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Soft robotics across scales: Fundamentals to applications

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As the name suggests, soft robots are recognized by their active "deformability" and passive "compliance". In comparison with their rigid-bodied counterparts, soft robots exhibit a library of unique and attractive characteristics, such as the compliant interaction with the environment, the resistance to damages and wear, the shape-morphing capability, the abundant degrees of freedom (DOFs), the ability to be controlled by non-electric signals, and the suitability for batch fabrication and minimization. Research efforts have been devoted to this field and a large variety of intriguing soft robots have been proposed. Some examples are octopus-inspired soft arms, hand-like soft grippers, skin-mimicking soft electronics, and shape-morphing miniature robots.

The recent emergence of novel soft materials and advanced fabrication techniques have spurred a new wave of rapid development of soft robots. In addition, the growing interest in miniaturized robots for healthcare, exploratory, and rescue applications has provided new opportunities to take good advantages of the traits of soft robots. Soft robots have become one of the most promising candidates to undertake the tasks at small size scales, where conventional mechanical components can no longer be utilized due to the difficulties in downscaling.

In view of the entrancing potential of soft robots in addressing real-world challenges, we have organized this special issue to include high-quality research, review, and perspective articles that study soft robots with a characteristic length ranging from meter to centimeter, then further down to millimeter and micrometer.

Meter

Most conventional rigid-bodied robots are at the meter size scale. In comparison, soft robots at this size scale excel as agile manipulators that could handle delicate and brittle objects, and also as an advantageous option to build safe interactions with humans. **Hao *et al.*** (doi: 10.1002/aisy.202300079) reported a tensegrity joint for low-inertia, compact, and compliant soft manipulators, aiming to reinforce the joint motion stability and enable self-contained sensing feedback. The proposed design avoids the requirement of complex kinematics modeling and sophisticated control model with sensing feedback. And the controller was trained with the proper joint configurations selected by a two-step sampling method.

Centimeter

Soft robots at the centimeter size scale have a perfect size to go inside human body via natural orifices and ducts. They are small enough to access inner cavities in a minimally invasive manner, while at the same time they are also big enough to conduct meaningful interventional operations such as biopsy and drug delivery. **Koszowska *et al.*** (doi: 10.1002/aisy.202300062) reported a pair of independently actuated soft magnetic continuum manipulators for bimanual operations in the same confined anatomical cavities. The developed bimanual system was deployed in the confined anatomy of a skull-base phantom to simulate minimally invasive ablation of a pituitary adenoma. **Zhang *et al.*** (doi: 10.1002/aisy.202300325) reported a flexible biopsy robot with force sensing for deep lung examination. By cooperating with commercial bronchoscope, the proposed robot can reach narrow areas of the lung to perform biopsy operations. Soft robots at this size scale could also interact with organs or parts of human bodies. **Lourdes *et al.*** (doi: 10.1002/aisy.202200465) reported a magnetically actuated variable stiffness manipulator based on deployable shape memory polymer springs. **Wang *et al.*** (doi: 10.1002/aisy.202300127) reported a wearable glove with electrothermal-controlled Ionogels for adhesive gripping.

Centimeter size scale also corresponds to many fishes and insects we see in our daily lives. These animals demonstrate excellent capabilities in navigating in cluttered spaces and performing challenging functions. Intrigued researchers aim to mimic these capabilities using similar sized soft robots and harness them for transformative applications. **Tan *et al.*** (doi: 10.1002/aisy.202300083) reported liquid superspreading on surface with microhexagonal structure inspired by rock-climbing fish. **Qu *et al.*** (doi: 10.1002/aisy.202300299) reviewed recent advances on underwater soft robots. **Hsiao *et al.*** (doi: 10.1002/aisy.202300059) reported modular and scalable fabrication of insect-scale aerial robots toward demonstrating swarm flights. This study substantially improves the fabrication scalability of subgram micro-aerial-vehicles (MAVs).

At this size scale, soft robots can also be made into robotic parts such as actuators, sensors, and color-shifting glasses. **Tang *et al.*** (doi: 10.1002/aisy.202300047) presented a review on

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high-frequency dielectric elastomer actuators (DEAs). **Mak *et al.*** (doi: 10.1002/aisy.202300082) reported intelligent shape decoding of a soft optical waveguide sensor. **Li *et al.*** (doi: 10.1002/aisy.202200415) reported switchable and tunable chemical/structure color in a flexible hierarchical surface.

