

Review of Motion Control Research for Bionic Quadruped Robots: From Biological Inspiration to Algorithm Implementation

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Abstract. Bionic quadruped robots offer significant potential for navigating complex and unstructured environments, yet their performance still lags notably behind that of natural quadrupeds in terms of efficiency and adaptability. This review systematically explores the progress and challenges in motion control technologies for biomimetic quadruped robots, drawing insights from biological models and robotic algorithms. It analyzes essential biological mechanisms such as the spring-mass model and tendon elasticity principles, alongside robotic control approaches including central pattern generators (CPGs) and reinforcement learning. A quantitative analysis of current robot performance indicates that existing systems exhibit limited obstacle negotiation abilities and substantial inefficiencies. The paper identifies core challenges in structural design rigidity, environmental adaptability, and computational efficiency. Recommendations for future research include integrating biologically inspired elasticity into structural designs, refining reinforcement learning algorithms to lower computational costs, and conducting extensive field testing in complex scenarios. Addressing these priorities promises significant advancements toward practical deployment in rescue, exploration, and similar demanding applications.

Keywords: Biomimetic quadruped robot; motion control; spring-mass model; reinforcement learning; energy efficiency.

1. Introduction

Bionic quadruped robots are robotic systems that mimic natural quadruped animals' locomotion mechanisms and movement capabilities. These robots are essential in many fields. For example, during disaster response, they can be deployed to hazardous areas, such as earthquake rubble, to search for survivors. In exploration missions, they can navigate through severe and uncharted terrains, like deep forests or desolate mountains, where human access is difficult or impossible. By imitating the excellent motion abilities of natural quadrupeds, these robots aim to provide practical solutions for tasks in unstructured environments, thereby expanding the reach of human-controlled operations and improving work efficiency and safety.

Despite notable advancements, bionic quadruped robots still face substantial technological gaps compared to natural quadruped animals. Regarding energy efficiency, robots consume 3 - 5 times more energy than their biological counterparts. This high energy consumption limits their operational time in the field, restricting their ability to complete long-term tasks. Regarding adaptability, the average success rate of robots crossing 20-cm obstacles is only about 60%, indicating insufficient adaptability to complex terrains. These existing gaps underscore the clear need for more in-depth and targeted research efforts to advance the motion control technology of bionic quadruped robots. By dedicating greater resources to exploring and refining this key area, we can work toward narrowing the performance and efficiency gaps between these artificial systems and their natural quadruped counterparts. Ultimately, such advancements would enable bionic quadruped robots to achieve functionality and operational effectiveness that more closely mirrors the remarkable capabilities of natural quadrupeds, enhancing their practical value and expanding their potential applications across various fields.

Current research on bionic quadruped robots has several limitations. For example, integrating biological motion principles and robotic control systems is not yet seamless, leading to design-control system incompatibility. In addition, the rigid structural design of most robots fails to fully mimic the flexible and adaptive musculoskeletal systems of animals. This study is significant as it aims to address these limitations by systematically exploring the technological evolution and core challenges in the field. By integrating qualitative and quantitative research methods, it seeks to provide a comprehensive analysis of the current state of motion control research for bionic quadruped robots, identify existing problems, and propose potential solutions, thereby contributing to the advancement of this technology and its practical application in various fields.

2. Biological Basis of Quadrupedal Motion

2.1 Animal Gait Mechanisms

Blickhan proposed a spring-mass model to describe animals' running and hopping gaits [1]. This model simplifies the animal's body as a mass attached to a springy leg. The leg acts like a spring during locomotion, storing and releasing elastic energy. When the animal lands, the leg compresses, storing energy, and when it pushes off, the spring extends, releasing the stored energy to propel the animal forward. This model reveals how animals achieve efficient locomotion through elastic mechanisms, providing a fundamental theoretical framework for designing bionic quadruped robots.

Geyer expanded upon the traditional spring-mass model to provide a more detailed description of the walking gait observed in various animals [2]. This enhanced model considers the distinct phases of the gait cycle, including the stance phase, where the foot is in contact with the ground, and the swing phase, where the foot is in motion through the air. By incorporating these elements, Geyer's model delves into the intricate mechanisms by which animals achieve and sustain balance and efficiency while walking. It elucidates how creatures modulate the stiffness and damping properties of their "springy" legs to adapt to different terrains and walking speeds. This sophisticated understanding enriches biomechanics and significantly contributes to developing bionic quadruped robots. The model offers essential theoretical insights that support the dynamic design of these robotic systems, enabling engineers to replicate the natural walking gaits observed in animals more accurately. This advancement is crucial for creating robots that can navigate diverse environments with the same grace and adaptability as their biological counterparts.

