Recent Advances in Legged Robot Locomotion and Control

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Abstract. In recent years, legged robots have emerged as powerful mobile robots capable of navigating complex and uncontrolled environments where wheeled robots often fail. This review provides a comprehensive overview of recent studies and advances in legged robot locomotion and control, focusing on integrating fundamental control strategies. The paper begins by examining the evolution of legged robot designs, from early prototypes to quadrupeds and humanoids. It then discusses critical locomotion modeling, including simplified spring-mass systems and full-body dynamic simulations, and highlights how they utilize control strategies. Recent developments in model-based control, such as whole-body and model predictive control, are compared with emerging learning-based methods like reinforcement learning and hybrid control architectures. This paper additionally focuses on addressing the challenges of sensing, terrain adaptation, and the integration of perception for real-time gait adjustment. Finally, the paper identifies ongoing challenges such as energy efficiency, robustness, and sim-to-real transfer, offering perspectives on future research directions. This review aims to serve as a valuable resource for researchers and practitioners seeking to advance the capabilities of legged robotic systems.

Keywords: Legged Robotics; Locomotion Control; Dynamic Stability; Terrain Adaptation

1. Introduction

Legged robots represent a rapidly advancing frontier in mobile robotics. Mobile robotics has been transitioning from having a wheeled structure in flat ground environments to having end effectors on limbs to push off from the environment, referred to as feet. This offers the robot the unique ability to move in complex and unstructured environments inaccessible to traditional wheeled or tracked systems. Inspired by biological locomotion, these systems aim to replicate animals' and humans' versatility, adaptability, and efficiency in walking, running, and climbing. The development of legged robots has accelerated in recent years due to progress in mechanical design, control algorithms, sensor technologies, and machine learning.

Unlike wheeled robots requiring continuous ground contact and flat terrain, legged robots must dynamically interact with their environment through discontinuous ground contact. This introduces significant stability, balance, control, and energy efficiency challenges. To address these challenges, researchers have developed a range of models and control strategies, including simplified spring-mass models that provide a simple model to depict the locomotion dynamics and complex full-body controllers that coordinate multiple degrees of freedom in real time. Advances in artificial intelligence, particularly reinforcement learning and sim-to-real transfer techniques, have further expanded the capabilities of legged robots in recent years.

This paper comprehensively reviews recent advances in legged robot locomotion and control. It begins by examining key milestones in the design and evolution of legged robotic platforms. The paper then explores foundational locomotion models, modern control frameworks, sensor integration techniques, and terrain adaptability strategies. By analyzing recent developments across disciplines, this review aims to provide a clear and up-to-date understanding of the state of legged robot locomotion and its trajectory toward practical deployment.

2. Evolution of Legged Robot Design

The design of legged robots has significantly transformed over the past few decades, moving from bulky, rigid prototypes to more agile, robust, and bio-inspired designs capable of complex locomotion in uncontrolled environments. Advancements in mechanical engineering, materials science, and control methods have driven this evolution. The design choices of legged robots—such as the number of limbs, actuation type, and joint configuration—directly impact their stability, mobility, energy efficiency, and ability to interact with the environment. Each configuration offers unique advantages and poses distinct engineering challenges. Understanding the working principles behind these designs is essential for evaluating their suitability across various applications [1].

Early legged robots focused on replicating human-like walking in a bipedal form. Locomotion is typically achieved through alternating leg swings and ground contact phases while maintaining balance through control strategies such as Zero Moment Point (ZMP). Actuation is usually joint-based using electric motors or hydraulic systems. Notable examples include Honda’s ASIMO and Boston Dynamics’ early bipedal systems. ASIMO, introduced in the early 2000s, showcased impressive static and dynamic walking on flat surfaces but relied heavily on predefined trajectories and flat terrain assumptions. These robots were primarily research products, highlighting the complexity of achieving bipedal balance and coordination. These bipedal robots can easily maneuver through environments designed for humans, such as climbing stairs or opening doors, since they mimic human locomotion. Their human-like form also facilitates human-robot interaction in collaborative settings. However, they also pose some disadvantages. Biped robots are inherently unstable, requiring complex balance control strategies, and they are often less robust on uneven terrain, limiting their use in outdoor or disaster response scenarios. After a period, quadrupedal robots emerged as a more stable and practical design option, offering better balance and redundancy than bipeds. Quadrupeds walk using four legs, often alternating gaits such as trot, walk, or gallop. This design enables dynamic stability, as the robot can maintain at least three points of ground contact at a time or use gait coordination for higher speed and agility. Boston Dynamics’ BigDog (2005–2010) demonstrated remarkable dynamic stability, capable of walking on ice, climbing steep inclines, and resisting lateral disturbances. However, the tradeoff to better balance and stability is increased mechanical complexity and computational demand, as coordinating four limbs in real time requires advanced control systems, which is still an area of study in the engineering field today [1].

