Proceedings of CONF-CDS 2026 Symposium: Machine Learning and Neural Network Applications in Engineering
DOI: 10.54254/2755-2721/2026.AST36955

Morphological Bionics and Functional Integration Technologies for Bio-inspired Robots

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Abstract. Probing tasks in complex and unknown working environments are placing increasingly demanding requirements on robots in terms of terrain adaptability and locomotion agility. Against this background, conventional rigid robots have shown obvious shortcomings, while bio-inspired robots—developed on the basis of biological body shapes and motion mechanisms—have gradually become one of the most compelling research directions in robotics. Taking operating scenarios as the organizing thread, this paper sorts out morphological bionic design methods and summarizes how representative bio-inspired robot configurations perform in terms of technical characteristics, locomotion capability, and suitable working conditions. The analysis shows that most existing bio-inspired robots are geared toward a single scenario, and their motion ability still falls noticeably short of the biological organisms they imitate. In response to these problems, follow-up research may draw on multimodal reconfigurable morphologies and deep-learning-assisted design to improve the overall performance of bio-inspired robots. The paper reviews the morphological design logic and functional integration schemes of bio-inspired robots under multi-scenario conditions, with the aim of offering a useful theoretical reference and technical route for the development of high-performance bio-inspired robots for specialized missions.

Keywords: Bionic Robot, Morphological Bionics, Functional Integration, Multi-scenario Robot, Special Detection

1. Introduction

Robotics started with industrialized assembly-line operations, then passed through the stages of rigid manipulators and wheeled mobile platforms, and is now moving toward specialized robots that combine strong environmental adaptability, lightweight construction, and high mobility. Traditional rigid robots are assembled from rigid linkages driven by motors and hydraulic transmissions. They can carry heavy loads and their control logic is relatively straightforward, but their fixed geometry and high-inertia structures make them rather poor at traversing unstructured and complex terrain such as gravel slopes, underground lava tubes, narrow pipes, high-altitude crevices, and loose lunar regolith. As a result, they struggle with specialized tasks that demand a high degree of precision, including exploration, sampling, and inspection.

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DOI: 10.54254/2755-2721/2026.AST36955

Over hundreds of millions of years of evolution, animals and plants have developed body shapes, muscle-driven structures, and gaits that closely match their living environments. These biological forms and motion mechanisms offer a natural reference for breaking through the performance limits of conventional robots, and it is under this logic that bio-inspired robotics came into being and grew rapidly. From the earliest single-degree-of-freedom bionic mechanical models to today's integrated bionic platforms that combine smart materials, micro-sensors, and multimodal reconfiguration, morphological bionic design has always sat at the core of bio-inspired robot development [1]. It directly determines how a robot performs in terrain traversability, locomotion speed, payload capacity, and environmental survivability, while the level of functional integration further sets the ceiling of task execution. The degree to which the two work together often decides whether a bio-inspired robot can genuinely move into engineering application.

Over the past five years, research on bio-inspired robots has grown at an explosive pace. Scholars in China and abroad have developed several largely independent technical routes for different operating scenarios such as land, water, air, and deep space, and the resulting prototypes have all been structurally optimized according to the mechanical constraints and task demands of their target environments. In terms of body configuration, two main branches can be identified. The first is the low-degree-of-freedom rigid bio-inspired robot, built with servo linkages and conventional transmission mechanisms. These machines offer high structural stiffness and clean control logic, which suits tasks that require little deformation, such as heavy-load transport and large-scale stable inspection. The second branch is the high-degree-of-freedom soft bio-inspired robot actuated by PVDF piezoelectric films, pneumatic silicone, and shape memory alloys. Relying on continuous deformation to conform to irregular surfaces, these robots are specifically designed for confined conditions such as narrow gaps, loose granular media, and sealed pipelines [2].

