From Imitation to Intelligence: Current Trends and Future Directions in Legged Bio-Inspired Robotics

Jiaming Chen

School of Automation Science and Engineering, Faculty of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an, China.

jiamingchentianjin@stu.xjtu.edu.cn

Abstract. Legged bio-inspired robots have emerged as a promising solution for locomotion in unstructured and complex environments. By drawing inspiration from animal morphology and biomechanics, researchers have developed robotic systems capable of achieving agility, adaptability, and energy efficiency beyond the limits of traditional wheeled and tracked platforms. Advances in structural design, such as compliant spines and segmented legs, have enhanced gait stability and natural motion. At the same time, progress in control strategies—including model predictive control, central pattern generators, and reinforcement learning—has significantly improved adaptability and robustness. This paper presents recent developments in legged bio-inspired robotics, focusing on structural innovations, control approaches, and perception-driven adaptability. It also discusses the growing application domains of these systems, including disaster response, industrial inspection, and agricultural monitoring. Finally, the paper outlines current challenges and future research directions, highlighting the path toward intelligent, efficient, and reliable legged robots capable of operating in real-world environments.

Keywords: legged robotics, bio-inspired design, compliant mechanisms, locomotion control, adaptive autonomy.

1. Introduction

Legged bio-inspired robots attract attention for their ability to traverse terrains inaccessible to wheeled or tracked systems. Animals such as cheetahs inspire compliant spines and segmented legs, enhancing speed, stability, and energy efficiency [1]. Advances in mechanical design and control, demonstrated by platforms like MIT Cheetah and Lynx, enable agile and robust locomotion. However, significant gaps remain. Few studies integrate biomechanical design, adaptive control, and perception-driven adaptability into a unified framework. Energy efficiency, adaptability, and scalability across diverse terrains are still challenging.

The design of legged biomimetic robots is fundamentally inspired by the morphology and locomotion strategies of animals that have evolved over millions of years to navigate complex terrains with speed, stability, and energy efficiency. From the spring-like tendons of kangaroos to the articulated joints of insects and goats, engineers seek to replicate these natural mechanisms using mechanical components such as compliant actuators, segmented limbs, and flexible spines.

Integrating mechanical compliance and multi-joint coordination is key to improving locomotion efficiency and enhancing robustness against impacts and terrain irregularities. Some designs, like the MIT Cheetah, have successfully demonstrated agile and efficient running by mimicking musculoskeletal dynamics through custom electric actuators and lightweight frames [2].

This paper reviews progress in structure, control, and perception of legged bio-inspired robots, highlights existing gaps, and outlines future directions for intelligent and reliable autonomous systems.

2. Bio-inspired Structure and Locomotion Design in Legged Robots

Ongoing innovations focus on modular limb architectures, bio-hybrid actuation, and variable stiffness joints to narrow the performance gap between robots and their biological counterparts.

2.1 Bio-inspired Structural Design: Mimicking Animal Morphology

Biological structures, such as segmented limbs and shock-absorbing joints, guide the design of legged robots to balance force density, impact resistance, and motion range. Modular, lightweight limbs inspired by mammalian bone architectures simplify actuation and improve agility [2, 3], while compliant, impact-resistant joints mimic tendons and muscle-tendon units to smooth forces and absorb impacts [4, 5]. Mechanisms such as four-bar linkages or low-friction actuators enable robots to handle dynamic loads and terrain irregularities, supporting robust and energy-efficient locomotion. Modularity, compliance, and adaptability principles form the foundation for contemporary legged robot structures, providing design guidance beyond specific platforms.

2.2 Bio-inspired Locomotion Control: Replicating Gait Dynamics

Animal locomotion provides key insights for robot control, including gait rhythm, terrain adaptation, and energy-efficient movement. Inspired by energy-efficient animal gaits, rhythmic gait planning enables stable trot, bounding, or pronking motions through model-predictive or optimization-based control strategies [6]. Reactive terrain adaptation leverages sensory feedback, such as force or vision sensors, to adjust posture, speed, and ground reaction forces in real time, allowing robots to respond to uneven or unpredictable terrain [5].

Energy-efficient control is another critical aspect. By distributing forces optimally and minimizing actuator losses, robots can reduce the cost of transport and sustain longer operations, reflecting principles observed in animal locomotion [7]. Rhythmic gait planning, reactive adaptation, and energy-aware strategies enable robots to achieve agile, robust, and efficient locomotion, forming a generalizable framework beyond specific platforms.

