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Analysis of Current Bipedal Robots by Comparative Method

Zixuan He

School of Materials Science and Engineering, University of Science and Technology Beijing, China

U202341045@xs.ustb.edu.cn

Abstract. Concerning the rapid development in the bipedal robot industry, it's hard for researchers to figure out their current merits and demerits, making it more difficult to make progress, especially for those who newly step into the robot industry. This paper aims at comparing the most established and creative breakthroughs in bipedal robots to help researchers get a general view of it, simultaneously proposing some thoughts on bipedal robots about how the future utilization of bipedal robots can be.

Keywords: Bipedal robot, creative design, robot control.

1. Introduction

The advancement of bipedal robots has become a focal point in robotics research, driven by their remarkable ability to traverse challenging environments like uneven terrain, busy urban spaces, and ever-changing surroundings. Their adaptability, much like that of humans, is crucial for applications where precision and stability are paramount. From rescue operations to daily assistance, these robots must execute complex tasks, and at the heart of this capability lies effective motion control.

This paper seeks to explore recent breakthroughs in bipedal robot control strategies, (especially taking robot Cassie as a main example) emphasizing solutions to challenges in dynamic and complex settings. Through an extensive review of the latest research—including methods like Model Predictive Control (MPC), Reinforcement Learning (RL), and hybrid algorithms—the study will dissect both the strengths and shortcomings of current technologies. The aim is to propose refined strategies to enhance the robots' ability to adapt and remain stable across various environments.

Rooted in a comprehensive analysis of key works, such as the application of RL in the Cassie robot and the blending of data-driven methods with classical control theory, this paper will not only chart the state-of-the-art but also offer future pathways for more robust and adaptive bipedal control systems designed to thrive in complex terrains.

Cassie, just like many modern bipedal robots, has legs bending backwards compared to human legs. This design choice is due to several practical advantages related to stability, efficiency, and mechanical simplification, enabling the robot to walk with more agility, be simultaneously easy to maintain its balance and have quick reflective modification on their motions without falling down [1]. The backwards-bending leg design is often inspired by animals like birds or the hind legs of quadrupeds (horses or dogs). These animals have knees that bend backwards, which provide greater stability and quick reaction capabilities, especially during dynamic motions [2].

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2. Mechanical design and basic sensor configuration of bipedal robots

Bipedal robots, designed to mimic human walking, are complex machines with a multi-joint structure and equipped with a variety of sensors that provide feedback to ensure balance, adaptability, and motion. The mechanical design and sensor systems are key to their effective locomotion.

2.1. Mechanical design

The leg configuration of most bipedal robots typically includes six degrees of freedom (DoF) in each leg: three at the hip (for rotational movement in multiple axes), one at the knee, and two at the ankle. This structure allows for flexible and precise control over each leg, mimicking human movement. Common actuation systems used in bipedal robots include rotary actuators and linear actuators to drive motion at each joint.

For instance, robots like ASIMO from Honda feature a serial mechanical structure with actuators at each joint. This configuration enables straightforward control, although it results in increased leg inertia, which affects dynamic performance [3]. Advanced designs incorporate lighter materials, such as aluminum and carbon fiber, to minimize weight and reduce the load on motors [4].

More complex leg configurations are found in spring-mass models, which include elastic elements in their structure. These robots, such as those employing compliant actuated legs, exhibit dynamic stability, absorbing shocks during movement and enabling more agile locomotion [4]. The leg structure might include a combination of active and passive joints, designed to absorb impacts and control movement in a more energy-efficient manner.

2.2. Sensor systems

Effective movement of bipedal robots heavily relies on sensor feedback for stability, trajectory control, and interaction with the environment. Inertial Measurement Units can track the robot's body orientation and are essential for maintaining balance. They are typically placed on the trunk and feet to measure tilt and motion, providing real-time orientation feedback using accelerometers and gyroscopes. Force/Torque Sensors which are located on the foot soles, these sensors measure ground reaction forces, ensuring that the robot maintains stability during walking by keeping these forces within a predefined range, known as the Zero Moment Point (ZMP). High-resolution encoders measure joint positions and velocities, providing accurate data for controlling the movement of the joints and allowing for precise gait adjustments during walking. Tactile Sensors are designed to interact with humans, tactile sensors are placed on joints to prevent injuries by reducing joint force when human contact is detected [5].

2.3. Bipedal robot application

Cassie, developed by Agility Robotics, incorporates several advanced mechanical and sensor systems that distinguish it from traditional bipedal robots. Cassie's leg design includes 12 joints with both active and passive components. What sets Cassie apart is its compliant actuation system, which mimics the behavior of natural biological legs by absorbing impacts during ground contact. The inclusion of elastic elements and a four-bar linkage mechanism reduces leg inertia, allowing Cassie to execute dynamic motions with higher energy efficiency and precision [4].