The underlying design criteria differ considerably from one scenario to another. In air and underwater environments, fluid mechanics is the dominant constraint: fuselage contours, surface micro-textures, and undulatory propulsion mechanisms are all optimized for drag reduction and thrust enhancement, as seen in flapping-wing aircraft and soft bionic fish, whose streamlined bodies cut down fluid losses. Land robots, by contrast, are designed around rigid-body contact mechanics and granular soil mechanics, with the focus on foot friction, ground pressure, and burrowing or gripping performance. Lunar and deep-space bionic robots have to satisfy both the constraints of granular media mechanics and the material behavior under extreme temperature swings and vacuum [3]. Meanwhile, as smart materials, embedded sensing, and motion control technology have matured in parallel, the disciplinary scope of morphological design for modern bio-inspired robots has continued to widen. The development framework is no longer limited to purely engineering matters such as mechanical structure, locomotion behavior, and actuation mechanisms, but has gradually become a multidisciplinary undertaking. On one side, it draws heavily on information science, using machine vision, reinforcement learning, and distributed sensing feedback to let gaits adjust themselves autonomously [2]. On the other side, it incorporates bionic aesthetics, reproducing the optimized body contours and limb layouts that organisms have acquired through long evolution, so that the mechanical performance is complemented by the locomotion traits native to living creatures. Together these strands have produced a multidisciplinary collaborative design paradigm.

Existing studies have made notable progress on bio-inspired robots for individual scenarios, yet most configurations still suffer from single-scenario adaptation and a performance gap relative to their biological counterparts. This paper uses operating scenarios as the organizing dimension to go through the available configurations, morphological design approaches, and integrated functional schemes, and then pinpoints the core technical limitations of the field and proposes corresponding

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solution paths. By consolidating the existing results in a systematic way, the paper tries to lay out a clearer direction for the morphological design of future high-performance bio-inspired robots that can operate across environments and integrate multiple functions.

2. Terrestrial bio-inspired robots

For land environments, rigid-body contact mechanics and granular soil mechanics form the basic design constraints. Terrestrial organisms have evolved three representative locomotion modes—legged support, jumping energy storage, and segmented peristalsis—and these correspond to three bionic branches: legged, jumping, and segmented-track robots. At the level of design morphology, the geometric configuration of biological limbs, the arrangement of joints, and the patterns of muscle actuation are extracted and converted into three kinds of engineering structures, namely servo linkages, piezoelectric resonance, and pneumatic segmented soft bodies.

2.1. Legged bio-inspired robots

Legged robots copy the coupled skeletal and limb morphology of vertebrates and arthropods. Multi-degree-of-freedom orthogonal servo joints are used to build multi-link kinematic chains, and the body is kept stable through a triangular support mechanics model: at any given moment, at least three limb groups form a support polygon with the ground, and the joint servos output torque to carry out locomotion and climbing. For granular media such as loose lunar regolith, hexapod configurations spread the ground contact across several limbs, which lowers the pressure per unit area and avoids sinking failure. Each limb is divided into three rotational joints at the hip, knee, and ankle, handling yaw, pitch, and limb extension respectively, and a flexible contact layer added to the sole changes the interfacial friction coefficient in a way that morphologically reproduces the contact structure of biological claws.

AQuRo, a cat-like quadruped bio-inspired robot, is a representative example. Its link length parameters are optimized on the basis of feline limb skeletal morphology. Each leg carries five compound orthogonal servo joints, and a distributed pressure sensor array is integrated into the sole for closed-loop force control. The robot weighs 1.82 kg, produces a maximum single-joint output torque of 3.4 N·m, moves at a steady straight-line speed of 0.42 m/s on flat ground, climbs vertical plates at up to 75°, and carries a rated payload equal to 0.6 times its own weight [4]. The lunar-surface spider hexapod bio-inspired robot, on the other hand, adopts a symmetric annular arrangement of six limbs, each with a 3-DOF servo structure, bringing the total ground pressure down to only 0.026 kPa. When its limbs are folded, the robot can be reconfigured into an arc-shaped rolling form, and its measured downhill rolling speed reaches 0.31 m/s; once the limbs are deployed, it falls back on a tripod gait to perform terrain mapping [3]. Through different combinations of leg number and gait, this class of robots manages to move stably and switch functions across flat ground, vertical surfaces, and soft lunar terrain.

