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ROADMAP

Soft robotics: what's next in bioinspired design and applications of soft robots?

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Abstract

The field of soft robotics has shown unprecedented growth in research efforts, scientific achievements, and technological advancements. Bioinspiration and biomimetics have played an instrumental role in the birth and growth of soft robotics. What is next for this field? To promote soft robotics research to the next level and have a broader impact in robotics and engineering fields, in this roadmap, we argue that two research directions should be strengthened (i) more structured, formal methods and tools for designing and developing soft robots and bioinspired robots (ii) more concrete applications of bioinspired soft robots in diverse sectors of human activities. This article provides a roadmap for the design of bioinspired soft robots, the integration of soft robot systems, and their applications in industry and services. Scientists and experts describe the state-of-the art and the perspectives of bioinspired, model-informed design of soft robots, outlining the challenges in developing complex soft robotic systems, and applications of soft robots in diverse fields.

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1. Introduction

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Soft robotics is currently undergoing rapid growth, driven by its potential to reshape various applications requiring compliance, adaptability, and versatility. This thriving field was born from and continues to be enhanced by bioinspired design, which draws on principles observed in animals to create more efficient, flexible, and capable robotic systems. As the field advances, we must ask the question: what's next in bioinspired design and the application of soft robots?

To explore this question, we invited scientists to provide overviews of the latest advancements and future directions across six typical subdivisions of bioinspired soft robotics. These areas represent the cutting edge of research, where innovation continues to push the boundaries of what soft robots can be.

Embodied intelligence refers to the concept that intelligent behaviour emerges from the dynamic interaction between an agent's physical body and its environment, where both physical interactions and informational processes play crucial roles in adaptive and functional motions. In their paper, Iida, Abdulali, and Hauser explore the close relationship between embodied intelligence and soft robotics, and analyse the current state of development and challenges from three key perspectives: behavioural diversity at the material level, structural complexity and design for emergence, and the emergence of distributed and hierarchical computation within soft robotic systems.

Metamaterials are engineered materials whose properties arise from their internal micro- or meso-structures rather than just their composition, providing unprecedented flexibility in the design of soft robots. In their paper, Wang and Liu examine the role of metamaterials in advancing soft robotics, focusing on programmable deformations, variable stiffness, and multifunctionality. They discuss current challenges and highlight future directions for the field.

Biohybrid robots are developed by integrating synthetic materials with living biological components, such as muscle tissues and cells. In their paper, Ricotti outlines the current development status and challenges from both basic science and technological perspectives, while also discussing future work to address these challenges.

Soft robots inspired by octopus tentacles offer promising solutions for minimally invasive surgery (MIS). In their paper, Cianchetti and Althoefer discuss the current status and challenges of octopus-inspired soft robots for MIS, focusing on issues including accurate positional control, sensor integration, achieving sufficient interaction forces, and miniaturization. They also highlight advancements in materials science, actuation technologies, soft sensors, and control algorithms in improving the performance of these robots.

Soft aerial robots offer promising solutions for environmental monitoring and sustainability. In their paper, Nguyen and Kovač outline the challenges in developing robots capable of multi-modal locomotion, soft manipulation, and collision resilience across different environments. They highlight advances that improve aerial robots' performance, and emphasize the use of biodegradable materials to reduce environmental impact.

Underwater walking soft robots offer advantages for seabed exploration, such as lower noise footprints, improved current resistance, and reduced energy consumption compared to traditional swimming robots. In their paper, Calisti discusses the current challenges and advancements in these robots, focusing on improving reliability, control algorithms, sensing capabilities, onboard processing, and achieving energetic and behavioural autonomy.

Through this collection of perspectives, we aim to provide a roadmap for the design of bioinspired soft robots, the integration of soft robotic systems, and their diverse applications in industry and services.

2. Soft robots and embodied intelligence: towards theory of embodied intelligence

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Status

Embodied intelligence research investigates intelligent adaptive behaviours of systems or agents that arise from their physical interactions with the environment. This is often, inspired by biological systems, in which embodied interactions occur over a large variety of scales in size and time, from molecular interactions in the cells to a large individual organism and groups of them, through fast chemical reactions, to phylogenetic evolution in the timescales of millions of years [1].

In the embodied intelligence research, the large diversity of physical interactions is regarded as the basis of systems' intelligent adaptive behaviours (such as locomotion, manipulation, social/group interactions in uncertain/unknown tasks-environments), and because of their dynamic nature, the dynamical systems approach is often employed for a systematic research bridging between physical and informational worlds [2].

In the physical world, behaviours can be described as dynamical systems realised in the forms of mechanical structures, material characteristics, and other physical properties (e.g. chemical and electromagnetical). This means behaviours are dictated by the laws of physics, including the rigid body dynamics such as inertial, resistive, and impact forces, that are well exploited for various intelligent functional motions. A famous example of this is a case study of a dead fish that is capable to swim upstream without any brain or muscle activities by its body simply reacting to the external flow forces [3]; Another mechanical case study, the so-called passive walker, shows that the pendulum dynamics of its legged structure can be exploited for down-hill natural bipedal walking without any actuation, sensing or control [4]. These case studies exemplified the importance of mechanical dynamics for the complex behaviours of animals and machines in the real physical world.

Behaviours of embodied systems can also be influenced by information processing of brains or controllers/computers. The swimming or walking behaviours above, for example, can be actively altered through neural/computational dynamics resulting in sensory-motor coordination for generating various gait patterns, or more general navigation through complex environments. These mechanisms of information processing are also studied by the embodied intelligence research community, as they cannot be regarded solely as computational processes in the abstract information paradigm, but many physical aspects of embodied systems play crucial role [5]. For example, for sensory information acquired through active motor coordination, it was shown that certain morphologies can give richer informational contents for efficient and effective decision making. This is known as information self-structuring through sensory-motor coordination [5]. Physical locations of sensory receptors, i.e. sensor morphology, play also an important role to provide more effective structures in sensor signals [6]; motor control can be significantly simplified or efficient when passive mechanical dynamics are properly exploited [7]; and physical dynamics of animal/robot bodies can also be used as the resources of computational functionality, often referred to as 'morphological computation' [8].

In this context, there is a considerable overlap in the research of embodied intelligence and soft robotics. The fact that soft robotics researchers investigate the dynamics of deformable materials to be used in autonomous robots, provides a common ground for mutual benefits in these two fields [9]. Previously a large number of research focused on how soft bodies can be used for passive dynamics of locomotion and manipulation robots for adaptive grasping of many complex objects in the physical world [10]. Soft functional materials are also used to demonstrate extensions of physical bodies, similar to biological body growth [10]. And the soft deformation can be also used as the resources of computational processes [11]. Many of these researches showed the conceptual design principles of embodied intelligence in both physical and information worlds in concrete engineering terms. Because of the intrinsic complexity of soft robots with a large (or infinity) degrees of freedom, these principles of embodied intelligence were particularly useful to effectively perform behavioural functions.

Current and future challenges

Researchers in embodied intelligence generally employ the synthetic methodology, i.e. the understanding-by-building approach, in order to gain further insights into biological systems in the form of theoretical models and design principles [12]. Some of the current challenges of embodied intelligence are centred around building methods of animal-like diverse and dynamic embodiment, and their interactions with complex environments, leading to the emergence of adaptive intelligent behaviours. In this context, soft robotics can provide unconventional bio-plausible body structures and mechanisms, which contribute to the systematic

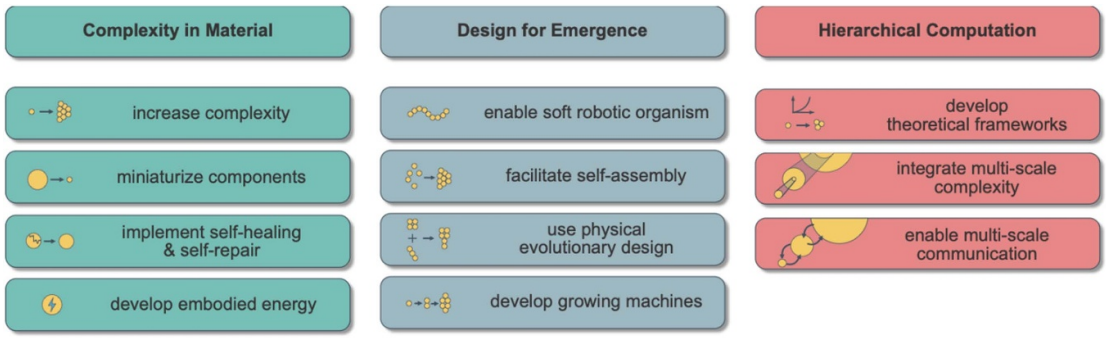

Figure 1. Research challenges in embodied intelligence for soft robotics.

investigations of high-level principles of embodied intelligence with concrete engineering case studies and practical applications. While there are many interesting and important overarching challenges in these two fields, this section summarises three research directions (see figure 1) that help us sketch subsets of problems and challenges that are related to each other with the long-term goals of embodied intelligence research.

Behavioural diversity at material levels

Each individual human consists of hundreds of muscles and bones, billions of neurons, and millions of millions of other kinds of cells, which are orchestrated into an organism surviving in the complex real world [1]. Complex body structures are pre-requisite for complex intelligent adaptive organisms. To understand the embodied intelligence in the complexity level of animals and humans by using the synthetic methodology, it is necessary to advance the material-level component technologies for sensing, actuating, and regulation of physical dynamics.

One of the most important challenges from this perspective is the miniaturization of sensors, actuators, and body structures. Technologies to obtain high spatiotemporal resolution in sensory information, integrated perception of multi-modal physical stimuli, while maintaining softness for versatile physical interactions with environments, are still lacking today. Soft actuators that are high-power density, while being robust and scalable, are probably an even more challenging problem. Beyond these sensing and actuation components, there are also a set of challenges to maintain the large complexity, such as technologies for self-repairing and self-healing materials [13], leading to the structural growth and evolution of sensor morphologies [6] and other embodied features. Energy supplies to the components and the entire embodied system can be regarded as material-level investigations of soft robotics, referred to as Embodied Energy [14].