3. The Development of Control Algorithms and Gait Planning

The progression of control and gait-planning strategies in legged robots has transitioned from classical model-based methods—such as Zero Moment Point (ZMP) and Central Pattern Generators (CPGs)—toward more flexible, adaptive techniques like Model Predictive Control (MPC) and deep Reinforcement Learning (RL). MPC enables real-time adjustment of trajectories and footholds, enhancing stability over uneven terrain [8]. In contrast, RL empowers robots to autonomously discover efficient gaits by learning from simulation and real-world interaction [9]. Emerging trends now advocate hybrid approaches that combine model-based control's reliability with learning's adaptability to achieve robust, terrain-adaptive locomotion.

The progression of control and gait-planning strategies in legged robots has transitioned from classical model-based methods, such as Zero Moment Point (ZMP) and Central Pattern Generators (CPGs), toward more flexible, adaptive approaches like Model Predictive Control (MPC) and deep Reinforcement Learning (RL) [8]. Classical methods provide foundational stability: ZMP ensures dynamic balance within the support polygon, while CPGs generate rhythmic motions inspired by biological neural circuits. However, these methods are limited in terrain adaptability and dynamic maneuvering [9].

3.1 Model-Based Control: From Classical Frameworks to Advanced MPC

MPC formulates locomotion as a finite-horizon optimization problem, updating real-time control inputs based on state estimates. It explicitly handles constraints and adapts to disturbances, offering high precision and stability across varied terrains [11, 12]. Compared with ZMP and CPGs, MPC improves adaptability, allows dynamic gait transitions, and can incorporate actuator and contact constraints.

3.2 Learning-Based and Hybrid Control: Enhancing Adaptability

Learning-based methods, particularly deep RL, allow robots to discover efficient gaits autonomously and adapt to complex environments [15]. RL excels in adaptability and generalization but often requires extensive training and may initially be less precise or stable. Hybrid frameworks combine model-based reliability with learning-based adaptability, balancing precision, stability, and responsiveness. For instance, MPC can enforce stability constraints while RL adjusts gait parameters to improve energy efficiency and environmental responsiveness [16].

Overall, the choice of control strategy involves trade-offs: model-based methods prioritize stability and predictability, RL emphasizes adaptability, and hybrid methods integrate the strengths of both to enable robust, terrain-adaptive locomotion.

4. Perception Systems and Environmental Interaction in Legged Robots

Efficient locomotion in legged robots relies on mechanical design, control, and the ability to perceive and interact with the environment in real time. Legged systems must monitor terrain, obstacles, and posture to adapt gait, maintain balance, and plan paths. Multi-modal sensors—including LiDAR, RGB-D cameras, IMUs, and foot-end force/torque sensors—fuse data to map terrain, estimate state, and predict terrain characteristics. Real-time feedback enables continuous adaptation to slopes, stairs, and uneven surfaces, with semantic perception guiding safer and more efficient paths [17, 18].

4.1 Multi-Modal Sensor Fusion for Terrain Perception and State Estimation

Legged robots rely on diverse sensors to acquire environmental and self-state information, with sensor fusion as the core to transform discrete data into unified decision-making. For terrain perception, the MIT Mini-Cheetah, a small-scale quadruped robot, integrates two Intel RealSense sensors: the D435 outputs 640×480 depth images at 90 Hz. At the same time, the T265 provides pose estimates at 200 Hz via visual-inertial SLAM. These two data sets are transformed into a global coordinate system through matrix operations to construct a 2.5D heightmap, laying the foundation for subsequent obstacle avoidance and foothold selection [19].

IMUs are combined with kinematic data to accurately track posture and motion for self-state estimation. The quadruped robot StarlETH uses an onboard Xsens MTi IMU to collect body acceleration and angular velocity data, which is fused with joint angle and spring deflection information from incremental encoders to achieve real-time state estimation. This fusion helps maintain balance during movement and provides reliable initial conditions for path planning [20]. In agricultural scenarios, portable robots can integrate CMD-Tiny electromagnetic induction (EMI) sensors to measure soil apparent electrical conductivity (ECa) for inferring moisture content. Optimizing sensor mounting positions (235 mm horizontally from the robot body and 50 mm above the ground) reduces electromagnetic interference from metal components, ensuring perception accuracy.

4.2 Closed-Loop Perception-Control for Adaptive Locomotion

The closed-loop integration of perception and control enables legged robots to dynamically adjust motion strategies via real-time environmental feedback, ensuring stability in complex terrains. StarlETH adopts a cascaded structure at the planning level: the global path planner first uses a circumscribed circle to approximate the robot’s footprint for fast searching, switching to an inscribed circle or rectangular footprint (considering orientation) for precision if no solution is found. The short-range planner verifies and updates the global path at a higher frequency, locally replanning invalid segments to maintain path validity amid continuous perception [21].

