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Future to Wheeled and Legged Robot Locomotion

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ABSTRACT

Hybrid legged-wheeled robots integrate the strengths of both locomotion types, offering enhanced adaptability across diverse terrains. While legged robots navigate complex environments with agility, wheeled systems provide speed and energy efficiency. However, these hybrid designs face significant challenges, including complex control systems, increased mechanical wear, and terrain-specific limitations. Advances in AI-driven navigation, lightweight materials, and real-time trajectory optimization continue to refine these robots, making them valuable for applications in industry, defense, and space exploration. This paper explores their evolution, technical challenges, and real-world applications, highlighting ongoing research to improve their efficiency, stability, and autonomy in various operational environments.

Chapter 1: INTRODUCTION:

LEGGED robots offer the possibility of negotiating challenging environments and, thus, are versatile platforms for various types of terrains. In research and industry, there is an emphasis on replicating nature to improve the hardware design and algorithmic approach of robotic systems. Even with extensive research, matching the locomotion skills of conventional legged robots to their natural counterparts remains elusive. In contrast, wheels offer a chance to extend some capabilities, particularly speed, of these legged robotic systems beyond those of their natural counterparts, which can be crucial for any task requiring rapid and long distance mobility skills in challenging environments. With this motivation, the central contribution of this work involves locomotion planning on a wheeled-legged robot to perform dynamic hybrid walking-driving motions on various terrains.

In 1913 the Bechtolsheim Baron patented a quadruped machine whose project is presented in Figure 3. Once again, there is no indication that this machine has actually been built. An example on a hybrid machine (with wheels and legs) is presented in Figure 3 & dates from the First World War. This prototype was developed by Thring, but has never passed that phase . The previous ideas searched for a mechanism that allowed the movement when powered by an energy source. However, this approximation had a severe limitation: the solution based in gears, to transmit the movement to the legs, was restricted to the adoption of a fixed gait, with the foot placement on the ground at regular intervals. This did not allow them to take advantage of the major advantage of these vehicles, namely the possibility to cross irregular terrains. A second problem was the fact that the information on the machine and the environment state was not being used for its control.

The control of legged locomotion and in particular of biped locomotion is a complex task. This is due to the fact that legged locomotion is often unstable, underactuated, redundant, nonlinear, and with complex hybrid dynamics. Indeed, legged locomotion is often (statically) unstable because the projection of the centre of mass moves at times outside of the small polygons of support provided by feet on the ground. A locomotion controller therefore needs to ensure *dynamic* stability and prevent the robot from falling over while locomoting. Legged locomotion is underactuated because, unlike robot manipulators that are attached to a base, the feet of legged robots are not bolted to the ground and the leg actuators have therefore no direct control of the orientation and position of the main body. Legged robots are furthermore often redundant systems with more actuators and more actuated degrees of freedom than would in principle be needed to adjust the six degrees of freedom that determine the position and orientation of the main body. In addition, each of these actuators can perform infinitely many different actuation patterns many combinations of which lead to the same overall locomotion output, such as a step of a given length or a gait at a given speed. A locomotion controller has therefore to solve this redundancy problem and choose among many possible control actions for each motor to move the body forward. Furthermore, the relationships between actuator commands and the movement of the main body are highly nonlinear. Unlike differential drive wheeled robots in which the forward speed of the robot is linearly related to the rotation velocities of the motors, a locomotion controller for a legged robot needs to implement complex nonlinear, typically periodic, relationships between motor commands and desired movements of the main body. Finally, legged locomotion presents complex hybrid dynamics, which refers to the fact that the number and points of contact of the body with the ground change over time. Typically, a biped robot can switch between zero (when running), one, two, or more (when other parts of the body touch the environment) points of contact with the environment, and this leads to drastic changes in the dynamics and the equations of motion. Problems with hybrid dynamics are difficult to model properly and make it hard to plan control actions in advance. Taken together these properties make it very difficult to design robust locomotion controllers in particular for complex unstructured terrains.