2.2. Jumping bio-inspired robots

Jumping bio-inspired robots take the jumping forms of various organisms as their main bionic reference. They adopt a symmetric double-spiral continuous soft-body configuration and rely on the inverse piezoelectric resonance effect of PVDF piezoelectric films to achieve high-frequency jumping. The actuator is generally formed by stacking a 12 μm PVDF active layer with a 50 μm copper passive layer. When voltage is applied, the piezoelectric layer expands in-plane while the

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copper layer restrains it, producing periodic bending deformation. The front and rear spiral legs are designed with different radii to create a difference in deformation amplitude, so that within one vibration cycle the robot sequentially completes expansion-to-ground-contact and contraction-to-reset motions. The resonance effect amplifies the deformation output, and electrical energy is converted directly into translational kinetic energy.

For slope-jumping scenarios, Chen Erdong's team built a double-spiral piezoelectric jumping robot with a total length of 10 mm, a total mass of 0.058 g, a standard spiral radius of 2 mm, and an actuator total thickness of 62 μm [5]. Finite element simulation gives a first-order natural resonance frequency of 176.5 Hz. Under 200 V peak-to-peak square-wave excitation, the maximum deformation of the rear leg reaches 1.8 mm. On a rubber substrate, the measured maximum relative speed is 42.8 BL/s and the maximum absolute speed is 428 mm/s, while its dual-robot parallel steering configuration records an average maximum steering angular velocity of 482°/s. The body can bear a mineral payload eight times its own weight, and its crawling speed on a 12° slope reaches 5.4 BL/s.

2.3. Segmented-track robots

In bionic burrowing robot research, multi-unit series-connected pneumatic soft-body structures are designed mainly by borrowing from the segmented muscle morphology of organisms such as earthworms and moles. Each segment unit integrates two independent pneumatic chambers in the radial and axial directions. Radial inflation expands the unit so that it contacts and anchors against the tunnel wall, while axial inflation produces stride elongation. Alternating actuation of the two chamber groups yields continuous burrowing locomotion.

In addition, pipeline inspection robots can be designed using the segmented soft-body deformation concept. Represented by the earthworm segmented pneumatic soft robot, a Kresling origami flexible skin is employed. Its single segment unit has a static length of 50 mm and a maximum axial extension deformation of 11.13 mm. After radial inflation, its diameter can expand to 275% of the original size. It operates within a standard working air pressure of 30–60 kPa, with a single peristaltic cycle of 0.8 s. Built-in thin-film pressure sensors are used to collect the radial stress of the surrounding stratum in real time [6].

3. Underwater bio-inspired robots

In underwater environments, fluid drag, hydrodynamic thrust, and hydrostatic pressure are the core mechanical constraints. Drawing on the evolved body forms of fish, water snakes, and frogs, three bionic systems are distinguished: snake-like, fish-like, and frog-like amphibious robots. Their design morphology reproduces streamlined body contours, undulating fins, and limb geometry to reduce boundary-layer separation losses and construct periodic fluid-thrust generation structures.

3.1. Underwater snake-like robots

Borrowing from the segmented body morphology of sea snakes and aquatic worms, underwater snake-like robots generally feature a multi-segment articulated flexible body without rigid fin protrusions. The entire robot generates a continuous sinusoidal lateral traveling wave along its longitudinal axis. From a fluid mechanics perspective, body undulation creates a pressure-difference field on both sides of the body; the high-pressure-side water is discharged backward to produce reaction thrust, while the phase of each segment lags in sequence, thereby reducing vortex losses

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during locomotion. In design, the overall geometric profile is typically smooth and free of protruding structures, which significantly lowers the fluid drag coefficient.

