A Review of Exploration of the Stable Operation Principle of Quadruped Robots in Complex Terrains

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Abstract. This review examines the principles enabling quadruped robots to operate stably in complex terrains. The review focuses on three key areas: mechanical design, control algorithms, and environmental perception. Inspired by quadrupedal animals, bionic design strategies such as implementing rigid and flexible joints and bio-inspired leg structures have been used in the mechanical design and have significantly improved terrain adaptability. While Model Predictive Control (MPC) handles constraints, Reinforcement Learning (RL) enables adaptive gait planning. LIDAR, visual sensors, and sensor fusion improve terrain recognition so that quadruped robots can recognize and quickly respond to changes in terrain or the environment. To this day, quadruped robots demonstrate practical value in industrial routing inspection, disaster rescue, complex-terrain exploration, and military fields. However, challenges remain in payload capacity, algorithm real-time performance, and sensor robustness, indicating that future research should emphasize integrated and interdisciplinary innovation.

Keywords: Quadruped Robots, Complex Terrain, Stable Operation, Mechanical Structure, Control Algorithm.

1. Introduction

With their bio-inspired structures and locomotion patterns similar to animals, Quadruped robots have demonstrated excellent environmental adaptability and mobility in complex terrain environments, gaining considerable attention in robotics[1]. Locomotion that mimics animals and humans holds a notable advantage over wheeled mobile robots: it enables traversal of unstructured, challenging terrains[2]. Due to the flexible movement, strong load capacity, and superior performance in complex terrains, quadruped robots have broad application prospects in industrial environment exploration and reconnaissance dominated by slope or height changes, residential area distribution, and emergency rescue[3].

Yet, the goal of achieving stable locomotion on complex terrains has always been a critical research topic in the domain of quadruped robots[4]. When quadruped robots traverse terrain with varying slopes or elevations, the uncertainty and complexity of the terrain environment make stable navigation across such complex landscapes a persistent challenge[3]. So, enabling quadruped robots to move freely and stably in those environments remains challenging.

In recent years, with the rapid development of robot technology, control theory, and sensor technology, significant progress has been made in the stable operation of quadruped robots in complex terrains. Researchers conducted studies from three aspects: mechanical structure design, control algorithm optimization, and environmental perception systems, and proposed a series of innovative methods and technologies. This paper aims to comprehensively sort out and analyze the relevant research on the stable operation principle of quadruped robots in complex terrains in the past 1-3 years. It will be carried out in three dimensions: mechanical structure, control algorithm, and environmental perception. It will summarize the latest research results, analyze the existing problems, and look forward to future development. The review in this article is expected to theoretically improve the theoretical motion control system for quadruped robots in complex terrains and promote the cross-integration of bionics and robotics.

2. Literature Review

2.1 Mechanical Structure

2.1.1 Biological Inspirations for the Limb Structure & Gait Characteristics of Quadruped Animals

Quadrupedal animals have evolved over a long period to develop limb structures and gait features adapted to various complex terrains. Studies have shown that the limb proportions, joint configurations, and elastic properties of the muscle-tendon system of animals play a crucial role in their movement efficiency and stability on rough terrain[5]. For example, Chen et al. found that the walking limbs of crabs living on rocky coasts have specific proportional relationships: the length of the distal segment is approximately 0.63 times the total leg length. This proportion enables them to effectively cross rock obstacles with a diameter of about 37% of their leg length[5]. This discovery provides important references for robot leg structure design; researchers have designed a hexapod crab-inspired robot based on this, which exhibits excellent passability on uneven terrain[5].

In addition, the passive compliance of animal limbs also inspires robot design. Schiebel et al. studied the impact of insect legs' passive compliance on their movement on complex terrain. They found that appropriate joint compliance can significantly improve the stability and passability of robots on uneven terrain[6]. Inspired by this, researchers have introduced passive compliant joints in robot leg design, such as asymmetric compliant knee joints, which significantly enhance the robot's ability to traverse obstacle terrain[6].