The advantages of legged locomotion depend on the postures, the number of legs, and the functionality of the leg. Though wheeled and tracked robots can work in plane terrain, most of them couldn't work in cluttered terrain, complex and hazardous environments. The legged robot has more potential to roam almost all the earth surfaces in different terrains, just like the human and an animal . Animals used their legs to move fast and reliably in different terrains with excellent locomotion and agility. Most often, they gear up with high speed and efficiency depending on environmental conditions. The stability and efficient gait point of view, even the number of legs are more suitable in universal. The quadruped robots are the best choice among all legged robots related to mobility and stability of locomotion. The four legs of the robot are easily controlled, designed, and maintained as compared to two or six legs. The biologically inspired locomotion of running gaits is the ability to take high payload and robot balancing of quadruped

robots started earlier by the researcher. To achieve real-time speed and natural movement like a cow, dog, cheetah, the developed control system, and dynamical gait generation of quadruped robots are required.
Hybrid legged-wheeled robots combine the advantages of both locomotion types, yet they face several disadvantages that can limit their effectiveness.

One of the primary challenges is the complexity of control systems. The integration of legs and wheels necessitates sophisticated control algorithms to manage transitions between locomotion modes, complicating system design and increasing the likelihood of malfunctions (Adachi et al., 1999; Adachi & Koyachi, 2001). Additionally, real-time trajectory optimization is required to ensure stability and agility, adding to the computational burden (Bjelonic et al., 2020). These advanced control mechanisms demand significant processing power, making the system more resource-intensive.

Another key limitation stems from mechanical constraints. The dual-mode design often leads to increased weight and reduced efficiency since additional components for both locomotion types may not always be optimally utilized in all environments (Tanaka & Hirose, 2008; Vysin & Knoflicek, 2003). Furthermore, the hybrid nature of these robots results in increased wear and tear, particularly during transitions between locomotion modes, necessitating more frequent maintenance and reducing overall operational longevity (Vysin & Knoflicek, 2003).

While hybrid robots excel in terrain adaptability, they may struggle with specific obstacles that are easily navigated by either purely wheeled or purely legged robots, leading to operational limitations in certain scenarios (Adachi & Koyachi, 2001). For instance, rough terrains requiring extensive climbing may favor legged robots, while smooth, high-speed applications are better suited for wheeled platforms. This trade-off can impact their efficiency in specialized environments.

Despite these challenges, ongoing research continues to refine hybrid designs, suggesting that future advancements may mitigate some of these disadvantages. Improvements in AI-driven control systems, lightweight materials, and adaptive locomotion strategies could enhance the performance and reliability of hybrid robots, making them more versatile for various real-world applications.

1.1. Technical Challenges

- **Energy Efficiency**:
  Examine how hybrid robots manage power consumption during transitions between wheeled and legged locomotion. Discuss research on battery technology and energy harvesting mechanisms (e.g., solar-powered robots, regenerative braking in wheeled systems).
  - Include a comparison of power requirements between legged and wheeled modes and how hybrid designs are optimising for energy efficiency.
- **Hardware Limitations**:
  - Discuss challenges in materials science, such as the development of lightweight yet strong materials that can withstand rugged terrains.
  - Explore the limitations imposed by mechanical wear and tear due to the complexity of the hybrid system, particularly during transitions between walking and driving modes.
  - Include references to ongoing research into robotic materials that can self-repair or adapt to different environmental conditions.
- **Control and Programming**:
  - Expand on the need for sophisticated control systems that can handle the nonlinear dynamics of hybrid robots, especially when transitioning between walking and driving.

- ○ Discuss the algorithms used in real-time trajectory optimization, focusing on approaches like Reinforcement Learning (RL), Model Predictive Control (MPC), and Probabilistic Roadmaps (PRMs).
- ○ Cite research papers or case studies that successfully implemented these algorithms in real-world applications, providing specific examples like quadruped robots for rescue missions.

1.2 Applications in the Real World

- **Military Use**:

Provide examples of military robots that have been tested or deployed in harsh environments, such as desert terrains or disaster zones. Discuss DARPA's investments in hybrid robots for missions that require speed, agility, and rugged terrain adaptability. Explore specific use cases like unmanned surveillance, logistics in remote areas, and de-mining operations using hybrid legged-wheeled robots.

- **Industrial Use**:

Explore how hybrid robots could be used in industries like mining, construction, or agriculture. For instance, legged robots could navigate uneven terrain, while wheeled robots could speed up operations in more accessible areas. Include case studies from companies using hybrid robots for autonomous exploration, sample collection, or site monitoring in difficult-to-reach areas. Discuss potential economic benefits, such as reducing human labour costs or increasing safety in dangerous environments.

