The control technique and modeling of quadruped robots

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Abstract. Quadruped robots, distinguished by their exceptional terrain adaptability, enabling seamless navigation across rough landscapes like uneven farmlands, cluttered construction sites, and debris-strewn disaster-stricken areas, and versatile task capabilities, have emerged as a pivotal technology in diverse fields. In agriculture, they utilize built-in sensors to conduct high-precision crop monitoring, detect pests early, and apply targeted precision spraying, thereby reducing manual labor and waste of resources. In the industry, they access narrow pipelines or high-risk, hazardous zones to perform equipment inspections, thereby avoiding potential threats to human workers. In public service, they play a critical role in search-and-rescue missions by locating survivors in collapsed buildings and support urban patrols to enhance public safety, significantly boosting operational efficiency and safety levels. Despite existing limitations, such as persistent challenges in dynamic balance control on slippery surfaces and energy consumption optimization for long-duration tasks, quadruped robots have advanced rapidly under the empowerment of AI. AI-driven algorithms have revolutionized core aspects, such as mechanical modeling, enabling more accurate simulation of limb movement mechanics and intelligent control techniques, thereby enhancing real-time responsiveness to sudden environmental changes. These advancements collectively fuel their promising prospects, positioning them as key players in the future of intelligent robotics.

Keywords: quadruped robots, control technique, modeling, AI.

1. Introduction

Quadruped robots, as bionic systems with four legs, have evolved into a pivotal area of robotics research, with their development rooted in decades of technological advancement. The journey of quadruped robots began in the 1960s, marked by the creation of the "walking truck" by Mosher in the United States in 1968, the first practical quadruped robot prototype. A significant milestone followed in 2005 when Boston Dynamics unveiled Big Dog, which revolutionized the field by demonstrating enhanced mobility and stability. In recent decades, progress has accelerated globally: Zhejiang University's White Rhino set a Guinness World Record by completing a 100-meter sprint in 16.33 seconds, while Kawasaki Heavy Industries' CORLEO, a hydrogen-powered model showcased at the 2025 Osaka-Kansai Expo, achieved breakthroughs in load-bearing (capable of carrying humans) and range (approximately 240 kilometers).

These robots possess distinct advantages that make them indispensable in dynamic, unstructured environments. Their superior land mobility and terrain adaptability enable them to outperform tracked robots on complex surfaces, such as stairs, muddy terrain, and rocky ground. They can easily step over obstacles, adjust foot placement, and maintain stability, making them ideal for outdoor tasks. Additionally, equipped with cameras, sensors, and flexible robotic arms, they exhibit remarkable versatility across various fields, aiding in post-disaster rescue by navigating tight spaces to locate survivors, supporting industrial inspections of hard-to-reach pipelines or power lines, and enabling agricultural monitoring to assess crop health. Empowered by AI, they also gain intelligence and flexibility, capable of autonomous operation and "smart" decision-making without human intervention, reducing labor costs and minimizing human risk in hazardous scenarios.

Despite these advancements, current quadruped robot research faces notable limitations, including challenges in optimizing dynamic balance control for high-speed movements, improving energy efficiency to extend operational duration, and enhancing adaptability to extreme environmental conditions (e.g., severe weather or complex rubble). Addressing these gaps is crucial to unlocking the full potential of quadruped robots and expanding their applications in critical sectors.

This review aims to systematically summarize the historical development and key technological breakthroughs of quadruped robots, analyze their core advantages and existing limitations, and explore the role of emerging technologies (such as advanced AI algorithms and new energy sources) in addressing current challenges. By providing a comprehensive overview, this review seeks to offer insights for researchers in the field and lay a foundation for future innovations that will drive the practical application and advancement of quadruped robots.

2. Working Mechanism of Quadruped Robots

The primary focus of the technology built into quadruped robots is precise movement control, which enables them to adapt to various terrains and, most importantly, execute multiple tasks.

2.1 Control hierarchy

To achieve specific movements and break down complex tasks, the system is designed with a layered structure, which specifically includes the following three levels: High-level Control is responsible for defining the robots' overall goal and generating motion plans. For example, if the overall goal is to climb a slope, the high-level control will calculate the desired speed and direction based on this goal to form a macroscopic execution plan. Mid-level Control breaks down the macroscopic plan developed by high-level control into specific movement parameters. Taking slope climbing as an example, this level needs to determine the gait pattern required to climb the slope, as well as the ideal step length and step height. Low-level Control executes the commands issued by the mid-level control. Controlling the robot's joints enables it to reach specific positions, perform specific movements, or exert specific forces.