At the control execution level, real-time feedback drives gait adjustments. For instance, when the Mini-Cheetah detects an obstacle exceeding its 25 cm ground clearance, it triggers a precomputed jump motion (optimized via 2D nonlinear methods for stable landing). It switches to wide-stance joint PD control during landing to maintain balance. In agricultural scenarios, a soil ECa measurement robot uses GNSS to record geospatial coordinates, fuses data to generate moisture maps, and adjusts speed/path in real time if ±25 mm terrain deviations are detected, preventing postural instability-induced data errors [22].

5. Applications and Future Directions

Legged biomimetic robots are widely adopted in disaster response, industrial inspection, and environmental monitoring domains. Their ability to traverse uneven and dangerous terrain makes them ideal for post-disaster search and rescue. At the same time, robots like ANYmal have shown promise in autonomous inspection tasks in complex settings [23]. In agriculture and ecology, legged systems can operate in fields or forests to gather data that would be hard for wheeled robots to access.

Research is moving toward more adaptive, intelligent, and energy-efficient designs by integrating reinforcement learning, bio-inspired control, and modular architectures [24]. With the aid of onboard AI and improved perception, future legged robots are expected to function autonomously in increasingly dynamic and human-centered environments.

5.1 Advanced Actuation and Dynamic Locomotion

The pursuit of high-performance legged robots hinges on breakthroughs in actuation systems that balance force, efficiency, and compliance. Recent studies have highlighted the critical role of series elastic actuators (SEAs) in achieving torque controllability and impact robustness, as demonstrated in robots like StarlETH, which leverages compliant elements to enable dynamic gaits from static walking to running while maintaining energy efficiency [25]. Similarly, the MIT Cheetah project has advanced actuator design by prioritizing torque density and transmission transparency, using dimensional analysis to optimize motor geometry and gear ratios. This allows for high-force proprioceptive control without relying on external force sensors, a key capability for fast, adaptive locomotion over rough terrain [26]. These innovations lay the groundwork for robots to handle high acceleration and variable loading, essential for navigating unstructured environments such as disaster zone rubble or uneven industrial landscapes.

5.2 Adaptive Control Strategies for Uncertain Environments

Legged robots require control frameworks that adapt to unperceived disturbances and terrain variations. Model-based approaches, such as floating-base inverse dynamics control, enhance robustness by considering full-body dynamics and contact constraints, as demonstrated by LittleDog, which combines inverse dynamics with predictive force control to traverse rocky terrain [27]. Complementary bio-inspired strategies, including compliance tuning and real-time trajectory adjustment, maintain stability during high-speed motions, compensating for ground irregularities [28]. Integrating these methods with reinforcement learning further improves adaptability, enabling robots to refine gaits and recovery behaviors through environmental interaction.

5.3 Integration of Perception, Autonomy, and Human-Robot Interaction

Future legged robots rely on integrated perception, autonomous decision-making, and safe human-robot collaboration. Advanced sensors and state estimation enable precise terrain mapping and foothold selection, which are critical for complex environments. For example, TITAN XI adjusts gait in real time to maintain slope stability [29], while StarlETH demonstrates long-duration autonomous operation in unstructured terrain. Onboard AI allows end-to-end autonomy, interpreting sensory data to plan motion, avoid hazards, and optimize energy use. Low-impedance actuation and compliant control, such as series elastic actuators in StarlETH and transparent transmission in MIT Cheetah, enhance performance and safety in human-centric tasks [26].

6. Conclusion

Legged bio-inspired robotics has rapidly evolved from simple mechanical imitations of animal morphology to intelligent systems capable of adaptive locomotion in complex environments. Researchers have significantly narrowed the performance gap between robots and their natural counterparts by integrating biologically inspired structures, advanced actuation technologies, and energy-efficient gaits. The development of model predictive control, reinforcement learning, and hybrid frameworks has further enhanced the adaptability and robustness of locomotion strategies, allowing robots to navigate unstructured terrains with unprecedented autonomy.

Perception and environment interaction have emerged as critical enablers, with multi-modal sensing and closed-loop control providing the foundation for real-time adaptability. These advances have expanded the application scope of legged robots from laboratory demonstrations to real-world scenarios such as disaster response, industrial inspection, and agricultural monitoring. Meanwhile, the integration of autonomy and human-robot collaboration is paving the way for safe, versatile systems operating in human-centered environments.