A representative example is the seven-segment articulated underwater snake-like robot. Each segment unit is 112 mm long and the total robot length is 833 mm. The maximum swing angle of a single joint is ±90°. The optimal traveling-wave amplitude is 25 mm, the steady straight-line speed is 0.103 m/s, and the drag coefficient is reduced by 63% compared with a rigid pipeline robot [7].

3.2. Fish-like bio-inspired robots

The propulsion design of fish-like bio-inspired robots usually replicates the composite morphology of the arched trunk and flexible caudal fin of bony fish. The smooth curved body surface suppresses fluid boundary-layer separation. The tail pneumatic actuator performs periodic sinusoidal oscillation and, based on vortex ring theory, generates a reverse jet for efficient propulsion. Taking the segmented soft bionic fish as an example, this robot adopts a three-layer silicone integrated streamlined structure and drives the caudal fin through segmented pneumatic actuation. At an optimal oscillation frequency of 1.25 Hz, its straight-line speed reaches 10.5 cm/s, with a relatively low unit transport cost. Fluid simulation results show that the vortex intensity on its body surface is 57% lower than that of a rigid robotic fish. In addition, the body integrates water pressure and ion concentration sensing modules, giving it a certain environmental perception capability [8].

3.3. Frog-like amphibious bio-inspired robots

Frog-like amphibious bio-inspired robots use the hind-limb flexion–extension motion of frogs as their bionic prototype and adopt two groups of 3-DOF servo articulated hind limbs. In water, the hind limbs spread to enlarge the force-bearing area and fold to reduce drag, generating thrust through momentum exchange with the surrounding water. On land, they rely on contact mechanics to absorb jump impacts, thereby achieving amphibious locomotion in both media with a single set of limb structures. Chen et al. proposed a frog-like amphibious bionic configuration with a maximum single-servo swing angle of 120°, a single water-kicking cycle of 0.6 s, a maximum underwater speed of 0.078 m/s, and a single on-land jump distance of 0.32 m. The body uses a sealed pressure-resistant structure with a maximum underwater working depth of 3.5 m [5].

4. Aerial bio-inspired robots

In the design of aerial bio-inspired robots, aerodynamics is the core basis for configuration design. Existing schemes fall mainly into two categories: bird-like flapping-wing robots and modular snake-like deformable aircraft. The former reproduces the reciprocating flapping motion of bird wings to generate aerodynamic forces, while the latter innovatively combines segmented articulation with vectored rotors. At the design morphology level, key morphological parameters are extracted from wing-surface geometry and multi-link series configurations, and corresponding aerodynamic models and multi-body coupled dynamic models are established to support flight mechanism analysis and structural optimization.

4.1. Bird-like flapping-wing bio-inspired robots

The bird-inspired flapping-wing robot with grasping and perching functions replicates the complete perching and grasping physiological structure of birds. It uses thin-film lightweight wing surfaces to achieve differentiated flapping deformation: during the downstroke, the wing is fully spread to

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increase the pressure-bearing area and efficiently generate lift; during the upstroke, the wing passively folds and twists to reduce frontal aerodynamic drag. Through periodic pressure-difference alternation, the robot achieves sustained forward flight and low-speed approach maneuvers toward branches. The lightweight airframe reduces cruise drag, but the grasping claws and actuation linkages consume part of the payload, limiting endurance and maximum flight speed. Building on the bionic flight and grasping mechanism of the bird-like flapping-wing robot with grasping and perching functions, Milana et al. developed a medium-sized bird-like flapping-wing aircraft equipped with actively driven leg-claw mechanisms. The aircraft has a mass of 700 g and a wingspan of 1500 mm, with a stable flapping frequency of 12 Hz. Its straight-line speed in a windless indoor environment reaches 2.8 m/s. The supporting bistable grasping claw weighs 184 g and can clamp onto a branch within 25 ms. The maximum perching grasping success rate reaches 88.3%, and the claw can stably support the entire aircraft's weight for long-duration fixed-point perching monitoring, demonstrating outstanding combined flight and grasping performance [9].

