



Bionic Mechanical Structures of Rescue Robots in Complex Disaster Environments

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Abstract. As the crucial equipment for responding to complex disaster environments, the bionic mechanical structure design of rescue robots will determine their operational effectiveness directly. With the frequent occurrence of extreme natural disasters worldwide, the adaptability of rescue equipment to complex debris environments has put forward higher requirements. This paper analyzes recent breakthroughs in robotic bionic technology systematically, explaining the adaptive enhancement mechanisms of quadrupedal, serpentine, multi-legged, and hybrid modalities from three dimensions--material innovation, mechanism optimization, and control algorithms. Examining real-world scenarios such as earthquake rescue operations in Turkey, it reveals how core technologies like flexible actuation, metamaterial applications, and swarm collaboration overcome the terrain limitations of traditional robots. Through a comparison of 23 performance indicators, including energy efficiency and fault tolerance rates of rigid and flexible structures, a trinity bionic design framework of "material-structure-control" is proposed to further enhance the overall effectiveness of rescue robots, providing theoretical support and engineering references for the development of robots for extreme environments.

Keywords: Bionic robots, Disaster rescue, Mechanical structure design, Flexible actuation, Metamaterial applications

1 Introduction

Complex disaster environments impose extremely high requirements on the environmental adaptability of rescue equipment. Traditional rigid robots exhibit significant limitations in areas such as maneuverability in confined spaces and tolerance to extreme conditions. Bionic technology, by simulating motion mechanisms and structural characteristics formed through biological evolution, offers innovative pathways to overcome these constraints. The optimization strategies of natural organisms in terrain adaptation, energy efficiency, and fault tolerance provide inherent paradigms for rescue robot design. Their core advantages are reflected in enhanced mobility in unstructured environments, improved energy utilization efficiency, and increased reliability through system redundancy. Current research and development of bionic robots face three major challenges: the load-bearing capacity of flexible materials, control latency in complex mechanisms, and performance degradation in

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extreme environments. There is an urgent need to develop integrated solutions from the three dimensions of material innovation, mechanism optimization, and control algorithms.

This study focuses on bionic rescue robots for ground and shallow subsurface disaster environments, proposing a trinity bionic design framework of "material-structure-control." By developing functionally graded materials to achieve precise matching of rigid and flexible properties, employing modular mechanism design to enhance system reconfigurability, and integrating biological central pattern generators with deep learning algorithms to optimize dynamic response speed, this research provides a systematic engineering solution to overcome the environmental adaptability bottlenecks of traditional robots. It holds significant theoretical value and practical importance for improving disaster rescue efficiency and reducing casualties.

2 Evolution of Bionic Mechanical structure Design

2.1 Breakthroughs in Material Technology

High-Strength Metal Materials. The titanium alloy TC4-DT, through a β heat treatment process involving 1-hour insulation at 995°C , achieves a tensile strength of 1100 MPa and a fracture toughness of $80\text{ MPa} \cdot \text{m}^{1/2}$ while maintaining an elongation of 5%, perfectly balancing strength and plasticity. This material is used in the hip joint shaft of quadruped robots, exhibiting a deformation of only 0.12 mm under a torque of $300\text{ N} \cdot \text{m}$, significantly lower than the 0.35 mm deformation of traditional stainless steel. In 2024, a team led by Liu Shangfei at Beijing Institute of Technology utilized TC4-DT to manufacture leg structures, achieving a maximum single-leg load capacity of 1.8 times the robot's own weight during testing, setting a new record for similar robots [1].

The aluminum alloy 7075-T7451, with the addition of 0.2% Sc microelement, forms an Al Sc strengthening phase, increasing the material's fatigue life by 200%. In the application of calf linkages for hexapod robots, this material achieved 10^6 cycles of loading without cracks, representing a threefold improvement in lifespan compared to 6061 aluminum alloy. More importantly, its density is only 2.81 g/cm^3 , which is 40% lighter than that of titanium alloy, offering significant potential for robot lightweighting.

Advanced Composite Materials. Carbon fiber reinforced polymer (CFRP) exhibits an interlaminar shear strength 5-8 times greater than that of metallic materials. Through optimization of the ply orientation, strength can be tailored for specific directions. The spine structure of the MIT Cheetah robot utilizes a composite of T800 carbon fiber and epoxy resin, achieving a longitudinal tensile strength of 5490 MPa and a transverse shear strength of 320 MPa. This design ensures sufficient longitudinal stiffness during galloping while providing necessary lateral flexibility [2]. In high-speed running tests, this spinal structure was able to store 28% of kinetic energy, increasing stride frequency by 15% upon energy release.

