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# Bioinspired Synergy Strategies Empower Small-Scale Robots with Higher Performance

*Haochen Yong, Xingxing Ke, Fukang Xu, Shuo Zhang, Han Ding, and Zhigang Wu**

**Small-scale robots need to be agile to perform various tasks in complex environments and the design faces great challenges with limited size and power consumption. However, the advent of advanced functional materials, compliant structures/mechanisms, and flexible fabrication techniques has brought new evolution directions to robotics. These technologies enrich the robots' actuation strategies, improving their performance of small robots while simplifying the complexity of the system and thus making it possible to be applied in diverse scenarios, such as disaster rescue, medical, and environmental exploration. In nature, small organisms have shown numerous efficient survival strategies. They can easily achieve locomotion tasks with low energy consumption. For example, dragonflies complete long flights with the help of wind, and stenus (one kind of rove beetle) uses the surface tension of liquids to dodge prey quickly. Insects are usually considered to be agile, efficient, and intelligent, which is the same requirement as for small robots. Yet the corresponding bioinspired design strategies bring new opportunities and challenges to the development of small-scale robots. Herein, the development trends of small-scale robots are analyzed and discussed, and several potential bioinspired synergy strategies are induced, which may be useful for the future design of insect-level soft robots.**

## 1. Introduction

Small-scale robots, which attract a large number of researchers, are in small dimensions ranging from microns to centimeters[1] and are, usually, more agile, reliable, and gentle to the environment.[2–5] Owing to the above unique features, they have shown great advantages in numerous scenarios over their macrocounterparts. Small-scale robots can adapt to complex,[2,6] multilandforms,[1,7] and fragile[8,9] environments. For instance, they can enter the ruins after a disaster to achieve rescue in a small space, can enter the human body and release drugs in complex environments to accomplish precision medicine, can also explore space in multiple scenes (air, ground, water), and detect the natural environment like insects (**Figure 1**). Achieving excellent performance in the above scenarios requires consideration of a complex set of systems, such as actuators/structures, energy harvest/storage/manipulation, signal transmission, control, and so on. In general, scale laws have shown that the magnitude of robot energy storage is related to $L^3$ ($L$, the characteristic length of the robot), while external forces such as frictional resistance, wind resistance, flow resistance, and surface tension are related to $L^1$ or $L^2$. It means that as the size decreases, the attenuation of power is much larger than the attenuation of resistance.[10] Notably, as revealed by the studies in the past few decades, the miniaturization of traditional mechanical components such as connecting rods, gears, and motors is difficult and suffers from low strength and complex design problems.[11]

Compared with traditional mechanical parts, some new functional soft materials/structures have simple structures and various functions to achieve complex tasks.[12] They can be excited by natural factors such as electricity,[13] magnetism,[14] light,[15] heat,[16] air pressure,[17] and humidity.[18] Typical functional materials include hydrogels,[19] polymers,[20] dielectric elastic materials,[21] shape memory alloys,[22] ionic conductive polymers,[23] and so on. Moreover, flexible/underactuated structures (e.g., springs,[24] rods,[25] wires,[26] etc.) also exhibit good conformability, high performance,[27] and simple control,[28] with a wide range of applications in small mobile robots (drone),[29] grippers,[30] and medical apparatus.[31] Especially, with a low modulus of elasticity, simple structure, good conformability, and gentle interaction, these soft functional materials have shown great potential in medical fields, such as cell manipulation,[32] drug delivery,[33] grasping,[9] minimally invasive surgery,[34] and in vivo testing.[35] Soft materials have formed a new research trend in the field of small robots. However, there are still some tough challenges to be solved to realize widely practical applications of these small-scale soft robots, such as efficient movement, rich functions, untethered actuation, and low power consumption.[36]

To solve such tough challenges, many elegant and efficient designs can be inspired by the creatures in nature, especially insects. In nature, many kinds of insects are usually efficient,