Structural complexity and design for emergence

With miniaturized sensory-motor components being developed, the next challenge is to integrate them into a coherent structure of a 'soft robotic organism', that accommodates high-density sensory-motor components, while dynamically change at both component and system levels. The conventional piecewise manual assembly approaches of individual components have their own limitations, and we will need to develop automated and self-organizing assemblying and growth technologies.

Computational design optimization and computer-controlled manufacturing/assembly are the first technological steps to substantially increase the complexity level of integration. Computational optimization techniques such as evolutionary algorithms and Baysian optimization methods were used to explore design parameters of robot embodiment in the past [15]. These automated design methods, however, also need to consider physical implementation of manufacturing and assemblying. Multi-material 3D printing of various functional materials, and robotic assembly of components are being investigated for these reasons [16]. Self-assembly of more dynamic modules were also investigated through mechanical and material-based mechanisms such as soft modular robots, origami-/kirigami-based robots, pop-up structures, and structural growth by using 3D printing technology [17]. The design optimization through the large-scale physical experimentations became also feasible as the low-cost design iterations were made available [18]. As illustrated here, manufacturing and assembly methods will play essential roles to achieve higher-level integrations and, therefore, they are one of the central challenges in the embodied intelligence research.

In biology, animals are continuously exposed to the pressure of survival in which corresponding criteria can change dynamically. In such situations, systems need to deal with tasks and environments that are previously unknown or uncertain, and require a capacity to create solutions for survival

on the fly, which is referred to as 'design for emergence' [12]. Soft robotics can provide important perspectives for such requirements. On the one hand, miniaturized sensory-motor components enable systems to afford more redundancies in sensory-motor capabilities, for unexpected situations. More importantly, soft robots can grow their embodiment over time, just like many animals starting their lives smaller, lighter, and simpler, which then develop themselves into more specialized embodiment for demanding requirements later, which is usually called the developmental strategy of embodied agents [5, 10]. In addition, such growing capabilities have also been shown to accelerate and facilitate learning [19].

Emergence of distributed and hierarchical computation

The origins of biological computation mechanisms do not seem to be fully understood, as they are broadly and deeply rooted down in evolutionary, developmental, and neural processes, to name a few [20]. While these variations of computational processes are essential for complex large-scale intelligent autonomous systems in nature, we have so far a very limited knowledge about the what kind of computations can be implemented in the soft robots.

The main body of computation research in soft robotics lies in the control and learning of behaviours, such as motor control based on explicit or reduced-order modelling techniques [21], and state estimation and control of soft robots by using machine learning techniques [22]. These case studies illustrate the importance of significant computation for complex coordinated behaviours of soft robots, but computation in soft robots so far is almost always exclusively based on the conventional digital processes, very limited compared to the large diversity of computation mechanisms in biological systems.

In this context, there is an increasing interest of exploiting the dynamic characteristics of materials in soft robots for the purpose of computation, including those approaches based on fluid mechanics [23] and electrically conductive functional materials [24]. More generally, one of the main challenges in this strand of research is to develop a unified theory to systematically explain diverse mechanisms of computational processes. Since dynamic process are at the core of embodied intelligence (i.e. mechanical, chemical, electro-magnetic systems can all be described as such), a promising approach is to consider analog computation described in form of dynamical systems. A first step towards this has been made by providing theoretical models that explain how.soft bodies can be exploited as computational resources [8, 25], often referred to as 'physical reservoir computing' [26]. More importantly, the feasibility of this approach in real physical systems has been demonstrated as well, including the use of soft silicone-based octopus tentacles [11] for computation, soft spines for locomotion [27], and pneumatic arm for control [28].

While there are still many challenges to be resolved, this framework provides the first step towards how more complex computation can be achieved by exploiting dynamic embodiment. This, in turn, also indicates that the principles of how the physical dynamic body should be developed, in order to used them as a computational resource.

Concluding remarks towards theories of embodied intelligence

As illustrated in this article, the soft robotics research on the material-level autonomy, adaptability, and intelligence provides a fertile foundation for systematic research of embodied intelligence at various scales and in a wide range of domains. Although the main stream of current soft robotics research focuses on the design, fabrication, and control of deformable structures in robotic applications such as manipulation and locomotion, soft robotics needs to explore more fundamental challenges related to the self-organizing phenomena, that are comparable to biological systems, in order to significantly scale up the complexity of behaviours and functions.

For these broad spectrum of research challenges, more theoretical means are also required to explain the principles of dynamical systems exhibiting self-organizing complex structures and patterns of behaviours. Looking back in history, there have been many attempts to formulate biological self-organizing phenomena, including Ashby's principle of Requisite Variety to explain feedback/feedforward self-regulation [29], Bellman's principle of optimality proposing a formulation of simpler action sequences leading to globally optimal solutions [30], or more recently Friston's principle of Free Energy considering the information theoretic aspects of self-organizing information processing [31]. These fundamental theoretical questions need to be discussed in soft robotics research to bridge the gap of our more indepth understanding of embodied intelligence.

3. Metamaterials for soft robotics

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Status, Current and Future Challenges

Robots are multi-material systems that must leverage the properties of different materials to create functionality. Traditional robots realize their functions by connecting separate actuation and sensing modules to central computing units, in which each part is made from different materials and typically plays a single role. This modular assembly strategy has low manufacturing scalability, making it difficult to miniaturize these robots and integrate them in material-like systems [32]. In contrast, in soft robots whose functions and structures are highly integrated, one material may contribute to different functions, and one functions could rely on the properties of several materials. However, material properties are given factors in the design process, which are in general discrete and cannot be continuously selected. Such mismatch between demand and supply makes the design of soft robots unusually difficult, especially on the selection of materials. Therefore, if we can also design and fine tune material properties, we can then make the design of soft robots much easier. This can be done by means of metamaterials.

Metamaterials are structured materials whose properties arise from the selection of both their constitutive composition and underlying micro- or meso-structures [33]. The ability to control materials' properties via their architectures offers great flexibility in soft robot design [34]. By engineering and optimizing their architectures, metamaterials can achieve both high mechanical strength and low density simultaneously [35, 36], which is highly desirable for robotic applications. In terms of actuation, large and complex deformations can be tailored by designing the metamaterial structure [33, 34, 37, 38] (i.e. using origami folds or multistable structures), which is difficult to achieve with traditional rigid actuators. More importantly, the ability to manufacture these metamaterials with emerging additive manufacturing technologies allows the integration of multi-materials, various structures and functions into a monolithic body [39, 40]. The great challenge for soft robots, which is to create autonomous material-like systems, may be achieved with metamaterials that are multifunctional, adaptive, and responsive to environmental signals, similar to those observed in biological organisms.

Advances in Science and Technology to Meet Challenges

In this section of the roadmap, we would like to provide a perspective on advances in science and technology to meet these challenges in metamaterials for soft robotics: A. Programmable deformations and shape-morphing; B. Variable stiffness structures; and C. Integration of multifunctionality using metamaterials.

Programmable deformations and shape-morphing

Metamaterial provides a way to program nonlinear deformation of materials, which play the same role as gears and linkages in traditional robots for soft robots [34]. For example, metamaterial can be used to convert linear motion to rotary motion. Lipton *et al* [41] proposed a metamaterial with a helical microstructure that creates shear auxeticity and tunable stiffness. The property of handedness in shearing auxetics can be applied in designing soft robots that can bend or stretch in specific directions, which is useful for soft robots that need to perform specific movements or tasks, such as grasping or crawling. Heterogeneous metamaterial could further expand the range of types of nonlinear motion. Coulais *et al* [42] proposed a method for designing mechanical metamaterials as programmable shape-shifters using a combinatorial approach. By changing the microstructure of the material, the stiffness and other mechanical properties of the metamaterial can be changed, allowing for precise control over the deformation and movement of the soft robot.

Certain types of metamaterials have already been applied in soft robots for multimodal transformations through shape morphing. Origami and kirigami metamaterials have already demonstrated many successful applications [51]. Faber *et al* [43] drew inspiration from the way an earwig wing can fold in a predictable manner and combined this with the ability to bear weight and transform quickly through a design of bistable origami. The bistable origami is made of a combination of rigid plates and soft stretchable joints that can switch between two stable forms. In a separate investigation, Kamrava *et al* [52] used the Miura-Ori to create a robotic hand that uses a single-degree-of-freedom folding action to replace joints, which greatly reduces the structural complexity of robotic hand. To enhance the crawling abilities of soft robots, Rafsanjani *et al* [44] developed Kirigami structures inspired by snakeskin, which has special properties such as stretchiness, directional friction, and active anchoring. Metamaterials made with elastic beams that buckle under axial compression has also been used to trigger homogeneous and reversible shape transformations of soft robots. Liu *et al* [45] created a three-layered metamaterial composed of two active