Millimeter

Soft robots at millimeter scale have been widely acknowledged as promising devices to undertake minimally invasive diagnostic and therapeutic tasks. Because of their minute body size, these robots often do not carry onboard power sources, but instead they rely on active matters that respond to external stimuli, such as magnetic field, for wireless actuation and control. These magnetic soft robots have been found useful in some healthcare applications. **Sun *et al.*** (doi: 10.1002/aisy.202300092) designed magnetic hydrogel micromachines (MHMs) with active release of antibacterial agent for biofilm eradication. **Wang *et al.*** (doi: 10.1002/aisy.202300108) reviewed recent research results in magnetic control methods and diverse microrobotic applications of reconfigurable liquid-bodied miniature machines.

The fabrication of these magnetic robots remains as a challenge, especially when complex designs are desired. **Li *et al.*** (doi: 10.1002/aisy.202300052) reported a 3D printing platform to fabricate multilayer magnetic miniature soft robots with programmable magnetization. This study relaxes the constraint on the design space and enables the realization of complex robot designs. Beside fabrication, control of these untethered devices is also a challenge. **Liu *et al.*** (doi: 10.1002/aisy.202300325) reported a computer-aided teleoperation system for a stomach capsule robot. The developed teleoperation platform offers an intuitive virtual linkage between the user's inputs and the robot's actions, lowering the barrier for users to employ such novel robotic systems.

In addition to magnetically responsive materials, other stimuli-responsive materials could also be utilized to make soft robots at this size scale. A particularly interesting one is liquid crystal elastomer (LCE) that combines the anisotropy of liquid crystals with the elasticity of loosely cross-linked polymers. **Nemati *et al.*** (doi: 10.1002/aisy.202300054) reported a scalable, incoherent-light-powered, omnidirectional self-oscillator made of LCEs. And **Li *et al.*** (doi: 10.1002/aisy.202200402) proposed a novel operation mode of LCE actuators based on the wrinkling behavior of an LCE-elastomer bilayer architecture. Liquid-metal-based conductive ink were embedded inside the LCE as soft Joule heating element to enable electrical control. To contextualize these robots, **Li *et al.*** (doi: 10.1002/aisy.202300070) reviewed recent advances in 2D and 3D electrically driven soft actuators across dimensional scales.

Finally, to identify some common challenges found in various kinds of millimeter-scale soft robots employing different working principles, **Chi *et al.*** (article number 10.1002/aisy.202300063) presented a perspective on miniature soft robotics in terms of the actuation, fabrication, control, and application, and **Yong *et al.*** (doi: 10.1002/aisy.202300061) presented a perspective on bioinspired synergy strategies empower small-scale robots with higher performance.

Micrometer

Robots at micrometer size scale can interact with individual cells and organisms. A large number of soft robots at this size scale can be categorized as bio-microrobots, meaning that either they are biologically inspired to imitate biological systems, or they are bio-hybrid ones that combine motile micro-organisms or cells with functional components. **Wang *et al.*** (doi: 10.1002/aisy.202300093) reviewed the design principles, energy sources, and biomedical applications of existing soft bio-microrobots.

Although significant process has been made in soft robotics, there remains several grant challenges to be overcome in future. One is the lack of coordination between the development of new materials, fabrication methods, and control strategies. Many studies only focus on one aspect and lack considerations of the others, causing the developed soft robots unable to function as standalone systems. To bolster the convergence and co-development of these aspects, **Berrueta *et al.*** (doi: 10.1002/aisy.202300111) put forward a perspective on materializing autonomy in soft robots across scales. This perspective emphasized that researchers should use tasks alone to impose material and information constraints on soft robot design and proposed a conceptual framework for a task-first design paradigm that sidesteps limitations imposed by control strategies.

We hope that this special issue could bring knowledge, insight, and inspiration to readers of different background who share our interest in soft robotics. With a concerted effort made by researchers from copious fields and communities, we envision the growth of soft robotics will continue into the next decade at a breakneck pace, with many disruptive application-oriented, standalone soft robotic systems to be conceived and deployed for real-world tasks. Lastly, we thank all the authors for their valuable contribution and the editorial team of ***Advanced Intelligent Systems*** for their support.

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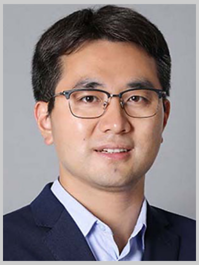

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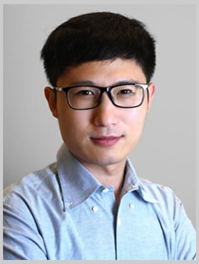

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