sometimes have to be able to operate in harsh environmental conditions, such as high humidity or extreme temperatures. The safety concerns are also associated with mechanical and environmental stress. A strategic approach to mitigating such risks involves the development of embedded sensors and monitors designed for

batteries integrated into soft robots. These specialized sensors and monitors provide timely warnings in the event of malfunction and trigger the systematic shutdown of compromised batteries.

Perspectives

The core challenge revolves around bridging the energy gap required to power intelligent electronic functions. Regarding materials, the developmental objectives align with those of full-sized batteries: attaining high energy density, excellent rate capability, prolonged cycle life, and optimal safety. This developmental trajectory introduces an additional facet: integration. This can be realized through the traditional "hard" integration approach, focusing on advanced battery materials to enhance centralized power supply, or the "soft" integration approach, which involves infusing energy into diverse robot components to establish distributed energy sources.

Irrespective of the chosen path, the ultimate objective is to liberate small-scale robots from tethers. A straightforward energy calculation further emphasizes this need: considering the electronic and actuation consumption of a miniaturized robot, which can bottom out at 75 nW[15], and factoring in an energy expenditure of roughly 5% from the battery for system operation, a 10-h operation demands a battery capacity of no less than 1.5 μWh. Notably, such a tiny system has a footprint of only around 0.07 mm^2. Consequently, for an aqueous battery with a 1.5-V operational voltage, the footprint capacity must be roughly 1 mAh cm^{-2}, and for a lithium-ion battery with a 3-V operational voltage, it should be approximately 0.5 mAh cm^2. The energy demand also applies to other emerging battery technologies such as sodium-ion batteries. Numerous studies have highlighted comparable or even superior footprint capacities, for instance, a centimeter-scale lithium-ion battery with a capacity ranging from 7 to 12 mAh cm^{-2}.[33] In this context, envisioning a robot operating at the same scale, which requires approximately 0.1 J (equivalent to about 28 μWh) of energy to traverse a distance of 1 m, implies the potential for such a robot to travel over 1 km with the energy provided by such a battery.[95] However, the accomplishment of such capacities within millimeter or even smaller footprints remains questionable. This accentuates the importance of accurately documenting specific capacity or energy density alongside battery dimensions. Equally important is the need to transparently state whether the reported capacity is related to a single electrode or the full cell. Furthermore, the practicality of assessing battery performance extends beyond conventional cycle numbers, particularly for small-scale robots with specific, well-defined tasks and energy demands over their operational lifespan. Traditional recharge cycle figures may not align with these use-case scenarios. Instead, evaluating lifetime capacity or energy becomes paramount in guiding robot design. In the case of rechargeable batteries, optimizing recharging protocols to maximize lifetime capacity introduces an additional layer of complexity to the design process for small-scale robots. Primary batteries, on the other hand, offer the advantage of full discharge. Reliability and durability of batteries for small-scale robots under different operating conditions also need to be evaluated. A fundamental methodology involves conducting accelerated aging tests. These tests entail subjecting batteries to elevated temperatures, high humidity, and various environmental stressors to simulate the cumulative effects of long-term usage. Modeling and simulation tools can be used to predict the behavior of batteries under different operating conditions. To make informed decisions regarding battery selection, it is crucial to have access to direct data on lifetime capacity/energy and cycle protocols for secondary batteries. Such information is invaluable in tailoring battery choices to the specific requirements of small-scale robotic applications. In a nutshell, providing direct information on the capacity and energy of the developed full cell, similar to how full-sized batteries present their capacity, operating voltage, and lifetime metrics would greatly aid in identifying suitable batteries for specific applications. Moreover, the integration of safety considerations introduces an additional criterion. Sometimes, batteries have to work under extreme temperatures and pressures that are inherently harmful to batteries. In addition to advances in materials, a strategic approach to mitigating these multifaceted challenges involves the integration of sensors, monitors, and temperature control systems directly into the battery. Although the integration of batteries is essential to eliminate tethers in small-scale robots, entirely new paradigms inspired by biological systems, where robots harness surrounding fuels to power their functions, could become predominant as robots shrink down to the cellular level. This concept could lead to a "battery-less" design approach, prompting further exploration into methods to replicate metabolic processes in these miniature robotic systems.