2.2 Elastic Mechanisms and Energy Efficiency

Alexander's research on tendon elasticity and muscle function has shown that animals achieve energy-efficient movement by coordinating lightweight structures and elastic components [3]. Tendons, as elastic elements, can store elastic energy during muscle contraction and release it during movement, reducing the energy consumption of the muscles. In the context of bionic quadruped robots, this finding is crucial. By imitating the tendon-muscle system of animals, robots can be designed with elastic components in their limbs. For example, incorporating elastic materials similar to tendons can help robots store and release energy during locomotion, optimizing energy efficiency. This biological principle provides a key basis for improving the energy performance of bionic quadruped robots, enabling them to operate for longer durations in the field.

3. Evolution of Motion Control Technologies

3.1 Early Stage: Shape Imitation and Mechanical Control

In the early stage of bionic quadruped robot research, the focus was on shape imitation and mechanical control. Raibert's work was pioneering in this regard [4]. Raibert designed legged robots that achieved balance control by adjusting step length. These robots mimicked the basic form of animal legs but had limited flexibility and environmental adaptability. The control strategies were

relatively simple, primarily using mechanical systems to accomplish fundamental movement functions. For example, the robots could perform simple walking motions on flat surfaces but struggled to adapt to uneven terrains or complex environments. This early stage laid the foundation for subsequent research but highlighted the need for more advanced control strategies and design concepts.

3.2 Intermediate Stage: CPGs

3.2.1 Stafford and Barnwell's Central Pattern Generator (CPG) Model

Stafford and Barnwell introduced the central pattern generator (CPG) model [5], which has become a cornerstone in developing rhythmic movement control mechanisms for bionic quadruped robots. The CPG model draws inspiration from the intricate neural mechanisms observed in animals that can produce rhythmic movements, such as the various walking or running gaits seen in horses, cats, and even insects. These biological systems generate coordinated rhythmic signals that enable smooth and efficient locomotion.

The CPG model aims to replicate this natural phenomenon by generating rhythmic signals that can coordinate the movement of a robot's limbs. One key advantage of this model is that it does not rely on continuous sensory feedback to execute these movements. Instead, it operates based on intrinsic neural networks that can produce rhythmic patterns autonomously, like the spinal cord circuits found in animals.

This autonomous generation of rhythmic signals allows robots equipped with the CPG model to perform movements that appear more natural and fluid. For instance, when a quadruped robot is fitted with a CPG, it can walk, trot, or run with a gait that resembles a real animal. This enhances the aesthetic appeal of the robot's movements and significantly improves its locomotion performance. The robot can navigate various terrains with greater stability and adaptability, as the CPG allows for more dynamic and responsive adjustments to environmental changes.

Moreover, the CPG model's ability to produce coordinated rhythmic signals without needing constant sensory input reduces the computational load on the robot's control systems. This makes the robot more energy-efficient and capable of real-time adjustments, crucial for tasks requiring quick and precise movements. As a result, the CPG model has become an essential component in designing advanced bionic quadruped robots, pushing the boundaries of what these machines can achieve in terms of natural movement and performance.

3.2.2 Ijspeert's Salamander Robot Controller and CPG-Based Research

Ijspeert and his team, in their pioneering work, developed a controller for a salamander robot inspired by the spinal neural mechanisms found in actual salamanders [6]. This innovative controller could facilitate a seamless transition between different modes of locomotion, specifically from swimming to walking, thereby showcasing the remarkable potential of CPG (Central Pattern Generator) - based control systems in empowering robots to adapt to various environments. Their research highlighted how these controllers could mimic the natural adaptive capabilities observed in biological organisms.

However, despite its numerous advantages, the CPG-based control approach also has limitations. The gaits produced by these controllers tend to be somewhat rigid and predetermined, which can result in a lack of flexibility when robots encounter sudden changes in their surroundings. For instance, when faced with unforeseen obstacles, robots operating under CPG control might find it challenging to swiftly and efficiently modify their gaits to navigate these impediments. This constraint underscores the need for further advancements in the field to enhance the adaptability and responsiveness of robots in dynamic environments.

4. Advanced Control Algorithms and Performance Analysis

4.1 Reinforcement Learning and Adaptive Control

Wei et al. proposed a hierarchical reinforcement learning algorithm [7]. This algorithm enables robots to learn multi-gait strategies autonomously. At the lower level, the robot learns basic

locomotion skills, and at the higher level, it learns to switch between different gaits according to the environment. This hierarchical structure significantly enhances the robot's adaptability to unknown environments.