2.1.2 Comparison and Optimization of Rigid and Flexible Joint Configurations

Rigid and flexible joints have advantages in the design of quadruped robots. Rigid joints can provide precise position control and large output force, making them suitable for scenarios requiring precise motion control; flexible joints, on the other hand, have better compliance and impact resistance, performing better on uneven terrain [2].

Spoljaric et al. proposed a new method that integrates variable stiffness control into joint position control, allowing grouped stiffness control, such as per-joint stiffness (PJS), per-leg stiffness (PLS), and hybrid joint-leg stiffness (HJLS). Experimental results show that the variable stiffness strategy using PLS grouping outperforms position-based control in speed tracking and thrust recovery, while HJLS excels in energy efficiency [2]. This research provides new ideas for the optimal design of joint stiffness in quadruped robots.

Gao et al. proposed a new quadruped robot design based on a tensegrity structure. The spine and limbs are designed as flexible multi-segment structures connected by tensegrity joints, significantly improving the robot's flexibility and adaptability to complex terrain. Experiments show that compared with traditional quadruped robots, this flexible structure robot exhibits excellent bending and deformation capabilities, enabling it to better adapt to narrow spaces and complex terrain [7].

2.1.3 Impact of Leg-Foot Structure Design on Terrain Adaptability

The leg-foot structure is the part of the quadruped robot that directly contacts the ground, and its design has a key impact on the robot's terrain adaptability. Researchers have conducted in-depth studies on various aspects such as foot-tip shape, leg link proportions, and joint configurations[5].

Yuan et al. designed a quadruped robot with a reconfigurable sprawling structure. This robot can switch between extension postures to cope with complex environments and adapt to back-down fall postures through reverse extension. Experiments show that this reconfigurable robot can crawl on inclined surfaces, continue crawling in a back-down posture after falling, and effectively navigate obstacles and narrow spaces after posture switching [8].

De Luca et al. studied the autonomous obstacle-crossing strategy of the hybrid wheel-leg robot Centauro. They found that foot shape and leg geometric parameters significantly impact the robot's passability in complex terrain. They designed a terrain segmentation method based on point cloud data to identify gaps or obstacles on the ground and autonomously select and adjust the most suitable crossing behavior according to terrain geometric parameters [9].

Wang et al. designed a parallel quadruped robot BQR-2 with a strong driving force, using customized high-torque motors and two-stage planetary reducers to improve torque density. Experiments show that this robot can generate large ground reaction forces on uneven terrain, achieving stable dynamic movement [10].

2.2 Control Algorithms

2.2.1 Application of Model Predictive Control (MPC) in Quadruped Robots

Model Predictive Control (MPC) is an advanced model-based control strategy that can predict the system's future state within a finite time domain and solve optimization problems. It has been widely used in the motion control of quadruped robots [1].

Li et al. combined MPC with Quadratic Programming (QP) torque control to ensure stable and efficient movement of the robot on steep slopes. They predicted the terrain slope by analyzing foot position and IMU data and then adjusted the robot's body orientation and height in real time to adapt to changing slope conditions[1].

Nan et al. proposed an MPC method based on fuzzy adaptive weight coefficients to enhance the motion balance performance of quadruped robots on unstructured terrain. This method designed an adaptive fuzzy algorithm that dynamically adjusts weight coefficients according to the robot's current roll angle and pitch angle errors and their rates of change [11].

MPC's advantage lies in its ability to explicitly handle system constraints and adjust control actions in advance based on predicted future states, making it particularly suitable for dynamic stability control in complex terrain [11]. Besides, as MPC can work with other programs such as QP and fuzzy adaptive weight, it is compatible with different requirements. Facing excessively long time domains or high-dimensional states will increase the computational load of MPC's ‘prediction time domain’ and ‘state dimension’, which can easily lead to control delays and affect dynamic responses. Moreover, MPC highly relies on the accuracy of the dynamic model. Simplified assumptions aimed at reducing computational load may fail in extreme scenarios.

2.2.2 Application of Reinforcement Learning (RL) in Gait Planning and Attitude Adjustment

Reinforcement Learning (RL) is a machine learning method that learns optimal behavior strategies through interaction with the environment. It has shown great potential in gait planning and attitude adjustment of quadruped robots [12].