2.2 Key control techniques

2.2.1 Gait planning

It determines the right gaits required for different scenarios to maintain balance, adapting its movement patterns to suit varying speed and stability needs. For slow, steady movement across relatively flat or slightly uneven terrain, the walking gait is employed, characterized by keeping three legs on the ground at any given time to ensure maximum stability—this allows the robot to navigate carefully without sacrificing balance, making it ideal for tasks that demand precision over speed, such as close-range inspection or gentle traversal of fragile surfaces.

When a faster pace is needed while still maintaining a moderate level of stability, the trotting gait comes into play, where diagonal pairs of legs move in synchronization. This gait strikes a balance between speed and steadiness, enabling the robot to cover more ground efficiently without compromising its ability to adjust to minor terrain changes. This is particularly useful for tasks such as patrolling large areas or moving between workstations in industrial settings.

For dynamic, high-speed movement, such as quickly responding to emergencies or traversing open spaces, the bounding gait is utilized, with legs moving in pairs to generate forward momentum. This gait prioritizes speed and agility, enabling the robot to accelerate rapidly while maintaining control through coordinated leg movements. However, it requires more advanced dynamic balance adjustments to handle the increased kinetic energy and potential terrain shifts.

2.2.2 Balance control

Sensors (gyroscopes, accelerometers, force sensors on feet) equipped on the robots can help detect the robot's posture (for example, whether there is any tilt or vibration) so that it can make real-time adjustments to prevent tipping and keep its balance on uneven surfaces.

2.2.3 Terrain adaptation

With the aid of sensors and cameras, the robot can map its environment and adjust its leg length, height, and step placement to navigate complex terrain and avoid obstacles.

3. Kinematic and dynamic modeling of quadruped robots

The core foundation of quadruped robot motion control lies in precisely modeling its kinematic and dynamic behavior. This section systematically elaborates on mechanical structure and joint configuration, forward/inverse kinematics modeling, and dynamic modeling methods. It then discusses current challenges and future development trends in modeling technologies.

3.1 Mechanical structure and joint configuration

Quadruped robots typically adopt a symmetrical mechanical structure, where the torso serves as the central body and the four legs are symmetrically distributed on both sides to ensure center-of-mass stability and structural balance. In most designs, each leg includes three main degrees of freedom (DOF): hip pitch, knee pitch, and hip roll or shoulder yaw (horizontal rotation). This 3-DOF configuration strikes a balance between trajectory control precision and manageable control complexity, and is widely adopted in mainstream quadruped robots, such as the MIT Cheetah, ANYmal, and Unitree.

The lateral degree of freedom at the hip is particularly crucial. It plays a significant role in posture adjustment, dynamic balance, and turning maneuvers, especially in complex terrains or during high-speed locomotion.

During the parameter modeling phase, it is essential to accurately measure and model the physical properties of each leg's links (such as the thigh and shank), including their length, mass, center of mass, and moment of inertia. These parameters directly influence the modeling accuracy and form the basis for ensuring the physical consistency of dynamic models and the effectiveness of control systems.

3.2 Forward and inverse kinematics modeling

A key element of quadruped motion control is establishing a precise mapping between joint angles and the foot-end spatial position. Each leg is often treated as a 2D two- or three-link mechanism for modeling simplification.

Let the hip pitch angle be θ_1 and the knee angle be θ_2, with link lengths of l_1 (thigh) and l_2 (shank). The foot position in the leg's local coordinate frame can be described as:

$$x = l_1 \cdot cos(\theta_1) + l_2 \cdot cos(\theta_1 + \theta_2)$$

$$y = l_1 \cdot sin(\theta_1) + l_2 \cdot sin(\theta_1 + \theta_2)$$

This model calculates foot position based on known joint angles, forming the basis for posture planning and feedforward control.

Given a desired foot position (x, y), the corresponding joint angles can be solved as:

$$\theta_2 = cos^{-1}(\frac{x^2 + y^2 - l_1{}^2 - l_2{}^2}{2 \cdot l_1 \cdot l_2})$$

$$\theta^1 = a \cdot tan^2(y, x) - a \cdot tan^2(l_2 \cdot sin(\theta_2), l_1 + l_2 \cdot cos(\theta_2))$$

The inverse kinematics model is crucial for foot trajectory tracking, as it decouples the relationship between spatial motion planning and joint-level actuation. Real-time computation of these inverse solutions enables coordinated joint actuation to perform tasks such as walking, turning, jumping, and other dynamic locomotion activities.