In contrast, conventional bipedal robots such as ASIMO rely on rigid actuation systems, which increase leg inertia and result in less efficient movement. Cassie's compliant leg structure, combined with its low inertia and elastic components, makes it ideal for research on agility algorithms, allowing for faster and more adaptive movement in real-world environments.

Cassie's compliant actuation gives it a significant advantage in research focused on robot agility. Its design allows it to handle dynamic locomotion, like quick directional changes or uneven terrain, more efficiently than rigidly actuated robots. Additionally, its energy-efficient design makes it an ideal platform for developing algorithms related to balance, dynamic walking, and running, contributing to its growing use in robotics research.

3. The basic control method of bipedal robots

When compare Proportional-Integral-Derivative (PID), MPC, and RL for Cassie, each algorithm demonstrates distinct advantages and disadvantages. These differences often arise due to the complexity of controlling nonlinear, high-dimensional systems like bipedal robots.

3.1. PID control

The PID controller is a classic method primarily used for low-level control, such as maintaining joint stability or motor control. It excels in tasks requiring immediate correction by adjusting based on errors. For Cassie, PD control (a variant of PID) is often used at the motor level to ensure smooth motion and minimize abrupt fluctuations in joint torques [6].

PID is straightforward and widely used, especially for tasks requiring fast response and low computational power. With low-level efficiency, PID excels in joint stabilization and smooth motor output, crucial in maintaining Cassie's balance during locomotion.

However, the limited adaptability of the PID control algorithm makes it struggle to cope with new environments or varying terrains. It did not predict future states, so it often requires manual tuning to account for different conditions [6, 7].

3.2. Model predictive control

MPC is more sophisticated and used for trajectory optimization. It models the robot's dynamics, allowing it to predict and plan motion over a longer time horizon. By formulating locomotion as an optimal control problem, MPC can compute gait patterns dynamically and adjust them in real-time for complex movements.

Unlike PID, MPC optimizes for future states, enabling long-horizon decision-making. It's essential for stable walking over uneven surfaces, where future foot placement needs careful planning [7]. It allows the integration of Hybrid Zero Dynamics (HZD), a model that helps generate highly stable gaits offline, which can be utilized online [6, 7]. However, MPC requires solving complex optimization problems in real-time, making it computationally expensive. And the same time, since it relies heavily on the robot's dynamic model, any discrepancies between the model and the real-world behavior can degrade performance, especially if unmodeled dynamics are significant [6, 7].

3.3. Reinforcement learning

Reinforcement Learning introduces a model-free approach, enabling the robot to learn from experience. By interacting with the environment, Cassie can learn walking, running, and jumping behaviors without requiring precise dynamic models. The RL algorithm has shown substantial success in controlling Cassie's complex movements, like versatile walking and running on uneven terrain [6, 7].

Beating PID in adaptability, RL is highly adaptive. Through trial and error, Cassie can handle unstructured environments, improving its ability to generalize across various terrains, perturbations, and scenarios [6]. RL has enabled Cassie to learn complex tasks like running and jumping, whereas other methods, such as PID and MPC, might struggle to manage unpredictability [7]. While, since REINFORCE is model-free, its learned behavior may sometimes result in unpredictable outcomes, particularly when facing unseen obstacles [6, 7].

3.4. Comparative insights

In summary, PID is reliable for low-level motor control, ensuring balance and immediate adjustments. However, it lacks the foresight needed for adaptive terrain traversal. MPC provides optimal trajectory control but struggles with the real-time computational burden and sensitivity to modeling errors. Reinforcement Learning introduces adaptive and flexible control that can generalize across varying terrains, though its data-hungry training process and occasional unpredictability remain limitations.

The key takeaway is that these algorithms, while powerful individually, are often used together to complement one another. For instance, a hybrid approach may use MPC for high-level trajectory

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planning, PID for motor stabilization, and RL to allow Cassie to adapt in real-time to unexpected environmental conditions [6, 7].

4. Present breakthroughs in bipedal robots

The whole present breakthroughs in bipedal robots are divided into two parts. The respective two parts are robot design and robot control.

4.1. Robots design

Bipedal robot design has rapidly evolved, with innovations pushing beyond traditional mechanisms like those seen in Cassie. Two such groundbreaking designs, Legged Exploration on Orbit (LEO) from Caltech and the Muscle-powered Biohybrid Robot from the University of Illinois, introduce new paradigms in bipedal locomotion by incorporating hybrid mobility and biological actuation. This chapter explores the design principles behind these robots, their differences from Cassie, and strategies to enhance future bipedal robots.