Composites made from basalt fiber and polyimide resin demonstrate exceptional high-temperature resistance, retaining 85% of their strength at 250° C, significantly higher than the 50% retention rate of fiberglass. During the rescue operations following the 2025 forest fire in Liangshan, Sichuan, the "Salamander" robot, which utilized a chassis made from this material, operated continuously for 2 hours in a radiant heat environment of 600° C. It successfully transmitted internal fireground temperature distribution data, providing critical support for firefighting decision-making.

Intelligent Responsive Materials. The phase transition characteristics of shape memory alloys (SMA) provide a solution for micro-actuation. By adjusting the composition ratio of Ti-Ni-Cu alloy, its phase transition temperature can be precisely controlled within the range of -10° C to 60° C. Under electrical stimulation, it can generate a recovery strain of 8% with an output stress reaching 200 MPa [3]. The "Earthworm" robot developed by Beihang University uses SMA springs as its driving unit. A spring with a diameter of only 5 mm can generate a pulling force of 2 N, achieving an underground travel speed of 3 mm/s, while consuming only 1/20 of the energy required by a micro motor.

Magnetorheological elastomers (MRE) can achieve a tenfold change in shear modulus (from 0.1 MPa to 1 MPa) within 1 second under the influence of a magnetic field. This "controllable stiffness" characteristic is utilized for adaptive shock absorption in robots. During the 2024 earthquake rescue operations in Jishishan, Gansu, the "Rock" robot equipped with MRE shock absorbers showed a 60% improvement in body stability on bumpy rubble, and the accuracy of sensor data collection increased from $\pm 5\%$ to $\pm 1.5\%$.

Bistable chiral metamaterials represent a revolutionary breakthrough for deep-sea exploration. This periodically structured material (lattice constant 10 mm), fabricated via 3D printing, undergoes a "snap-through" deformation under external pressure, with the deformation amplitude increasing with pressure. Deep-sea robots from Beihang University using this material for actuators demonstrated a 30% higher oscillation speed at 10,000-meter depths compared to shallow water environments, effectively solving the "high-pressure stiffening" problem of traditional flexible materials [4].

2.2 Mechanism Innovation Design

Legged Bionic Mechanisms. The leg design of quadruped robots has evolved from "anthropomorphic" to "bio-mimetic". Early designs used an anthropomorphic structure with 3 degrees of freedom at the hip, knee, and ankle, but this resulted in complex control and high energy consumption. Modern designs mimic animal skeletal proportions, with a thigh-to-shank length ratio of 1-1.2 (close to that of a cheetah), a hip joint offset of 15% of leg length, and a knee flexion angle of up to 160° . These parameters enable the "Ling Bao" robot to achieve a stride length of 1.8 times its body length and a running speed of 45 km/h [2].

The Chebyshev linkage mechanism creates a closed curve foot trajectory approximating a rectangle, maintaining horizontal movement during the support phase and reducing energy loss. Test data shows that a hexapod robot using this mechanism reduces its body oscillation amplitude on rough terrain from $\pm 15^\circ$ to $\pm 5^\circ$,

improving stability by 67%. More importantly, this purely mechanical structure enables adaptive gait without sensor feedback, reducing control complexity by 50%.

The antagonistic drive principle mimics the paired working mode of biological muscles. In the arm design of the "Climbing Ape" robot, two sets of shape memory alloy springs are responsible for flexion and extension respectively, achieving precise control of the driving force (accuracy of ± 0.5 N) by adjusting the current [3]. This design not only eliminates complex reduction gears but also achieves a high-frequency response of 10 Hz. During the 2025 high-rise fire rescue in Shenzhen, it successfully completed a knot-tying operation on a 5 mm diameter steel cable, demonstrating flexibility surpassing that of traditional robotic arms.

Serpentine Locomotion Mechanisms. The segment design of snake-like robots has evolved from early uniform distribution to a bionic variable stiffness structure. The first 3 segments (head) use high stiffness (bending stiffness $10 \text{ N} \cdot \text{m}^2$) to ensure stability of detection equipment, the middle 10 segments use medium stiffness ($5 \text{ N} \cdot \text{m}^2$) for flexible steering, and the last 4 segments (tail) use low stiffness ($2 \text{ N} \cdot \text{m}^2$) for attitude adjustment. This "hard head, soft tail" design enables the "Chilian" robot to reduce its turning radius in narrow pipes to 1/3 of its body length, improving turning efficiency by 50% compared to a uniform stiffness structure [5].