Cai et al. proposed a framework in which they innovatively set two interactive and complementary components in the control module: High-Performance HP-Student and High-Assurance HA-Teacher. HP-Student is a Deep Reinforcement Learning (DRL) agent that develops safe and efficient action strategies through self-learning and teaching-learning; HA-Teacher is a physics model-based controller responsible for teaching HP-Student safety knowledge and providing backup for the robot's safe movement [13].

Zhang et al. developed an offline RL benchmark, providing a standardized framework for evaluating the performance of offline reinforcement learning algorithms in the real world. This benchmark uses a real-world quadruped robot motion dataset from the classical Model Predictive Control (MPC) method [12].

The advantage of RL is that it does not require an accurate system model and can adapt to complex and changing environmental conditions through trial-and-error learning [13]. Experimental results show that the best-performing offline reinforcement learning algorithm can achieve performance comparable to model-free reinforcement learning and even surpass it in some functions. However, there is still a gap compared with MPC, especially in stability and rapid adaptation [12]. Besides, it also takes a long training cycle to teach RL models with massive data.

2.2.3 Development Trends of Hybrid Control Strategies

Nowadays, researchers are showing a growing tendency to integrate multiple control strategies, thereby developing hybrid control strategies that leverage the complementary strengths of each approach. This hybrid approach can fully utilize the advantages of various control strategies, overcome the limitations of a single strategy, and provide more effective solutions for the stable operation of quadruped robots in complex terrain [14].

Lyu et al. proposed an RL-based Rapid Online Adaptive Control (RL2AC) algorithm, which combines RL strategies with adaptive control. RL2AC runs at a high frequency of 1000Hz. It doesn’t require simultaneous training with RL; instead, RL handles terrain adaptation and adaptive control resists external disturbances, addressing RL’ s poor disturbance rejection[14].

Zhang et al. proposed a two-layer reinforcement learning algorithm, combining Deep Double Q-Network (DDQN) and Proximal Policy Optimization (PPO), to achieve rapid adaptation and high stability in complex terrain by utilizing their complementary advantages. The algorithm uses terrain information and robot state as observations, determines the walking speed command of the quadruped robot Unitree Go1 through DDQN, and dynamically adjusts the current walking speed in complex terrain based on the PPO-based machine action control system[15].

In both cases, hybrid control strategies demonstrate more efficient and excellent performance. By compensating for single-method limitations via synergy, they balance precision, adaptability, and robustness. However, most hybrid control strategies have high algorithm complexity, which makes them hard to debug. Moreover, these strategies need high-performance hardware to run precisely, increasing the research cost.

2.3 Environmental Perception: Multi-Source Information Fusion and Terrain Understanding

2.3.1 Application of LIDAR in Terrain Recognition and Modeling

As an active remote sensing technology, LIDAR can acquire 3D point cloud data of the surrounding environment in real time, providing precise terrain geometric information for quadruped robots and playing a key role in complex terrain recognition and modeling [16].

Cao et al. integrated LIDAR, cameras, and IMU. LIDAR supported Globally Consistent Dense Elevation Mapping (GEM) for map consistency, with ERFNet classifying terrains (soil, grassland) and matching step adaptations [16].

Su et al.’s GR-SLAM fused LIDAR-associated camera, IMU, and encoder data via manifold odometry and factor graph optimization, enabling robust state estimation and noise resistance in large 3D environments [17].

As we can see, LIDAR’s high-precision 3D point cloud data addresses the core demand for accurate terrain modeling. Because of this advantage, LIDAR-dominated multi-sensor fusion is the most robust choice for large-scale 3D complex terrains like field exploration and post-disaster rescue.

2.3.2 Role of Visual Sensors in Terrain Feature Extraction and Classification

Visual sensors can provide rich texture and color information, helping to identify different types of terrain materials and surface characteristics, and are important components of the environmental perception system of quadruped robots[16].

Zhou et al. proposed a terrain passability mapping method based on lidar and vision fusion. This method mainly consists of three modules: vision-based passable region segmentation, lidar-based passable region extraction, and Bayesian fusion. Experimental results show that this method can achieve real-time and reliable passability mapping and outperform existing technologies [18].