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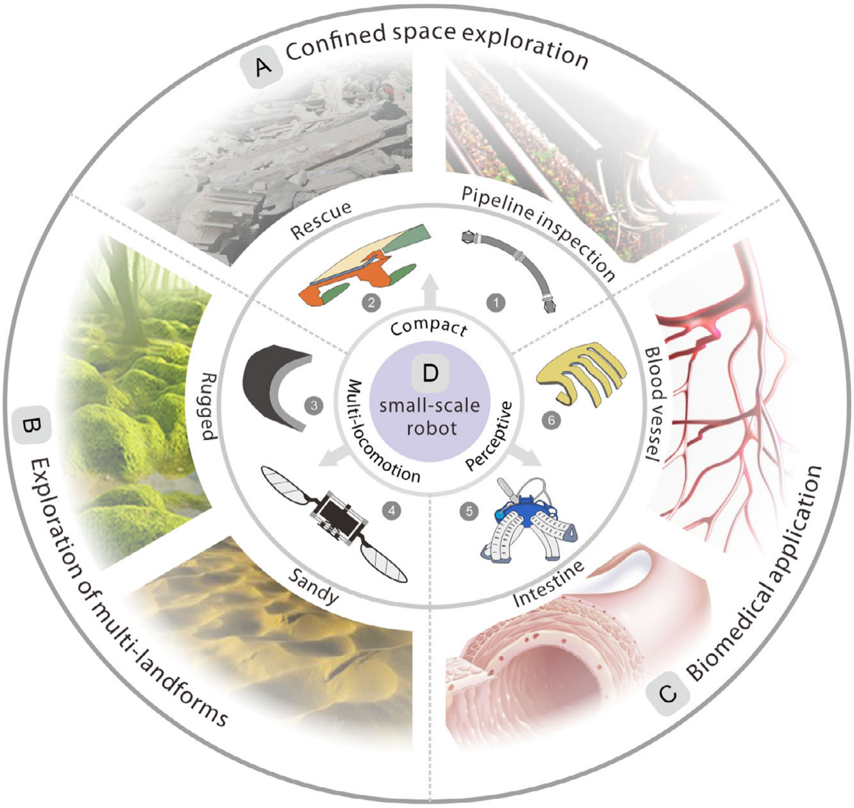

**Figure 1.** Application scenarios of small-scale robots. A) Confined space exploration, like earthquake rescue and pipeline inspection. B) Multilandform exploration requires robots with multiple motion modes. C) Fragile environments like inspection or drug delivery for intestine and blood vessels in biomedical applications. D) Robots that can be applied to the above scenarios, such as compact robots for confined environments: 1) a pipeline inspection robot,[6] 2) a soft robot that mimics cockroach[2]; a multilocomotion robot for multilandforms: 3) a magnetic robot with multilocomotion,[1] 4) a microrobot with soft artificial muscles[7]; and perceptive robots for fragile environments: 5) a soft-legged robot can overcome to obstacle,[8] 6) a soft robot which can hatch a snail egg.[9]

agile, and good at dodging and escaping, they can often survive in relatively harsh environments, such as dust, raindrops, and different interfaces. For large mammals or fishes, gravity, wind, and water resistance are the main factors affecting movements. As the size decreases, the influence of some microscopic relevant forces like surface tension becomes non-negligible and leads to completely different survival strategies for small-sized organisms. For instance, dragonflies can fly long distances with the help of wind, which is impossible to accomplish with their energy alone, *stenus* can quickly escape taking advantage of surface tension, and the microstructures of fly compound eyes can keep eyes clean.

Inspired by insects, there are three synergy strategies for small robot designs. First, the design strategy of functional synergy learns the cooperative relationship of insect organ systems, which can make robots more functional and efficient; second, the design strategy of environmental synergy allows robots to obtain higher performance in a specific environment with the help of external forces; third, inspired by animal clusters, the strategy of cluster synergy can make robots easily achieve swarm intelligence while simplifying the complexity of the overall system and making it more stable and adaptive.

Briefly, functional materials and flexible structures enable new forms of small robots that have multilocomotion strategies. They have high energy efficiency, agile performance, and flexible adaptability with limited complexity. To enable practical applications and performance beyond creatures for small robots, we must come up with new design strategies, **Figure 2**. This perspective briefly discusses and highlights a series of design developments in soft functional materials and flexible structures, focusing on synergy design strategies inspired by nature. It is aimed to provide new inspiration for the design of small robots and promote the early realization of practical applications of small robots.