As the intelligence of ever miniaturized robots continues to increase, there arises an escalating demand for power, even reaching milliwatt levels,[96] to facilitate data transfer, processing, and the execution of complex tasks. Evidently, achieving such elevated power demands through a single battery with substantially reduced size proves to be highly challenging, unless a revolutionary battery paradigm with substantially enhanced capacity compared to current technologies emerges. A hybrid solution that integrates energy-conversion technologies such as photovoltaic cells with batteries offers a feasible approach. In this setup, the battery functions as a backup energy source, stepping in when energy-conversion systems are not operational. In addition, the battery can provide high power for data processing and communication while it can be recharged during periods of low-power operation. This approach could alleviate the demand for extremely high energy density in batteries alone. Alternatively, a paradigm shift of regarding small batteries as autonomous robotic entities could present an innovative outlook. By introducing motion and docking mechanisms, these batteries could potentially self-assemble into collectives, resembling chains, to address peak power requirements during robot communication and data processing.[97] A single battery would then be adequate when the robot transitions into idle or low-power modes. This visionary approach would

combine small-scale robot and battery advancements, paving the way for a fresh trajectory in battery development.

Interdisciplinary concepts have the potential to provide innovative solutions for addressing the challenges associated with batteries for small-scale robots. For instance, drawing from the concept of "soft" integration, the utilization of active species from the operational environment can decouple energy storage from the electrode material mass in batteries, instead relying on harvestable sources from the surroundings. This approach can be especially effective for robots that move around, expanding the reachable area and offering a new direction for battery development. Moreover, the realm of engineered living materials could offer a novel avenue for materials development in tiny batteries. For instance, fungal mycelium can autonomously grow and seal electronic components, including batteries, when supplied with nutrients.[98] This kind of proof-of-concept demonstration, particularly relevant to small-scale robots used in bio applications, holds the potential to open up new possibilities.

In conclusion, batteries designed for small-scale robots are not simple scaled-down versions of their full-sized counterparts. Their development necessitates careful consideration of integration with other components, with performance being heavily influenced by the specific requirements of the robot. Consequently, an accurate and detailed documentation of battery specifications serves as the initial crucial step. Moreover, it is imperative to broaden the perspective by encompassing insights from various disciplines such as robotics and biological systems.

Acknowledgments

M.Z. gratefully acknowledges support from European Union (ERC, SMADBINS, 101039802). O.G.S. gratefully acknowledges support from European Union (ERC, MicroRepro, 835268). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

Author contributions

M.Z. and O.G.S. conceived the idea and wrote the manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. European Union: ERC, SMADBINS (Grant No. 101039802); ERC, MicroRepro (Grant No. 835268).

Conflict of interest

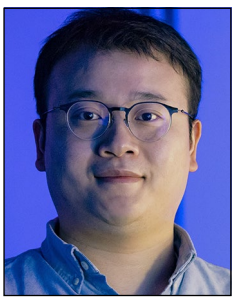
The authors state that there is no conflict of interest.