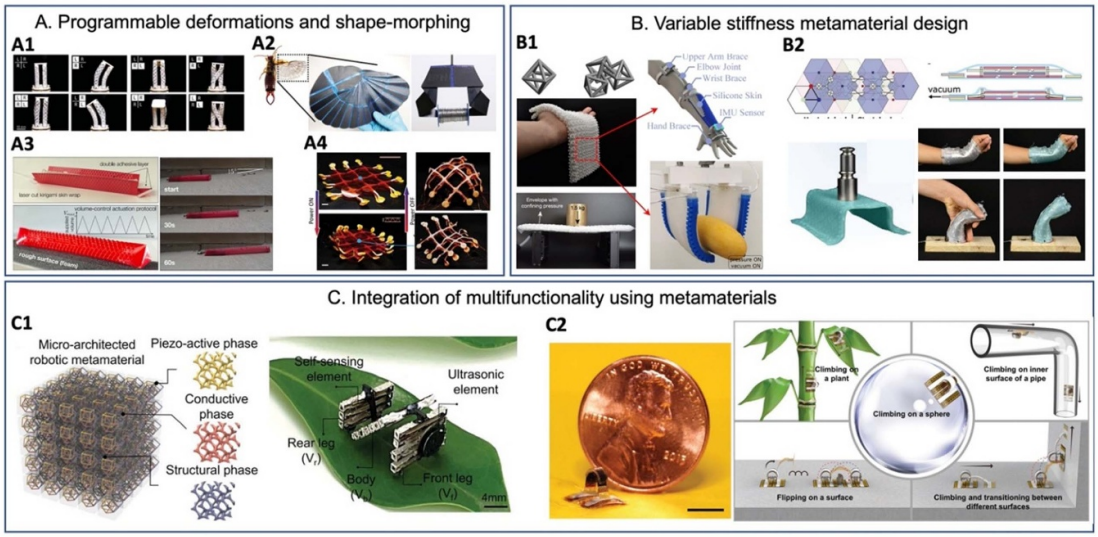

Figure 2. Metamaterials for soft robotics. (A) Programmable deformations and shape-morphing. (A1) Actuators made from handed shearing auxetics (HAS). Four HAS cylinders are combined to make a 4-degree-of-freedom actuator. Controlling the twist of each HSA allows the system to move up and down, side to side, and front to back and to twist left and right. From [41]. Reprinted with permission from AAAS. (A2) Spring origami inspired from warwig wing as multifunctional programmable folding, and a spring origami gripper application. From [43]. Reprinted with permission from AAAS. (A3) Kirigami-skinned soft crawler built by wrapping the kirigami skin around an actuator. The untethered soft crawler can climb a concrete ramp. From [44]. Reprinted with permission from AAAS. (A4) Robotic surfaces with reversible, spatiotemporal control for shape morphing driven by liquid crystal elastomers. From [45]. Reprinted with permission from AAAS. (B) Variable stiffness metamaterial design. (B1) Structured fabrics with interlocking architected particles have large stiffness variation under jamming transition. The tunable fabrics can be further made into wrist exoskeleton devices and variable stiffness soft grippers. Reproduced with permission from [46]. Copyright © 2021, The Author(s), under exclusive licence to Springer Nature Limited. © [2023] IEEE. Reprinted, with permission, from [47]. © [2023] IEEE. Reprinted, with permission, from [48]. (B2) Jamming skins consisting of a stretchable membrane and interleaved inextensible elements can control system rigidity from the surface by jamming. [49] John Wiley & Sons. © 2020 Wiley-VCH GmbH. (C) Integration of multifunctionality using metamaterials. (C1) Additive manufactured robotic metamaterials that can deform with multiple degrees of freedom, respond to electric fields with self-sensing and feedback control. From [39]. Reprinted with permission from AAAS. (C2) A soft microrobot with highly deformable 3D actuators that can climb and transit in complex surfaces and terrains. Reproduced with permission from [50]. Copyright © 2022 the Author(s). CC BY-NC-ND 4.0.

networks made of smart materials serving as artificial muscles, one passive network of beams serving as skeletons. Contraction of the artificial muscles drives the passive beams to buckle out-of-plane, and non-uniform contraction of the artificial muscles throughout the body of the soft robot leads to reversible and complex shape morphing. This is a great example of multi-material metamaterials with active constituents for soft robots, which mimics the structure of biological organisms.

Despite significant progress, substantial challenges remain in the application of programmable and shape-morphing metamaterials for soft robotics. One of the major challenges is the inherent material limitations and the scalability of manufacturing processes. Most current metamaterials are constructed from polymers or composites, which often exhibit limited durability and insufficient recovery speeds required for shape-morphing applications. Furthermore, scaling these structures down to micro- or nanometer scales for medical or swarm robotics, as well as scaling them up for use in aerospace or underwater applications, presents considerable difficulties. Future advances in the development of novel materials, such as nanocomposites or bio-inspired materials with enhanced resilience, flexibility, and tunability, are critical. Integrating these materials with advanced manufacturing techniques, such as 3D/4D printing, could enable the creation of multi-scale hierarchical designs that maintain functionality across a wide range of scales.

Variable stiffness metamaterial design

Variable stiffness mechanisms are highly important in soft robotics, as the robot needs to be compliant and flexible during large deformation, but also needs to be stiffened to perform useful functions, output work, or protect their internal bodies. Smart materials that can change and adapt their stiffness have been widely explored. These include hydrogels that respond to temperature, pH, light and water content; shape memory alloys and polymers; liquid crystal elastomers (LCEs) that respond to temperature and light; and magnetorheological (MR) or electroactive polymers (EAPs). These materials, however, are either mechanically too soft for robotic applications (hydrogels), require large temperature changes (LCEs) and actuate slowly, need re-programming at high temperatures (SMAs and SMPs), or require strong electromagnetic fields (MR materials, EAPs),

which are not easily accessible in most practical scenarios.

An emerging technology to achieve variable stiffness in robotics is to use layered or discrete metamaterial design and utilize their jamming transition. Jamming is a physical phase transition in which aggregates of solid discrete particles or stacked layers switch from a compliant soft state to a solid-like rigid state, with a small increase of packing fraction controlled by the boundary confinements [53–56] This type of transition is extremely useful for robotic applications, since the soft unjammed state allows safe interactions with soft bodies such as humans, while the stiff jammed state provides load bearing capacity and protection on demand. In contrast to previous studies on jamming that focused on disordered systems with irregular particle shapes [53–55],Wang *et al* [46] recently demonstrated that the macroscopic mechanical behaviour of jammed particles can be tailored by the microscopic particle architecture. In this work, by designing architectured particles as building blocks, a metamaterial type interlocked fabric is designed and manufactured using selective laser sintering technology. The resulting fabric is lightweight, highly conformable in the soft state, and can stiffen significantly to provide protection or support. The fabric is further explored as robotic grippers, manipulators, and wearable exoskeletons [47, 48]. In addition, structured layer or laminar structures have also been explored on their jamming transition. Shah *et al* [49] created a scale like metamaterial skin that can conform to various target geometries and jam into the shape to provide protection. Compared to continuum metamaterials, this discrete type of metamaterial structure design may have huge application potential in soft robotics, since their degree of deformation is no longer restricted by continuum material elasticity limit and their stiffness can be easily tuned via jamming.

A major challenge in the application of variable stiffness metamaterials is the limited range of stiffness modulation. Most existing materials provide only a narrow stiffness range, restricting their utility in practical engineering applications. Future advancements must focus on developing metamaterials with a broader variable stiffness range, capable of transitioning between soft and rigid states rapidly and with minimal energy input. Additionally, current variable stiffness metamaterials are often incapable of shape-morphing and require the integration of external actuators for functionality. However, combining stiffness modulation with actuation in a compact, efficient design remains challenging, as it typically necessitates additional components that increase weight and control complexity. A promising future direction involves designing variable stiffness metamaterials that can concurrently morph shape within a compact structure [57]. Finally, inspiration from biological systems, such as the natural stiffness modulation seen in the armadillo's shell, could provide valuable insights into developing more efficient and adaptive metamaterial designs.

Integration of multifunctionality using metamaterials

Advanced manufacturing of multi-materials with programmed functions in a tightly integrated body without mechanical failures or delamination, which mimic biological organisms, has long remained a challenge. In contrast, biological organisms typically exhibit tight integration of functionality into compact volumes [32]. For example, the octopus' arms integrate sensors, muscles, and nervous systems into autonomous material-like systems that can change shape and stiffness in response to the environment. Scorpions and spiders have rigid structured skeletons or shells connected with soft materials (i.e. muscles and skins) for integrated shape transformation, sensing and feedback [58]. Integrating robotic functions into intelligent metamaterials mimicking biological systems is highly desirable, as it eliminates the potential mechanical mismatch and delamination of separately bonded actuator, sensor, and computation components which have very different mechanical properties, while significantly improving manufacturing scalability.

To integrate multifunctionality into soft robots with metamaterials, Xiao *et al* [59] reported an electrically driven soft robots capable of executing various types of biomimetic locomotion. The soft robots integrate smart material and elastic film. Contraction of smart materials can cause robots' bending and twisting, which allows soft robots to achieve multifunctionality such as complex shape morphing, self-locking grippers, crawling and walking. Pang *et al* [50] developed a multi-gait, soft microrobot which can climb on surfaces with diverse shapes and transition between two distinct surfaces. The microrobot consists of morphable footpads and body that can bend to conform to different curved surfaces and stiffness-variable smart joints that allow different locomotion gaits in a single microrobot. The utilization of the same metamaterials in different parts of the soft robot makes the best use of the properties of the metamaterials and reduces the complexity of the structure. Hao *et al* [60] designed a multistate switch based on metamaterial and Kirigami structures. The swelling metamaterial strips buckle out of plane with large amplitude to achieve three-dimensional deformation, and rotation of the upper floor is realized by designing chiral pattern of gel strips. Multistate switch demonstrates metamaterial's multi-stable morphing capability in soft robots. Alapan *et al* [61] introduced a heat-assisted magnetization to encode reprogrammable shape-morphing instructions into magnetic soft machines. These magnetic soft machines demonstrate reconfigurable mechanical behaviour, tunable locomotion of surface-walking, and adaptive grasping through different external magnetic field

application and metamaterial arrangements. This discretization design scheme and metamaterial application establishes a rich design space and mass-manufacturing capability for multiscale and reprogrammable soft machines. Li *et al* [62] developed an untethered soft robot for deep-sea exploration. Metamaterial is applied to drive this soft robot fish's flapping behaviour and successfully actuates at over 10 000 m deep-sea. This research result shows the potential of metamaterials for applications in extreme conditions. Cui *et al* [39] designed and manufactured robotic metamaterials capable of motion with multiple degrees of freedom, strain amplification in response to electric fields, and programmed motions with self-sensing and feedback control. The created metamaterial acts as proprioceptive microrobots that can actively sense and move.

The integration of multifunctionality into soft robotics is inherently complex, requiring precise control over material composition, structure, and geometry. This necessitates advancements in manufacturing technologies, such as multi-material 3D printing and microfabrication, to enable the production of multifunctional metamaterials. Research into scalable manufacturing techniques is also critical for the widespread adoption of these technologies. Modular design approaches, in which individual functional metamaterials or components are fabricated separately and assembled into the final robotic structure, offer another promising direction.