4.2. Modular snake-like aerial robots

Unlike the bird-like external bionic approach, the modular snake-like deformable aircraft borrows from the segmented body series morphology of terrestrial snakes. It uses carbon-fiber links connected in series through 2-DOF orthogonal servo joints (pitch and yaw), with each section carrying a dual-rotor vectored propulsion unit. Counter-rotating twin rotors cancel gyroscopic disturbances. To achieve six-degree-of-freedom pose control of the entire aircraft, a quasi-static multi-body dynamic model is established. Assuming that joint angular acceleration can be neglected during low-speed joint motion, the coupled equations are simplified, and an iterative thrust allocation algorithm is used to match the required pose. This type of aircraft can be divided into underactuated three-link and fully actuated four-link configurations.

The DRAGON snake-like aircraft is a typical snake-like aerial bio-inspired robot. Its fully actuated four-link version has a single-section link length of 0.42 m and a total weight of 8.0 kg. The 12-blade ducted single rotor produces a maximum thrust of 32 N, and the onboard battery provides 3 min of endurance. The position control frequency is 40 Hz and the attitude control frequency is 200 Hz. The trajectory tracking position RMSE is 0.036 m and the attitude RMSE is 0.033 rad, and the aircraft can pass through narrow passages 0.8 m wide. Its underactuated three-link prototype weighs 3.35 kg with a maximum single-rotor thrust of 25 N. Although its joint deformation degrees of freedom are fewer than those of the fully actuated configuration, flexible control of the aircraft shape can still be achieved [10].

5. Challenges and prospects

5.1. Multi-function bionic design limitation

Currently, the various bio-inspired robots developed on the basis of design morphology exhibit clear characteristics of functional and scenario singleness. Their morphological structures, actuation systems, and locomotion modes are all directionally designed for a single medium and a single task. Terrestrial piezoelectric jumping robots and earthworm burrowing soft robots are suitable only for hard ground or underground tunnels; fish-like and frog-like underwater robots can only propel themselves in water; bird-like and insect-like flapping-wing aircraft are confined to aerial movement; and modular snake-like aerial robots only possess aerial deformation flight capability. None of these body structures can achieve cross-medium adaptive morphological switching.

DOI: 10.54254/2755-2721/2026.AST36955

Existing bionic "external structures" are rigidly bound one-to-one with built-in actuation, sensing, and execution functions. A single geometric form corresponds to only one locomotion behavior, and there is no reconfigurable modular structure capable of switching among multiple behaviors. At the same time, the function integration approach of the whole robot is limited. A single prototype is equipped only with scenario-specific sensing and payload modules, so it cannot simultaneously satisfy the detection, transport, and obstacle-crossing requirements of composite water–land–air operating conditions. Most prototypes can only pass single-condition laboratory tests and cannot cope with complex field conditions involving multiple coupled environments, which greatly restricts the practical engineering scope of bio-inspired robots.

In the future, multimodal behavior fusion and reconfigurable bionic morphology can be co-designed, reconstructing the modular layered system of "form" through design morphology to achieve intelligent switching of body structures. At the body morphology level, segmented articulation and intelligent flexible composite materials can be used to build reconfigurable bionic bodies. Drawing on the multi-unit series structure concepts of snake-like aerial robots and earthworm segmented soft bodies, the overall geometric profile can be adjusted through servo joints and piezoelectric flexible actuation to autonomously switch among locomotion forms such as terrestrial crawling, underwater undulation, and aerial deformation, thereby creating an integrated amphibious water–land–air bionic platform. At the function integration level, standardized detachable actuation–sensing integrated modules [11] can be designed, with propulsion units and environmental perception components replaced according to the operating medium. Multi-condition compatible protective skins can also be integrated to address the constraints of fluid, granular, and hard-contact mechanical environments simultaneously. At the control level, multimodal autonomous decision-making algorithms can be deployed. Relying on real-time environmental sensing feedback, the system can automatically match the appropriate bionic gait, structural deformation amplitude, and actuation output parameters, enabling a single robot to perform continuous cross-medium operations and breaking the single-scenario constraint at both the morphological and functional levels.

