

Review

Advances in Gecko-Inspired Climbing Robots: From Biology to Robotics—A Review

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Abstract

Wall-climbing robots have garnered significant attention for their ability to operate in hazardous environments. Among these, bioinspired gecko robots exhibit exceptional adaptability and climbing performance due to their flexible morphology and intelligent motion strategies. This review systematically analyzes studies published between 2000–2025, sourced from IEEE Xplore, Web of Science, and Scopus databases, to explore the biological principles of gecko adhesion and locomotion. A structured literature review methodology is employed, through which representative climbing robots are systematically categorized based on spine flexibility (rigid vs. flexible) and attachment mechanisms (adhesive, suction, claw-based). We analyze various motion control strategies, from hierarchical architectures to advanced neural algorithms, with a focus on central pattern generator (CPG)-based systems. By synthesizing current research and technological advancements, this paper provides a roadmap for developing more efficient, adaptive, and intelligent wall-climbing robots, addressing key challenges and future directions in the field.

Keywords: gecko-inspired robots; motion control strategies; bioinspired robotics; adhesion mechanisms; CPG-based control



Academic Editors: Dong Chen and Mingle Xu

Received: 19 June 2025

Revised: 7 July 2025

Accepted: 10 July 2025

Published: 12 July 2025

Citation: Xiang, W.; Honarvar Shakibaei Asli, B. Advances in Gecko-Inspired Climbing Robots: From Biology to Robotics—A Review. *Electronics* **2025**, *14*, 2810. <https://doi.org/10.3390/electronics14142810>

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1. Introduction

In recent years, with the advancement of disciplines such as mechanics, hydraulics, electronics, computer science, and bionics, a variety of automated mechanical systems have been developed to perform tasks on vertical surfaces. These electromechanical systems increasingly replace manual labor in hazardous or hard-to-reach environments, becoming an important trend in robotics development [1–7]. By undertaking repetitive and dangerous tasks, robots not only safeguard human life and property but also ensure efficient task completion and reduced operational costs [8].

Among these, tasks such as bridge inspections, high-rise window cleaning, and ship hull flaw detection pose particular challenges, requiring robots to adhere to vertical surfaces or even ceilings. This is beyond the capabilities of conventional ground robots [2]. In response, researchers have developed various wall-climbing robots tailored for specific applications [4]. These robots have been successfully deployed in a range of high-altitude and hazardous work scenarios, including nuclear leakage monitoring [9–12], wall thickness measurement [13,14], weld inspection [15–17], ship hull cleaning and rust removal [18–23], bridge maintenance [24–27], building cleaning [28–33], as well as rescue and disaster response [7,34–37].

Bioinspired wall climbing robots have attracted increasing interest due to their improved adaptability and flexibility in complex and vertical environments, as shown in Figure 1. These wall climbing robots employ various adhesion methods, including negative pressure adsorption, shown in Figure 1a–c; claw adsorption, shown in Figure 1d,e; adhesive hexapod, shown in Figure 1f; magnetic adhesion, shown in Figure 1g,h; and electrostatic adhesion, shown in Figure 1i [38–40].

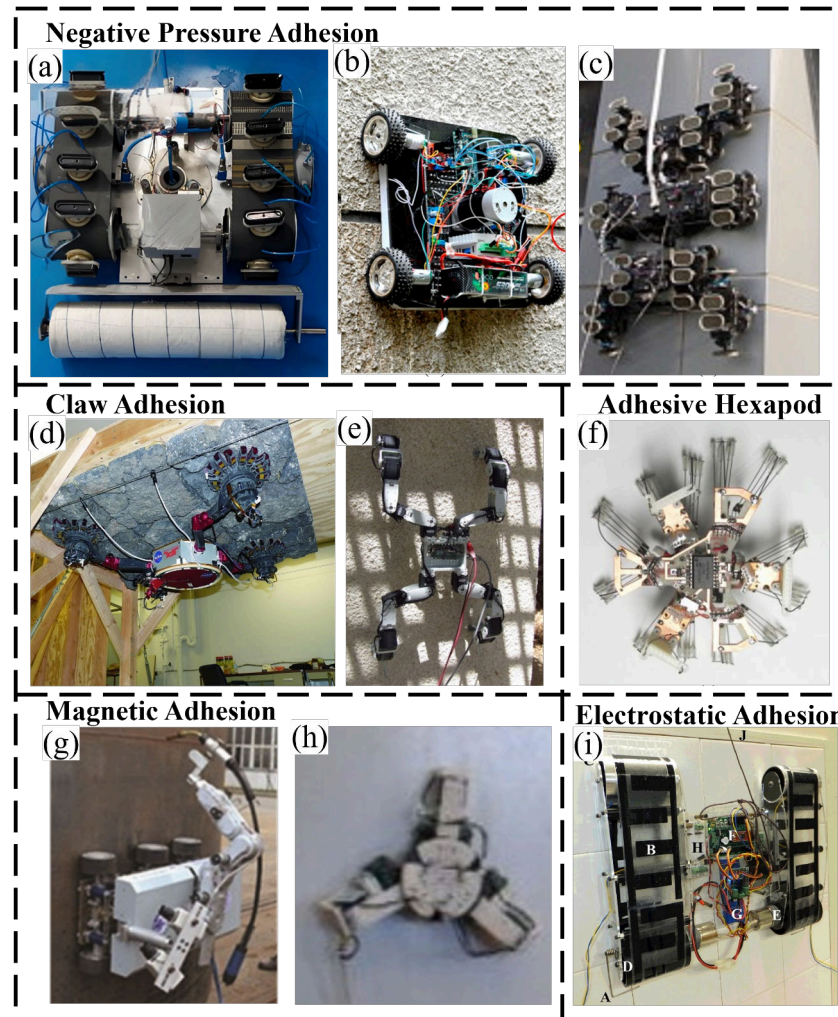


Figure 1. Wall-climbing robots including negative pressure adhesion, claw adhesion, adhesive hexapod, magnetic adhesion and electrostatic adhesion: (a) Ref. [41], (b) Ref. [42], (c) Ref. [43], (d) Ref. [44], (e) Ref. [42], (f) Ref. [45], (g) Ref. [17], (h) Ref. [46], and (i) Ref. [47].

A key source of inspiration for these robots comes from nature—particularly the gecko, which has been a central biological prototype over the past two decades [48]. Geckos are known for their exceptional climbing abilities [49], which allow them to traverse vertical and even inverted surfaces easily. This is achieved through a rapid attachment-detachment mechanism enabled by specialized foot structures [50–52]. These abilities are based on the functional cooperation of the musculoskeletal system [53–55], flexible attachment organs [56], fine-grained attachment structures, and fine-tuned regulation [51,52]. The principle of the gecko’s adhesion ability has been studied in detail, and a wall-climbing robot based on the gecko’s bionic adhesion has been proposed [57].

Dai and Zaaf’s work shows that geckos use periodic lateral bending of the spine to coordinate with the swinging of the limbs to achieve a greater range of motion [58–60]. By mimicking the biological characteristics of geckos, the bioinspired gecko robot not only

improves motion stability and energy efficiency on vertical and uneven surfaces but also provides a promising solution for tasks such as aerial inspection and emergency response. The concept of gecko-like climbing robots began in 1966 with Mod-1, designed at the University of Miyazaki to adhere to vertical and overhead surfaces [61]. Its successor, Mod-2, was built nearly a decade later in 1975 [62]. This pioneering work led to the development of many similar robots in subsequent years [2,7,63].

At present, research results in the field of bioinspired gecko robots are becoming more mature. These advances have laid a solid foundation for the development of a new generation of wall-climbing robots. This paper hopes to provide useful ideas and references for relevant researchers who are interested in developing more intelligent robot systems that are closer to practical application needs.

The remainder of this paper is organized as follows. Section 2 delves into the biological inspiration behind the climbing mechanisms of the gecko, focusing on the hierarchical microstructure of setae and van der Waals-based adhesion. Section 3 classifies gecko-inspired robots based on spine flexibility (rigid and flexible) and attachment mechanisms (claw-type and adhesion-type), while reviewing key developments in the field. Section 4 examines motion control strategies, including hierarchical architectures, neural control algorithms, and CPG-based adaptive systems. Section 5 systematically reviews the real-world applications of gecko-inspired climbing robots. Finally, Sections 6 and 7 discuss current challenges and future directions, followed by concluding remarks.

2. Biological Inspiration

Throughout biological evolution, animals have optimized their morphology and organ systems to adapt to diverse environments [64–66]. Their locomotion strategies, particularly those of climbing species such as geckos, provide abundant inspiration for the design of bioinspired robots [7,67].

Geckos have an efficient synergistic mechanism between the spine and limbs. They use their flexible spine to coordinate the movements of the limbs during locomotion, which can give them agile movement capabilities, such as increased movement speed [68–72], increased flexibility when turning [73], making the body more stable [74,75], and improving the energy efficiency of the body [76]. Movement stability can also be improved by changing the angles of the spine and limbs [77]. The full research team at the California Institute of Technology, Berkeley [75] used geckos as research subjects and used a motion reaction force test system to find that wall climbing geckos have similar dynamic characteristics to cockroaches and can achieve high-speed wall climbing motion owing to the dynamic characteristics of the center of mass oscillating left and right on the coronal plane.

Hildebrand [78] recorded the moment when the hind foot of an animal touched the ground as the beginning of the gait cycle and the time it took for the foot to touch the ground again as one gait cycle. Figure 2 shows the diagonal gait of the gecko.

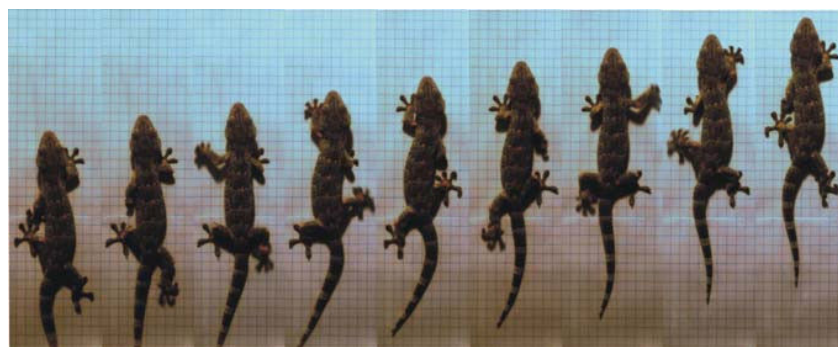


Figure 2. The gait cycle of the giant gecko's crawling movement [79].