In addition to manufacturing challenges, multifunctional metamaterials require various energy inputs—such as electrical, thermal, or magnetic stimuli—to activate different functions, which poses significant challenges in energy management and efficiency. The development of self-powered metamaterials or those with integrated energy-harvesting capabilities could help address this issue.

Finally, managing multiple functions simultaneously demands sophisticated control systems, particularly when tasks such as locomotion, sensing, and manipulation need to be performed in real time. Adaptive control systems that leverage machine learning algorithms can optimize the coordination of multiple functions by learning from the robot's interactions with its environment. Furthermore, closed-loop control systems that use real-time data from embedded sensors to dynamically adjust stiffness, shape, and movement could significantly enhance the robot's performance and versatility.

Concluding Remarks

In summary, these mentioned works demonstrate the great potential of integrating multi-materials and multifunctionality into soft robots with metamaterial design and additive manufacturing technologies. Indeed, future soft robotics development requires interdisciplinary efforts and collaborations from various fields including metamaterial design, advanced manufacturing, smart responsive materials, robotic sensing and control, *etc*. By coupling the different functions with closed-loop feedback, we will be able to achieve intelligent robotic metamaterials, mimicking the fast reflexes and adaptation mechanisms of biological organisms. This area of research has great potential in creating the future generation of intelligent robotic systems, with great potential in wearable robotics, micro- or nanoscale robots, surgical robots, *etc*.

4. Biohybrid for soft robotics; what should happen for biohybrid materials to benefit the soft robot designing?

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Status

Biohybrid technologies rely on the intimate interaction between living cells/tissues and artificial materials/mechanisms. Such an exciting alliance paves the way for functionalities that are currently precluded to entirely artificial machines [63].

The biohybrid robotics field dates back to 2004 when Herr and Dennis proposed a swimming robot actuated by two explanted frog semitendinosus muscles powered through a high-glucose medium in which the robot was immersed. The robot swam for 4 h over a 42 h lifespan, over which its performance gradually degraded due to the lack of the crucial interfaces (vascular, neural, etc) available *in vivo* [64].

This pioneering step showed the possibility of using biological materials as controllable components of robots to execute specific tasks. It launched an exciting perspective, namely exploiting the unique properties of living tissues, refined over millions of years of natural evolution, for engineering purposes. The key muscle properties that make it attractive for applications in robotics are: high scalability, performance invariance from the macro- to the micro-scale (down to the cell dimensions), chemical fuelling (thus avoiding the need for batteries, which are hard to scale down in size), stiffness control by recruiting a variable number of myofibers, intrinsic silence during operation, self-healing properties, degradability, and eco-compatibility.

However, the community soon realized that the top-down approach proposed by Herr and Dennis could not guarantee the long-term stability of explanted mature tissues. A bottom-up approach instead, in which single cells are organized to form a functional tissue, built around artificial components, has been soon considered the winning one. Unfortunately, such an approach is much more complicated and requires harnessing the secrets behind tissue biophysics and those behind the embryogenesis process (or at least part of it), to develop a fully mature and stable living tissue starting from single (stem) cells. Thus, in the following two decades, efforts focused on this challenge. Some key milestones in this journey are briefly described below.

A series of swimming biohybrid devices based on cardiomyocytes have been proposed starting from 2007, first based on simple thin films [65], then inspired by a jellyfish [66], a ray [67] and a fish [68] (figure 3(a)). Although grounded on the same paradigm (elastomeric substrates coupled with beating cardiomyocytes), these systems progressively improved in terms of controllability. They evolved from continuously self-beating cardiac cells (hard to control) to optogenetically modified ones (partly controllable through light pulses).

In parallel, other groups aimed at differentiating myoblasts into mature and functional skeletal muscle tissues (easier to control), and exploiting them to power robots. Despite several efforts in this field, only in the last decade appreciable forces and robot movements have been obtained. Additive manufacturing technologies started playing an important role, with several examples of 3D-printed biohybrid machines capable of exerting increasing levels of stress and driving robot locomotion [69, 70] (figures 3(b) and (c)). Morimoto and colleagues showed the potential of an antagonistic pair of skeletal muscle tissues assembled in a biohybrid gripper used for pick-and-place manipulation of objects [71] (figure 3(d)). Optogenetics and wireless power transfer enabled remote and battery-free control of skeletal muscle-based biohybrid devices [72].

In this research arena, it is worth also mentioning insect cell-based systems, which tolerate higher fluctuations in temperature, osmolarity, oxygen availability and pH with respect to those based on mammalian cells [73], and micro-scale bacteria-based biohybrid machines, which have been proposed for navigation in the human vasculature and targeted therapies [74].

This field is in a flourishing period at present, with intense research activities focused on different aspects. More and more, governments and funding agencies bet on biohybrid technologies, which are increasingly recognized as possible game-changing actors in robotics.

Current and future challenges

Biohybrid materials are riding an exciting wave of interest in the robotics community. However, to bring concrete benefits to the design of advanced soft robots, they need to overcome some challenges, both from a basic science and a technology development viewpoint.

Pieces of basic knowledge concerning epigenetic phenomena driving stem cell differentiation are still missing. This is particularly true in the case of human pluripotent stem cells. Although the differentiation process of skeletal muscle precursors (myoblasts) has been reasonably established in murine models and other relatively simple immortalized cell lines, further efforts are needed to fully understand how human induced pluripotent stem cells (iPSCs) and other stem cell types can reach the final muscle maturation stages, possibly in co-culture with other cells (e.g. neural cells, fibroblasts, etc) [75]. This may have a twofold impact: (1) iPSCs would open a series of

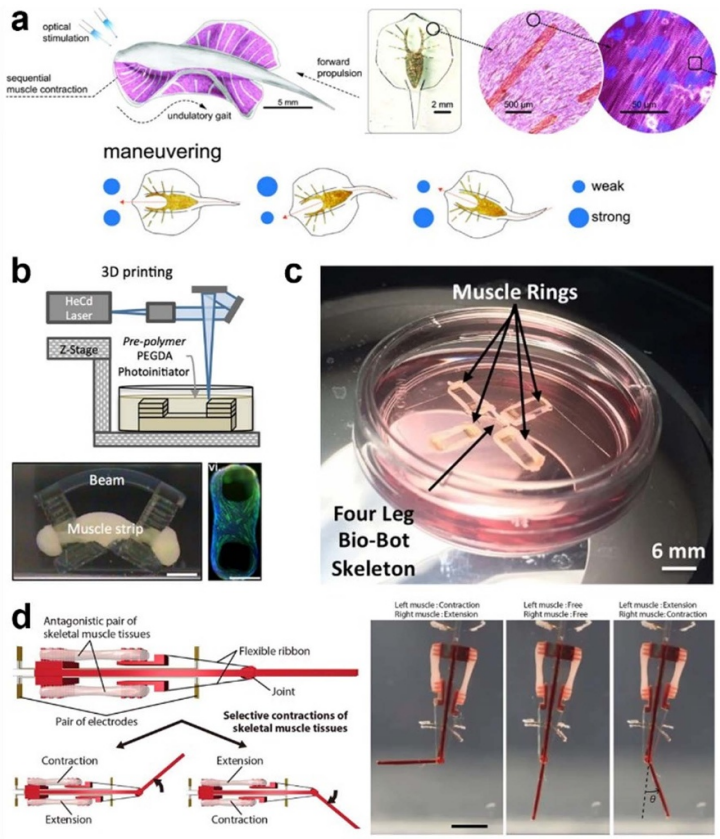

Figure 3. Examples of biohybrid machines described in the state-of-the-art: (a) biohybrid ray powered by optogenetically modified cardiomyocytes, enabling maneuvering through light pulses. From [67]. Reprinted with permission from AAAS.; (b), (c) biohybrid robots based on contractile skeletal muscle tissues and obtained through additive manufacturing technologies. (b) Reproduced from [69]. CC BY 4.0. (c) Reproduced with permission from [70]. Copyright © 2025 National Academy of Sciences. All rights reserved.; (d) biohybrid gripper based on agonistic and antagonistic skeletal muscles controlled by electrodes integrated into the system. From [71]. Reprinted with permission from AAAS.

biomedical applications for biohybrid soft robots, since they would allow using the own patient's cells to build them, avoiding rejection risks; (2) fully differentiated iPSCs may be much more stable over time than immortalized cell line-based counterparts.

A similar gap affects the entomology field. On the one hand, the knowledge of the precise processes driving the differentiation of insect embryonic stem cells into functional muscle tissues is largely unknown. On the other hand, a few species have been studied as possible sources of cells for biohybrid devices. For example, some insects can recover from temperatures well below 0 °C, as their myocytes tolerate extreme temperatures [76], but they have never been explored for building biohybrid machines. These and probably other species, still unknown, could avoid the need for life-sustaining systems, as they autonomously withstand extreme and rapidly changing environmental conditions. Furthermore, a series of technologies will also be necessary to improve the fabrication of large-scale contractile muscle tissues. This involves not only the synthesis of appropriate materials (e.g. hydrogels hosting cells, driving their spatial organization and supporting their functions), but also the fabrication of a vasculature system. Indeed, blood vessel-like structures would guarantee an appropriate transport of nutrients and waste in 3D tissues, thus supporting their metabolic requirements.

Among the technological challenges, controllability also has an important role. Muscle tissue contraction can be controlled using electrical pulses to depolarize myotubes. However, this strategy has drawbacks, such as electrolysis risks, bubble formation, electrochemical cell damage, and the need for on-board electrodes and batteries to produce the stimulus. Optogenetics allows turning the cells into light-triggerable ones, keeping the optical triggering source external to the biohybrid unit. This strategy must also evolve to enable the independent control of multiple degrees of freedom, e.g. exploiting different wavelengths acting on different bioactuator parts. Light attenuation in specific environments, e.g. the body tissues, must be also addressed.