Despite remarkable progress, challenges remain in energy efficiency, long-term autonomy, and scalability of learning-based methods. Future research must focus on harmonizing biological inspiration with artificial intelligence, exploring bio-hybrid actuators, modular architectures, and perception-driven adaptive control. By addressing these challenges, legged bio-inspired robots are expected to transform from specialized machines into intelligent, reliable agents capable of seamlessly supporting society across diverse domains.

References

[1] Eckert, P., Spröwitz, A., Witte, H., & Ijspeert, A. J. (2015, May). Comparing the effect of different spine and leg designs for a small bounding quadruped robot. In 2015, IEEE International Conference on Robotics and Automation (ICRA) (pp. 3128–3133). IEEE. https://doi.org/10.1109/ICRA.2015.7139576

[2] Katz, B., Di Carlo, J., & Kim, S. (2019). Mini Cheetah: A platform for pushing the limits of dynamic quadruped control. 2019 International Conference on Robotics and Automation (ICRA), 6295–6301. https://doi.org/10.1109/ICRA.2019.8793865

[3] Bledt, G., Powell, M. J., Katz, B., Di Carlo, J., Wensing, P. M., & Kim, S. (2018, October). Mit cheetah 3: Design and control of a robust, dynamic quadruped robot. 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 2245-2252). IEEE. https://doi.org/10.1109/IROS.2018.8593885

[4] Semini, C., Barasuol, V., Goldsmith, J., Frigerio, M., Focchi, M., Gao, Y., & Caldwell, D. G. (2016). Design of the hydraulically actuated, torque-controlled quadruped robot HyQ2Max. IEEE/ASME Transactions on Mechatronics, 22(2), 635-646. https://doi.org/10.1109/TMECH.2016.2616284

[5] Raibert, M., Blankespoor, K., Nelson, G., & Playter, R. (2008). Bigdog, the rough-terrain quadruped robot. IFAC Proceedings Volumes, 41(2), 10822-10825. https://doi.org/10.3182/20080706-5-KR-1001.01833

[6] Park, H. W., Wensing, P. M., & Kim, S. (2015). Online planning for autonomous running jumps over obstacles in high-speed quadrupeds. https://doi.org/10.15607/RSS.2015.XI.047

[7] Kenneally, G., De, A., & Koditschek, D. E. (2016). Design principles for a family of direct-drive legged robots. IEEE Robotics and Automation Letters, 1(2), 900-907. https://doi.org/10.1109/LRA.2016.2528294

[8] Bjelonic, M., Sankar, P. K., Bellicoso, C. D., Vallery, H., & Hutter, M. (2020). Rolling in the deep–hybrid locomotion for wheeled-legged robots using online trajectory optimization. IEEE Robotics and Automation Letters, 5(2), 3626-3633. https://doi.org/10.1109/LRA.2020.2972869

[9] Lee, J., Hwangbo, J., Wellhausen, L., Koltun, V., & Hutter, M. (2020). Learning quadrupedal locomotion over challenging terrain. Science Robotics, 5(47), eabc5986. https://doi.org/10.1126/scirobotics.abc5986

[10] Bjelonic, M., Bellicoso, C. D., de Viragh, Y., Sako, D., Tresoldi, F. D., Jenelten, F., & Hutter, M. (2019). Keep rollin'—whole-body motion control and planning for wheeled quadrupedal robots. IEEE Robotics and Automation Letters, 4(2), 2116-2123. https://doi.org/10.1109/LRA.2019.2899750

[11] Winkler, A. W., Bellicoso, C. D., Hutter, M., & Buchli, J. (2018). Gait and trajectory optimization for legged systems through phase-based end-effector parameterization. IEEE Robotics and Automation Letters, 3(3), 1560-1567. https://doi.org/10.1109/LRA.2018.2798285

[12] Grandia, R., Farshidian, F., Ranftl, R., & Hutter, M. (2019, November). Feedback mpc for torque-controlled legged robots. 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 4730-4737). IEEE. https://doi.org/10.1109/IROS40897.2019.8968251

[13] Mordatch, I., Todorov, E., & Popović, Z. (2012). Discovery of complex behaviors through contact-invariant optimization. ACM Transactions on Graphics (ToG), 31(4), 1-8. https://doi.org/10.1145/2185520.2185539

[14] Kalakrishnan, M., Buchli, J., Pastor, P., & Schaal, S. (2009, October). Learning locomotion over rough terrain using terrain templates. 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 167-172). IEEE. https://doi.org/10.1109/IROS.2009.5354701

[15] Magana, O. A. V., Barasuol, V., Camurri, M., Franceschi, L., Focchi, M., Pontil, M., ... & Semini, C. (2019). Fast and continuous foothold adaptation for dynamic locomotion through cnns. IEEE Robotics and Automation Letters, 4(2), 2140-2147. https://doi.org/10.1109/LRA.2019.2899434