Edwards [80] proposed that flexion and swinging of the trunk can assist the limbs in generating propulsion to propel the body forward. At the same step frequency, animals can achieve a higher crawling speed by periodically curling and stretching their trunk.

Not only does the gecko's efficient motion coordination mechanism provide a lot of design inspiration for gecko-like robots, but its adhesion mechanism also provides many new ideas for robot design. They are exceptional in their ability to climb rapidly up smooth vertical surfaces [50,51,81], relying primarily on van der Waals forces generated by nanoscale bristle-like structures on the multilayered fibrous surface of their feet [52]. The mechanisms of attachment and detachment of the gecko are controlled by the morphology of the gecko's foot [82].

Microscopy has shown that a gecko's foot has nearly 500,000 keratinous hairs or setae. Each 30–13 μm long seta is only one-tenth the diameter of a human hair and contains hundreds of projections terminating in 0.2–0.5 μm spatula-shaped structures [51,52,83]. Figure 3 shows the hierarchical structure of the gecko's toepad, consisting of macro-, meso-, and microstructures [48]. Gecko toe pads are sticky because of their multi-level microstructures, which act as smart adhesives [84].

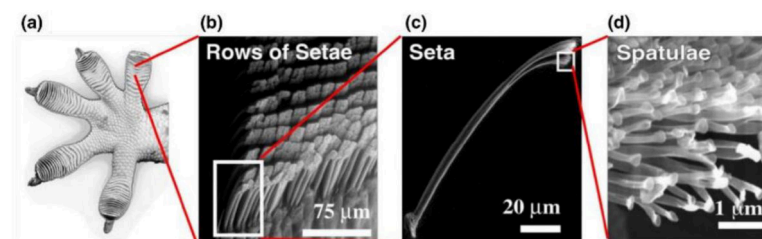


Figure 3. Hierarchical structure of a gecko toepad: (a) lamellar structures; (b) rows of setae; (c) tip of one single setae; (d) spatulae image. Reprinted with permission from [85] 2018, Springer.

Gecko attachment occurs through intermolecular forces [86–88]. Autumn et al. [52,89,90] confirmed the molecular adhesion by measuring the adhesion force generated by a single bristle, which can generate up to 200 μN of force. As illustrated in Figure 4, the Tokay gecko's adhesive system features a layered microstructure. The setae, primarily made of β -keratin with a modulus of approximately 1.6 GPa, contribute to self-cleaning and resistance to entanglement [91–93]. Thanks to the hierarchical structure of the setae, the equivalent elastic modulus of the adhesive system is reduced to around 80–90 kPa, significantly enhancing its ability to conform to various surfaces [94,95]. Micro-nano scale setae structures have been successfully fabricated via molding [96,97] and direct molding processes [98,99].

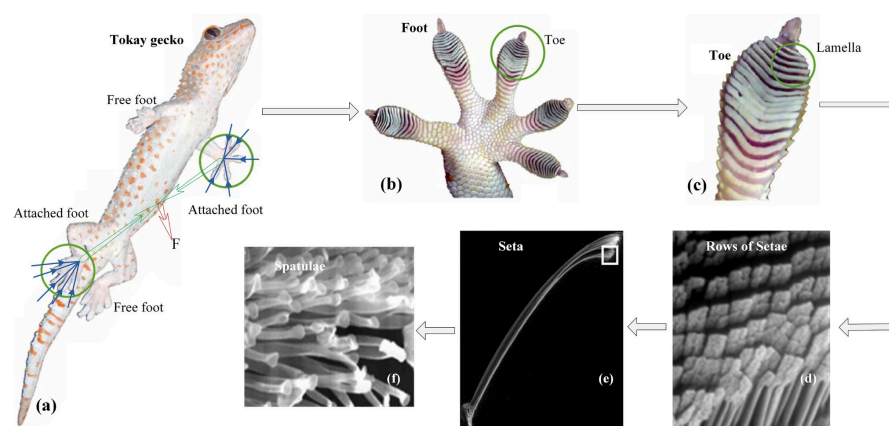


Figure 4. The gecko's adhesive system. (a–c) The macroscopic compositions of gecko's adhesive system; (d–f) The microscopic compositions of gecko's adhesive system [95].

Its unique multi-scale layered bristles based on van der Waals interactions not only give geckos strong adhesion but also give them unique adhesion properties, allowing geckos to climb on various surfaces easily and quickly, as shown in Figure 5 [95].

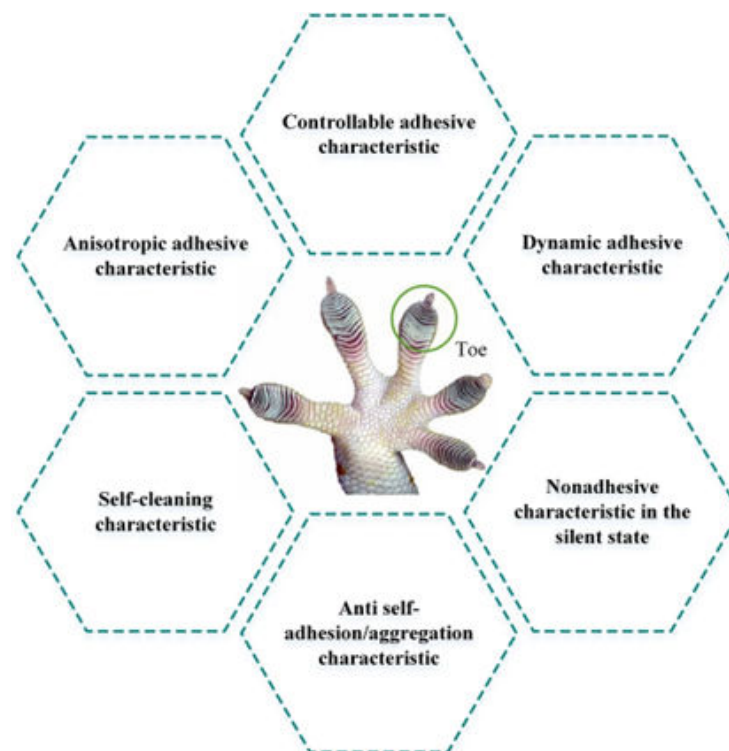


Figure 5. The adhesive characteristics of gecko's foot [95].

Geckos have excellent adaptability, which is due to several key factors in their movement, such as biomechanics, sensory feedback, and neural control. If these factors are incorporated into the design of bioinspired robots, it will help develop a more adaptive, versatile, and efficient bioinspired wall-climbing robot [95]. The schematic diagram of the bioinspired gecko robot research process is shown in Figure 6.

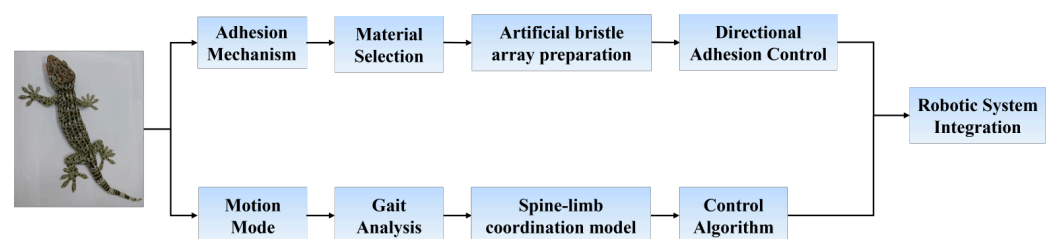


Figure 6. Schematic diagram of the bioinspired gecko robot research process.

3. Classification and Development of Bioinspired Gecko Robots

Understanding both spine flexibility and adhesion as co-evolving traits in climbing biology allows for a more comprehensive classification of gecko-inspired robots. In this review, we group representative robots according to spine design (rigid vs. flexible) and attachment mechanisms (claw-based vs. adhesive), since these two dimensions most directly influence control strategy, mechanical complexity, and application scope. This classification provides a systematic framework to analyze trade-offs and guide future design decisions.

3.1. Classification Based on Spine Flexibility

The classification based on spine flexibility is critical for optimizing climbing performance in different environments. Rigid-spine robots prioritize structural simplicity and precise force control, excelling in predictable environments like smooth walls, but limit adaptability to uneven terrain. Flexible-spine robots mimic the dynamic body coordination of geckos, enabling energy-efficient gait transitions. This classification thus combines biomimicry with engineering practicality to guide designers in matching spine design to the target application.

To illustrate the differences between rigid spine and flexible spine designs in robots, a comparative summary is presented in Table 1, focusing on their structural characteristics, advantages and disadvantages, and representative models.

Table 1. Comparison of rigid spine and flexible spine robots.

Classification	Rigid-Spine Robots	Flexible-Spine Robots
Structural features	Rigid torso with fixed geometry Few joints and simple mechanical structure	Flexible torso that can be actively bent or twisted Multi-degree-of-freedom spinal joint design
Advantage	High stability	High flexibility of movement and strong adaptability to complex terrain [100,101]
Disdvantage	Poor steering flexibility [8,102]	Complex control algorithm
Drive mode	Servo motors	Motors, pneumatic fluid, rope or SMA [8,103–105]
Representative models	Mini-Whegs IV [106], RHex [107,108]	Whegs II [109], SoSpider [110]

3.1.1. Rigid-Spine Gecko Robots

In 2006, O. Unver et al. designed a gecko-inspired climbing robot, as shown in Figure 7a, which used peeling and steering mechanisms and an active tail for robust and agile climbing [111]. Stanford University's Cutkosky research group developed Stickybot [112,113], a gecko-inspired climbing robot that closely mimics the biological morphology of real geckos, as shown in Figure 7b. Stickybot can climb many surfaces, from smooth glass to rough wood, at a maximum speed of 4 cm/s. The team successfully developed Stickybot III [114] in 2011, as shown in Figure 7c. The moving speed of this generation of robots has been improved accordingly, reaching 5 cm/s. According to existing research data, although these two robots have successfully achieved climbing motion on vertical walls, their adhesion stability on inverted surfaces still needs improvement.