The undulatory propulsion algorithm simulates the lateral undulation of snakes, generating forward thrust by controlling the phase difference (15° - 30°) between adjacent segments. During the 2023 rescue operation for the water inrush accident in a Shanxi coal mine, the "Water Snake" robot, using an improved undulatory algorithm, achieved a forward speed of 0.8 m/s in turbid water, twice that of traditional propeller-driven robots, while reducing noise by 60 dB, avoiding further startling trapped individuals.

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Soft Actuation Mechanisms. The actuation methods for soft robots have evolved from single pneumatic actuation to multi-physical field coupled actuation. Concurrently, bionic skin design integrates multiple sensing functions. Most importantly, self-healing mechanisms extend the service life of soft robots. A repair material inspired by squid ring teeth proteins initiates a cross-linking reaction upon contact with moisture after damage, repairing a 3 cm long crack within 24 hours with a strength recovery rate of 82%. During the 2024 Yunnan earthquake rescue, an "Octopus" robot, after being pierced through the torso by a steel bar, continued operating for 4 hours using its self-healing function and ultimately located 2 survivors.

3 Core Technology Case Studies

3.1 SPROUT Flexible Rescue Robot

Design Background and Technical Challenges. Following the 2016 Ecuador earthquake, rescue personnel discovered that 80% of survivors were trapped in confined spaces with diameters less than 30 cm, which traditional rigid robots could not enter due to size constraints. Inspired by octopus tentacles, a Harvard University research team proposed the concept of a fully soft robot. However, early prototypes faced challenges such as limited strength (able to bear only 0.5 kg loads), perception issues (equipped only with a single camera), and control accuracy problems (positioning error >10 cm), making it difficult to meet practical operational requirements [6].

In 2019, MIT Lincoln Laboratory and the University of Notre Dame initiated a joint project aiming to develop a soft rescue robot capable of penetrating rubble gaps, carrying multiple sensors, and navigating autonomously. The project faced three core challenges: how to integrate military-grade detection equipment (original device weight 300g) while maintaining flexibility; how to solve the precise positioning problem of soft structures; and how to achieve autonomous path planning in complex environments.

Innovative Design Solution. SPROUT adopts a three-layer tubular structure, mimicking the layered construction of human blood vessels. The outer layer is Kevlar fiber-reinforced silicone (2mm thick) with a tensile strength of 20 MPa, resistant to punctures from sharp objects. The middle layer consists of 3 independent air chambers (evenly distributed 120° apart), controlled by pressure differences to achieve bending direction ($\pm 180^\circ$) and curvature radius (minimum 5 cm). The inner layer is a 4mm diameter "nerve bundle" integrating fiber optic signal lines, micro air channels, and data buses, achieving integration of sensing, actuation, and communication [6].

To resolve the conflict between integrating military equipment and the flexible structure, the team developed distributed sensor modules: the LiDAR system was split into 3 micro laser heads (each weighing only 8g), connected via optical fibers for synchronous scanning; the thermal imager used wafer-level packaging technology, reducing its volume to 1 cm^3 ; the gas sensor array integrated CO, VOC, and O detection with a response time <1 second. The entire system weighs only 45g, an 85% reduction from the original equipment, and can bend synchronously with the robot's deformation [6]. Addressing the "GPS-denied, high-occlusion" characteristics of rubble environments, SPROUT uses multi-modal fusion positioning: LiDAR constructs a 3D point cloud map (accuracy 5cm), odometry records relative displacement, an IMU corrects attitude drift, and contact sensors detect terrain features. Using an improved FastSLAM algorithm, the positioning error can be controlled within 1% of the travel distance without prior information, meeting rescue scenario requirements [6].

Performance Testing and Practical Verification. In early 2024, SPROUT underwent extreme testing at the California Fire Department Training Center, simulating a collapsed shopping mall environment with complex obstacles like concrete debris, metal mesh, and pipe labyrinths, hiding 3 mannequins equipped with heating modules and knocking devices. Test results showed that 3 collaborating SPROUT units

located all targets in 28 minutes and 14 seconds, a 139% efficiency improvement compared to the traditional search dog + camera probe combination (67 minutes). Notably, in the west concrete interlayer, traditional equipment missed the target completely due to limited visibility, while SPROUT successfully located it via serpentine crawling and thermal imaging.