## 2. Current Development of Small-Scale Robots

As discussed earlier, small-scale robots are often expected to perform complex tasks in a variety of unstructured environments. To achieve these requirements, small robots usually need to be agile,[2] stable,[5] gentle to the environment,[37] and have efficient energy management strategies[38] and flexible forms of locomotion.[1] The emergence of functional soft materials and structures has brought a new evolution direction to small robots,

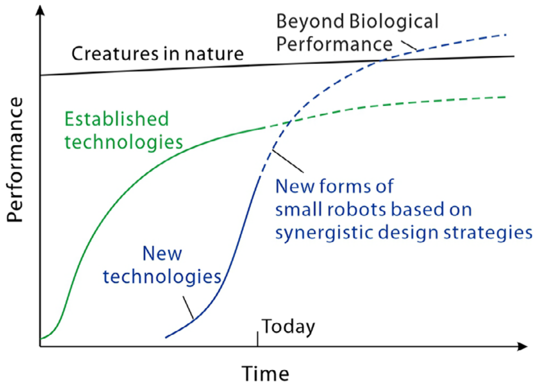

**Figure 2.** Trends in the performance development of small-scale robots. Emerging technologies based on functional soft materials and flexible structures make it possible for new forms of small robots to greatly exceed the performance of the established robotics technologies in the future and even beyond biological performance (as shown by the dotted lines). However, to reach very high values close to the predicted performance, it will require new design strategies to take advantage of functional materials and flexible structures as much as possible.

enabling the robots to be more functional, better performing, more stable, and more efficient.

Functional materials and flexible structures can empower robots with more functionality while maintaining a simple structure. It is known that the space in a small-scale robot is valuable, combining actuation with the body can effectively reduce the structural complexity of the robot. For instance, Hu et al. studied a thin sheet robot based on soft active materials with a specific magnetization direction, which has a simple structure and can perform a variety of actions, such as tumbling, jumping, and crossing barriers under a magnetic field.[1] Further, the surface of the robot's body structure is also used to give the robot more functionality. For instance, Zhang et al. have conducted a lot of research on surface functionalization to give more functions to surfaces of elastomeric structures.[39] These robotic design methods are very similar to the insects in nature, such as a butterfly has a beautiful pattern on the wing. Usually, robots are expected to have the same capability to adapt to complex terrains and cross-obstacles as creatures to complete space exploration and monitoring tasks. For instance, Chen et al. demonstrated an insect-scale robot capable of flying, swimming, and transitioning between air and water,[40] offering the possibility of movement across different terrains.

At the same time, new materials and structures also improve the performance of small-scale robots. For instance, Chen et al. used dielectric elastomers that can endure the impacts to obtain higher energy densities, illustrating the potential of developing next-generation agile small-scale soft robots[7]; Chi et al. reported a pneumatic soft robot realizing rapid butterfly swimming on the water surface with comparable high performance to biological counterparts.[41] To make the robot more efficient, Wang et al. integrated suction cups into underwater soft robots, which can save energy consumption by hitchhiking just like remora suckerfish[42]; while Bai et al. designed an underactuated spin structure on a rotorcraft inspired by samara, using unsteady aerodynamics to save twice the power consumption compared to a multirotor robot.[38]

## 3. Emerging Challenges of Small-Scale Robots and Solutions in Nature

Although new materials and structures have enabled breakthroughs in functionality,[43] performance,[2] and energy efficiency,[44] there are still some emerging challenges. The main challenge is that the robots with multifunctionalities based on new materials/structures are always constrained by strong magnetic fields, high voltage, or some specific conditions that are only met in the laboratory.[36] It is difficult to be used in an open natural environment. Several recent studies have made exciting breakthroughs in their respective areas of interest, such as speed of movement,[41] energy density,[44] functionality,[39] stability,[45] and so on. However, these performance breakthroughs still fall short of expectations that the small-scale robot can be comparable to or even beyond biological counterparts. Additionally, due to its small size, such kind of robot is often more vulnerable to damage.

During natural evolution, insects comparable in size to small-scale robots typically have agile, efficient locomotor strategies to survive. For example, the surface of insects usually has regular microscopic structures that can sense changes in the environment, help insects escape from raindrops and dust, and appear in different color patterns by reflecting light. Such strategies to give structural functionality can help small robots have more functionality with limited spaces. Another example is when the activity requires significant energy, insects tend to use the environment to save energy just like dragonflies. Such similar strategies are common with other organisms, such as remora suckerfish and pine cones. If this strategy is applied to small robots, it has a high potential to simplify complex external energy supply devices. In addition to the clustering behavior of organisms such as bees and ants can also inspire the design of small-scale robots, which is possible to reduce the dependence on individual stability/capability while improving the overall efficiency.

## 4. Bioinspired Synergy Design Strategy

Targeting to achieve performance close to or even beyond that of natural organisms as that in Figure 2 requires small robots to have efficient energy distribution strategies and multimodal motion capabilities. New design strategies should be sought to utilize various functional materials and flexible structures as much as possible. This section will focus on the bioinspired synergy design strategies to empower small-scale robots with higher performance (**Figure 3**).