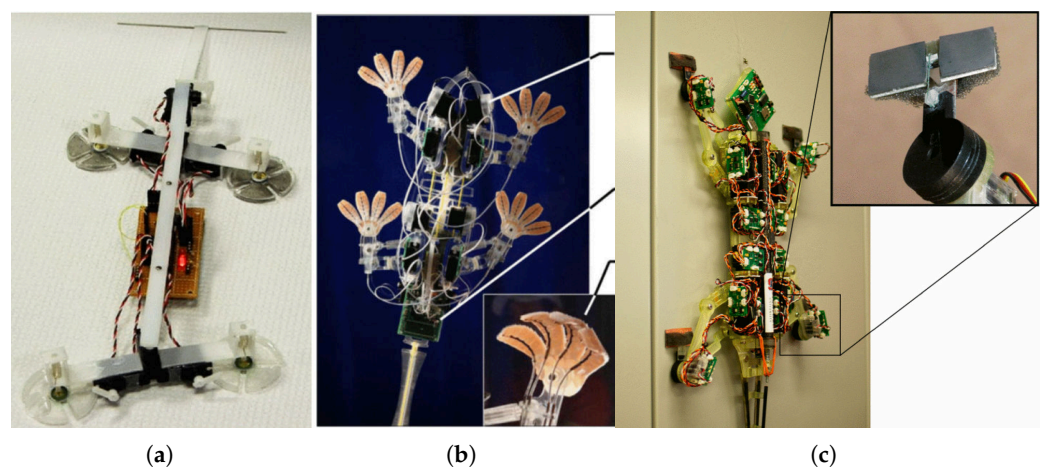


Figure 7. Quadrupedal gecko-inspired robot. (a) Geckobot [115]; (b) Stickybot I [115]; (c) Stickybot III [116].

In the early 21st century, the American RiSE (Robotics in Scansorial Environments) research team conducted systematic research in the field of bioinspired wall-climbing robots. Since 2005, Boston Dynamics has developed three generations of RiSE series wall-climbing robots based on this project [117–119]. Among them, the RiSE V3 is a 5.4 kg climbing robot with four legs and a flexible body. At 70 cm long, it can climb poles at 21 cm/s using its special claw feet and moving torso joint [119].

In 2014, Kalouche et al. designed a gecko-adhesive-equipped robot that can climb surfaces in any gravitational orientation or operate in complete zero gravity [120], as shown in Figure 8a. In 2018, Yu et al. [121] designed a bioinspired gecko robot that can stably climb a smooth ceiling surface.

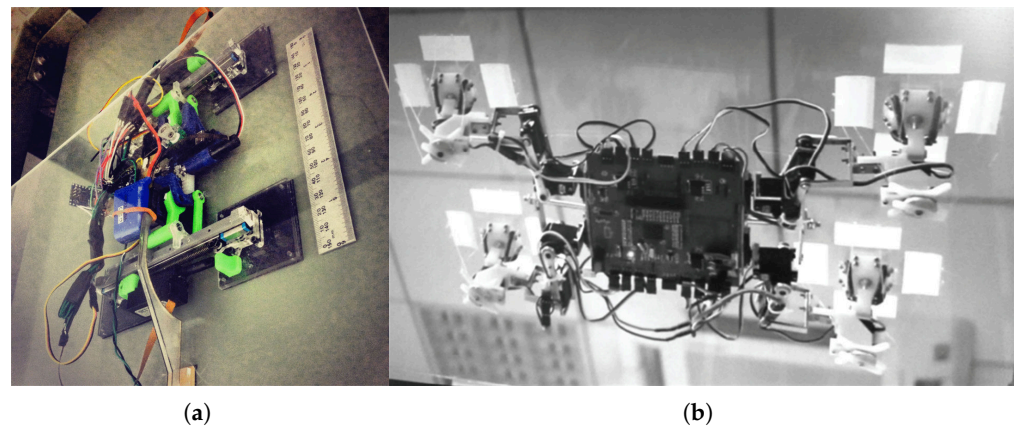


Figure 8. Gecko-inspired robot. (a) ACROBOT [120]; (b) quadruped climbing robot with the imitated gecko foot [121].

In 2021, Bian et al. designed a four-legged wall climbing robot (Figure 9) with spines and a miniature setae array inspired by longicorn and gecko for rough or smooth surfaces, which has a rigid spine [122].

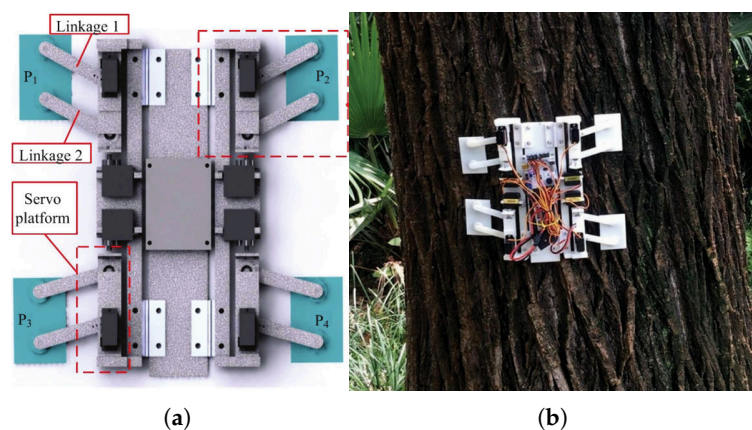


Figure 9. Wall-climbing robot inspired by longicorn and gecko. (a) A prototype of a cylinder climbing robot with three parts. (b) The prototype of this robot was made by the 3D printing equipment [122].

Pei's research group engineered a gecko-inspired robot combining pneumatic and electric drive systems. As depicted in Figure 10, the robotic platform incorporates a rigid body structure, four active limbs with two-degree-of-freedom shoulder joints powered by electric motors, and four pleated pneumatic feet for controlled adhesion [123].

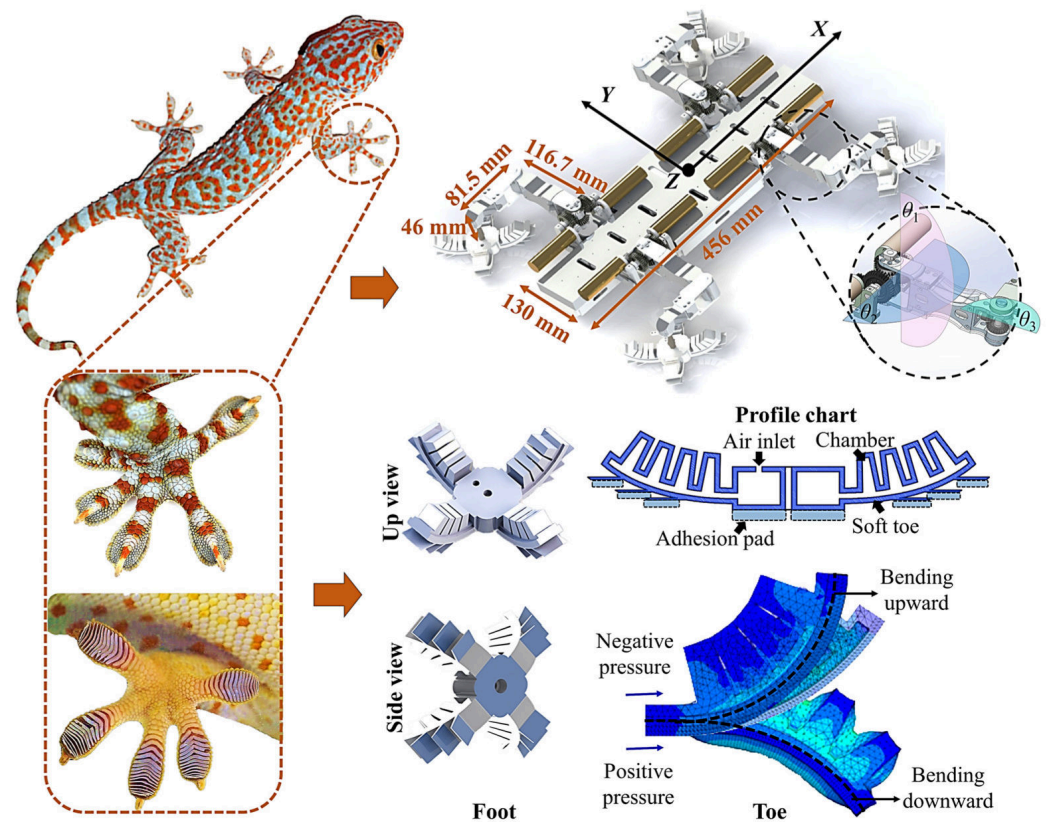


Figure 10. Biomimetic schematic of a gecko robot and its feet [123].

3.1.2. Flexible-Spine Gecko Robots

Geckos exhibit distinct spinal movements depending on environmental conditions—adopting a C-shaped standing wave pattern during low-speed locomotion or in open areas, while transitioning to an S-shaped traveling wave for high-speed movement or in constrained spaces [77,124]. This dynamic spinal flexibility significantly improves the lizard’s maneuverability and balance in complex terrains [125], highlighting the importance of developing biomimetic spines with active shape-adjustment capabilities for environmental adaptation.

Lars et al. design a gecko-inspired soft robot (Figure 11) that can climb inclined flat surfaces. The energy consumption of the robot has been reduced, and its ability to climb and its speed of movement has also been increased by the flexible design [126].