Open Access

References

1. B.J. Nelson, I.K. Kaliakatsos, J.J. Abbott, *Annu. Rev. Biomed. Eng.* **12**, 55 (2010)
2. J. Li, B. Esteban-Fernández de Ávila, W. Gao, L. Zhang, J. Wang, *Sci. Robot.* **2**, eaam6431 (2017)
3. M. Medina-Sánchez, O.G. Schmidt, *Nature* **545**, 406 (2017)
4. U. Kaur, R. Sriramdas, X. Li, X. Ma, A. Datta, B. Roqueto Dos Reis, S. Sen, K. Daniels, R. White, R.M. Voyles, S. Priya, *Smart Agric. Technol.* **3**, 100109 (2023)
5. R. Maria-Hormigos, C.C. Mayorga-Martinez, M. Pumera, *Small* **19**(51), 2204887 (2023)
6. W. Duan, W. Wang, S. Das, V. Yadav, T.E. Mallouk, A. Sen, *Annu. Rev. Anal. Chem.* **8**, 311 (2015)
7. T.-Y. Huang, H. Gu, B.J. Nelson, *Annu. Rev. Control Robot. Auton. Syst.* **5**, 279 (2022)
8. Y. Chen, H. Zhao, J. Mao, P. Chirarattananon, E.F. Helbling, N.P. Hyun, D.R. Clarke, R.J. Wood, *Nature* **575**, 324 (2019)
9. Y. Zhang, R. Zhu, J. Wu, H. Wang, *IEEE ASME Trans. Mechatron.* **27**, 5748 (2022)
10. Z. Ren, J. Yang, S. Kim, Y.-H. Hsiao, J. Lang, Y. Chen, "A Lightweight High-Voltage Boost Circuit for Soft-Actuated Micro-Aerial-Robots," *2023 IEEE International Conference on Robotics and Automation (ICRA)* (London, May 29–June 2, 2023), pp. 3397–3403
11. B. Goldberg, R. Zufferey, N. Doshi, E.F. Helbling, G. Whittredge, M. Kovac, R.J. Wood, *IEEE Robot. Autom. Lett.* **3**, 987 (2018)
12. X. Yang, L. Chang, N.O. Pérez-Arancibia, *Sci. Robot.* **5**, eaba0015 (2020)
13. X. Wu, I. Lee, Q. Dong, K. Yang, D. Kim, J. Wang, Y. Peng, Y. Zhang, M. Saligane, M. Yasuda, K. Kumeno, F. Ohno, S. Miyoshi, M. Kawaminami, D. Sylvester, D. Blaauw, "A 0.04mm^{3}16nW Wireless and Batteryless Sensor System with Integrated Cortex-M0+ Processor and Optical Communication for Cellular Temperature Measurement," *2018 IEEE Symposium on VLSI Circuits* (Honolulu, June 18–22, 2018), pp. 191–192
14. M.Z. Miskin, A.J. Cortese, K. Dorsey, E.P. Esposito, M.F. Reynolds, Q. Liu, M. Cao, D.A. Muller, P.L. McEuen, I. Cohen, *Nature* **584**, 557 (2020)
15. L. Xu, M. Lassiter, X. Wu, Y. Kim, J. Lee, M. Yasuda, M. Kawaminami, M. Miskin, D. Blaauw, D. Sylvester, "A 210 × 340 × 50 µm Integrated CMOS System for Micro-Robots with Energy Harvesting, Sensing, Processing, Communication and Actuation," *2022 IEEE International Conference on Solid-State Circuits (ISSCC)* (San Francisco, February 20–26, 2022), vol. 65, pp. 1–3
16. V.K. Bandari, O.G. Schmidt, *Adv. Intell. Syst.* **3**, 2000284 (2021)
17. Z. Li, J. Xu, Z. Wu, B. Guo, Q. He, *Acc. Mater. Res.* **3**, 122 (2022)
18. F. Wei, L. Wang, C. Yin, T. Zhong, Z. Lu, L. Yao, *ChemNanoMat* **8**, e202100326 (2022)
19. J. Li, H. Shen, H. Zhou, R. Shi, C. Wu, P.K. Chu, *Mater. Sci. Eng. R Rep.* **152**, 100712 (2023)
20. J. Law, J. Yu, W. Tang, Z. Gong, X. Wang, Y. Sun, *ACS Nano* **17**, 12971 (2023)
21. Y. Zhou, M. Ye, C. Hu, H. Qian, B.J. Nelson, X. Wang, *ACS Nano* **17**, 15254 (2023)
22. M. Medina-Sánchez, V. Magdanz, M. Guix, V.M. Fomin, O.G. Schmidt, *Adv. Funct. Mater.* **28**, 1707228 (2018)
23. M. Urso, M. Ussia, M. Pumera, *Nat. Rev. Bioeng.* **1**, 236 (2023)
24. J. Li, L. Dekanovsky, B. Khezri, B. Wu, H. Zhou, Z. Sofer, *Cyborg Bionic Syst.* **2022**, 9824057 (2022)
25. V.K. Bandari, Y. Nan, D. Karnaushenko, Y. Hong, B. Sun, F. Striggow, D.D. Karnaushenko, C. Becker, M. Faghih, M. Medina-Sánchez, F. Zhu, O.G. Schmidt, *Nat. Electron.* **3**, 172 (2020)
26. F. Maksimovic, B. Wheeler, D.C. Burnett, O. Khan, S. Mesri, I. Suciu, L. Lee, A. Moreno, A. Sundararajan, B. Zhou, R. Zoll, A. Ng, T. Chang, X. Villajosana, T. Watteyne, A. Niknejad, K.S.J. Pister, "A Crystal-Free Single-Chip Micro Mote with Integrated 802.15.4 Compatible Transceiver, Sub-mW BLE Compatible Beacon Transmitter, and Cortex m0," *2019 Symposium on VLSI Circuits* (Kyoto, June 9–14, 2019), pp. C88–C89
27. Q. Wang, J. Zhang, J. Yu, J. Lang, Z. Lyu, Y. Chen, L. Zhang, *ACS Nano* **17**, 13081 (2023)
28. Z. Chen, Q. Liang, Z. Wei, X. Chen, Q. Shi, Z. Yu, T. Sun, *Cyborg Bionic Syst.* **4**, 0001 (2023)
29. M. Zhu, O.G. Schmidt, *Nature* **589**, 195 (2021)