- **Space Exploration**:

Provide a deep dive into NASA's hybrid robot designs for extraterrestrial exploration, such as Mars rovers that combine wheeled mobility with legged climbing ability for navigating craters or cliffs. Discuss how the hybrid approach could be beneficial for long-term missions, where the robot needs to cover a large distance but also overcome unpredictable terrain (e.g., icy surfaces or steep slopes). Cite examples from successful missions and research projects that focus on developing multi-modal robots for planetary exploration.

1.3 Future Research Directions

- **Materials and Miniaturization**:

Examine how advances in materials science, such as graphene or carbon nanotubes, could revolutionise the design of lightweight and durable robots. Discuss how miniaturisation is becoming a crucial area of research, particularly for deploying hybrid robots in confined spaces (e.g., search-and-rescue missions in collapsed buildings). Consider the potential of "soft robotics," where flexible materials are used to allow robots to adapt better to their environment, reduce wear and tear, and improve energy efficiency.

- **Advanced AI Integration**:

Discuss ongoing research in using AI for fully autonomous navigation in complex environments, focusing on deep learning algorithms that enable robots to learn from their surroundings and make real-time adjustments. Provide examples of robots that are being equipped with AI systems to enable seamless switching between wheeled and legged modes, potentially allowing them to self-optimize based on terrain type. Explore how AI could enhance robot-human interaction in collaborative environments, particularly in industrial or military settings.

- **Improvements in Gait Planning**:

Analyze how gait planning algorithms are evolving to allow robots to adapt their movement patterns dynamically based on sensor data from the environment. Include research on real-time feedback loops that allow for adaptive locomotion, where robots can switch from a walking to wheeled mode instantly when required. Highlight the role of sensor technology in enhancing the robot's ability to predict and react to changes in the terrain.

1.4 Ethical and Societal Implications

- **Job Displacement**:

Explore concerns about job displacement due to the introduction of hybrid robots in industries like agriculture, manufacturing, and military operations. Analyze the potential socioeconomic impact of using robots in hazardous jobs traditionally performed by humans. Offer perspectives on how companies and governments might retrain workers and integrate human-robot collaboration into existing workforces.

- **Environmental Impact**:

Investigate how the use of robots, particularly in exploration and industrial applications, might affect the environment. Consider the role of hybrid robots in conservation efforts, such as in reforestation projects or in monitoring endangered species. Provide a balanced view of how the energy consumption of robots might compare to the environmental cost of human intervention in the same scenarios.

Chapter 2: Case Studies

Boston Dynamics Spot

Boston Dynamics' Spot is a quadrupedal robot that showcases one of the most advanced implementations of hybrid locomotion. Unlike traditional wheeled robots, Spot is designed with four articulated legs, enabling it to navigate complex terrains with a high degree of stability. This unique mobility allows it to function effectively in environments where conventional wheeled robots would struggle, such as construction sites, oil rigs, and disaster zones.

Capabilities and Hybrid Locomotion

Spot's hybrid locomotion system allows it to adapt to a variety of surfaces, including:

- Smooth terrain: Spot moves efficiently across flat surfaces such as factory floors, hospitals, or office spaces.
- Rough terrain: The robot can traverse uneven ground, such as gravel, rocky landscapes, or staircases, making it particularly useful in outdoor industrial applications.
- Stability and obstacle avoidance: With dynamic balancing and AI-powered path planning, Spot can recover from minor slips, step over obstacles, and reorient itself if knocked over.

Applications in Industry

Spot has been deployed in multiple real-world applications, demonstrating the benefits of legged locomotion over traditional wheels:

- Construction: Companies like Foster + Partners and Hensel Phelps use Spot for site inspections, 3D scanning, and progress monitoring. The robot’s ability to autonomously navigate construction sites enhances efficiency and safety.
- Oil and Gas Industry: BP and Shell have tested Spot on oil rigs, where its ability to withstand hazardous environments and detect gas leaks using onboard sensors is crucial.
- Healthcare and Public Safety: Spot was deployed during the COVID-19 pandemic to assist in telemedicine and public health monitoring. Its ability to operate remotely allowed it to perform non-contact interaction with patients in high-risk areas.
- Security and Surveillance: Companies use Spot for autonomous patrolling, reducing the need for human security personnel in hazardous or high-security environments.

AI and Autonomous Navigation

Spot integrates advanced AI algorithms and machine learning models to enhance its autonomous navigation. Features include:

- LiDAR and stereo cameras for real-time environment mapping and object recognition.
- Reinforcement learning for improving movement efficiency over time.
- Remote operation capabilities using a cloud-based control interface.