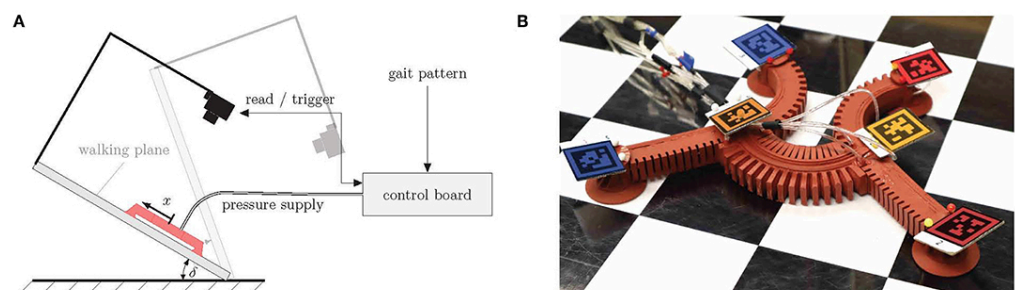


Figure 11. Experimental setting. (A) Principal sketch, (B) April tags are attached to the robot’s feet and to both ends of its torso. The individual tags are indicated by different colors (red—front left, dark red—front right, orange—front center, dark orange—rear center, blue—rear left, dark blue—rear right) [126].

In 2020, Johanna et al. from the University of the Sunshine Coast in Australia developed a modular gecko-like robot X4, as shown in Figure 12 [127]. The front and rear ends of the robot's trunk are each equipped with a motion joint, which is driven by a servo motor. The addition of these two degrees of freedom of the trunk gives the robot's limbs a larger range of motion. The robot's parts are made using 3D printing technology, and the total weight of the machine is 312 g. Johanna's team used the robot to demonstrate the trade-off between speed and stability and to explore the optimal angle for coordination between the limbs and the torso.

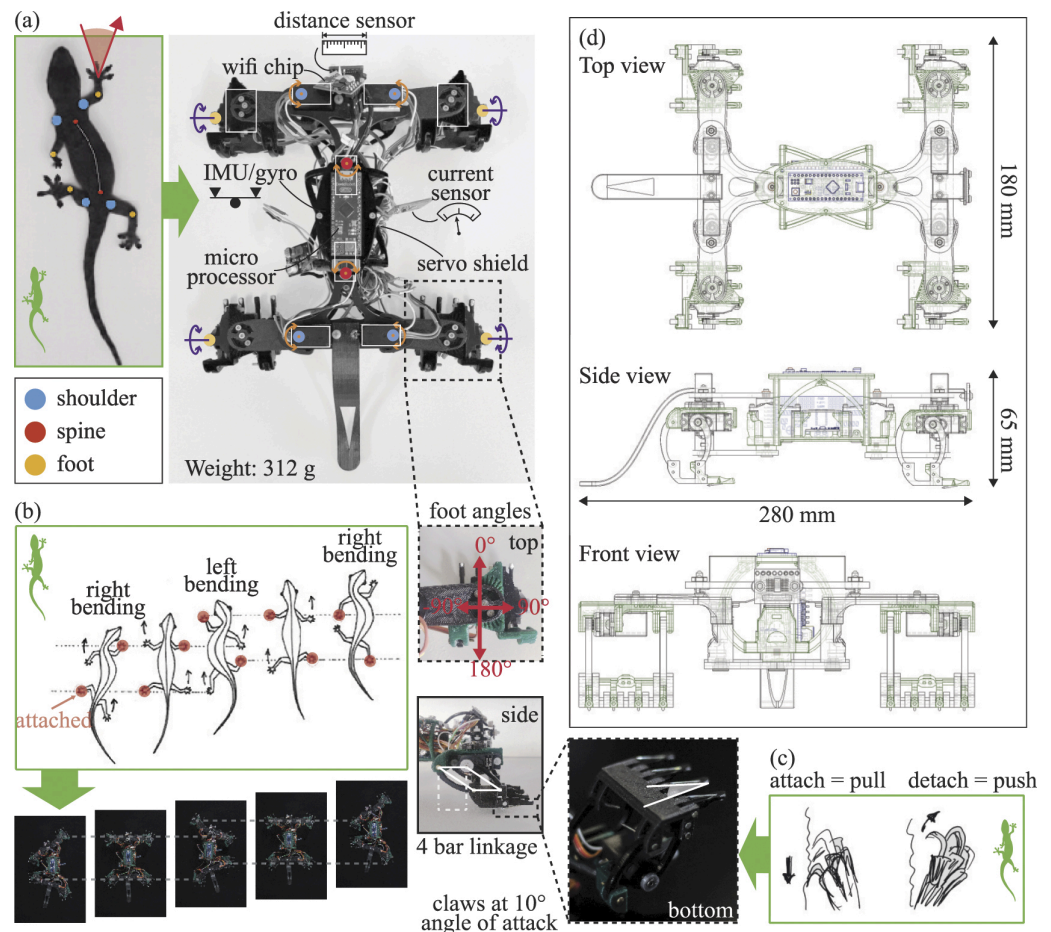


Figure 12. Bioinspired Gecko Robot X4. (a) Shows the abstraction process using biomimetically derived joint locations, based on the main degrees of freedom among climbing lizards. The corresponding active joint locations in the robot and their rotational axis are displayed. (b) Shows the design of a standard gait based on the lizard trot, where diagonal limb pairs act in unison to be raised or lowered. The two spine joints, combined with the shoulder joints, drive the robot forward. (c) Shows the four-bar linkage design—a passive joint in each leg—which is used to raise and detach or lower and attach the claws. (d) Shows a full schematic for the shape and incorporation of 3D printed and laser-cut parts [127].

In 2021, Worasuchad et al. from Nanjing University of Aeronautics and Astronautics proposed a gecko-like robot, Slalom, with a bendable spine [72], which adopts a 19-DOF design, with 4 DOF in each leg and 3 DOF in the spine, all driven by servo motors. In 2023, Ji Aihong's team from Nanjing University of Aeronautics and Astronautics proposed a gecko-like robot based on a flexible spring-driven spine with a shape memory alloy [10] (Figure 13a) [8].

Li et al. designed a flexible spine with active bending and torsion capabilities using pneumatic soft actuators and demonstrated its effectiveness in wall-crawling through theoretical modeling, finite element simulation, and experimental verification [125]. In

2024, Paul et al. designed a bioinspired robot LORIS [128] (Figure 13b), with a degree of longitudinal bending freedom that can crawl on uneven ground.

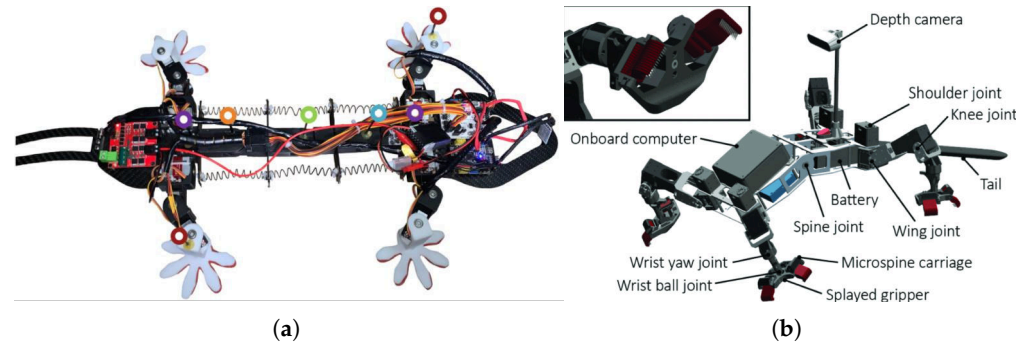


Figure 13. (a) SMA-driven flexible-spine gecko-inspired robot [8]; (b) An annotated visualization of the LORIS robot design [128].

3.2. Classification by Attachment Mechanisms

Wall-climbing robots can be divided into wheeled, tracked, and bionic-footed robots, depending on their form of movement. Most bioinspired gecko robots use bionic foot structures. Bionic-footed robots imitate the multilegged structure of animals, have strong environmental adaptability, and have excellent obstacle crossing capabilities. Still, because they need to coordinate the movement of multiple legs, the mechanical structure and control method is generally more complex [129–134].

Within the domain of bionic-footed robots, attachment mechanisms play an important role in determining climbing performance. The adhesion mechanism of the bioinspired gecko robot can be primarily classified into two categories: claw-based and adhesion-based systems. Claw-type robots rely on mechanical interlocking with surface asperities, making them particularly effective on rough or porous substrates [65,135], but they face significant challenges when navigating smooth or complex-shaped surfaces [8,122,136]. Adhesion-type robots employ biomimetic materials or synthetic adhesives to generate attachment forces, enabling them to climb smooth surfaces [52,137]; however, this method requires very clean surfaces, which makes them less reproducible and severely affected by surface impurities such as oil, dust, humidity, and temperature changes [138,139].

3.2.1. Claw-Based Attachment

Claw-based robotic adhesion systems typically achieve stability on rough surfaces through mechanical interlocking between gripper elements and surface irregularities [66]. Xu and colleagues [140] established a theoretical framework analyzing spike-particle interactions, considering both cases where the spherical contact center lies either inside or outside the wall surface. Their analysis determined that the maximum allowable hook radius r_{max} must comply with Equation (1), with distinct values r_{max1} and r_{max2} corresponding to external and internal sphere center positions, respectively.

$$r_{max} \Rightarrow \begin{cases} r_{max1} = \frac{R_z(1 - \Lambda) - \frac{S_m^2}{16R_z}(1 + \Lambda)}{2(1 + \Lambda)} \\ r_{max2} = \frac{\frac{S_m^2}{16R_z}(1 - \Lambda) - R_z(1 + \Lambda)}{2(1 - \Lambda)} \end{cases} ; \text{ where } \Lambda = \sin\left(\arctan\left(\frac{\tan \alpha - \mu}{\mu \cdot \tan \alpha + 1}\right)\right), \quad (1)$$

where R_z is the maximum height of the particle, α is the contact angle, μ is the friction coefficient, and S_m is the length of the chord. This model provides a theoretical basis for the design of the claw of the claw robot. Based on this model, Xu et al. optimized

the geometric parameters of the robot claw to maximize its mechanical interlocking force on rough surfaces. Subsequent studies verified the applicability of this model through experiments and further proposed a multi-claw collaborative control strategy to improve the stability of the robot on rough surfaces.

The RiSE series robots can successfully climb on a vertical surface. They adopt a claw design. Each leg of the robot has two degrees of freedom. The four-bar mechanism is used to coordinate the up-and-down swing of the legs to control the landing point of the soles of the feet. The center of gravity of the robot can be changed to adapt to the conversion of different surface motion states [114].