The study pointed out that LIDAR and vision have advantages: LIDAR is better at identifying regions with strong structural features, while vision methods can distinguish different regions with semantic significance but may sometimes lead to misclassification due to domain gaps or other reasons[18]. This case shows that visual sensors are unstable to operate in complex, changeable outdoor terrains. However, visual sensors can operate well in a stable environment like an industrial curb. Furthermore, capturing texture or color can cooperate with other multi-sensor fusion strategies to perform better in complex terrains.

2.3.3 Multi-Sensor Fusion Strategies and Terrain Classification Methods

In complex terrain environments, providing sufficient environmental information with a single sensor is often difficult, so multi-sensor fusion technology has become an effective way to improve the environmental perception ability of quadruped robots[19].

Pan et al. proposed a pose estimation algorithm fusing stereo cameras, joint encoders, and IMUs [19]. It uses two sub-filters (forward kinematics + IMU trajectory, stereo camera + IMU attitude) for joint filtering, then integrates results for global optimal pose estimation—experiments confirm its accuracy and robustness against VIO data[19]. Its advantage lies in high pose precision, as stereo cameras and IMUs complement each other to balance local foot-tip positioning and global attitude; however, it relies on multiple hardware components, increasing system complexity and cost. It is suitable for structured or semi-structured environments (e.g., indoor factories, planned outdoor inspection routes) where hardware volume and cost are less constrained.

Yu et al. developed a neuromorphic + traditional sensor fusion scheme via the MHNN network, integrating data from neuromorphic sensors and traditional sensors (LIDAR/visual/IMU), and deployed it on the Tianji neuromorphic chip[20]. Its strengths are strong anti-interference and low energy use; the downside is high technical thresholds for neuromorphic chip integration. It is ideal for dynamic, unstructured environments (e.g., post-disaster rubble, outdoor fast locomotion) with frequent environmental disturbances.

The two multi-sensor fusion schemes demonstrate the core value of multi-sensor fusion technology. In terms of their results, they both highly improve their performance against complex terrains, but they are not easy to popularize in general research or low-tech threshold application scenarios. This indicates that multi-sensor fusion design for quadruped robots must align with specific application scenarios and balance performance demands with implementation feasibility.

3. Conclusion

This review systematically explores the core principles that enable quadruped robots to achieve stable operation in complex terrains, focusing on three interconnected dimensions: mechanical structure, control algorithms, and environmental perception.

From a mechanical structure perspective, bio-inspired designs enhance a robot's terrain adaptability. Research shows that optimizing limb proportions, integrating rigid-flexible hybrid joints, and developing reconfigurable leg-foot structures can significantly improve a robot's ability to navigate uneven ground. MPC is a dominant method in control algorithms due to its ability to handle constraints and ensure dynamic stability. At the same time, RL shows great potential for adaptive gait planning because it does not require an accurate system model and learns through trial and error. The future trend is to combine these approaches into hybrid control strategies to balance MPC's precision with RL's adaptability, achieving a balance of accuracy, robustness, and adaptability. Such hybrid strategies are increasingly becoming a mainstream research direction. The trend of multi-source information fusion dominates the field of environmental perception. A single sensor (such as a LiDAR or a visual sensor) has limitations in complex environments. Therefore, researchers commonly fuse data from multiple sources, including LiDAR, visual sensors, and Inertial Measurement Units (IMUs), to achieve more precise terrain recognition and 3D environment modeling. This fusion strategy effectively balances local positioning and global attitude, significantly improving the robot's anti-interference capability.

This review also has some limitations. First, due to the rapid evolution of robotics, some emerging technologies (such as the latest breakthroughs in neuromorphic computing for perception) may not be fully covered. Second, the comparative analysis of different control algorithms and mechanical configurations is primarily based on published experimental data, lacking standardized benchmarks for cross-study validation, especially in extreme environments. Finally, the practical challenges of scaling lab-proven technologies to real-world applications, such as cost reduction, durability, and maintenance, are not exhaustively discussed. Future research should focus on bridging the gap between theoretical progress and practical deployment, emphasizing integrated innovation across disciplines, and strengthening field validation.

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