3.3 Dynamic modeling methods

Dynamic modeling captures the robot's response to external forces or internal actuations, forming the theoretical foundation for motion prediction, dynamic control, stability analysis, and simulation. Common methods include:

3.3.1 Euler-Lagrange method

This method constructs a Lagrangian function based on the system's kinetic energy (T) and potential energy (V):

$$L = T - V$$

The system dynamics are derived using the Euler-Lagrange equation:

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{q}_{\mathrm{i}}}) - \frac{\partial L}{\partial \dot{q}_{\mathrm{i}}} = \tau_{\mathrm{i}}$$

Here, q_i denotes generalized coordinates, and τ_i represents generalized forces acting on those coordinates. This approach provides a clear structure and symbolic expressiveness, making it suitable for analytical modeling and system-level behavior analysis, particularly when combined with symbolic simulation tools.

3.3.2 Newton-Euler method

This method employs a bottom-up recursive approach, comprising two stages: Forward recursion calculates the velocity and acceleration of each link. In contrast, Backward recursion propagates forces and torques from the end-effector to the base. The Newton-Euler method offers high numerical stability and computational efficiency, making it ideal for embedded systems and real-time control algorithms.

3.3.3 Simplified dynamic models

To balance real-time control performance with engineering feasibility, the following simplified models are often used:

Linear Inverted Pendulum Model (LIPM) assumes a constant center of mass (CoM) height and neglects the mass of the legs. It is suitable for ZMP-based walking control and stable gait planning. Centroidal Model treats the robot as a lumped-mass system, focusing on CoM dynamics and angular momentum. It is helpful for high-dynamic tasks like jumping and flipping. The Floating Base Model represents the robot's main body as a free-floating rigid body, capable of describing full-body motion in multi-contact scenarios, thereby enabling whole-body control strategies. These models can be used independently or embedded as predictors or cost functions in higher-level control frameworks, such as Model Predictive Control (MPC), Whole-Body Control (WBC), or Reinforcement Learning (RL), to enhance system responsiveness and control efficiency.

3.4 Conclusion and outlook

Kinematic and dynamic modeling form the theoretical foundation for precise control and high-performance behavior in quadruped robots. Starting from mechanical design and parameter identification, the modeling chain progresses through kinematic mapping, dynamic formulation, and control-oriented simplifications, forming a complete loop from structure to control.

With the ongoing evolution toward high dynamic performance, environmental adaptability, and intelligent autonomy, future modeling approaches are expected to focus on: Multi-model fusion and switching mechanisms, which dynamically select appropriate modeling strategies based on task and terrain; High-fidelity yet real-time modeling pipelines, which ensures both physical consistency and computational efficiency; and Adaptive parameter estimation and learning-based modeling, which enable robots to self-optimize models and control strategies in unknown or changing environments.

This trend will lay a solid foundation for the deployment of quadruped robots in complex missions such as disaster rescue, autonomous inspection, precision agriculture, and planetary exploration.

4. AI empowering quadruped robots

AI can enhance the adaptability and autonomy of quadruped robots, enabling them to make more informed decisions and respond more effectively to their environment.

4.1 Adaptability

Sensors and cameras enable quadruped robots to capture images of their surroundings and map the terrain. However, AI algorithms can help them "see" and "understand" their environment, making real-time adjustments, avoiding obstacles, and preventing tripping.

Machine learning (ML) models, if heavily trained on a vast amount of terrain data, can help robots adjust their posture, position, gait, or force in different circumstances.

4.2 Autonomy

AI allows quadruped robots to function more autonomously. For example, they can conduct search missions independently by analyzing thermal images to quickly locate human survivors. They can even free the survivors with their robotic arms and carry them to safe places if the situation is not too tricky

All in all, quadruped robots can become intelligent systems that can learn, adapt, reason, and function independently with the power of AI, making them more capable of handling complicated problems in harsh environments.