30. V.A. Tucker, *Am. Sci.* **63**, 413 (1975)
31. R. Pierre, S. Bergbreiter, *Annu. Rev. Control Robot. Auton. Syst.* **2**, 231 (2019)
32. M. Armand, J.-M. Tarascon, *Nature* **451**, 652 (2008)
33. S. Kim, A. Patra, R.R. Kohlmeyer, S. Jo, X. Yue, A. Johnson, C.T. Kiggins, B. Zahiri, K. Jeong, J. Koo, T. Kang, P. Sun, J.B. Cook, J.H. Pikul, P.V. Braun, *Cell Rep. Phys. Sci.* **4**, 101205 (2023)
34. S. Moitzheim, B. Put, P.M. Vereecken, *Adv. Mater. Interfaces* **6**, 1900805 (2019)
35. A. Bielefeld, D.A. Weber, J. Janek, *ACS Appl. Mater. Interfaces* **12**, 12821 (2020)
36. J. Billaud, F. Bouville, T. Magrini, C. Villevieille, A.R. Studart, *Nat. Energy* **1**, 1 (2016)
37. J.S. Sander, R.M. Erb, L. Li, A. Gurijala, Y.-M. Chiang, *Nat. Energy* **1**, 16099 (2016)
38. B. Zahiri, A. Patra, C. Kiggins, A.X.B. Yong, E. Ertekin, J.B. Cook, P.V. Braun, *Nat. Mater.* **20**, 1392 (2021)
39. M. Balaish, J.C. Gonzalez-Rosillo, K.J. Kim, Y. Zhu, Z.D. Hood, J.L.M. Rupp, *Nat. Energy* **6**, 227 (2021)
40. N.A. Kyerematen, R. Hahn, *ACS Energy Lett.* **3**, 1172 (2018)
41. S. Oukassi, R. Salot, A. Bazin, C. Secouard, I. Chevalier, S. Poncet, S. Poulet, J.-M. Boissel, F. Geffraye, J. Brun, "Millimeter Scale Thin Film Batteries for Integrated High Energy Density Storage," *2019 IEEE International Electron Devices Meeting (IEDM)* (IEEE, San Francisco, December 7–11, 2019), pp. 26.1.1–26.1.4. https://ieeexplore.ieee.org/document/8993483/
42. X. Chen, J. Sastre, A. Aribia, E. Gilshtein, Y.E. Romanyuk, *ACS Appl. Energy Mater.* **4**, 5408 (2021)
43. X. Chen, J. Sastre, M. Rumpel, A. Flegler, A. Singhania, J. Balta Bonner, P. Hoffmann, Y.E. Romanyuk, *J. Power Sources* **495**, 229424 (2021)
44. V.C. Ferrari, N.S. Kim, S.B. Lee, G.W. Rubloff, D.M. Stewart, *J. Mater. Chem. A* **10**, 12518 (2022)
45. I. Garbayo, M. Struzik, W.J. Bowman, R. Pfenninger, E. Stilp, J.L.M. Rupp, *Adv. Energy Mater.* **8**, 1702265 (2018)
46. S. Lobe, C. Dellen, M. Finsterbusch, H.-G. Gehrke, D. Sebold, C.-L. Tsai, S. Uhlenbruck, O. Guillon, *J. Power Sources* **307**, 684 (2016)
47. E. Kazyak, K.-H. Chen, K.N. Wood, A.L. Davis, T. Thompson, A.R. Bielinski, A.J. Sanchez, X. Wang, C. Wang, J. Sakamoto, N.P. Dasgupta, *Chem. Mater.* **29**, 3785 (2017)
48. C. Loho, R. Djenadic, M. Bruns, O. Clemens, H. Hahn, *J. Electrochem. Soc.* **164**, A6131 (2016)
49. Z.D. Hood, Y. Zhu, L.J. Miara, W. Seok Chang, P. Simons, J.L.M. Rupp, *Energy Environ. Sci.* **15**, 2927 (2022)
50. J. Sastre, A. Priebe, M. Döbeli, J. Michler, A.N. Tiwari, Y.E. Romanyuk, *Adv. Mater. Interfaces* **7**, 2000425 (2020)