All types of legged robots generally share some of the same design principles. First, compliance-joints or limbs' ability to passively absorb shocks or adapt to terrain—has become a central feature in modern designs. Series Elastic Actuators (SEAs) and spring-loaded leg mechanisms enable more natural and efficient motion, especially in uneven terrain. Second, actuation has evolved from hydraulic systems, known for their power and responsiveness, to electric actuation, which offers better efficiency, weight reduction, and control precision. Modern platforms increasingly use electric motors with high torque density, enabling compact, responsive designs.

3. Modelling of Locomotion

Effective locomotion modeling is fundamental to the design and control of legged robots. These models help engineers understand the physics of movement, plan gaits, and develop control strategies that ensure balance, efficiency, and adaptability. Models can range from simplified models that capture the essence of the motion to full-body simulations that account for the detailed dynamics of all joints and limbs.

Simplified models are often used to gain some level of insight into the mechanics of the robot’s motion. The Spring-Loaded Inverted Pendulum (SLIP) model is one of the most widely used models. This model approximates a legged robot as a point mass supported by a massless, vertical spring, capturing the essential dynamics of walking, running, and hopping. The leg compresses upon touchdown, storing kinetic energy as potential energy in the spring, and then releases it to propel the body forward in the flight phase. This model captures the essential dynamics of bouncing gaits using only a few parameters—mass, leg stiffness, and landing angle—making it highly straightforward and computationally efficient. Even though this model is one of the most influential models in legged locomotion, it also has significant limitations. It oversimplifies the body and leg structure by assuming a point mass and ignoring rotational dynamics, joint torques, and multi-legged coordination. It cannot simulate uneven terrain interactions, realistic actuation delays, or energy losses due to friction and impact. Therefore, while the SLIP model is invaluable for high-level insights and initial control design, it must be complemented with more detailed models or simulations when designing controllers for real-world legged robots [1].

On the other hand, accurate full-body modeling is required for high-performance locomotion. Full-body dynamic models provide a detailed and physically correct representation of a legged robot's entire mechanical structure, including all links, joints, actuators, contact forces, and inertial properties. Unlike simplified models like SLIP, this approach captures the complex, multi-degree-of-freedom dynamics of the robot, accounting for interactions between limbs, torso motion, and external forces such as ground contacts and disturbances. They are essential for simulating real robot behavior, tuning control algorithms, and optimizing gaits in simulation. The key advantage of full-body dynamic modeling is how accurate and detailed it is, allowing for precise torque computations, trajectory planning, and verification of locomotion controllers under realistic physical constraints. This enables the development of advanced control techniques such as whole-body control and model predictive control. However, the tradeoff lies in computational complexity and the need for accurate physical parameters, which can be challenging to obtain or estimate in real-world settings [1].

Most often, simplified and full-body models are used together in a hybrid control architecture to leverage the strengths of both models. Simplified models, such as the SLIP, are used to quickly generate approximate motion plans—like desired foot placements, step timing, or center-of-mass trajectories—due to their low computational cost and analytical clarity. These plans guide the robot's overall locomotion strategy in real time, especially in dynamic or uncertain environments. Meanwhile, full-body dynamic models translate high-level plans into joint-level commands by computing physically accurate torques or forces through inverse dynamics or optimization-based whole-body control. This layered approach balances fast decision-making with precise physical execution, allowing the robot to remain agile and stable. Combining simplified models' efficiency with the fidelity of full-body dynamics enables robust, adaptable, and physically consistent control in real-world legged locomotion [1].