4.1.1. Current design landscape: cassie. Cassie, developed by Agility Robotics, is a legged robot known for its dynamic stability and efficient control algorithms. Using motor-driven actuation and feedback systems like inertial measurement units (IMUs), Cassie can traverse uneven terrain with a high degree of stability [8]. Cassie's design heavily relies on MPC and PID algorithms to ensure balance and smooth gait transitions across various environments [9].

Cassie excels in walking on stable surfaces and uneven terrain, offering consistent performance for tasks that involve continuous movement. Despite its robustness, Cassie is limited by its reliance on ground-based locomotion. It cannot jump or navigate obstacles that require a change in locomotion type [8].

4.1.2. Hybrid locomotion design: LEO. The LEO robot introduces a novel hybrid locomotion system, enabling it to both walk and fly, combining the benefits of bipedal robots with those of aerial systems [9]. Unlike Cassie, which is limited to terrestrial motion, LEO uses propeller thrusters to hover, fly over obstacles, and perform aerial maneuvers.

When concerning the dual locomotion of LEO, it can switch between walking and flying, allowing it to adapt to environments where traditional bipedal robots like Cassie would be ineffective [9]. The propeller-assisted flight capability enhances LEO's agility, enabling tasks such as jumping, balancing, and crossing large gaps. LEO's control system harmonizes the movements of its legs and propellers, ensuring seamless transitions between walking and flying. This offers unmatched versatility and makes LEO suitable for complex environments like space missions or disaster areas [9].

LEO's hybrid design enables it to bypass many of the limitations faced by robots like Cassie, offering increased adaptability in overcoming obstacles. While, the integration of propellers adds mechanical complexity and increases energy consumption, particularly during flight maneuvers [9].

4.1.3. Muscle-powered robots. The Muscle-powered Biohybrid Robot marks a major shift in bipedal robot design, incorporating lab-grown skeletal muscle tissues as actuators. Unlike Cassie, which relies on electric motors and mechanical components, this robot uses biological tissues to perform movements, mimicking the natural contractions of human muscles [10].

When it comes to the design principles of Muscle-powered Robots, the use of living muscle tissue enables more fluid, natural movements that are not easily achieved by mechanical systems. These muscles contract when stimulated electrically, making the robot more energy-efficient and capable of more delicate maneuvers than traditional robots [10]. One of the key advantages of biohybrid robots is their ability to self-repair, an advantage that mechanical robots like Cassie lack. This capability reduces long-term maintenance and enhances the robot's operational lifespan [10].

The biological actuation in muscle-powered robots allows for more organic and adaptive movement. Additionally, their energy efficiency is higher, as muscle contractions require less power than motor-driven systems [10]. But current designs face challenges such as slow movement speeds and the limited lifespan of muscle tissues, which require a continuous supply of nutrients to maintain [10].

4.1.4. Key differences in design philosophy. Firstly, when comparing these three robots' mobility, Cassie is built for stable and efficient walking on various surfaces, making it ideal for logistics and exploration. LEO surpasses Cassie in terms of versatility with its ability to switch between walking and flying, making it more suitable for environments that involve gaps or obstacles that require jumping or aerial maneuvers [9]. Muscle-powered robots offer a more biological approach to locomotion, providing more fluid, adaptable movements. Their energy efficiency and potential for self-repair give them an edge over mechanically driven robots like Cassie [10].

Secondly, each of the robots has its own advantages over others in actuation driving. Cassie relies on traditional motor-driven actuation, which requires precise control systems to maintain balance and dynamic stability [8]. LEO integrates propeller-based control, adding aerial capabilities that significantly expand the range of potential tasks but also introduce greater complexity in managing both ground and flight control [9]. Muscle-powered robots use biohybrid actuators for smoother movements, but the current challenge lies in developing nutrient systems to sustain muscle tissue over time [10].

4.1.5. Future directions for bipedal robot design. To optimize future bipedal robots, researchers can integrate the strengths of each system while overcoming their limitations.

Designers can draw from LEO's hybrid locomotion approach, combining walking with aerial capabilities to develop robots that can operate in a wider range of environments. Integrating lightweight propellers or jumping mechanisms could enable future robots to bypass obstacles more efficiently [9].

The potential for biohybrid actuators to enhance energy efficiency and fluidity in movement is significant. However, further advancements are required in nutrient delivery systems and tissue engineering to make muscle-powered robots a viable alternative for long-term use [10].