In 2016, Ji Aihong's team at Nanjing University of Aeronautics and Astronautics successfully developed a bioinspired quadruped wall climbing robot with a bionic claw design that can move at a speed of 4.6 cm/s on rough walls [141], as shown in Figure 14a. In 2017, the team further developed a six-legged grasping robot that can generate sufficient adhesion through the synergy of multiple legs, able not only to stably adhere to rough walls but also to achieve omnidirectional movement [142], as shown in Figure 14b.

In 2021, the Kong Deyi team from the University of Science and Technology of China proposed a new type of gecko-like robot to support different moving surfaces. As shown in Figure 14c [143], the robot's limbs are composed of a five-link and a gear transmission device, and the extension and contraction of the legs are driven by servo motors. The robot's foot end is integrated with a claw system and bionic adhesive materials, which can climb on rough surfaces and move on smooth surfaces. The robot has a mass of 360 g and moves at a speed of 8.86 cm/s on a cloth surface, 9.14 cm/s on a rock surface, and 9.34 cm/s on a glass surface.

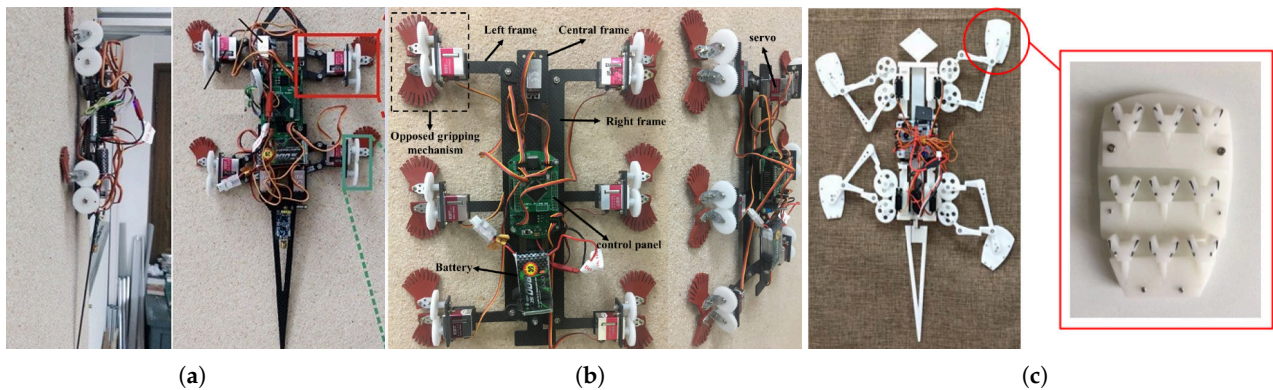


Figure 14. Wall-climbing robot developed by NUA. (a) Quadruped wall-climbing robot [141]; (b) hexapod wall-climbing robot [142]; (c) gecko-like robot from University of Science and Technology of China [143].

3.2.2. Adhesive-Based Attachment

Liu et al. [144] analyzed the dynamic properties of the large gecko bristle adhesion system, as shown in Equation (2).

$$\begin{bmatrix} m\ddot{x} \\ m\ddot{y} \\ I\ddot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos \varphi & -\sin \varphi & 0 \\ \sin \varphi & \cos \varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -4f_u dB - G \sin \varphi \\ F_L + F_R - G \cos \varphi - \mu F_s - 2F_P \cos \varphi \\ (F_R - F_L)\frac{b}{2} - 2f_u B \left(\frac{L^2}{4} - d^2 \right) \end{bmatrix}, \quad (2)$$

where m , I , φ , x , and y are the mass, the moment of inertia, navigation angle, and center of mass coordinates of the robot, respectively. f_u is the friction force per unit area, d is the instantaneous center offset, B is the width of the wheel, L is the distance between the two wheels, G is gravity, μ is the friction coefficient, and F_s is the adhesion

force. Equation (2) reveals the coupling relationship between force and motion, provides a theoretical framework for the design of adhesive bioinspired gecko robots, can guide the subsequent mechanical design of robots, and provides a basis for the robot's control strategy. In addition, the key parameters in Equation (2) also promote the performance improvement of adhesive materials.

Inspired by geckos, the quadruped climbing robot Stickybot [113] (as shown in Figure 15a) uses a gecko-like stem adhesive surface based on oriented polymer stems as the foot adhesive unit. The robot's legs use a parallel four-bar mechanism, with four toes distributed on each sole, and each toe is integrated with tens of thousands of artificial bristles made of special rubber materials, using the van der Waals force between molecules to make the sole adhere to the wall. The robot's foot end is equipped with an active pulling mechanism, which can realize the eversion and flattening of the toes, thereby controlling the attachment and detachment of the robot's sole.

SpinybotII [145] (as shown in Figure 15b), the robot's toes utilize a single structure composed of both hard and soft materials, which enables them to adhere to the wall. The robot Stickybot III (shown in Figure 15e) has been improved. The robot's tendon-shaped foot structure can make the dry adhesive material more evenly stressed, and the toes with greater stiffness can also prevent the adhesive material from falling off prematurely. The leg structure of Stickybot II has added a degree of freedom, enabling leg-lifting movements that are more conducive to desorption. Based on the above optimization, the movement speed of this generation of robots has also been improved accordingly, reaching 5 cm/s.

The robot Waalbot II [146] uses a mushroom-shaped synthetic gecko adhesive that has no directional properties. Abigail III [147] also uses a mushroom-shaped microfiber adhesive and requires a preload. It generates preload and pull-off forces in a more stable manner than the Waalbot, albeit at a slower rate. The robot ACROBOT's [120] (as shown in Figure 15c) adhesive mechanism couples two gecko pads in opposite directions so that the adhesive can be controlled to be in an open or closed state regardless of the robot's orientation or the presence of significant gravity. The robot shown in Figure 15d also uses a mushroom-shaped microstructured gecko foot. The normal adhesion ability of the gecko foot does not depend on the direction of the pre-pressure and can assist a 700 g quadruped climbing robot to achieve smooth inverted climbing with a diagonal gait [121].

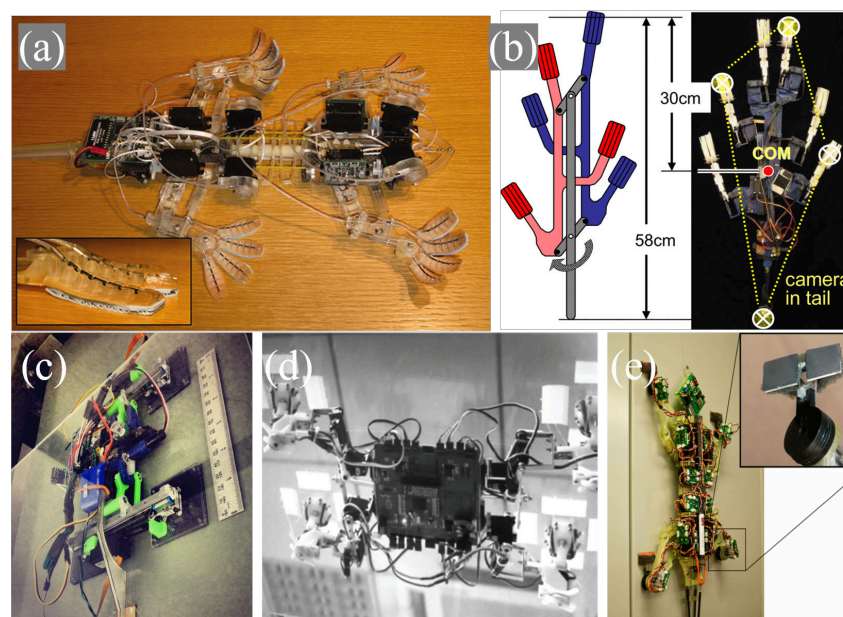


Figure 15. Adhesive bioinspired gecko robots. (a) Ref. [148]; (b) Ref. [149]; (c) Ref. [120]; (d) Ref. [121]; (e) Ref. [116].

In 2021, Wang et al. [150] proposed an online impedance control strategy based on Equation (2) to control the peeling angle and achieve compliant motion based on the adhesion characteristics of gecko paws. By dynamically adjusting the navigation angle (φ) and adhesion force (F_s), they achieved compliant detachment on vertical walls without losing stability. When applied in a vertical wall-climbing robot, IBSS-8 (Figure 16), can reliably achieve compliant separation.

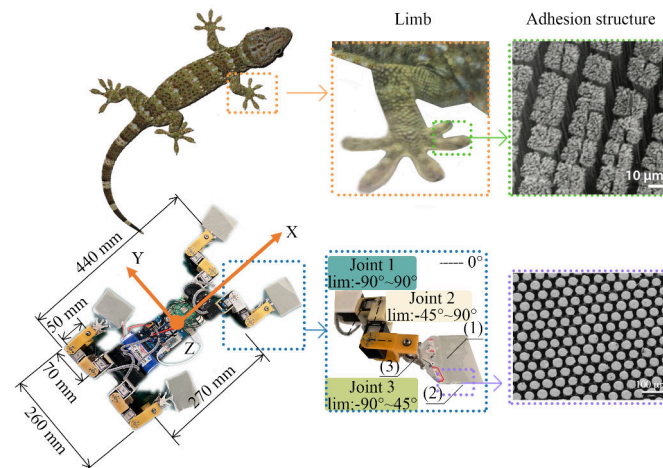


Figure 16. Bionic structure design of IBSS-8 for the body, limb, and adhesion unit [150].

Table 2 systematically sorts 18 bio-inspired gecko robots developed between 2006 and 2024, and classifies them according to the two dimensions of spine flexibility (rigidity/flexibility) and movement mode (adhesion/claw type), providing a theoretical framework for the subsequent optimization of robot performance.

Table 2. Classification of bioinspired gecko robots.

