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A Review of Recent Developments in Quadruped Robots

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Abstract: Quadrupedal robots have emerged as a leading platform for navigating complex and uneven terrains, owing to their biomimetic design and superior adaptability compared to wheeled and tracked counterparts. This review provides an overview of the historical development of quadruped robots, from early mechanical designs to modern advancements in actuation, control, and artificial intelligence. Recent progress in hydraulic, electric, and pneumatic actuation systems, combined with improvements in motion planning algorithms and terrain recognition technologies, have significantly enhanced the performance of these robots in real-world applications. Additionally, key trends such as the integration of artificial intelligence for autonomy and the use of advanced materials for flexible body designs are highlighted. The paper concludes with a discussion of future research directions aimed at further improving the efficiency, stability, and versatility of quadrupedal robots.

Keywords: Quadruped robot, Actuator, Artificial intelligence.

1. Introduction

The field of ground-mobile robotics has gained substantial interest in recent years, resulting in the development of various robotic platforms, including tracked, wheeled, and legged robots. Both tracked and wheeled robots maintain continuous ground contact, which supports high-speed movement and low energy consumption. However, these designs exhibit limited adaptability to uneven terrains, such as steep slopes, potholes, and other challenging surfaces [1].

The growing demand for robots capable of navigating rough and complex environments has led to significant advancements in legged robots, particularly in the past decade. Their discrete point-contact motion offers superior adaptability in environments such as mountainous terrain, grasslands, and staircases [2]. The performance of legged robots is influenced by factors such as the number of legs, leg design, and overall posture. Quadrupedal robots, in particular, have demonstrated excellent stability and versatility. Compared to bipedal, hexapod, or octopod robots, quadrupedal designs are generally simpler to construct, control, and maintain, while offering comparable efficiency [3].

Quadrupedal robots, a key category of bio-inspired robots, mimic the movement of four-legged animals. These quadrupedal mobile robots (QMRs) excel in traversing cluttered environments and can perform holonomic movements without constraints in lateral motion or load-bearing capacity [4]. Recent advances in high-torque-density motors, electric-hydraulic systems, and 3D printing technologies have significantly enhanced the energy efficiency, robustness, and dynamic capabilities of QMRs in real-world applications [5-7].

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This paper reviews the historical and current advancements in quadrupedal robots, focusing on design, mobility, and the integration of artificial intelligence. Future directions for the field will also be discussed.

2. Historical Development of Quadruped Robots

Quadrupedal robots are inspired by the locomotion of four-legged animals, with articulated joints in the knees, hips, and neck allowing them to replicate animal-like movement. The earliest example of such a robot dates back to 1870, when Chebyshev designed a quadrupedal mechanism that could stand and walk but lacked terrain adaptability. In 1893, Rygg received the first patent for a footed machine, a pedal-powered horse-riding simulator [8].

A notable step in quadrupedal robotics occurred in 1940, when Hutchinson designed an independently controlled legged robot, emphasizing the advantages of footed systems over wheeled or tracked vehicles for heavy-load applications [9]. The culmination of this approach was the construction of the largest footed machine, Big Muskie, by Bucyrus-Eire in 1969. This massive robot operated in open-pit mines for 22 years, demonstrating the feasibility of quadrupedal designs for large-scale industrial applications.

In the 1980s, Professor Hirose of the Tokyo Institute of Technology pioneered a family of quadrupedal robots, with PV-II being a key milestone. This robot featured a motorized drive for each leg, enabling it to walk efficiently[10]. Further developments, such as Stanford's OSQ quadrupedal robot, advanced the understanding of galloping gaits and energy-efficient locomotion [11]. More recently, Chinese institutions such as Shandong University have developed quadrupedal robots like SCalf-1 and SCalf-2, which feature advanced hydraulic systems for improved terrain adaptability and speed [12].