Another essential technological challenge concerns the development of reliable life-sustaining systems. This is particularly relevant in the case of biohybrid systems based on mammalian cells, which need precise environmental conditions to operate

correctly (37 °C, accurate CO_2 and pH levels, frequent nutrient exchange, etc). To move from research prototypes working in laboratory conditions (incubators) to systems integrated into soft robots working in the real world, ad hoc bioreactors will be needed. They need to be light, highly deformable to not hamper muscle contraction, but at the same time they must guarantee cell-protecting and feeding functions. This issue is still largely unsolved.

Advances in science and technology to meet challenges

Enormous steps have been taken in the last few years concerning knowledge of how stem cells organize into complex tissues during embryogenesis. However, due to ethical concerns, our detailed understanding of the biological processes occurring in a human embryo is still limited to the initial weeks [77]. Fully unveiling all steps bringing to organogenesis seems a rather far perspective. However, to develop efficient and stable biohybrid machines, only part of this knowledge will be needed. To fill the knowledge gap currently affecting this field, indeed, scientific advancements should focus on identifying the most effective combination of stimuli capable of driving the differentiation of myoblasts, possibly in co-culture with a few other cell types, into phenotypically and functionally mature muscle tissues. These stimuli include biochemical, biomaterial-related ones (stiffness, surface chemistry and topography) and external biophysical ones (electric and magnetic stimulation, mechanical traction, ultrasound stimulation, optical stimulation and fluidic perfusion). A systematic exploration of all possible stimuli combinations is a demanding task, and it should be repeated for each muscle cell type (human myoblasts, insect ones, etc). However, the field can enormously benefit from recent and continuously growing industrial efforts in the area of cultured meat [78]. In fact, although companies are performing only part of the above-mentioned systematic exploration, their effort to achieve mature muscle tissues for business-oriented purposes will be precious to get important hints and to reduce the complexity of this analysis. Furthermore, artificial intelligence is increasingly emerging as a tool that can dramatically help the field of tissue engineering and regenerative medicine, avoiding just relying on experimental efforts and trial-and-error approaches [79].

To tackle the fabrication of large-scale engineered tissues, 3D bioprinting undoubtedly plays a primary role [80]. This bio-applied additive manufacturing technology promises to selectively organize cells, point-by-point and layer-by-layer, shaping the construct according to the desired criteria. Although exciting, this technology still needs improvements. First, advances will be required concerning bioinks, namely the materials in which cells are immersed and printed to achieve the final construct. The ideal bioink must match physical, mechanical, and biological properties. It is currently hard to match all these specifications using the currently available hydrogels. Novel composite bioinks exploiting the strength points of different materials will probably constitute an essential step ahead. Supramolecular hydrogels also represent a promising route. Sacrificial material-based extrusion bioprinting allows the fabrication of vascular networks (macro-constructs with internal voids). However, there is still a considerable difference between such permeable tubular structures and natural blood vessels. Future advancements should thus target micro-to-large vascular networks reflecting the complex and hierarchical natural vascular tree, also promoting the creation of endothelial cells- and pericytesbased vessel inner surfaces, through the use of appropriate cells and growth factors. This will require a synergistic effort in which both printable materials and fabrication technologies should evolve in parallel to match those requirements. Finally, in the bioprinting of skeletal muscles, anisotropic alignment of cells during printing is also a challenge, which should see a balance between cell safety and means to promote its alignment (e.g. high shear stresses applied during the process, or micro/nanofibrous structures embedded in the bioink providing topographical cues).

Gene editing is a tool with enormous potential in several fields [81]. No gene editing techniques have been proposed for biohybrid soft robots so far, but this field may enormously benefit from this approach. CRISPR-Cas9 (figure 4(a)) or similar techniques may allow obtaining muscle tissues that are more resilient to external environmental changes or that carry additional functionalities not guaranteed by non-modified biological tissues.

Concerning controllability, electrically triggered biohybrid robots may evolve by targeting wireless energy transfer, as recently proposed [85]. Optical triggers should also considerably advance. First, overcoming the complications of optogenetic techniques: membrane-targeted azobenzene molecules, for example, constitute an exciting perspective for non-genetic optical cell triggering [82] (figure 4(b)). On-board optical triggering systems raise the need for high integrability, portability, and low power consumption. Advances in stretchable electronics can lead to thin, flexible, lightweight and ultra-low-power light-emitting diodes or similar optical triggering units, fully integrated into the constructs, and appropriately patterned thus to selectively activate single muscle bundles. When inbody applications are targeted, a viable option to deal with light attenuation is to design dedicated miniaturized technologies (e.g. tiny optical fibres) that can bring the light to the

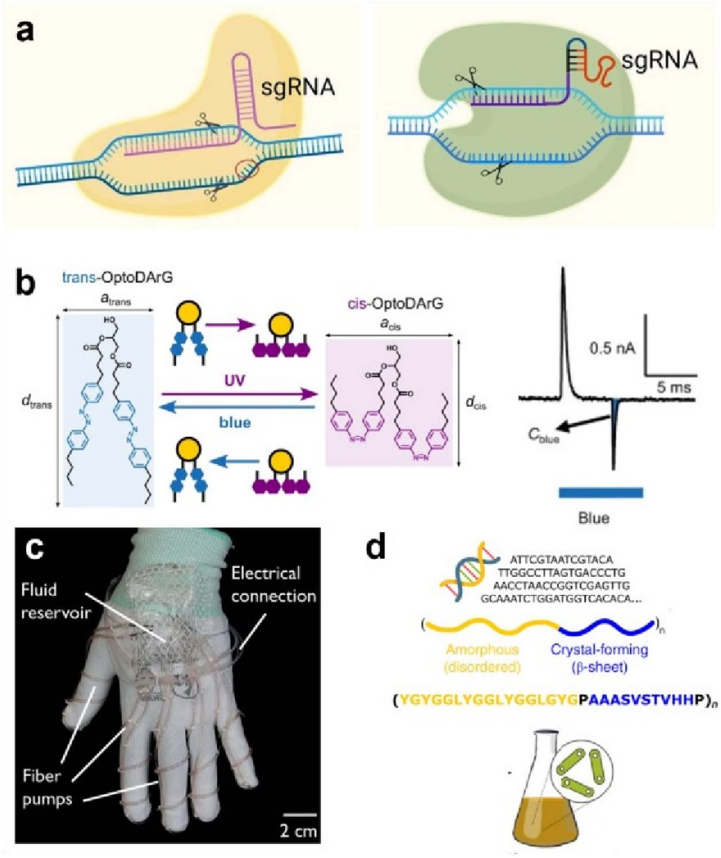

Figure 4. Examples of scientific and technological advancements that may play a crucial role in the future development of biohybrid machines: (a) depiction og gene editing tools. From [67]. Reprinted with permission from AAAS; (b) formula of the photolipid OptoDArG and its depolarization action on HEK cells. Reproduced from [82]. CC BY 4.0.; (c) haptic glove provided with a wearable soft fluidic system. From [83]. Reprinted with permission from AAAS.; (d) depiction of the design of a squid-inspired master sequence, and corresponding biosynthesis of protein libraries leading to protein-based functional self-healing materials. Reproduced from [84], with permission from Springer Nature.

target area, while still pursuing a minimally invasive paradigm.

To enable lightweight, integrable and sensorized life-sustaining systems, stretchable electronics should again play an important role. Patterned liquid metals, graphene and other materials raise high hopes in this framework. Similar considerations can be made for soft and stretchable fluidic systems [83] (figure 4(c)). Bioreactors for tissue engineering do not match, at present, the requirements set for their possible integration in biohybrid machines. However, key technologies are reaching a good level of maturity, and this challenge could be addressed in the near future.

Both triggering units and life-sustaining systems constitute miniaturized mechatronic devices that require an energy supply. Thus, technological advancements in the field of biohybrid machines should also focus on novel powering strategies. Biohybrid soft robots may be equipped with advanced miniaturized solar panels, metal-air batteries, or entirely novel powering units, still to be devised.

Concluding remarks

Bioinspiration has proved to be an effective paradigm for the design of soft robots. However, a complementary and synergetic strategy is represented by biointegration, namely the use of biohybrid materials that exploit the unique features of living cells and tissues to enable robot functions. Since the first attempts of lab-scale prototypes two decades ago, this field has now evolved rapidly and holds great promise for soft robot evolution. However, crucial challenges still need to be addressed, with a necessarily highly interdisciplinary approach. Living muscle-based biohybrid actuators represent a possible game-changing technology to drive soft robot movements, as they guarantee lifelike behaviour, high energy density, silent operation, self-healing properties, and other intriguing features. However, exciting examples of biohybrid sensors, biohybrid power units, and

biohybrid computation units have also been recently proposed. These technologies will evolve in synergy with other promising innovations from a materials science viewpoint, such as biosynthetic self-healing materials, e.g. proteins consisting of segmented amino acid sequences expressed in genetically modified host organisms, to develop protein-based functional materials with programmable properties [84] (figure 4(d)). Overall, these elements may constitute a series of constitutive bricks that will enable chemically powered, fully biodegradable, and highly biointegrated soft robots with unprecedented performance and properties in the near future.

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5. Octopus-inspired soft robots for MIS

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Status

Current surgical robotic systems are generally made of rigid components—laparoscopic tools combined with traditional robotic arms. There are now several robot-assisted surgical systems on the market, of which Intuitive Surgical's da Vinci system is the most widely used in clinical practise. It has been refined over the years, and now boasts intuitive tele-operation position control to counter the motion reversal problem caused by the pivot point created at the trocar port. Other features include tremor filtering and high-res stereo vision as well as its capability for on-the-job training of novice surgeons through a secondary console. Despite considerable competition, this system still dominates the robot-assisted MIS (RAMIS) market.

Soft tentacle-like structures have also been considered as a potential approach to RAMIS. The first large-scale research project on soft robots for MIS was EU Project STIFF-FLOP (2012–2015). The project set out to develop novel solutions based on the biological role model provided by the octopus [86]. Soft robot arms were created and adapted for MIS with the help of expert surgeons. The project concluded with a study in human cadavers [87], setting a new benchmark and representing a milestone for soft robotics in MIS [88]. Since then, several octopus-inspired robotic systems have been developed, generally using silicone rubber structures, with internal air chambers for actuation, bending and navigation [89]. Flexible continuum and snake-like robots (or variants of these concepts) have also made significant progress [90, 91], although all are still confined to the research lab.