Robots	Spine Flexibility	Movement Mode	Accuracy	Cost	Reference
Geckobot	Rigid-Spine	Adhesion	Low	Low	[111]
SpinybotII	Rigid-Spine	Adhesion	Medium	Low	[145]
StickybotI	Rigid-Spine	Adhesion	Low	Low	[112]
StickybotII	Rigid-Spine	Adhesion	Medium	Low	[151]
StickybotIII	Rigid-Spine	Adhesion	High	Medium	[114]
RiSE V3	Rigid-Spine	Claw	Low	Medium	[119]
ACROBOT	Rigid-Spine	Adhesion	High	High	[120]
Ji et al.	Rigid-Spine	Claw	Medium	Low	[141]
Kong et al.	Rigid-Spine	Claw	Medium	Medium	[142]
Yu et al.	Rigid-Spine	Adhesion	Medium	Medium	[121]
Bian et al.	Rigid-Spine	Claw	High	Medium	[122]
Lars et al.	Flexible-Spine	Adhesion	Medium	Medium	[126]
Pei et al.	Rigid-Spine	Adhesion	Medium	Medium	[123]
Wang et al.	Rigid-Spine	Adhesion	Medium	High	[150]
X4	Flexible-Spine	Claw	High	High	[127]
Slalom	Flexible-Spine	Adhesion	High	High	[72]
Qiu et al.	Flexible-Spine	Claw	Medium	High	[8]
LORIS	Flexible-Spine	Claw	Low	High	[128]

Table 2 provides a foundational classification framework that can significantly inform future control design decisions in gecko-inspired climbing robots. By organizing representative robots along the axes of spine flexibility and movement modality (adhesion-based or claw-based), the table highlights how structural choices affect the demands placed on control systems. For instance, robots with flexible spines exhibit superior mobility and surface adaptability but often require more complex control algorithms, such as high-DOF coordination and neural oscillators (e.g., CPG networks), which can incur higher computational costs and require fine-tuned parameterization. In contrast, rigid-spine robots, although more limited in adaptability, allow for simplified control models and generally lower hardware and computational requirements.

Similarly, the type of attachment mechanism has implications for the accuracy of the sense and control. Adhesion-based systems often require accurate force feedback and environmental sensing to obtain stable performance, especially on smooth or variable surfaces. In contrast, claw-based systems are generally more robust on rough surfaces and may allow for lower frequency control loops due to mechanical interlocking.

Therefore, this classification offers not only a historical summary but also a practical reference for selecting control strategies. To make this classification more practical for engineering use, future research could consider adding measurable indicators, like how much computing power is needed, how much energy the robot consumes, or how well it adapts to different surfaces. Including such data would allow for clearer comparisons between different robot designs and help engineers match control systems more effectively to mechanical structures based on specific application goals.

4. Motion Control Strategy of Bioinspired Gecko Robot

The structural design of the wall climbing robot is the basis of the robot [38,152]. Control of movement stands as the pivotal system in bioinspired robotic climbers. The motion control system must have key characteristics, such as good stability, fast response time, and high control accuracy [66]. The control of the gecko robot usually adopts an open-loop position control strategy [111,118,153].

While biological motion appears simple, it involves complex multi-joint coordination that robots must replicate. Adaptive control and real-time learning help robots better handle dynamic environments. Simmons developed a three-layer control architecture that integrates sensor feedback, enabling adaptive planning through coordinated hierarchical control [154]. Rosenblatt's hybrid control architecture combines centralized coordination with decentralized autonomous modules, enabling adaptive, bioinspired robotic control through the integration of top-down commands and reactive behaviors from the bottom-up [155]. Chua and Yang proposed the Cellular Neural Network (CNN) [156], its core concept being that each cell generates output through a piecewise function of input weights, making it applicable to image classification, object detection, joint detection, and other related domains [157,158]. Arena et al. [159] adapted this parallel architecture for robotic control, using local cell interactions to enable efficient and adaptive control through neural networks. Recent advances in deep reinforcement learning (e.g. PPO, SAC) have enabled robots to autonomously learn adaptive locomotion policies through trial and error in simulation [160,161]. Modern bioinspired systems integrate vision, tactile sensors, and proprioception to achieve real-time terrain adaptation.

Gecko-inspired robotic control has advanced through hierarchical and adaptive strategies, and the central pattern generator (CPG) is an efficient bionic neural mechanism control algorithm that controls the rhythmic movements of organisms such as walking, running, and flying by simulating the oscillation signals generated by the central nervous system of vertebrates [162]. Compared to conventional robot motion, which is usually scheduled in a

single cycle, CPG-controlled motion is continuous [163]. The CPG control model is usually based on the following neural oscillators, such as the Matsuoka neural oscillator [164], the VanderPol oscillator [165], and the Hopf oscillator [166], to build a network composed of multiple neural oscillatory units to achieve coordination and control of the robot's movement rhythm. CPG plays a vital role in homogenizing errors and coordinating multiple degrees of freedom [167].

To better compare and understand the strengths and limitations of different motion control strategies applied in bioinspired gecko robots, a summary of commonly used methods is provided in Table 3. This comparison includes hierarchical control, CPG-based neural control, reinforcement learning, impedance control, and motion matching.

Table 3. Summary of common motion control strategies in gecko-inspired robots.

Control Method	Description	Advantages	Limitations	Example Studies
Hierarchical control	Multi-layered system integrating perception and action	Modular, adaptive, task-specific	Complex integration, latency issues	Simmons [154], Rosenblatt [155]
CPG-based neural control	Uses biological-like oscillators to generate rhythmic motion	Rhythmic, low computational load, biologically plausible	Sensitive to parameters, hard to stabilize	Kim et al. [129], Cai et al. [164]
Reinforcement learning	Learns policies from trial-and-error in simulation	High adaptability, end-to-end training	Data-hungry, sim-to-real gap	PPO/SAC in simulation
Impedance control	Adjusts force compliance via dynamic equations	Effective for interaction tasks	Requires accurate force/torque estimation	Pei et al. [123]
Motion matching	Learns and reconstructs periodic joint data from biological gaits	Accurate reproduction, biologically inspired	Relies heavily on training data	Wang et al. [158]

Kim et al. [129] demonstrated this in their Stickybot robot, where coupled non-linear oscillators enabled stable vertical climbing at 21 cm/s on glass surfaces. Cai et al. proposed a motion control method for a gecko-like robot based on CPG, which used the Matsuoka oscillator model to generate rhythmic signals through a mutually inhibiting neuronal network to simulate the periodicity of biological motion [168].

In 2018, the study by Alizadehyazdi et al. [169] introduced an electrostatic self-cleaning method for gecko-inspired adhesives, addressing a critical limitation of conventional adhesives in dusty environments. The principle is: utilizes electrostatic repulsion to remove contaminants without physical contact. Electrodes embedded in the adhesive generate alternating electric fields to repel particles via Coulomb and dielectrophoretic forces, overcoming van der Waals adhesion. By synchronizing electrostatic activation with robot gait cycles, contamination resilience can be achieved without compromising mobility. Future work should explore closed-loop control systems that dynamically adjust cleaning parameters based on real-time data.

In 2019, Arthicha, Shao et al. proposed a multi-gait generation and adaptation algorithm for a gecko-like robot based on neural control, which enabled the robot to climb efficiently on different slopes through a central pattern generator (CPG) and dynamic feedback. The control consists of three main components: a central pattern generator (CPG) for generating various rhythmic patterns, CPG post-processing to shape the CPG signals, and a delay line to transmit the shaped CPG signals to drive the legs of the gecko robot. The CPG network consists of two neurons with full connections [170]. The CPG network consists of two neurons with full connections as presented in Figure 17 [170]. The activity of neurons is presented in Equation (3).

$$\begin{aligned} c_1[t] &= f(w_{11}c_1[t-1] + (w_{12} + MI)c_2[t-1]), \\ c_2[t] &= f(w_{22}c_2[t-1] + (w_{21} - MI)c_1[t-1]), \end{aligned} \quad (3)$$

where $c_i[t]$ is the CPG signal from neuron i at time step t . f describes the activation function, which is a hyperbolic tangent function, w_{ij} is the synaptic weights of the network, and MI is a modulatory input.

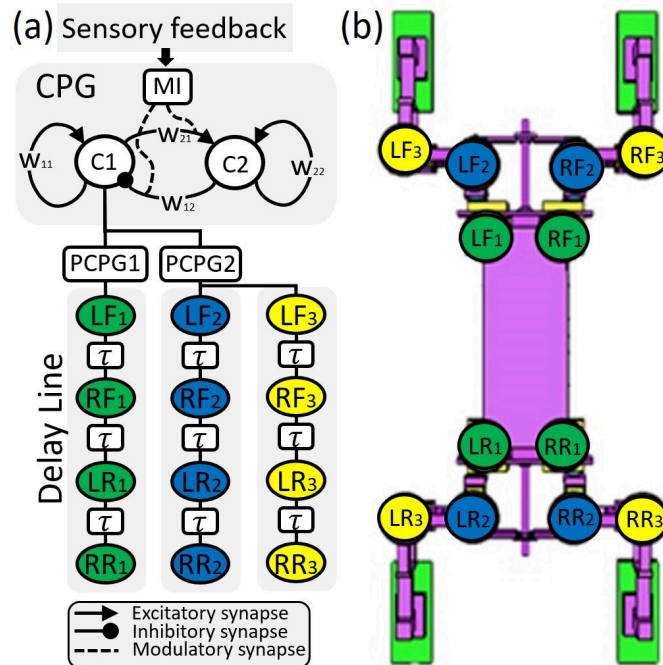


Figure 17. (a) Architecture of modular neural control for controlling the gecko robot. (b) The gecko robot with corresponding labeled joints [170].

In 2020, Wang et al. investigated how geckos modulate their adhesive systems under reduced gravity conditions [171], revealing key insights into shear-induced adhesion control and toe kinematics. The gecko's stereotyped toe-gripping motion enables rapid response to perturbations without neuronal feedback, ideal for robotic applications requiring energy efficiency and speed.

Pei et al. proposed a bioinspired adaptive control strategy for gecko-like robots in space stations, combining rigid-flexible coupling and real-time force feedback. The system dynamically adjusts the impedance parameters to enable stable climbing, compliant detachment, and disturbance rejection in microgravity, demonstrating precise motion control and robust performance for space applications. The control structure of the robot gecko is presented in Figure 18 [123].