### 4.1. Multifunctional Synergy

The size of the robot and the complexity of its structure determine the richness and integration level of its functionality, and thus this competitive relationship is more evident in small-scale robots. Traditional robot design strategy divides the robot system into various subsystem modules, such as structure module, actuation module, and control module, which can be easily assembled into a complete robot via a common interface (mechanical/electrical interface). Such a strategy greatly reduces

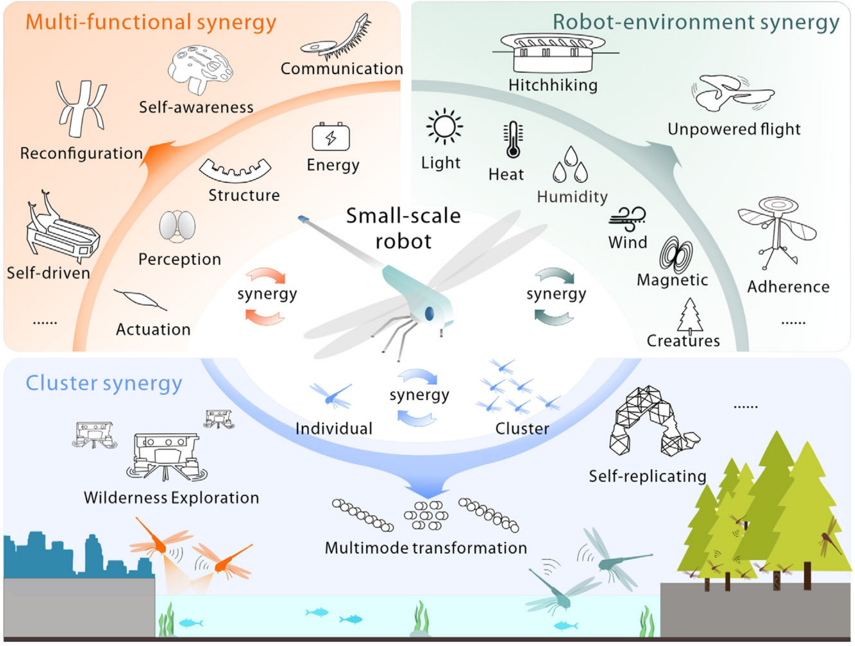

**Figure 3.** Synergy strategies for small-scale soft robots. Multifunctional synergy: considering both the functions of individual subsystems and the synergistic relationships between different functional modules, improving performance and simplifying system complexity; robot-environment synergy: considering the robot's working environment during the design process and using the conditions of the environment itself to make the robot more effective at performing specific tasks; cluster synergy: reducing the reliance on individual stability while increasing overall efficiency.

the cost of robot design, manufacturing, and maintenance. However, for small-scale robots, due to the many constraints described above, the need for codesigning the entire system and miniaturization of each subsystem poses significant design and manufacturing challenges.

Some insects in nature integrate many functions into a structure within limited space. For instance, butterfly wings as flight actuators in nature have fine microscopic structures that can be seen under microscopes.[46] These structures enable the wings to avoid getting wet from rain and show various color patterns in sunlight for concealment, escape, or courtship. This inspires the potential multifunctional synergy design strategies that consider not only the functions of individual subsystems but also the synergistic relationships between different functional modules. For example, to adapt to unstructured environments, a flexible sensing system is integrated into the actuator for self-awareness of the robot body,[47] which avoids complex external sensing devices, saving space, and simplifying the structure. The synergy of sensing and actuation functions requires consideration of many issues such as signal acquisition, decoupling, and mechanical matching of different material interfaces. One possible approach to realize the multifunctional synergy is treating the surface of soft materials such as polydimethylsiloxane (PDMS) with a laser, which not only can adjust the properties of the material itself but also enables more functions to the surface.[39] Such synergy between different functional modules allows the robot to achieve an overall optimal state for various tasks.

In addition to integrating various functions in the structure, the synergy between different systems also improves performance and simplifies the system's complexity. An ingenious case is a small-scale robot that only weighs 88 mg, where the synergy between the energy system, structure system, actuation system, and self-control system allows the robot to accomplish motion independently and continuously through the conversion of chemical and mechanical energy.[48] Multifunctional synergy strategies take advantage of the unique properties of functional materials and the freedom of flexible structures to effectively simplify the complexity of robot control systems and improve the space utilization efficiency of robot structures.