Current and future challenges

The main challenges for soft robot use in MIS applications are:

- Accurate positional control
- Integration of sensing capability (position, force)
- Sufficiently high interaction forces
- Miniaturization

Positional control: given their highly compliant nature, soft robots exhibit nonlinear motion behaviour in response to external forces experienced. These can be caused by physical interaction with the environment, grasped payload or gravity. In contrast, robotic arm structures made from rigid components are virtually unaffected by external forces. Robots made from soft materials, especially those that aim to emulate the highly dexterous motion capabilities of the octopus, deform in difficult to predict ways when physically interacting with an unstructured environment, and standard kinematic models fail to provide adequate position control. Current approaches heavily rely on tele-operational approaches in which an operator controls the robot in a closed-loop control scheme with a camera providing the necessary feedback. More advanced methods using data-driven/learning methods are currently being developed to provide reasonable estimates for the inverse kinematics of soft robot arms when operating in free space; however, challenges remain when the environment is more complex [92, 93].

Sensor integration: there are countless sensors suitable for traditional rigid-component robot arms, including those that measure position and force. Although proven to be very useful for traditional rigid-component robots, these sensors are not suitable for soft robots because they themselves are made from rigid materials and would significantly compromise the most desirable feature of the soft robot: its compliance. The current challenge is to develop soft sensors capable of measuring important parameters such as position and interaction force—a challenge heightened by the fact that these two parameters are tightly coupled in soft structures. By way of example, the tip position of a soft robot arm is not only a function of the actuation but also of the forces imparted onto the robot arm through interaction with the external environment. It is therefore difficult to discern whether a robot is in a certain position because of the actuator output or because it has been pushed by an external force into this position, or indeed a combination of the two [94]. Current work is focused on the development of soft sensors, such as e-Gain, capacitive, fibre optics, including fibre Bragg grating (FBG), or magnetic. These sensors can be integrated into soft structures without significantly compromising compliance. Bending sensors (e.g. based on optic fibres) can be used to determine the shape of a soft robot structure and its configuration then computed [95]. Soft capacitive sensors using soft conductive materials (e.g. graphite inside a layer of silicone) can be used to measure imparted forces, by relating the changes of the capacity of these deformable sensors to the forces applied. To address the remaining challenges (low accuracy, high noise levels, impact on stretchability—as when using optic fibres), and the decoupling of force from position, we

can take inspiration from the octopus with its multitude of sensor nerves throughout its arms [96].

Interaction with the environment: one of their greatest assets—compliance when interacting with the environment can, at the same time, be a major drawback. Procedures such as tissue retraction and dissection require a degree of force, yet soft robot arms, made from pneumatically actuated silicone are often incapable of achieving the requisite tip forces. Research is ongoing in this area and octopus-inspired robots that can change the stiffness of their tentacle limbs are in development. One approach uses granules integrated into chambers inside the robot limbs that can be jammed under negative pressure to produce a stiffening effect [97]. This, in turn, enables the robot to apply higher forces onto its surroundings. The main downside to granular jamming is the quantity of granules necessary to achieve significant stiffening and the consequent reduction in dexterity and compliance. This is why, more recently, layer and fibre jamming have been identified as alternative solutions and further investigated [98].

Other approaches involve the incorporation of inextensible fabric or polyethylene sheets in the structure of the robot limbs. Such structures are highly flexible and compliant when partially inflated; however, their stiffness increases with rising pressure. At high chamber pressure, considerable stiffness can be achieved in inflatable structures made from inextensible sheets, outperforming silicone rubber limbs which suffer from ballooning at high pressures [99]. In an attempt to take bio-inspiration even further, inflatable endoscopes made from fabric have been paired with tendons for navigation, allowing a limb to reach a desired location in space whilst concurrently controlling its stiffness [100].

Miniaturization: achieving miniaturization in soft robotics remains a complex challenge. While the manufacture of small-diameter laparoscopic and endoscopic tools using rigid materials can be easily accomplished, a number of technological hurdles would need to be overcome in order to create small-sized robotic limbs from soft materials. Researchers are exploring a range of approaches, including the use of microfabrication, rapid prototyping techniques and the development of new materials. The successful miniaturization of soft robotic components could open up new possibilities for medical interventions.

Advances in science and technology to meet these challenges

Soft robotic solutions potentially offer many advantages but are themselves reliant on developments and advances in related technologies. One such example is its reliance on structural compliance (1/k) that can be achieved with materials with high softness (low Young's modulus, such as elastomers), or high slenderness ratio (L/A). If we consider the fluidic approach (the most common approach on account of its high versatility, safety, scalability and compatibility), there is a wide range of candidate materials available, the choice being dependent on the following factors:

- Scale. Especially in relation to current manufacturing technologies.
- Biocompatibility. Medical grade materials are needed if in direct contact with human tissue.
- Energetic considerations. Using deformable materials requires more energy, but with usable elastic return, while inextensible materials deploy rather than deform and allow higher pressures.
- Life/durability. Working cycles usually degrade mechanical performances, especially in chemically aggressive environments.
- Recyclability/re-usability. Low cost would allow disposability, but environmental considerations may underline a low level of sustainability in the use of polymers. Re-usable devices must also take sterilization into consideration.

Whatever the material choice is, the intrinsic safety, usually cited as an undeniable advantage of soft robots, becomes a limitation in tasks where high forces are necessary to execute a procedure. Variable stiffness becomes a key requirement to strengthen the device and to allow the propagation and transmission of forces. The choice of the actuation technology often implies either the use of antagonistic configurations or the combination of an active and a semi-active technology.

Other than improving mechanical performance, variable stiffness also enables variable kinematics, that on the one hand makes soft robotics extremely versatile, but on the other, introduces additional control complexity. This complexity is still an open issue, but in medical procedures the surgeon does not always need to have complete awareness and control of the device shape and spatial configuration. AI-based methods can manage this computation, releasing the anthropomorphic design approach, and leaving more critical decisions to the surgeon. The same applies to collisions and obstacle interaction. If the device maintains its flexibility and intrinsic safety, precise control is not mandatory. High precision would be necessary only at the operating tip, but that would, in any case, be under strict visual control.

In the context of control algorithm and interaction schemes, soft sensors cover a fundamental role. Transduction principles that can guarantee sufficient reliability without affecting mechanical characteristics are currently under investigation with promising results [101], but practical use is still hindered by certain shortcomings: the continuum nature of soft robots makes sensing modalities fully coupled and difficult to monitor separately; sensing systems

should be made of materials with electrical and mechanical properties that allow their seamless fusion into the robotic structure, rather than from discrete components that need to be embedded.

Concluding remarks

Soft robotics is demonstrating the importance of soft materials in the development of advanced robotic tools, especially in application fields like RAMIS, while the octopus offers an unparalleled source of inspiration for approaching technological hurdles (figure 5). Despite gaps, a significant body of knowledge has been established, although technological bottlenecks still hinder its full exploitation. Ultimately, we need to see technological advances in material science, chemistry, manufacturing, engineering and computer science, while continuing to learn smart biological approaches and simplification schemes.

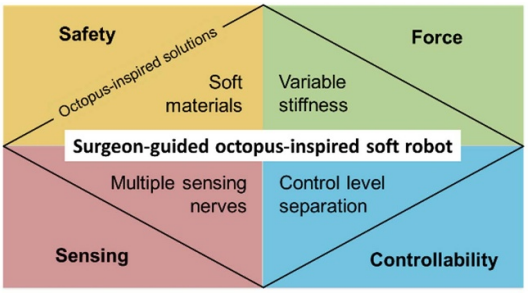

Figure 5. Desired combination of characteristics for a RAMIS tool and solutions that are inspired by the octopus.

Acknowledgments

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6. Soft aerial robots for environmental sustainability

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Status

How can we develop aerial robots that can make a profound impact on the world's sustainability goals? In this article, we want to provide a balanced perspective on the promising opportunities soft aerial robotics can provide in supporting this effort. Whether that is through designing robots with materials that are environmentally responsible and/or robots that can monitor and alert us about the changing environment and its biodiversity [102–104].

Because of their scalable form factor, capability to cover large grounds, and ability to access difficult-to-reach locations, aerial systems have the potential to collect valuable data in a wide range of environments, at vast scales [105, 106]. The collected data can range from ecophysiological/biological data, climate change indicators, to air/water indices [103, 105], as seen in figure 6. These surveys will then play an essential role in assessing the habitat quality, biodiversity and indicate the climate and pollution levels of the region, in order for us to make timely decisions on the conservation and preservation of our natural environment.

For aerial robots, to traverse unstructured environments, there has been a conscious trend in studying nature to develop bioinspired aerial robots that are more robust, agile, multifunctional, energy efficient, and can access multiple terrains [105, 106]. Researchers from multiple disciplines not only study the function of biological flyers, but also their structure, anatomy, material, behaviour, and chemistry in order to synthesize life-like aerial robots with these physical artificial intelligent features [32, 131–133].

The bioinspiration for the next generation aerial robotic systems not only seeks to improve its aerodynamic adaptability, efficiency, and maneuverability. It also aims to extend its range of operation to adaptive manipulation and perching, aerial-aquatic-terrestrial transitions, withstanding dynamic collisions, reconfiguration for traversing through tight spaces, self-healing from damages, and adhesion in unconstrained environments [132, 134, 135]. Capabilities often highlighted in our biological flying counterparts. The opportunity for bioinspiration stems from not only birds, bats, and insects but also aerial plant seeds, amphibians, reptiles, and aquatic animals, such as the flying fish and squid, among others [132, 135], as shown in figure 6. Offering a vast opportunity for researchers to conceptualize the novel future aerial robotic organisms for the monitoring of our biospheres.

Current and future challenges

The challenge of developing future aerial robotic organisms that can support multiple ecosystems is a multi-pronged problem: (1) how do we study nature, inspire designs from it, and sustainably manufacture these systems? (2) How do we study their interaction with the unstructured environment in multiple mediums and the transitions between them (land-water-air)? (3) How and what should they be able to sense, measure and interact with, in the environment?