4. Control Strategies

The control of legged robots presents a significant challenge due to their interaction with uncontrolled environments. These systems often experience phases of continuous dynamics (e.g., during a stride) and discrete events (e.g., foot impacts) to overcome discontinuous terrains. Various control strategies have been developed to address these challenges, ranging from classical feedback control methods to advanced optimization-based and machine learning techniques. This section provides an overview of the most widely used control strategies in legged locomotion.

Proportional-Integral-Derivative (PID) controllers are often used in low-speed and structured environments due to their simplicity and effectiveness in such operating conditions. These controllers regulate joint positions or torques based on desired path trajectories. While easy to implement, PID controllers require significant manual tuning and struggle with complex, dynamic motions. Another essential control concept is Zero Moment Point (ZMP) control, often used in humanoid robots to maintain dynamic balance during motion. ZMP control ensures that the net moment about the contact point remains zero, preventing the robot from tipping or falling. However, ZMP control often results in stiff, unnatural motions and does not generalize well to uneven or unstructured terrains. It also requires continuous ground contact, limiting its application to more agile or aerial locomotion behaviors [2].

Recent advances in artificial intelligence and data-driven modeling have led to increased utilization of machine learning techniques, including deep reinforcement learning (DRL), in legged robot control. By interacting with a simulated environment, these methods enable robots to learn complex behaviors—such as running, jumping, or recovering from a fall. In DRL, policies are usually trained in simulation and transferred to the real world. Successful applications include agility training on quadrupeds like the MIT Mini Cheetah and the ANYmal robot, which have learned to traverse challenging terrains and perform dynamic maneuvers [3, 4].

Additionally, sensors enable real-time feedback and adaptability in legged robot control systems. They provide the essential data needed to estimate the robot's state—such as joint positions, velocities, body orientation, contact forces, and terrain features—which forms the basis for making continuous control adjustments during locomotion. In model-based control strategies, precise and low-latency sensor feedback is crucial for maintaining balance, computing joint torques and adapting to disturbances. In learning-based approaches, sensor data is often passed through neural networks to inform action selection, enabling behaviors like terrain adaptation or gait switching. The effectiveness of any control strategy is tightly linked to the quality and reliability of its sensory input; without accurate sensing, the robot cannot correctly perceive its environment or respond to unexpected events, leading to degraded performance or instability. As such, sensing and state estimation are foundational to achieving robust, agile, and autonomous locomotion in legged robots [5, 6].

Overall, the evolution of control strategies in legged robotics presents a shift from rigid, hand-tuned controllers toward adaptive, predictive, and data-driven artificial systems. This transition enables robots to operate effectively in complex, real-world environments.

5. Challenges and Future Directions

Despite remarkable progress in legged robot locomotion and control, many technical and practical challenges remain unresolved. Real-world deployment of legged robots in specific applications continues to face limitations in robustness, energy efficiency, terrain adaptability, and safety. This section highlights several critical open problems and research directions for advancing the field.

A significant challenge in legged locomotion is maintaining dynamic stability and balance when encountering unpredictable disturbances such as slippery terrain, debris, or unexpected collisions. While modern controllers can handle predefined perturbations in simulation, real-world conditions often include uncertainties like variable friction or ground deformability. Developing controllers that can generalize across such variations without overfitting to simulation assumptions remains a key research problem [7].

Another practical challenge or possible improvement is that legged robots typically consume more energy than wheeled robots, primarily due to the mechanical complexity and control effort required for balance and actuation. Improving energy efficiency through better mechanical design and energy-optimal control strategies is a priority for making legged robots more autonomous, efficient, and practical.

6. Conclusion

Legged robots have made remarkable progress in recent years, transitioning from experimental platforms to capable systems with real-world applications in exploration, inspection, and disaster response. This review has examined the evolution of legged robot design, key locomotion models, and a spectrum of control strategies ranging from classical methods to cutting-edge machine learning approaches. While significant progress has been made, ongoing challenges such as robustness and energy efficiency limit widespread application uses. Addressing these open problems will require interdisciplinary efforts across multiple fields. As research continues to bridge the gap between simulation and reality, legged robots are poised to play an increasingly vital role in dynamic and unstructured environments in real-world settings.

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