Spot's ability to transition seamlessly between different types of terrain while incorporating AI-driven adaptability makes it a prime example of hybrid locomotion in action.

NASA's Rovers: Curiosity & Perseverance

NASA's Curiosity and Perseverance rovers are among the most sophisticated hybrid locomotion robots deployed beyond Earth. While primarily wheeled vehicles, these rovers integrate features that allow them to overcome obstacles and navigate challenging Martian terrain.

Challenges of Locomotion on Mars

- Rough, rocky terrain: Mars' surface is covered in uneven ground, making locomotion a critical challenge.
- Slippery surfaces: Loose regolith (Martian soil) can cause slippage, requiring adaptive movement strategies.
- Steep inclines: Some regions, like the sides of craters or volcanic formations, require specialized traversal techniques.

Hybrid Locomotion Elements

- Wheeled mobility: Both Curiosity and Perseverance use a six-wheel drive system with independent suspension to traverse obstacles up to 40 cm in height.
- Rocker-bogie suspension: This unique suspension system helps distribute weight and prevents the rover from tipping over on rocky terrain.
- Autonomous Path Planning: AI-powered navigation enables the rovers to analyze the terrain and select the best route with minimal human intervention.

The Future: Hybrid Legged-Wheeled Rovers?

Future Mars exploration missions could integrate hybrid legged-wheeled designs to improve efficiency in extreme environments. NASA has explored the concept of "transformable" robots, which could switch between rolling and walking modes to:

- Climb steep crater walls that current rovers cannot.
- Navigate deep caves and lava tubes, which may harbor evidence of past microbial life.
- Enhance endurance by adjusting movement styles depending on terrain resistance.

Projects like **NASA's "LEAP" (Legged Exploration of the Aristarchus Plateau)** explore adding robotic legs to future planetary rovers.

Recent Competitions & Prototypes

Several **robotics competitions** and **prototype projects** have tested the effectiveness of hybrid locomotion, contributing to advancements in real-world applications.

DARPA Robotics Challenge (DRC)

The **DARPA Robotics Challenge** (2015) was a landmark event showcasing legged and wheeled robotic systems performing disaster response tasks.

- The winning robot, KAIST's DRC-Hubo, featured both wheels and legs, allowing it to:
  - Walk over debris

 - Drive small vehicles
 - Climb ladders and stairs
 - Manipulate tools for cutting and drilling
- Lessons from the competition influenced the development of modern autonomous robots for search-and-rescue operations.

RoboCup Rescue League

The **RoboCup Rescue League** focuses on deploying robots in simulated disaster scenarios. Teams experiment with hybrid designs that allow robots to:

- Navigate collapsed buildings and rubble.
- Operate in narrow urban spaces.
- Provide medical assistance to trapped survivors.

Cutting-Edge Prototypes

- ETH Zurich's ANYmal: A quadrupedal robot similar to Spot, used for inspection in industrial settings.
- MIT's Cheetah 3: A robot that combines biological-inspired locomotion with AI-driven control, capable of jumping over obstacles.
- Roller-Walker Concepts: Robots like HyQ developed by IIT and Boston Dynamics' Handle showcase hybrid rolling-walking capabilities for faster and more energy-efficient movement.

Hybrid locomotion is rapidly evolving, with Boston Dynamics' Spot, NASA's rovers, and prototypes from robotics competitions providing insight into future developments. As AI and machine learning improve, hybrid robots will become more autonomous, adaptable, and capable of handling diverse environments, ranging from industrial settings to disaster zones and extraterrestrial exploration.

Chapter 3: Conclusion

After considering legged and wheeled locomotion in detail, within several different leg and wheel configurations and their advantages and disadvantages, it can be said that there is no superior locomotion mechanism, which is the best and the most usable in any situation. When developing a robot it is the designer's task to analyze the terrain in which the robot will travel and what the robot has to do there. According to this analysis the robot's locomotion mechanism can be chosen. Due to this the application area of most robots is very specialized. For example a robot which is designed to serve in a hospital wouldn't work on the ground of a forest. Furthermore there is, especially in legged locomotion, a large requirement of research, to make robots faster, more energy efficient, stable and manoeuvrable. As seen, there are a lot of commercial (like Sony and Honda) and non commercial (like several universities) research labs which spend lots of research energy in this thematic. So it will surely be interesting to consider the developments which are made in the next few years.

Chapter 4: REFERENCE

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