As the next generation of aerial robots looks to widen its functionality and access to multiple environments, the conditions required for its successful deployment has also multiplied. Previously, classical challenges aerial robots have had to face ranged from scalability, propeller noise, payload capacity, operational longevity (with LiPo batteries), and robustness to collision and disturbances (obstacles and natural), just to name a few. But in order for the aerial system to effectively study natural habitats, such as the different rainforest canopies, aerial robots need to be capable of safely adapting and interacting with the unconstrained environment without creating too many disturbances [105].

With the cluttered rainforest as an example, we want to study the multitude of behaviours of arboreal life. This could be to study the interaction between plants and animals, or the influence that the environmental conditions have on the particular tropical rainforest life [106]. Imagine a world where aerial robots can mobilize from the forest floor to the various canopy layers, whether through flight, multi-functional mobility, hitchhiking onto animals/plants, or even following animals/plants side-by-side. In order to do so, we need adaptive aerial robots that are agile, stealthy, robust, equipped with an array of sensors for proprioception and exteroception, and capable of semi-autonomous operation for long-term observational periods. This is where the biggest tradeoff-problem of aerial robots comes into play. The balance between flight endurance, system agility and maneuverability, payload capacity for onboard computing and sensors, structural adaptability, and structural robustness.

Another major consideration is based on how the systems we build impact the environment it operates in. How can we reduce the e-waste and harmful

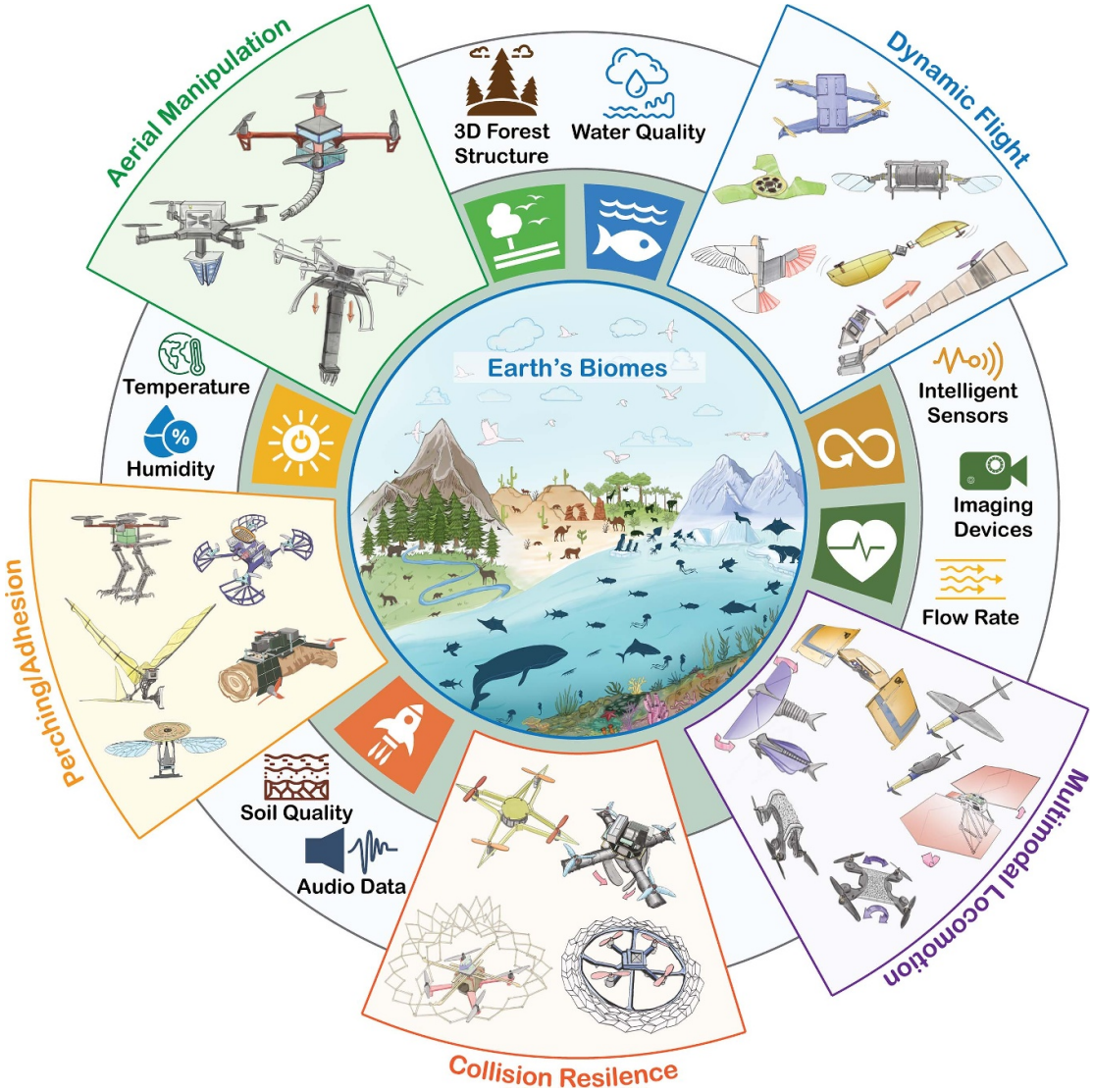

Figure 6. Soft Aerial Robots for Environmental Monitoring and Sustainability. [First Ring] Different earth biomes to be accessed by multimodal aerial robots. [Second Ring] The European Union Sustainable Development Goals that are supported with soft aerial robots: (1) Life on Land (2) Life Below Water (3) Responsible Consumption and Production (4) Good Health and Well-Being (5) Industry, Innovation, and Infrastructure (6) Affordable and Clean Energy. [Third Ring] The different types of ecological data that soft aerial robots would want to collect for environmental monitoring [105]. [Last Ring] Highlights the different technologies, function, and examples of soft aerial robots. Such as aerial manipulation [107–109], dynamic flight [110–116], multimodal locomotion [117–121], collision resilience [122–125], perching and adhesion [126–130].

materials generated by aerial robots deployed in these different environments? One approach is to trend towards the development of aerial subsystems made of biodegradable materials [136]. It could be parts of the system that are biodegradable, such as the sensor, or the entire system itself.

With such a burgeoning multi-disciplinary field of research, collaboration between ecologists, biologists, material scientists, and engineers of various fields, is key. The challenge here is trying to establish a strong communication and understanding between researchers of different fields that are less familiar to each other. Furthermore, multi-disciplinary education is required to push forth the next generation of researchers in the intersection of all of these approaches.

Advances in science and technology

The step towards impactful and long-term operation of the new generation of aerial robotic systems, will combine the design of bio-inspired systems with energy-efficient and agile mobility, with structural adaptation through shared functionality and soft materials, capable of intermittent operation through perching-and-resting, equipped with sensors that are simple yet provide high-frequency information for real-time interaction with the environment, and powered by actuation methods that have higher power-to-weight ratios [126, 137, 138].

Currently there are various exciting development in the field of soft aerial robotics such as: adaptive dynamic perching [126, 137], morphing wings [115, 139], adaptive landing and collision resilience

[124, 140], soft manipulation [137, 141, 142], plant and seed-inspired fliers [111, 143–145], multimodal and multi-environment aerial systems [146, 147], adaptive sensing (soft proprioceptive and optic flow) [148], self-healing systems [114], and bio-hybrid fliers [115, 149–151]. In contrast to the trend in classical flight vehicle design, aerial robotic systems take a more bio-informed design approach, observed from nature. This approach is still founded on aviation engineering theory, which is also a fundamental tool utilized by biologists for biological analysis of animal mobility and flight. The collaborative efforts between engineers and biologists will continue to deepen our understanding of biological flyers, while building systems that incorporate behavioural, material, structural, communication, perception, actuation, navigation and control principles from nature [127, 152, 153]. These efforts aim to develop new engineered systems that embed fundamental biological principles within the engineering design process and advance engineering methods through research aimed at identifying these principles [127, 152, 153].

In order to transition between flying to other modes of modality or other mediums of operation, researchers are addressing the challenge of robot structures that change its shape and/or modulate its stiffness [126, 135, 154]. Fundamental studies are being made to model the interaction between the robot's body, as it changes shape and stiffness, and the fluid medium it operates in [155]. These studies will shed light on how adaptive aerial robots can be optimally controlled to reconfigure and move between mediums in a stable and energetically efficient manner [147, 155].

The utilization of soft robotic manufacturing and design principles in aerial robotics, has aided in the utilization of non-linear materials that can adapt well to irregular structures, enhance robustness through elasticity, and assist with programmable shape change and stiffness modulation [135, 156]. These features have also enabled shared functionality in soft aerial robots, where the same structure can switch between modes of operation for different tasks requirements [132].

The goal of soft aerial robots for ecological monitoring is to collect invaluable data in various environments on scales that exceeded previous limits by weather stations, satellites, and human sensor placement [105]. This includes information on both biotic (animals, plants, fungi, and microorganisms, etc) and abiotic (temperature, light, water, humidity, pH, etc) factors in different ecosystems [105]. With multi-modal and multi-functional aerial robots, the goal is to be able to perform these surveys in locations with limited accessibility.

For sustainable management of various biomes it is essential to monitor which species are there, how that diversity changes over time, with the impact of climate change [105, 106]. In both terrestrial or aquatic ecosystems, these robot networks will be able to perform visual and auditory observations at larger scales, by being able to naturally move and quietly track subjects with minimal disturbance [106]. Further, these systems can also operate as mobile labs to collect environmental DNA by employing techniques such as metabarcoding to monitor the status and distribution of the biodiversity of the region [157, 158].

To capture abiotic factors, aerial robots that can perch-and-rest and intermittently move from location-to-location for long missions and even recharge itself through that process, can monitor temperature, light, humidity, air quality, etc [106]. But to cover large monitoring areas, perhaps networks of flying plant-seed-inspired sensors can be launched or dispersed utilizing aerial robots [159, 160]. The challenge here is to have these sensors collect data, communicate data with the host system and each other, and possibly degrade at the end of its usage lifecycle.