51. M.H. Futscher, L. Brinkman, A. Müller, J. Casella, A. Aribia, Y.E. Romanyuk, *Commun. Chem.* **6**, 110 (2023)
52. E. Eustache, P. Tilmant, L. Morgenroth, P. Roussel, G. Patriarche, D. Troadec, N. Rolland, T. Brousse, C. Lethien, *Adv. Energy Mater.* **4**, 1301612 (2014)
53. M. Létiche, E. Eustache, J. Freixas, A. Demortière, V. De Andrade, L. Morgenroth, P. Tilmant, F. Vaurette, D. Troadec, P. Roussel, T. Brousse, C. Lethien, *Adv. Energy Mater.* **7**, 1601402 (2017)
54. A. Pearse, T. Schmitt, E. Sahadeo, D.M. Stewart, A. Kozen, K. Gerasopoulos, A.A. Talin, S.B. Lee, G.W. Rubloff, K.E. Gregorczyk, *ACS Nano* **12**, 4286 (2018)
55. M. Hallot, V. Nikitin, O.I. Lebedev, R. Retoux, D. Troadec, V. De Andrade, P. Roussel, C. Lethien, *Small* **18**, 2107054 (2022)
56. J.I. Hur, L.C. Smith, B. Dunn, *Joule* **2**, 1187 (2018)
57. K. Sun, T.-S. Wei, B.Y. Ahn, J.Y. Seo, S.J. Dillon, J.A. Lewis, *Adv. Mater.* **25**, 4539 (2013)
58. J. Yan, S. Huang, Y.V. Lim, T. Xu, D. Kong, X. Li, H.Y. Yang, Y. Wang, *Mater. Today* **54**, 110 (2022)
59. Q. Xia, F. Zan, Q. Zhang, W. Liu, Q. Li, Y. He, J. Hua, J. Liu, J. Xu, J. Wang, C. Wu, H. Xia, *Adv. Mater.* **35**, 2200538 (2023)
60. N. Fonseca, S.V. Thummalapalli, S. Jambhulkar, D. Ravichandran, Y. Zhu, D. Patil, V. Thippanna, A. Ramanathan, W. Xu, S. Guo, H. Ko, M. Fagade, A.M. Kannan, Q. Nian, A. Asadi, G. Miquelard-Garnier, A. Dmochowska, M.K. Hassan, M. Al-Ejji, H.M. El-Dessouky, F. Stan, K. Song, *Small* **19**(50), 2302718 (2023)
61. D.P. Finegan, M. Scheel, J.B. Robinson, B. Tjaden, I. Hunt, T.J. Mason, J. Millichamp, M. Di Michiel, G.J. Offer, G. Hinds, D.J.L. Brett, P.R. Shearing, *Nat. Commun.* **6**, 6924 (2015)
62. S. Moradi, E.S.G. Naz, G. Li, N. Bandari, V.K. Bandari, F. Zhu, H. Wendrock, O.G. Schmidt, *Adv. Mater. Interfaces* **7**, 1902048 (2020)
63. Y. Mei, G. Huang, A.A. Solovev, E.B. Ureña, I. Mönch, F. Ding, T. Reindl, R.K.Y. Fu, P.K. Chu, O.G. Schmidt, *Adv. Mater.* **20**, 4085 (2008)
64. Y. Mei, A.A. Solovev, S. Sanchez, O.G. Schmidt, *Chem. Soc. Rev.* **40**, 2109 (2011)
65. Y. Li, M. Zhu, V.K. Bandari, D.D. Karnaushenko, D. Karnaushenko, F. Zhu, O.G. Schmidt, *Adv. Energy Mater.* **12**, 2103641 (2022)
66. Z. Qu, M. Zhu, Y. Yin, Y. Huang, H. Tang, J. Ge, Y. Li, D.D. Karnaushenko, D. Karnaushenko, O.G. Schmidt, *Adv. Energy Mater.* **12**, 2200714 (2022)
67. F. Gabler, D.D. Karnaushenko, D. Karnaushenko, O.G. Schmidt, *Nat. Commun.* **10**, 3013 (2019)
68. J. Ma, R. Quhe, W. Zhang, Y. Yan, H. Tang, Z. Qu, Y. Cheng, O.G. Schmidt, M. Zhu, *Small* **19**, 2300230 (2023)