5.2. Significant performance gap between bio-inspired robots and native organisms

Although the existing bionic design process performs morphological extraction, mechanical modeling, and engineering transformation based on biological prototypes, artificial prototypes still lag behind native organisms in structural processing accuracy and real-time motion control. From the perspective of design morphology, biological bodies are continuous gradient flexible composite tissues in which muscles, skin, and bones are coupled and coordinated at multiple levels. In contrast, robots adopt discrete rigid links and single flexible thin-film layered structures. Assembly gaps and actuation response lags exist between segmented structures, and the reproduced gaits and deformation amplitudes deviate considerably from the motion patterns of native organisms. As a result, core performance indicators such as propulsion efficiency, obstacle crossing, and load capacity remain inferior to those of biological bodies. Furthermore, at present, the mining of bionic inspiration sources and cross-domain analogy depend heavily on researchers' biological knowledge and engineering experience. The design reasoning process lacks standardized and intelligent auxiliary tools, relying only on manual literature review and qualitative observation of biological motion to extract morphological features. This tends to miss key biological mechanisms such as microstructures and dynamic gaits. Design schemes are therefore one-sided, making it difficult to fully exploit the high-performance morphological advantages accumulated through biological evolution and limiting the iteration speed of new high-performance bionic configurations [12].

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In the future, deep learning techniques can be embedded into the entire design morphology process to build an intelligent bionic design reasoning system and narrow the performance gap between robots and native organisms. The first stage is intelligent mining of biological inspiration sources. A multimodal biological motion database can be constructed, collecting image data of micro-skin, limb structures, and dynamic gaits of terrestrial, aquatic, and flying animals. Through image segmentation and temporal motion neural networks, the geometric parameters of biological "form" and the motion mechanics features of biological "state" can be extracted automatically, eliminating the design blind spots introduced by human experience without manual subjective screening. The second stage is cross-medium bionic intelligent reasoning. Using existing configurations such as lunar multi-legged robots, piezoelectric soft robots, and snake-like aerial vehicles [4, 3, 10] as training samples, reasoning models can automatically generate multiple sets of bionic structural dimensions and actuation matching schemes, replacing manual trial-and-error modeling and improving morphological design accuracy. The third stage is real-time compensation in motion control. Using temporal data of various biological native gaits as training sets, reinforcement learning control networks can be trained to compensate in real time for the deformation lags and motion deviations caused by discrete mechanical structures, dynamically adjusting the output amplitude and frequency of piezoelectric and servo actuation so that robot gaits increasingly approach the motion patterns of native organisms. At the same time, finite element simulation and deep learning joint optimization can be combined to iteratively revise the layered structure of bionic bodies and the proportions of composite flexible materials, narrowing the gap between artificial prototypes and natural organisms from both the morphological design and control algorithm directions.

6. Conclusion

In summary, relying on the "form–state" coupled analysis approach of design morphology and using the three operating domains of land, water, and air as the organizing framework, this paper systematically reviews the research status of mainstream bio-inspired robots. Although various single-scenario bionic prototypes have achieved breakthroughs in specific laboratory performance indicators such as speed, obstacle crossing, and small-scale detection, the field as a whole still has two core shortcomings. First, the morphologies of most robots are tightly bound to their actuation and sensing modules and adapt to only a single medium, making cross-medium water–land–air adaptive operation difficult. Second, artificial bionic structural design depends heavily on researcher experience and lacks intelligent auxiliary reasoning tools, so overall locomotion performance still falls significantly short of native organisms. In the future, two optimization paths, which are multimodal reconfigurable integrated morphology schemes and deep-learning-assisted full-process bionic design. They may open up possibilities for developing amphibious specialized detection bionic platforms.

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