The road to developing completely transient aerial robotic devices that can completely biodegrade is still at the nascent stage of its development [102, 136]. So far biodegradable structures, sensing and soft actuation show great promise in short-term implementation [102–105]. But, there still needs to be development in biodegradable electronics, computational devices, transmission systems, and power sources [102–105]. These steps will lead towards aerial robotic deployment systems that do not need to be retrieved after usage, increasing the scalability of these complicated sensing development operations.

To unlock the full potential of soft aerial robotic systems, requires a multidisciplinary intersection between various fields of research, burgeoning the next generation of adaptable flyers to tackle environmental monitoring across the biome landscapes.

Concluding remarks

The investigation of physical intelligence of natural systems is a profound undertaking to synthesize better engineered systems that are inspired by nature and also enhance our comprehension of life itself. Soft aerial robots can play an essential role in studying the behaviour of aerial, terrestrial, and marine life by adapting to different environments through multifunctional and multi-modal shape changing adaptations. Through these long-term deployments, together with ecologists and biologists, we seek to get an in-depth view on how life thrives through collaboration, competition, and the constantly changing climate. In addition, the tracking of multiple generations of species, will provide us a glimpse into further understanding the evolution

of species itself. This goes hand-in-hand with minimizing the environmental impact we create during missions, whether that is noise disturbances or e-wastes. To truly deliver on these goals, future collaborations and educational efforts need to be enhanced with interdisciplinary collaboration between fields of engineering, ecology, biology, and material science. This will transform how we comprehend, engage with, and oversee our world and its natural habitats.

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7. Underwater walking soft robots for seabed exploration

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Status

Oceans are challenging environments for human exploration but the opportunities for scientific discoveries and commercial exploitation drove the development of underwater robotics. Due to the unstructured, unpredictable, and physically and chemically aggressive nature of the sea, underwater robotics faces strict efficacy requirements and, as a consequence, it relies on robust, traditional designs that have only recently been challenged [161]. The limitations in environment interactions of traditional underwater robots have invited researchers to explore novel solutions, and a recent trend is directed toward the employment of underwater legged robots (ULRs) [162]. ULRs have several advantages for seabed exploration with respect to their swimming counterparts: they have a lower noise footprint [163], can withstand stronger currents [164], and they can reduce energy consumption during operations [165].

Among the different categories of ULRs, the employment of soft components in the legs, body, and feet appears as an attractive opportunity to exploit water/body interactions. Compliance in the legs is exploited to move inside ground fissures or structures, negotiate obstacles without explicit sensory feedback, and create multi-gait locomotion [166]. Compliant and morphing bodies are used to exploit hydrodynamic forces to improve stability, locomotion, or current withstanding [167]. Soft/compliant feet are used to improve grip, adapt to uneven grounds, and grip underwater surfaces [168].

Besides the practical employment of underwater legged soft robots, many biomimetic robots (i.e. where the artificial copy of the biological system can be used as a proxy for the living animals) are used to prove biological observations, such as sensory-motor coordination, multi-gait locomotion, or neuronal circuitries [169]. The field of underwater legged soft robots is still in its infancy, but it offers several scientific and technologic opportunities.

Current and future challenges

The main issue with innovative underwater robots is reliability. Working in water is demanding in terms of hardware, software, and integration of components. Moreover, the intrinsic limitations in communication demand exceptional reliability, coupled with the challenging tasks field robots are assigned to. Employing soft robots in actual missions would require the challenging fusion of soft and field robotics.

Unfortunately, soft robotics is still relatively young, and only recently we have witnessed the transition from exploratory research toward a more mature employment of soft robots. Across all domains of soft robotics (manipulation, locomotion, wearables, etc), the reliability of the devices is still low, and only a few scientific works report statistically relevant experiments in the field.

Similarly, we are witnessing the transition from open-loop approaches toward closed-loop approaches that can pave the way for novel exploration opportunities. To do so, the underwater environment poses additional challenges: the limited number of sensors available and the aggressive water environment hinder most of the sensing technologies adopted so far in the terrestrial domain. Both exteroception and proprioception require innovative approaches to deal with soft, continuum bodies, but they are pivotal in increasing robustness of behaviours and, therefore, promoting more reliable underwater soft robots.

Onboard processing is another complex task for soft robots devoted to exploration. The compromise in softness posed by electronic elements (which are commonly made of hard materials) and the high pressure impair most of the current electronic technologies applied in soft robotics. Specifically for pneumatic actuation, its adoption is possible only in shallow water or at the expense of a significant amount of space devoted to pressurized tanks.

Eventually, energetic and behavioural autonomy are significant challenges for underwater soft robots in general, and particularly for underwater walking robots. The absence of effective ways to perceive the surrounding environment and the lack of communication with the surface make autonomous behaviour desirable but extremely difficult, and a direct translation of the algorithms developed for the terrestrial environment is not always possible. Energetic autonomy is also a significant issue when considering robots for exploration: nowadays, batteries are the most common choice to power autonomous vehicles, but their weight (or their specific energy) is still far from the payload most mobile soft robots can sustain for a long time.

While most of the challenges of underwater walking soft robots are shared with other soft robots, the underwater environment poses additional challenges but also opportunities.

Advances in science and technology to meet challenges

Novel experimental protocols and application scenarios are challenging the robustness of robots in general, and the reliability of innovative robots (including soft robots) is becoming a key research aspect. The soft robotics community is aware of

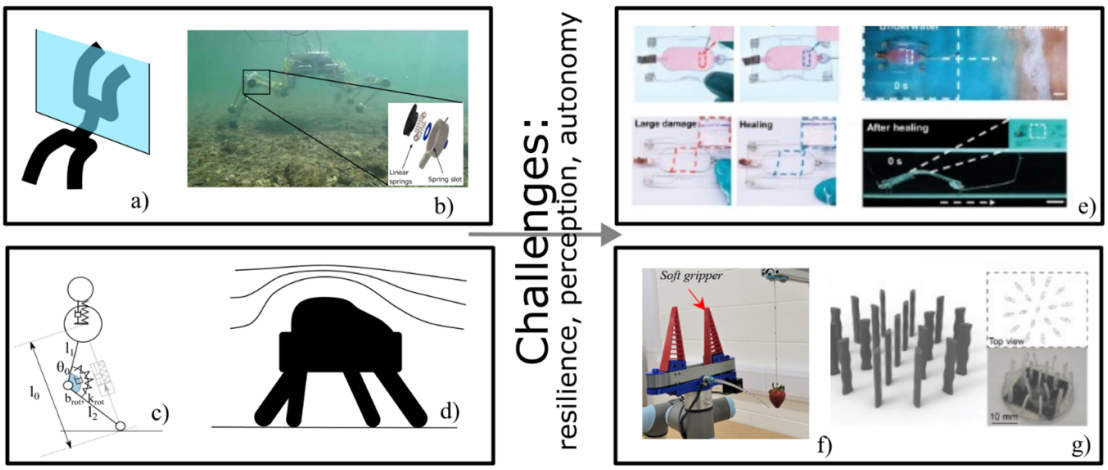

Figure 7. Soft Robotics already demonstrated the capability to exploit soft bodies to move within confined environments (a) [166], adapt to unknown grounds (b) [173], exploit compliance for energy (c) [174] or friction (d) [175]. The next challenges posed by walking underwater robots will include self-healing capabilities (e) [176], delicate sensing (f) [171], (g) [177], energy generation, compliant electronics, exploitation of water density for control with appropriate modelling. From [173]. Reprinted with permission from AAAS. © [2023] IEEE. Reprinted, with permission, from [174]. [176] John Wiley & Sons. © 2023 Wiley-VCH GmbH. Reproduced with permission from [171]. Copyright 2024, Mary Ann Liebert, Inc., publishers. Reproduced from [177]. CC BY 4.0.

such bottleneck, and started investigating self-healing materials, adaptive algorithms capable of dealing with the loss of limbs, and improved fabrication technologies. Although the research is still in its infancy, these promising activities are contributing to the creation of more robust and reliable robots [13], that can pave the way to deployment of robust underwater walking machine.

Regarding sensing and processing, a recent research trend is exploring fluidic circuits and control logics, moving beyond traditional computing based on silica. These innovative analogic fluidic controls can be applied underwater for simple processing and sensing, with the expectation of improving their performance to achieve greater processing capabilities and miniaturization [170].

Soft bodies could sense the surroundings in light-deprived environments. The intrinsic safety of soft bodies allows for unprecedented levels of haptic exploration and sensing, constituting a valid alternative to range, vision, and global positioning sensing, which are difficult to rely upon underwater. Especially in cluttered environments, such as man-made structures, natural caves, and coral reefs, lightweight soft underwater robots capable of sensing their surroundings with low disturbances could be a breakthrough for underwater exploration [171].

By coupling soft sensing and fluidic logic with reduced-order models, minimal feedback control, and mechanical intelligence, it could be possible to go beyond the traditional high-level control paradigm that requires complete knowledge of the environment. Research in morphological computation and swarm intelligence can deliver the required tasks by exploiting body compliance and safe interactions with the environment [172].

Eventually, the soft materials that constitute the robot bodies are usually of similar density to salt water; this fortunate match significantly reduces the gravitational force and naturally reduces the power required for soft actuators to move mobile robots underwater. If the required energy is significantly reduced by exploiting the soft material and suitable shapes, it would be possible to employ novel powering solutions, such as microbial batteries, to power a completely new generation of underwater soft robots [103].

Concluding remarks

The underwater environment presents many challenges for robotics. Most of these challenges can be addressed with the unique characteristics of soft robots. By merging legged robotics and soft robotics, a new generation of underwater explorers could be developed. Leveraging current research in soft robotics to achieve 'field-rated' robustness seems like a technical challenge, but it must be embraced as a scientific endeavour to better understand how complex systems—such as robots—behave and operate in unpredictable environments. Soft robotics has the opportunity to tackle this challenge and pave the way for methods, research protocols, and experimental deployments that could be instrumental for the entire robotics community.

Data availability statement

No new data were created or analysed in this study.

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