### 4.2. Robot–Environment Synergy

The small size limits energy storage, which directly constrains truly untethered small robots applied in a real environment. If traditional motors are used, it is difficult to trade off their weight and energy density. Looking for new power sources that are easier to harvest and more efficient, such as light energy, chemical energy, and more advanced battery technology, is a viable option.

It is also a good idea to consider robot–environment synergy which refers to considering the robot's working environment during the design process and using the conditions of the environment itself, ultimately making the robot more effective when performing specific tasks. In nature, it is a common and efficient movement strategy. For instance, dragonflies can fly across the ocean with the help of wind, wild geese migrate by using airflow to save energy, and pinecone seeds can migrate by taking advantage of day and night humidity changes. These creatures can use the natural environment to complete the whole process with minimal energy consumption or even no internal energy consumption. They bring new inspirations for the researchers to design various interesting new small robots, such as seed-inspired microaircraft that can passively achieve air flight.[49] The emergence of functional soft materials also provides many novel solutions for this untethered design. There are more examples, such as hydrogels excited by light/heat,[50] and hollow structures inspired by pine cones that move in response to changes in the humidity of environment.[51]

Hitchhiking is also a typical case of robot–environment synergy. In nature, many plants and animals use hitchhiking to conserve energy expenditure. For example, some plants rely on barbs on the surface of the fruit to adhere to animal furs to help spread seeds, and remora suckerfish often use suction cups to attach to the bottom of boats or other large fish to swim farther and claim food. Inspired by this, a bionic suction cup was integrated into a soft robotic fish that can be attached to various surfaces underwater.[42] Further, this strategy of attaching to surfaces was also applied to flying vehicles,[52,53] which greatly enhanced the range of the vehicle and enriched the application scenarios.

### 4.3. Cluster Synergy

Small-scale robots are usually limited by their size, which often restricts the upper limit of individual performance. In nature, cluster creatures such as bees and ants show amazing intelligence in many aspects of foraging, nest building, and regulating nest temperature, despite the very limited capabilities of individuals. It has inspired famous intelligent algorithms, such as ant colony algorithms.[54] A colony of many weak, limited behavioral abilities, and low intelligence individuals can accomplish more complex tasks through mutual collaboration among numerous individuals. Clustering strategies can reduce the reliance on individual stability while increasing overall efficiency, such as microvascular robots, which can respond to potential risks in the in vivo environment by increasing their number,[55] and swarms of drones, which can improve the efficiency of spatial search and recognition.[56] Recently, Amira and collaborators introduced a discrete modular material–robot system that is capable of serial, recursive (making more robots), and hierarchical (making larger robots) assembly and demonstrated applications in the construction field.[57] While Miskin et al. have made an important advance toward mass-manufactured, silicon-based, functional robots that are micron scale.[58] With the increased cluster intelligence, individuals will no longer need to have all the functional modules required by the task at the same time, simplifying the complexity of small robots in terms of requirements.

## 5. Outlook and Conclusion

In this perspective, we discuss three bioinspired synergies design strategies with great potential to empower small-scale robots with higher performance. Often mechanical structures and intelligent algorithms tend to learn from nature, which is natural selection in evolutionary processes. However, in some application scenarios, robots need to exhibit greater performance than living beings to accomplish specific tasks. The emergence of functional materials and structures makes it possible and multifunctional synergy, robot–environment synergy, and cluster synergy will likely be key in the design of next-generation small robots that can applicate in real-world environments.

Based on the multifunctional synergy strategy, creatures always perform optimally in their survival environment, which is the result of synergy between different systems rather than mere accumulation. For example, the mosquito achieves flexible flight through the synergy of airflow perception and flexible wing agitation.[59] Such a strategy has inspired new collision avoidance technology for drones.[60] To make this strategy more widely available in the field of small-scale robots, in addition to tapping into the versatile properties of new materials, a universal information transmission medium is needed. However, there is no unified energy/signal transmission medium for robotics based on new functional materials, so there is an urgent need to propose a universal interface technology that applies to soft robots.[61] Jiang et al. reported a universal interface that can reliably connect soft, rigid, and encapsulation modules together[62] and demonstrated the possibility of information transmission interfaces for soft functional materials. Universal interface technologies will also endow robots with better interaction with the ambit environment or external objectives.