69. Y. Liang, Y. Yao, *Nat. Rev. Mater.* **8**(2), 109 (2022)
70. F.L. Cras, B. Pecquenard, V. Dubois, V.-P. Phan, D. Guy-Bouyssou, *Adv. Energy Mater.* **5**, 1501061 (2015)
71. X. Yue, A.C. Johnson, S. Kim, R.R. Kohlmeyer, A. Patra, J. Grzyb, A. Padmanabha, M. Wang, Z. Jiang, P. Sun, C.T. Kiggins, M.N. Ates, S.V. Singh, E.M. Beale, M. Daroux, A.J. Blake, J.B. Cook, P.V. Braun, J.H. Pikul, *Adv. Mater.* **33**, 2101760 (2021)
72. J. Biggs, J. Myers, J. Kufel, E. Ozer, S. Craske, A. Sou, C. Ramsdale, K. Williamson, R. Price, S. White, *Nature* **595**, 532 (2021)
73. M. Han, L. Chen, K. Aras, C. Liang, X. Chen, H. Zhao, K. Li, N.R. Faye, B. Sun, J.-H. Kim, W. Bai, Q. Yang, Y. Ma, W. Lu, E. Song, J.M. Baek, Y. Lee, C. Liu, J.B. Model, G. Yang, R. Ghaffari, Y. Huang, I.R. Efimov, J.A. Rogers, *Nat. Biomed. Eng.* **4**, 997 (2020)
74. B. Rivkin, C. Becker, B. Singh, A. Aziz, F. Akbar, A. Egunov, D.D. Karnaushenko, R. Naumann, R. Schäfer, M. Medina-Sánchez, D. Karnaushenko, O.G. Schmidt, *Sci. Adv.* **7**, eabl5408 (2021)
75. M. Li, A. Pal, A. Aghakhani, A. Pena-Francesch, M. Sitti, *Nat. Rev. Mater.* **7**, 235 (2022)
76. P. Rothemund, Y. Kim, R.H. Heisser, X. Zhao, R.F. Shepherd, C. Keplinger, *Nat. Mater.* **20**, 1582 (2021)
77. S. Kim, C. Laschi, B. Trimmer, *Trends Biotechnol.* **31**, 287 (2013)
78. K. Liu, Y. Jiang, Z. Bao, X. Yan, *CCS Chem.* **1**, 431 (2019)
79. J.C. Yang, J. Mun, S.Y. Kwon, S. Park, Z. Bao, S. Park, *Adv. Mater.* **31**, 1904765 (2019)
80. N. Matsuhisa, X. Chen, Z. Bao, T. Someya, *Chem. Soc. Rev.* **48**, 2946 (2019)
81. J. Park, D.B. Ahn, J. Kim, E. Cha, B.-S. Bae, S.-Y. Lee, J.-U. Park, *Sci. Adv.* **5**, eaay0764 (2019)
82. S. Zheng, X. Shi, P. Das, Z.-S. Wu, X. Bao, *Adv. Mater.* **31**, 1900583 (2019)
83. M.G. Say, M.J. Donahue, R. Kroon, M. Berggren, I. Engquist, *Org. Electron.* **115**, 106751 (2023)
84. C.A. Aubin, B. Gorissen, E. Milana, P.R. Buskohl, N. Lazarus, G.A. Slipher, C. Keplinger, J. Bongard, F. Iida, J.A. Lewis, R.F. Shepherd, *Nature* **602**, 393 (2022)
85. H. Song, G. Luo, Z. Ji, R. Bo, Z. Xue, D. Yan, F. Zhang, K. Bai, J. Liu, X. Cheng, W. Pang, Z. Shen, Y. Zhang, *Sci. Adv.* **8**, eabm3785 (2022)
86. X. Xia, J. Yang, Y. Liu, J. Zhang, J. Shang, B. Liu, S. Li, W. Li, *Adv. Sci.* **10**, 2204875 (2023)
87. X. Xiao, J. Yin, S. Shen, Z. Che, X. Wan, S. Wang, J. Chen, *Curr. Opin. Solid State Mater. Sci.* **26**, 101042 (2022)
88. J. He, C. Lu, H. Jiang, F. Han, X. Shi, J. Wu, L. Wang, T. Chen, J. Wang, Y. Zhang, H. Yang, G. Zhang, X. Sun, B. Wang, P. Chen, Y. Wang, Y. Xia, H. Peng, *Nature* **597**, 57 (2021)