[16] Farshidian, F., Neunert, M., Winkler, A. W., Rey, G., & Buchli, J. (2017, May). An efficient optimal planning and control framework for quadrupedal locomotion. 2017 IEEE International Conference on Robotics and Automation (ICRA) (pp. 93-100). IEEE. https://doi.org/10.1109/ICRA.2017.7989016

[17] Dudzik, T., Chignoli, M., Bledt, G., Lim, B., Miller, A., Kim, D., & Kim, S. (2020, October). Robust autonomous navigation of a small-scale quadruped robot in real-world environments. 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 3664-3671). IEEE. https://doi.org/10.1109/IROS45743.2020.9340701

[18] Satoh, M., Bhat, A., Usami, T., & Tatsumi, K. (2023, August). A multi-purpose autonomous mobile robot as a part of agricultural decision support systems. 2023 IEEE 19th International Conference on Automation Science and Engineering (CASE) (pp. 1-7). IEEE. https://doi.org/10.1109/CASE56687.2023.10260483

[19] Kim, D., Carballo, D., Di Carlo, J., Katz, B., Bledt, G., Lim, B., & Kim, S. (2020, May). Vision aided dynamic exploration of unstructured terrain with a small-scale quadruped robot. 2020 IEEE International Conference on Robotics and Automation (ICRA) (pp. 2464-2470). IEEE. https://doi.org/10.1109/ICRA40940.2020.9196777

[20] Shafi, U., Mumtaz, R., Iqbal, N., Zaidi, S. M. H., Zaidi, S. A. R., Hussain, I., & Mahmood, Z. (2020). A multi-modal approach for crop health mapping using low altitude remote sensing, internet of things (IoT) and machine learning. IEEE Access, 8, 112708-112724. https://doi.org/10.1109/ACCESS.2020.3002948

[21] Wermelinger, M., Fankhauser, P., Diethelm, R., Krüsi, P., Siegwart, R., & Hutter, M. (2016, October). Navigation planning for legged robots in challenging terrain. 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 1184-1189). IEEE. https://doi.org/10.1109/IROS.2016.7759199

[22] Campbell, M., Ye, K., Scudiero, E., & Karydis, K. (2021, August). A portable agricultural robot for continuous apparent soil electrical conductivity measurements to improve irrigation practices. 2021 IEEE 17th International Conference on Automation Science and Engineering (CASE) (pp. 2228-2234). IEEE. https://doi.org/10.1109/CASE49439.2021.9551401

[23] Hutter, M., Gehring, C., Jud, D., Lauber, A., Bellicoso, C. D., Tsounis, V., ... & Hoepflinger, M. (2016, October). Anymal-a highly mobile and dynamic quadrupedal robot. 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 38-44). IEEE. https://doi.org/10.1109/IROS.2016.7758092

[24] Hutter, M., Gehring, C., Höpflinger, M. A., Blösch, M., & Siegwart, R. (2014). Toward combining speed, efficiency, versatility, and robustness in an autonomous quadruped. IEEE Transactions on Robotics, 30(6), 1427-1440. https://doi.org/10.1109/TRO.2014.2360493

[25] Buchli, J., Kalakrishnan, M., Mistry, M., Pastor, P., & Schaal, S. (2009, October). Compliant quadruped locomotion over rough terrain. 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 814-820). IEEE. https://doi.org/10.1109/IROS.2009.5354681

[26] Seok, S., Wang, A., Otten, D., & Kim, S. (2012, October). Actuator design for high force proprioceptive control in fast legged locomotion. 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 1970-1975). IEEE. https://doi.org/10.1109/IROS.2012.6386252

[27] Zico Kolter, J., & Ng, A. Y. (2011). The stanford littledog: A learning and rapid replanning approach to quadruped locomotion. The International Journal of Robotics Research, 30(2), 150-174. https://doi.org/10.1109/ROBOT.2010.5509229

[28] Tajima, R., Honda, D., & Suga, K. (2009, May). Fast running experiments involving a humanoid robot. 2009 IEEE International Conference on Robotics and Automation (pp. 1571-1576). IEEE. https://doi.org/10.1109/ROBOT.2009.5152404

[29] Hodoshima, R., Doi, T., Fukuda, Y., Hirose, S., Okamoto, T., & Mori, J. (2004, September). Development of TITAN XI: a quadruped walking robot to work on slopes. In 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566) (Vol. 1, pp. 792-797). IEEE. https://doi.org/10.1109/IROS.2004.1389449