The robot–environment synergy strategy is a design method that matches the target environment without a unified form. Depending on the type of robot working environment, any beneficial factors in nature can be utilized by the robot to improve its efficiency of the robot itself. It requires a deep understanding of functional materials or structures which can perceive and interact with the environment. Basic research at small/micro scales should receive more attention, such as interface mechanics, fluid dynamics, and aerodynamics.

In addition, current robots implement environmental synergistic strategies that are often not actively controlled during locomotion in real time. Although magnetic materials show the possibility of solving such a problem, for example, controlling the motion process of a robot by rewriting the magnetic domain orientation of the magnetic material in real time,[63] the current need for controlled magnetic fields still requires complex equipment and consume huge amount energy.[64] It remains a challenge to achieve real-time control of small robots based on functional materials and structures.

Cluster synergy can reduce the dependence of individuals and improve overall intelligence. Individuals in the cluster need to pass information to each other to determine location and status. This usually relies on an intelligent system to regulate and, thus, avoid collisions, failures, and other accidents. Memristor has shown the potential in neuromorphic computing with its simple structure and neuron-like behavior.[65] For instance, Wang et al. designed memristor-based biomimetic compound eyes and demonstrated an application in robot navigation with obstacle avoidance capability.[66] The intelligent behavior exhibited by the materials and structures themselves would be a powerful complement to traditional artificial intelligence.[67]

Moreover, there are still many other issues and directions that need to be studied and developed: design and manufacturing process of functional materials, efficient general interface technology, and cross-fertilization of multiple disciplines, such as materials, mechanics, control, and biology. We should identify promising techniques to implement synergy design strategies that allow small robots to achieve the predicted performance

**Table 1.** Summary and outlook of bioinspired synergy strategies.

| Synergy strategies | Biological behavior | Major advantages | Typical examples | Possible research trends |
|---|---|---|---|---|
| Multifunctional synergy | Wings with microscopic structures enable the butterfly to fly, keep the wings from getting wet from rain, be colorful for concealment, escape, or courtship[46] | Improving performance and simplifying system complexity through the synergy of different functional systems | Surface functionalization empowers diverse functions to surface structures;[39]<br>An untethered small robot at 88 mg can move independently and continuously[48] | 1) Tapping into the versatile properties of new materials;<br>2) Functional–structural integration;<br>3) Universal interface technologies; |
| Robot–environment synergy | Dragonflies can fly across the ocean with the help of wind;<br>Pinecone seeds can migrate by using changes in humidity;<br>Remora suckerfish use suction cups to attach to the bottom of boats or other large fish to swim farther and claim food | Reducing the energy required for locomotion with the help of environments[a)] | Seed-inspired microaircraft can fly passively;[49]<br>Hollow structures inspired by pine cones accomplish motion driven by humidity;[51]<br>Soft fish with a bionic suction cup reduce energy consumption by hitchhiking.[42] | 1) Basic research at small/micro scales, such as interface mechanics, fluid dynamics, and aerodynamics;<br>2) Active control in real time. |
| Cluster synergy | Bees and ants show amazing intelligence in foraging, nest building, and regulating nest temperature | Reducing the dependence of individuals on each other to accomplish tasks | Microvascular robotic clusters reduce risks of movement in vivo environment;[55]<br>Swarms of drones improve the efficiency of spatial search.[56] | 1) Decision making and obstacle avoidance;<br>2) Studies about neuron-like principles and devices |

[a)] Include light, wind, humidity, temperature, animals, plants, and so on.

(high energy efficiency, agile performance, and flexible adaptability) with limited complexity and even beyond biological performance. Technologies such as flexible electronics,[68] liquid metals,[69] 3D printing additive manufacturing,[70] soft robotics,[71] flexible structures,[72] and cyborg insects[73] all show strong potential. With a deeper exploration/understanding of the natural mechanism, especially the study of neuronal systems, more new design strategies are likely to be generated for designing next-generation robots with more intelligence.

Finally, this perspective induces three synergy design strategies, particularly for small-scale robot design, and highlights their intrinsic advantages with some typical examples. Further, for each synergistic strategy, we discussed some possible research trends, as summarized in **Table 1**. These synergy strategies provide potential solutions to the energy utilization and motion performance problems of small robots and are already present in several existing robot designs. It is promising that they will empower small-scale robots with higher performance for many expected applications.

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## Conflict of Interest

The authors declare no conflict of interest.

## Keywords

bionics, small-scale robots, soft robots, synergy strategies

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