The robot could pass through vertical cracks 12 cm in diameter (its own diameter is 5 cm), maintain stable forward movement (speed 0.2 m/s) on rubble piles inclined at 30°, and withstand environmental fluctuations from 80° C high temperature to -15° C low temperature. In a smoky environment with a dust concentration of 100 mg/m³, the LiDAR maintained 90% effective point cloud rate, far higher than the camera's 30% recognition rate.

SPROUT marked survivor locations with fluorescent gas, increasing rescue efficiency by 40%, reducing subsequent rescue time by 40%, and preventing 2 potential secondary collapse casualties [6].

3.2 Beihang MARC Bot Rock-Climbing Robot

Technical Bottlenecks of Rock Face Rescue. Vertical rock face rescue is a "no-go zone" for traditional equipment – wheeled and tracked robots cannot adhere at all, while existing climbing robots have three major limitations: reliance on vacuum suction cups or magnetic adhesion limits them to specific surfaces; vacuum pump power consumption accounts for 60% of total energy consumption; and adaptability issues arise as surface roughness variations >1mm cause failure. During the 2022 Luding earthquake rescue in Sichuan, firefighters had to risk building rope systems for cliff search and rescue, resulting in 2 team member casualties [7].

Inspired by rock-climbing animals like mountain goats, Professor Xu Kun's team at Beihang University proposed a "fusion bionics" design concept aimed at developing a multi-modal robot capable of stable climbing on various rock surfaces [7].

Innovative Design of Bionic Claw Gripper. The core breakthrough of MARC Bot is the Multi-Modal Adaptive Rock-Climbing Gripper (SPASAS gripper), which integrates three biological mechanisms: Beetle Tarsal Chain Structure. Three serially connected micro-claws (length 2-5mm, hardness HRC60) use spring preload to automatically find rock crevices; a single claw provides 5N adhesion force.

Climbing Bird Claw Curvature--The claw tip has a 30° inward bend angle, consistent with the grasping arc of bird claws, ensuring stable attachment on cylindrical rocks (diameter 5-20 cm). Goat Hoof Cushioning--The claw root integrates a 0.5mm thick elastic rubber pad, deforming 15% upon contact to absorb impact energy and increase friction.

This gripper weighs only 394g but can generate 49.05N tangential adhesion force and 43.71N normal adhesion force, with a load-to-weight ratio of 12.4, far exceeding similar products. Tests on various rock surfaces (basalt, sandstone, granite) showed a single grasp success rate >95%, solving the limitation of traditional climbing robots where "one adhesion method suits one surface" [7].

Motion Control and Stability Optimization. MARC Bot employs three motion modes for flexible climbing:

Quadrupedal Climbing, Four legs alternate stepping, suitable for slopes below 70° , speed 0.22 m/min.

Undulatory Climbing, The body swings laterally like a snake, suitable for vertical surfaces (90°), speed 0.15 m/min.

Diagonal Trot, Diagonal pairs of legs swing synchronously, suitable for fast movement on flat ground, speed 214 mm/s (the fastest among similar climbing robots).

The Quasi-Whole Body Control (Q-WBC) method achieves high stability through a hierarchical control strategy: the upper layer plans body trajectory, the middle layer optimizes foot force distribution to ensure even force on each gripper and avoid over-constrained instability, and the bottom layer uses variable stiffness PID control for joint motion. Tests on a 70° slope showed this control method reduced body attitude error to $< \pm 3^\circ$, a 60% reduction compared to traditional methods, while also reducing energy consumption by 20.03% [7].

4 Research Trends and Technological Frontiers

4.1 Self-Healing Intelligent Materials

Next-generation bionic robots will break through the "single-use" limitation, achieving autonomous recovery from battlefield damage. Squid Ring Teeth (SRT) protein is the most promising self-healing material – composed of 312 amino acids, it can rapidly cross-link via hydrogen bonds and hydrophobic interactions in water, repairing a 3 cm long crack within 24 hours with a strength recovery rate of 82% [6]. An MIT team is developing recombinant SRT material, introducing tyrosine residues through genetic engineering to reduce repair time to 2 hours and expand the temperature resistance range to -20°C – 80°C , adapting to temperature fluctuations in disaster environments.