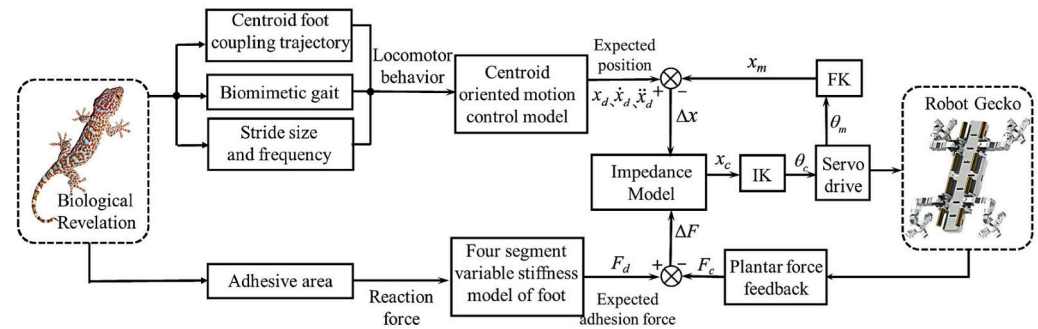


Figure 18. The control structure of the robot gecko [123].

The mathematical relationship for an impedance model is established as follows:

$$m\ddot{x} + b\dot{x} + kx = f, \quad (4)$$

where x represents the position, m is the mass, b is the damping coefficient, k is the stiffness coefficient, and f is the applied external force. By applying the Laplace transform to Equation (4), we obtain [123]:

$$(ms^2 + bs + k)X(s) = F(s). \quad (5)$$

The relationship between the position error of the robotic gecko foot and the contact force applied to the foot can be described by an impedance equation as follows:

$$M(\ddot{x}_d - \ddot{x}_c) + B(\dot{x}_d - \dot{x}_c) + K(x_d - x_c) = F_d - F_e, \quad (6)$$

where M , B , and K are impedance parameters, representing the inertia coefficient, damping coefficient, and stiffness coefficient, respectively. x_d , $\dot{x}_d$, and $\ddot{x}_d$ represent the desired values of the position, velocity, and acceleration, respectively. x_c , $\dot{x}_c$, and $\ddot{x}_c$ represent the actual values of the position, velocity, and acceleration. F_d represents the desired external force/torque, while F_e denotes the actual external force/torque from the environment [123].

Based on the idea of biological neural control and the analysis of the kinematic characteristics of the gecko, Wang proposed a motion-matching control algorithm based on the gecko kinematic model [162]. Motion matching refers to building an oscillation centre, learning and reconstructing the gecko joint motion parameters as control signals, and accurately controlling robot motion by adjusting the amplitude and frequency, as shown in Figure 19.

As shown in Figure 19, the discrete values of multi-joint variables of a stable gait cycle $x_i[n]$ ($i = S1, \dots, S15$) are input into the algorithm framework as learning objects. The parameters are calculated by Equation (7) [162].

$$\begin{cases} A_{ki} = \left| \frac{1}{N} X_i(e^{jk\omega_0}) \right| = \left| \frac{1}{N} \sum_{n=0}^{N-1} x_i[n] e^{-jk\omega_0 n} \right|, (k, n = 0, 1, \dots, N-1), \\ p_{ki} = \arg\left(\frac{1}{N} X_i(e^{jk\omega_0})\right) = \arg\left(\frac{1}{N} \sum_{n=0}^{N-1} x_i[n] e^{-jk\omega_0 n}\right), \\ v = F/T, \\ dt = 1/F, \end{cases} \quad (7)$$

Among them,

i represents the trunk joint variable $y_i[n]$, $i = 1, \dots, 7$, among which, $i = 6, i = 7$ represent the shoulder girdle and pelvic girdle joint variables, respectively, and $i = 8, \dots, 15$ represent the limb joint variables;

N represents data dimension, that is the number of data sampling points in a gait cycle (in this paper, $N = 256$);

$A_k p_k$ represents signal amplitude and phase value;

T represents sampling time of a gait cycle;

v represents the rate of change in the discrete value $F[n]$ of the sampling frequency F ;

dt represents the sampling period.

In addition, the symbol $\arg(\cdot)$ represents the argument of the complex number.
 $\omega_0 = 2\pi/N$.

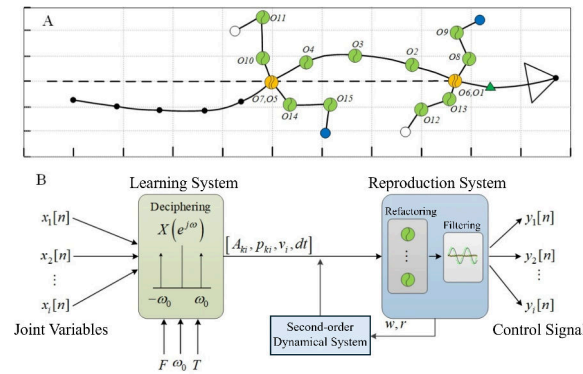


Figure 19. Motion matching algorithm framework. (A) is the oscillation center; (B) is the algorithm framework [162].

Shao et al. proposed a neural control method based on central pattern generator (CPG) and radial basis function (RBF) networks for motion control and adaptation to body height of a gecko-like robot (Nyxbot) [172]. The method adopts a layered architecture, including a sensory input layer (an infrared sensor detects obstacles), a CPG layer (generates periodic motion signals), an RBF premotor network (converts signals into complex joint trajectories), and a motor neuron layer (executes actions). An overview of the neural network connections is presented in Figure 20.

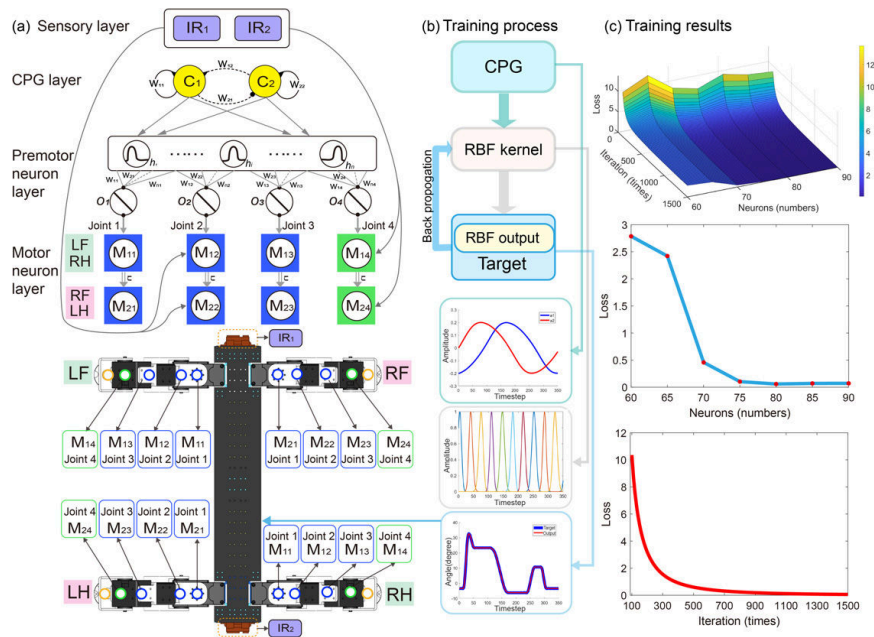


Figure 20. Neural control network of the gecko-inspired robot (Nyxbot). (a) Connections and structure of the neural network (CPG combined with RBF). (b) Training process of the RBF network. The insets are one period of rhythmic generation (CPG), RBF kernels, and a shaped CPG signal. (c) Training analysis of the RBF network with varying RBF neurons [172].

For hybrid-driven motion, Wang et al. introduced a Neural Coordination Strategy (NCS) based on central pattern generators. Figure 21 illustrates its four components: (a) a CPG module, an adjustable-frequency neural oscillator; (b) a PCPG module, a signal processor converting CPG outputs to motion commands; (c) a DL module, a phase synchronizer for limb/adhesion coordination; (d) a signal mapping module, an actuator-specific signal conditioning module [173].

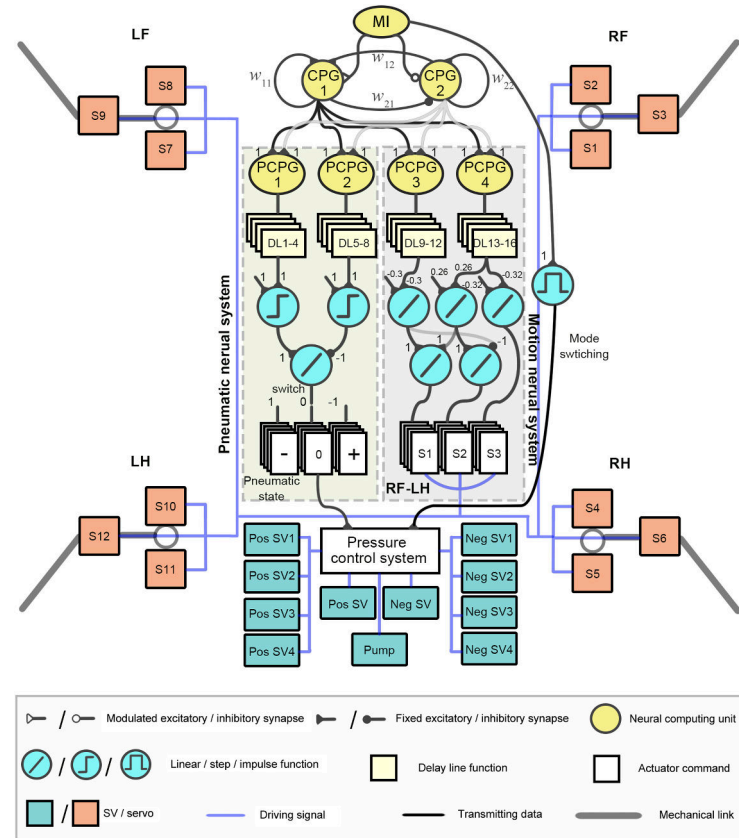


Figure 21. The control framework of the NCS, which is composed of the following 4 parts: CPG module, a rhythm generator with neural characteristics and adjustable frequency; postprocessing of CPG (PCPG) module, which converted the CPG signal into a signal matching to the robot motion; delay line (DL) module, a function to form the coordination between the adhesion and motion organs and the phase relationship between the limbs; and signal mapping module, which adjusted the signal of the PCPG, according to the mechanical/electronic properties of the components and sent it to the actuator [173].