4.2 Performance Data and Key Findings

Suwanratchatamane et al. conducted a study on haptic sensing systems, offering valuable insights into the adaptive foot design [8], which is pertinent to enhancing the obstacle-crossing capabilities of robots. Their research demonstrates that accurate environmental feedback enables robots to modify their movements instantaneously. By incorporating haptic sensors into the feet of robots, these machines can detect and interpret various surfaces and obstacles they encounter. This real-time data allows the robots to adjust their gait, balance, and overall movement patterns, improving their ability to navigate complex environments. The findings of this research highlight the importance of haptic feedback in creating more adaptable and efficient robotic systems, ultimately paving the way for advancements in robotics and automation.

Kuehn et al. conducted a study revealing robots' ongoing difficulties when navigating rough terrain [9]. Their findings are consistent with existing data showing that the average success rate for robots attempting to traverse obstacles that are 20 centimeters in height is roughly 60%. This statistic underscores the fact that robots still possess considerable potential for enhancement in their ability to adapt to various environmental conditions.

5. Core Challenges and Future Directions

5.1 Current Challenges

The core challenges that must be addressed revolve around several key issues, including the incompatibility between design and control mechanisms, the inflexibility of structural components, and the significant delay in environmental perception. When it comes to the design of mechanical systems or robots, the control systems that manage their operations must be seamlessly integrated. However, achieving this harmony is often problematic, leading to inefficiencies and malfunctions. Additionally, the structures of these systems tend to be overly rigid, lacking the necessary adaptability to navigate through varied and unpredictable environments. This rigidity can impede their functionality and limit their range of motion.

Another critical issue is the delay in detecting the surrounding environment. This lag can result from various factors, such as sensor limitations, processing speed, or algorithmic inefficiencies. Such delays can severely impact the system's responsiveness and effectiveness, making reacting to sudden changes or obstacles in real time challenging.

On the other hand, incorporating more joints into these systems can enhance their ability to cross obstacles by providing greater degrees of freedom. This added complexity allows for more nuanced movements and can improve the system's adaptability to challenging terrain. However, this benefit comes with trade-offs. More joints typically mean higher energy consumption, as each additional joint requires power to move and be controlled. Furthermore, increasing the number of joints also complicates the control systems, making it more challenging to manage and coordinate the movements of each joint effectively. This complexity can lead to increased computational demands and potential points of failure, posing significant control challenges. Balancing these factors is crucial for the optimal performance of such systems, ensuring they are both capable and efficient in their operations.

5.2 Future Directions

Future investigations and studies should focus on refining and optimizing the structural design by incorporating principles of biological elasticity, which can enhance the flexibility and resilience of materials and systems. Additionally, exploring methods to minimize computational expenses associated with reinforcement learning algorithms is crucial, making these advanced techniques more

accessible and efficient. Furthermore, intensifying and enhancing the testing protocols within complex and dynamic environments will be essential to ensure that the developed technologies and methodologies are reliable enough for real-world applications. By addressing these areas, researchers can pave the way for the practical implementation and widespread adoption of innovative solutions across various industries.

6. Conclusion

Bionic quadruped robot motion control research has evolved from simple form imitation to an interdisciplinary field integrating biology, mechanics, and computer science. Despite significant progress, challenges such as low energy efficiency (3 - 5 times higher than natural quadrupeds), limited environmental adaptability (only 60% success rate in crossing 20-cm obstacles), and structural-control mismatches remain.

Future research should focus on optimizing structural design using biological elasticity mechanisms, reducing the computational cost of reinforcement learning, and enhancing field tests in complex environments. By addressing these issues, bionic quadruped robots can be better applied in rescue, exploration, and other fields, bridging the gap with their natural counterparts and unlocking their full potential in unstructured environments.

In practical applications, continuous algorithm optimization is essential to ensure the efficiency and effectiveness of systems. This process involves conducting extensive and thorough tests in various complex and diverse environments to gather extensive real-world data. By doing so, developers and engineers can identify the strengths and weaknesses of the current control strategies. This empirical data allows them to make informed decisions and refine the algorithms accordingly, enhancing their performance and reliability. The iterative nature of this optimization process is crucial, as it ensures that the algorithms can adapt to various scenarios and conditions, thereby improving their overall robustness and applicability in real-world applications.

To sum up, combining bio-inspired modeling with data-driven algorithms represents a crucial path to advancing the development of biomimetic quadruped robots. This approach not only has the potential to significantly enhance their application capabilities in complex environments and fill the current technological gaps but also provides fresh perspectives for interdisciplinary research. It is crucial for advancing these robots' theoretical understanding and practical applications across various fields.

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