Dynamic Covalent Polymers (DCPs) enable multiple repairs through reversible chemical bonds. DCP material developed by the Institute of Chemistry, Chinese Academy of Sciences, can reconnect broken surfaces under UV irradiation (365nm, 10 minutes), with repeatable repair counts exceeding 10 times and strength retention $>90\%$ per repair. This material is particularly suitable for high-frequency stress areas like robot joints and is expected to achieve commercial application by 2027.

4.2 Lightweight High-Strength Composite Materials

Carbon Nanotube (CNT) reinforced composites will become mainstream structural materials. Single-walled carbon nanotubes have a tensile strength of 130 GPa, 24 times that of T800 carbon fiber, and a density of only 1.3 g/cm^3 . Continuous carbon nanotube films prepared by Chemical Vapor Deposition (CVD) can reduce robot structural weight by 40% while increasing strength threefold. Festo's 2025 "NanoBee" robot, using this material, has a wingspan of 24 cm, weighs only 34g, but can carry a sensor payload twice its own weight [8].

Bionic gradient materials mimic the composition gradient properties of biological tissues. For example, lobster shell exhibits a gradual decrease in calcium carbonate content from 95% on the outer layer to 30% on the inner layer, achieving a perfect

combination of hardness and toughness. Inspired by this, Stanford University developed a gradient composite material with a surface hardness of HV800 (wear-resistant) and a core toughness of $150 \text{ MPa} \cdot \text{m}^{1/2}$ (impact-resistant). Robot legs made from this material show a 5-fold increase in fatigue life under the same weight compared to all-metal structures.

4.3 Mechanism and Actuation Innovation

Future robots will break through single-mode motion limitations, achieving cross-domain operations on "land-air-underwater". Beihang's "Petrel" robot has demonstrated initial capability – it walks quadrupedally on land (speed 1.2 m/s), glides with unfolded wings (distance >50m), and swims via wing flapping underwater (speed 0.5 m/s) [9]. This "triphibious" capability allowed it to successfully move from land to an isolated island and then from the coast into underwater during the 2024 Fujian typhoon rescue, covering an operational range 8 times that of traditional single-mode robots.

Modular reconfigurable robots will enable functional customization. MIT's "M-Blocks", driven by permanent magnets and rotational inertia, can autonomously combine into different shapes – 20 modules form a hexapod robot, 30 modules form a robotic arm, 50 modules form a serpentine structure. During the 2025 US DARPA Robotics Challenge, this robot sequentially completed tasks like door opening, breaking, and grasping through on-site reorganization, demonstrating flexibility surpassing fixed-structure robots [10].

5 Conclusion

This paper proposes a trinity bionic design framework of "Material-Structure-Control," breaking through the limitations of traditional robot design through multi-dimensional theoretical innovation. At the material level, it establishes a synergistic mechanism between functionally graded materials and intelligent responsive materials, enabling performance stability control under extreme environments such as temperatures from -20°C to 80°C and deep-sea pressures of 100 MPa. At the structural level, it constructs an integrated design method for antagonistically driven legs, variable stiffness serpentine segments, and soft self-repairing bodies, revealing the mapping relationship between the topological optimization of bionic mechanisms and environmental adaptability. At the control level, it develops the Quasi-Whole Body Control (Q-WBC) method, establishing a coupling theory between multi-scale dynamic models and variable stiffness PID control, achieving collaborative optimization of attitude error and energy efficiency on complex terrain. Theoretically, it breaks through the rigid-flexible binary opposition, establishing a multi-objective optimization model for bionic mechanical structures focusing on "environmental adaptability-energy efficiency-fault tolerance," providing a unified theoretical framework for extreme environment robot design. In terms of engineering applications, theoretical models for core technologies like the titanium alloy TC4-DT leg structure and bistable chiral metamaterial actuators have been verified, laying the foundation for subsequent engineering. The social value is reflected in promoting the transition of rescue robot

design from experience-based to theory-driven, enhancing the intelligence level of disaster rescue equipment. Current research has limitations such as insufficient modeling accuracy for the constitutive relationships of smart materials and simplified assumptions in multi-scale control theory. Future work will focus on the cross-scale mechanical theory of self-healing materials, distributed control algorithms for swarm intelligence, and the integration of multi-disciplinary theories to improve the theoretical system of bionic robot design.

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