89. P. Yang, J.-L. Yang, K. Liu, H.J. Fan, *ACS Nano* **16**, 15528 (2022)
90. M. Karami-Mosammam, D. Danninger, D. Schiller, M. Kaltenbrunner, *Adv. Mater.* **34**, 2204457 (2022)
91. C.A. Aubin, S. Choudhury, R. Jerch, L.A. Archer, J.H. Pikul, R.F. Shepherd, *Nature* **571**, 51 (2019)
92. J. Huang, P. Yu, M. Liao, X. Dong, J. Xu, J. Ming, D. Bin, Y. Wang, F. Zhang, Y. Xia, *Sci. Adv.* **9**, eadf3992 (2023)
93. N. Mittal, A. Ojanguren, M. Niederberger, E. Lizundia, *Adv. Sci.* **8**, 2004814 (2021)
94. N.T. Garland, R. Kaveti, A.J. Bandodkar, *Adv. Mater.* **35**(52), 2303197 (2023)
95. W. Driesen, A. Rida, J.-M. Breguet, R. Clavel, "Friction Based Locomotion Module for Mobile MEMS Robots," in *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems* (2007), pp. 3815–3820
96. M. Yu, Y. Peng, X. Wang, F. Ran, *Adv. Funct. Mater.* **33**(37), 2301877 (2023)
97. J.S. McCaskill, D. Karnaushenko, M. Zhu, O.G. Schmidt, *Adv. Mater.* **35**, 2306344 (2023)
98. D. Danninger, R. Pruckner, L. Holzinger, R. Koeppe, M. Kaltenbrunner, *Sci. Adv.* **8**(45), eadd7118 (2022). https://doi.org/10.1126/sciadv.add7118



Minshen Zhu moved to the Research Center for Materials, Architectures and Integration of Nanomembranes at Technische Universität Chemnitz, Germany, in 2022. He received his PhD degree from City University of Hong Kong in 2017. He subsequently joined the Institute for Integrative Nanosciences at Leibniz IFW Dresden, Germany, and led the research of energy storage at the microscale. Supported by European Research Council Starting Funding, his research activities aim to develop on-chip manufacturable dust-sized batteries for monolithic integration in intelligent microsystems. Zhu can be reached by email at minshen.zhu@main.tu-chemnitz.de.

Oliver G. Schmidt is a full professor for materials systems for nanoelectronics and scientific director of the Research Center for Materials, Architectures and Integration of Nanomembranes at Technische Universität Chemitz, Germany. He is an adjunct professor for nanophysics at Technische Universität Dresden, Germany, and holds an honorary professorship at Fudan University, China. He received his DrRerNat degree from Technische Universität Berlin, Germany, in 1999. His interdisciplinary activities bridge across several research fields, ranging from microrobotics and flexible electronics to microbatteries and biomedical applications. Schmidt can be reached by email at oliver.schmidt@main.tu-chemnitz.de.