3. Current Research and Development Trends

3.1. Actuation and Design

Quadrupedal robots are inherently biomimetic, drawing inspiration from the locomotion of animals such as dogs, goats, rats, and cats. These robots typically feature a body, thighs, shanks, and feet, with multiple degrees of freedom (DoF) in the joints to enable smooth, coordinated movement [13-16]. Actuation systems for quadrupedal robots generally fall into three categories: hydraulic, electric, and pneumatic.

Hydraulic actuation provides high power density, enabling robots to bear heavier loads, though this comes at the cost of increased weight, size, and noise. Recent efforts have focused on developing more lightweight and efficient hydraulic systems [17]. Electrically actuated robots, powered by batteries, offer lower noise levels and precise torque control, though they require meticulous manufacturing and maintenance. Pneumatic systems, utilizing compressed air, are advantageous due to their low cost, light weight, and flexibility, though they suffer from lower control accuracy and oscillatory behavior. Innovations such as the origami pump actuator and McKibben pneumatic artificial muscles have improved the performance of pneumatically powered quadrupeds [18,19].

Body design is also a crucial factor in quadrupedal robots. Rigid bodies offer structural simplicity with fewer DoFs, but at the expense of flexibility and stability. Flexible body designs, on the other hand, enhance the robot's adaptability and dynamic stability in complex environments but introduce challenges related to material wear and maintenance. Research into torso compliance has shown that flexibility in the robot's body can significantly improve locomotion efficiency at higher speeds [20,21].

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3.2. Locomotion and Control

Motion planning and control are central to the operation of quadrupedal robots, involving gait generation and execution. Common gait generation methods include Central Pattern Generators (CPGs), the Spring-Loaded Inverted Pendulum (SLIP) model, the Zero Moment Point (ZMP) method, and Bezier curve trajectories.

CPGs are neural circuits capable of generating rhythmic motion patterns without external input, mimicking the movement of animals. Though effective in producing periodic locomotion, CPGs often struggle with performance in complex terrains due to disturbances. Enhanced versions, such as Multi-Layered CPGs (ML-CPGs), have been proposed to address these limitations[22,23].

The SLIP model simplifies the robot's legs into massless springs, making it useful for controlling jumping and high-speed running [24,25]. ZMP methods, which calculate the point at which the robot’s moment is zero, are effective for ensuring balance during slower motions[26,27]. Bezier curves provide smooth, continuous trajectories, reducing computational costs in motion planning [28,29].

3.3. Artificial Intelligence and Autonomy

Autonomy in quadrupedal robots is driven by advances in path planning and terrain recognition technologies. Path planning methods range from traditional algorithms, such as Dijkstra and A*, to learning-based approaches like reinforcement learning. Each approach has strengths and weaknesses in terms of efficiency, memory usage, and adaptability.

Terrain recognition involves using sensors to detect and classify the surrounding environment, allowing the robot to adjust its gait and movement accordingly. Techniques such as grid-based topography classification and HMC-based terrain classification are commonly employed to enhance the robot’s ability to navigate varied terrains [30,31].

4. Future Directions

Future research in quadrupedal robotics is likely to focus on improving structural design, motion control, and autonomy. While current quadrupedal robots have made significant strides, there remains a considerable gap between robotic and biological systems in terms of flexibility, balance, and energy efficiency. Efforts should be directed towards developing innovative materials and designs that closely mimic the flexibility and resilience of animal musculoskeletal systems. Additionally, advances in control algorithms and sensor integration will be critical for improving locomotion efficiency and autonomy in complex environments.

5. Conclusion

Quadrupedal robots have seen remarkable progress in recent years, particularly in their ability to traverse complex and uneven terrains where traditional robots fail. This review has highlighted the historical evolution of these robots, their current technological advancements, and the key areas for future research. Enhancements in actuation, control, and artificial intelligence will continue to shape the development of quadrupedal robots, bringing them closer to achieving the versatility, stability, and adaptability of their biological counterparts.

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