The neural control architecture employs a dual-neuron CPG network to produce fundamental oscillatory rhythms. These frequency-modulated CPG outputs establish the robot's periodic motion patterns, with the governing equations presented in Equation (8) [173]:

$$\begin{aligned} C_1(t) &= \tanh(w_{11}C_1(t-1) + (w_{12} + MI)C_2(t-1)), \\ C_2(t) &= \tanh(w_{22}C_2(t-1) + (w_{21} - MI)C_1(t-1)), \end{aligned} \quad (8)$$

where $C_1(t)$ and $C_2(t)$ represent the output of CPG 1 and 2 at time t . w_{11} , w_{12} , w_{21} , and w_{22} are the synaptic weights of the network.

In summary, the control strategies of gecko-inspired climbing robots have evolved significantly, transitioning from conventional hierarchical frameworks to biologically inspired neural control mechanisms and reinforcement-learning approaches. Among these, CPG-based methods are particularly notable for enabling rhythmic and coordinated movement patterns. However, despite their promise in simulation and controlled scenarios,

the practical deployment of these control strategies in real-world environments presents several notable challenges.

For instance, adhesion-based robots are highly dependent on force or tactile sensing for feedback, but environmental factors such as surface roughness, dust, humidity, or contamination can interfere with sensor accuracy, leading to unstable adhesion or unintentional detachment. Claw-based systems, while more robust on rough surfaces, often face difficulties in dynamically adjusting the force of the grip across variable terrain, which requires adaptive control schemes that increase computational demands. Similarly, CPG networks and reinforcement-learning methods typically require high-frequency real-time computation, posing hardware limitations, particularly in robots with high degrees of freedom (DOFs) or compliant spine structures. Although CPGs are well-suited to generate stable rhythmic motion, they may struggle to respond to sudden terrain transitions unless supplemented with parameter tuning.

Flexible spine architectures, while advantageous for maneuverability and terrain adaptability, introduce additional complexity in load distribution during climbing. This can lead to undesired deformation, such as spinal buckling or reduced adhesion force, especially under high payload conditions. In addition, electrostatic and gecko-inspired adhesive materials are prone to performance degradation over time as a result of wear, requiring regular cleaning, maintenance, or replacement.

To overcome these limitations, future research should explore hybrid control architectures that combine the adaptability of CPGs with the predictive capabilities of Model Predictive Control to better balance responsiveness and computational efficiency. Incorporating multimodal sensor fusion—including vision, force, and proprioceptive inputs can enhance situational awareness and control robustness. Moreover, the development of novel materials, such as self-cleaning adhesives or high durability-compliant spines, can significantly extend operational longevity and reduce maintenance overhead. By addressing these practical challenges, the field can move closer to realizing reliable, deployable gecko-inspired climbing robots suitable for complex real-world applications.

5. Applications of Gecko-Inspired Robots

The development of gecko-inspired robots is not merely an academic exercise but a pursuit with significant real-world engineering applications. These robots, with their unique climbing ability, are designed to operate in environments that are hazardous or inaccessible to humans. In the following, we discuss several key areas where gecko-inspired robots are making an impact or are promising for future deployment.

Gecko-inspired robots are particularly suited to inspect and maintain critical infrastructure such as bridges and pipelines. Traditional inspection methods often require scaffolding or human workers to operate at dangerous heights, posing significant safety risks. Robots like RiSE V3 [119] and Stickybot III [114] can navigate vertical and inverted surfaces with ease, and are equipped with sensors to detect cracks, corrosion, or structural weaknesses. The IBSS-8 robot [150] employs impedance control to ensure stable adhesion while performing inspections, reducing the need for human intervention in hazardous conditions.

With the completion of a large number of high-rise buildings in recent years, the demand for their maintenance and inspection has increased. Wall cleaning is also an important task to ensure the cleanliness of buildings [174–178]. In 2017, Kim et al. designed a gecko robot platform to automatically clean various exterior wall surfaces of buildings, especially glass curtain walls and concrete walls. Replacing traditional manual rope or hanging basket operations improves the safety, efficiency, and stability of operations [30].

The inspection of hazardous environments represents another important area. Wall-climbing robots with gecko-shaped feet have been used in nuclear power plants for

crack inspection and radiation detection, operating safely in zones inaccessible to humans [4,179–181]. In 2020, Kim et al. [11] developed a wall-climbing robot equipped with active sealing and vacuum suction systems specifically designed to operate in high-radiation zones within NPP structures, such as dry cask storage systems (DCSS). These environments are often inaccessible to humans due to safety concerns and complex geometries that involve vertical or curved surfaces.

In aerospace and space station environments, gecko-inspired adhesion technologies eliminate the need for suction or magnetic attachment, making them ideal for microgravity applications [182,183]. A hybrid-driven gecko robot developed by Pei et al. demonstrated stable surface locomotion in spacelike environments, with potential for maintenance and inspection in the interiors of spacecraft [123].

Table 4 summarizes the practical applications cases of bionic gecko robots in different fields. As these examples demonstrate, the bioinspired gecko robot will gradually move from the laboratory to engineering practice and become an important tool for high-risk, high-precision operation scenarios. Its development relies on the cross-breakthrough of bionics, material science, and robotics technology, and is expected to be applied on a large scale in the fields of industry, aerospace, and people's livelihoods in the future. Future work should prioritize interdisciplinary collaboration to bridge the gap between biomimetic design and real-world utility.

Table 4. Summary of real-world applications of bioinspired gecko robots.

Application	Task	Key Technologies	Reference
Infrastructure inspection	Bridge/high-rise crack detection	Force-sensitive adhesion, CPG control	Wang et al. [150]
Building maintenance	Glass wall/window cleaning	Modular cleaning unit, suction adhesion	Kim et al. [30]
Nuclear power plants	Radiation measurement, NDT in DCSS	Vacuum suction, active sealing, PID control, SLAM	Kim et al. [11]
Space applications	Surface mobility in microgravity	Gecko-inspired adhesion, pneumatic-electric hybrid	Pei et al. [123]

6. Discussion

Bioinspired gecko robots provide innovative technical solutions for wall-climbing tasks in complex environments. This type of robot improves its adaptability and motion stability on vertical surfaces by simulating the adhesion mechanism of geckos. At present, research has made important breakthroughs in the exploration of adhesion principles, the development of new materials, and motion control methods, but there are still several technical problems that need to be solved. Although the flexible spine design is closer to biological characteristics, it has problems such as complex control and insufficient structural reliability in practical applications. The optimization of the performance of adhesive materials is also a major challenge, and it is necessary to ensure that they can maintain a stable adhesion effect on surfaces of different materials. In addition, the robot's autonomous obstacle avoidance ability in complex environments still needs to be improved, which puts higher requirements on sensor systems and decision-making algorithms.

In the future, researchers can consider making breakthroughs in the following directions: first, combining flexible drive technology with traditional mechanical structures to improve the robot's motion performance; second, developing intelligent adhesive materials

with self-cleaning functions; and finally, building an environmental perception system with multi-sensor fusion. These technological advances will drive the bioinspired gecko robot in a smarter and more reliable direction, laying the foundation for its practical application in industrial inspection, disaster relief, and other fields.

7. Conclusions

In conclusion, this paper has presented a comprehensive examination of the progress made in the field of gecko-inspired climbing robots, tracing developments from their biological origins to engineering applications. Insights into gecko adhesion have played a role in adhesive technologies and attachment systems. These bioinspired adhesives have been successfully integrated into robotic systems, allowing them to climb vertical and inverted surfaces with remarkable stability. In addition, the dynamic locomotion of the gecko, driven by the flexibility of the spine and coordination of the limb, has inspired robotic designs that improve mobility, energy efficiency, and adaptability in complex environments.

By categorizing gecko-like robots according to spine stiffness and adhesion techniques, it becomes clear that different design choices reflect unique priorities. Robots with rigid spines are often easier to control and structurally simpler, making them ideal for well-defined tasks. In contrast, flexible-spine designs emulate the agility and coordinated movements of real geckos, offering improved adaptability and energy use. Similarly, claw-based and adhesion-based attachment methods each have unique advantages, with the former excelling on rough surfaces and the latter on smooth ones.

In terms of locomotion, bioinspired strategies, especially those utilizing central pattern generators (CPGs), have shown great potential in generating rhythmic and adaptive movement patterns. When paired with modern techniques like reinforcement learning and impedance control, these systems enhance a robot's capacity to adjust to unpredictable environments and terrain variations in real-time.

Although significant progress has been made in bioinspired gecko robots, some challenges remain. Further improvements in adhesive materials are needed to adapt to a wider range of surfaces, the mechanical reliability of the flexible spine needs to be improved, and attention needs to be paid to autonomous obstacle avoidance in complex unstructured environments. Future research can integrate sensing technology, self-cleaning smart materials, and more advanced control algorithms. Exploring hybrid designs that combine rigid-flexible structures and multiple control strategies may enable the design of more adaptable climbing robot systems.

Looking ahead, bioinspired gecko robots can be used in many fields - from inspecting infrastructure and performing hazardous maintenance to search and rescue missions and extraterrestrial exploration. Progress in these fields will continue to rely on the synergy of biology, materials science and robotics engineering. By connecting these disciplines, it will become increasingly feasible to develop efficient and versatile next-generation robotic systems.

Author Contributions: Conceptualization, W.X. and B.H.S.A.; methodology, W.X. and B.H.S.A.; resources, B.H.S.A.; writing—original draft preparation, B.H.S.A. and W.X.; writing—review and editing, B.H.S.A. and W.X.; supervision, B.H.S.A.; visualization, B.H.S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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2025-07-02

MDPI

<https://doi.org/10.3390/electronics14142810>

Xiang W, Honarvar Shakibaei Asli B. (2025) Advances in gecko-inspired climbing robots: from biology to robotics—a review. Electronics, Volume 14, Issue 14, July 2025, Article number 2810