Future robots could benefit from sophisticated control algorithms that merge machine learning and real-time feedback systems, allowing them to dynamically adjust between multiple modes of locomotion based on environmental conditions.

4.2. Robots control

In the world of bipedal robots, control systems are at the heart of stable, efficient movement. Traditional algorithms like PID, MPC, and RL have been widely used to enable these robots to walk, balance, and adjust to their environment. However, recent innovations in control mechanisms are pushing these systems to new heights.

4.2.1. Adaptive robust control. Adaptive robust control dynamically adjusts movements to compensate for disturbances, providing bipedal robots with enhanced stability in unpredictable environments. Unlike PID, which struggles with external forces like uneven terrain, adaptive robust control continuously adjusts its response. The result is that a robot can handle the unexpected environment without losing its balance. This method is more flexible and requires fewer pre-set parameters compared to traditional PID controllers [11].

4.2.2. Passive tendon-based control. Inspired by human biomechanics, passive tendon-based control enhances energy efficiency. By utilizing tendons to absorb and release energy, this method reduces the active control effort needed during walking or running. In comparison, traditional systems like MPC must compute and adjust for every step. This approach enables smoother, more natural movements, decreasing energy consumption, which is a clear advantage over traditional motor-based systems [12].

4.2.3. Electrically driven actuation systems. ARTEMIS, an advanced robot designed by UCLA, uses electrically driven actuators instead of traditional hydraulic systems. This innovation increases energy efficiency, reduces noise, and improves overall operation. Traditional actuators, particularly hydraulics, suffer from fluid leaks and inefficiency. Electric actuation, in contrast, offers more precise control and cleaner operations, representing a significant upgrade [13].

4.2.4. MPC enhancements. Although traditional MPC is widely used, recent advancements have made it even more effective. Today's MPC systems incorporate real-time terrain prediction, allowing robots to anticipate changes and adjust accordingly. While standard MPC models compute optimal movement paths, these enhanced systems offer faster response times and better adaptability on uneven surfaces, surpassing earlier versions in both complexity and performance [14].

4.2.5. Hierarchical control architectures. Hierarchical control systems divide robot control into high-level planning and low-level execution. This separation allows for more complex decision-making at the upper levels, while lower levels handle real-time adjustments. Traditional RL approaches often focus too much on singular tasks without multi-tiered planning. Hierarchical systems, however, provide the flexibility to adapt across a wide range of environments, making them more dynamic [15].

Compared to traditional control algorithms like PID, MPC, and RL, these newer methods provide enhanced stability, energy efficiency, and flexibility. Whether it's the natural movement enabled by passive tendon systems or the dynamic adaptability of hierarchical architectures, these advancements are shaping the future of bipedal robots, pushing beyond the limitations of their predecessors.

5. Conclusion

The rapid advancement in bipedal robot design and control is transforming the field of robotics. By focusing on Cassie, LEO, and muscle-powered robots, this paper has highlighted how novel designs and control methods offer more robust solutions for dynamic environments. Cassie demonstrates the success of traditional motor-driven systems, excelling in agility and stability on uneven terrain. However, its reliance on ground locomotion limits its ability to overcome obstacles or jump. In contrast, LEO integrates aerial mobility, allowing it to not only walk but fly over obstacles, expanding the possibilities for multi-modal robots that can handle diverse environments. While this hybrid design introduces more complexity, it sets a new standard for versatility in bipedal robots.

Meanwhile, muscle-powered robots offer a completely different approach, incorporating biological elements such as lab-grown muscle tissues for more natural, energy-efficient movement. This biohybrid model introduces a new frontier in robotics with the potential for self-repair, though challenges such as speed and longevity remain. These three examples demonstrate a significant shift from traditional mechanical designs toward more adaptive and versatile systems.

On the control side, innovations such as adaptive robust control, passive tendon-based control, and hierarchical control architectures provide improved stability, energy efficiency, and adaptability compared to conventional systems like PID and MPC. Adaptive robust control ensures stability in unpredictable environments by dynamically responding to disturbances, while passive tendon-based control mimics human biomechanics to reduce energy consumption. Hierarchical control architectures separate high-level planning from low-level execution, enabling robots to make complex real-time decisions, and further enhancing their adaptability.

The future of bipedal robots lies in the integration of multi-modal mobility and advanced control systems that are both predictive and adaptive. As researchers continue to refine these systems, people move closer to creating robots that can perform complex, real-world tasks with the agility, precision, and resilience needed for dynamic, ever-changing environments. These advancements set the stage for the next generation of bipedal robots, capable of pushing beyond current limitations.

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