5. The prospect of quadruped robot applications in various fields

Quadruped robots have been applied and will be further applied across multiple fields owing to their superior terrain adaptability and versatility in task completion: in agriculture, they can use sensors to monitor crop growth, assess crop health, and even assist in certain farming operations thanks to their ability to move on uneven farmland; in industry, they can inspect equipment such as pipelines or power lines in hard-to-reach areas; in construction, they can help carry and transport construction materials in harsh environments or narrow places where human access is impossible; in public services, they can monitor public facilities and infrastructures to detect wear and tear and prevent potential disasters, as well as perform security patrols in crowded places like parks, malls and transportation centers; in search and rescue, they can move on rubble and debris in post-disaster locations, navigate tight spaces and maneuver in complicated environments to locate survivors, and transmit real-time images to rescue teams; in military, they can carry supplies for soldiers or perform dangerous tasks to avoid casualties.

6. The limits of quadruped robots

Although quadruped robots have been used in many fields due to their strengths and merits, some downsides and limitations still prevent them from being widely applied in real-life scenarios: in terms of load-carrying capacity, most quadruped robots can only carry a small fraction of their weight (usually 5−15kg) compared to other types of robots, which makes them somewhat useless for transporting heavy materials on construction sites and even unable to carry survivors to safe places in rescue missions; in terms of speed, they are currently unable to move at high speed, and high-speed gaits (like bounding) further compromise stability, increasing the risk of tripping and falling in complex terrain; in terms of dexterity, their robotic arms are too chunky for precise control, and delays in sensor feedback and coordination between body parts add to the difficulty, making precise tasks such as picking up fragile items incredibly challenging; in terms of real-time adaptation, even with AI support, today′s quadruped robots cannot make quick and perfect adjustments when facing unexpected changes; in terms of efficiency and durability, they consume more energy to complete specific movements than other robots, with batteries usually dying within a couple of hours, making it difficult for them to operate for long periods in areas without charging conditions; in terms of fragility, slipping and falling can damage their delicate parts such as joints and sensors, and once damaged, they cannot continue working or recover; additionally, the high cost of producing and training quadruped robots also heavily limits their application in real-world scenarios.

7. Conclusion

Looking ahead, quadruped robots are poised to overcome the long-standing bottlenecks in complex-environment applications through the deep integration of cutting-edge technologies. By combining bionic structural designs that mimic the limb mechanics of animals like cheetahs or goats for enhanced agility, and advanced intelligent control systems, these robots will achieve more precise and adaptive movement, even in extreme terrains such as rubble-strewn disaster sites or uneven industrial facilities. Meanwhile, the fusion of autonomous perception technologies, including high-resolution sensors and AI-driven environmental recognition algorithms, will enable them to independently identify obstacles, assess risks, and make real-time navigation decisions, reducing reliance on human intervention.

As these technological advancements mature, the global market size of quadruped robots is expected to expand significantly, driven by growing demand across key sectors. In industrial inspection, they will replace manual labor in hazardous tasks, such as pipeline patrols or inspections of high-voltage equipment, thereby improving safety and efficiency. Their ability to access hard-to-reach areas in disaster relief will enhance survivor detection and emergency supply delivery. Additionally, in service fields such as elderly care and logistics, they will offer flexible support, becoming an integral part of smart living and work environments. Quadruped robots will evolve from specialized tools to versatile assistants, reshaping industries and contributing to societal progress.

References

[1] Zhang, J., Gao, F., Han, X., & Chen, X. (2014). Trot Gait Design and CPG Method for a Quadruped Robot. Journal of Bionic Engineering.

[2] Kim, D., Di Carlo, J., Katz, B., Bledt, G., & Kim, S. (2019). Highly Dynamic Quadruped Locomotion via Whole-Body Impulse Control and Model Predictive Control. arXiv.

[3] Gao, F., Zhang, J., Han, X., & Chen, X. (2015). Kinematic and Dynamic Modeling of a Quadruped Robot. Journal of Mechanical Science and Technology.

[4] Kucuk, S., & Bingul, Z. (2006). Robot Kinematics: Forward and Inverse Kinematics. In Industrial Robotics: Theory, Modelling and Control.

[5] Xu Haidong, Gan Su, Ren Jie, Wang Binrui, Jin Yinglian, Gait CPG Adjustment for a Quadruped Robot Based on Hopf Oscillator, Journal of System Simulation, 2017

[6] Li Junmin, Wang Jinge, Yang Simon X., Zhou Kedong, Tang Huijuan, Gait Planning and Stability Control of a Quadruped Robot, Computational Intelligence and Neuroscience, 2016 PMC

[7] Donghyun Kim, Jared Di Carlo, Benjamin Katz, Gerardo Bledt, Sangbae Kim, Highly Dynamic Quadruped Locomotion via Whole-Body Impulse Control and Model Predictive Control, (arXiv preprint), 2019 arXiv