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Multi-legged robots: Classification, technology, technical architecture and applications

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Abstract. Multi-legged robots have become a research hotspot in the field of robotics, and they have a wide range of applications in military, rescue, and detection fields. The current state of research in the field of multi-legged robots is reviewed in this paper, and the types of quadrupedal robots, hexapod robots, and biped robots are introduced in terms of multi-legged robot types. In terms of the technology of multi-legged robots, technology of multi-legged robots and the technical architecture are introduced. Some practical applications in the field of multi-legged robots are also presented. The comprehensive analysis shows that multi-legged robots have strong adaptability and flexibility, but there are still some challenges in control and stability. In the future, a focus will be placed on the enhancement of environment perception and intelligent control of multi-legged robots, which will result in an increase in their reliability and performance when they are applied in practical scenarios.

Keywords: multi-legged robots, quadrupedal robots, hexapod robots, biped robots.

1. Introduction

A multi-legged robot is a kind of robots that has multiple legs and is capable of walking on complex and uneven terrains. These robots achieve efficient and stable locomotion through biomimetic design and control techniques, as well as novel sensing and computation methods. Due to their excellent mobility and maneuverability, multi-legged robots have broad applications in various fields [1].

Over the past few decades, research and development of multi-legged robots have made significant progress. For example, insights from biological studies of insects, spiders, and other animals' locomotion patterns can be used to design biomimetic multi-legged robots. Additionally, the application of technologies such as artificial intelligence and machine learning has greatly promoted the development of multi-legged robots.

The technical architecture of multi-legged robots includes components such as sensors, controllers, actuators, and robot bodies. Sensors are used to perceive and respond to the robot's surrounding environment, such as vision sensors, force sensors, and muscle position sensors. Controllers generate commands to drive the actuators and determine the robot's motion, and actuators are typically electric motors, hydraulic and pneumatic systems, etc. A good design of the robot body means characteristics such as lightweight, high strength, and modularity.

Although multi-legged robots have broad applications in various fields, their design and control still face many challenges, including stability and coordination issues, as well as technical problems in robot

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control and sensing. However, with the continuous development of sensing, control, and design technologies, multi-legged robots are expected to further improve their performance and application value in the future.

In this article, related works within the domain of legged robots are reviewed, and the latest research achievements in this area are discussed, including technical architecture, and applications in various fields. The current development of multi-legged robots is introduced, emphasizing their advantages in crossing complex and uneven terrain. The advancements in the design and control of multi-legged robots, as well as the development of novel sensing and perception technologies, will be encompassed. A detailed description of the technical architecture of multi-legged robots is provided, encompassing their sensors, controllers, and robot body. The challenges associated with designing and controlling multi-legged robots, such as stability and coordination issues, are also delved into in this section.

In addition, examples are presented of how multi-legged robots are currently being utilized in various industries, such as agriculture, mining, and transportation. The potential for multi-legged robots to be used in medical applications, search and rescue operations, and exploration of extraterrestrial environments is also highlighted.

This paper is a reference for the design and research of multi-legged robots.

2. Classification of multi-legged robots

A legged robot is a kind of mobile robot with legs instead of wheels, tracks or other types of locomotion mechanisms. Legged robots are well suited for crossing complex terrains where wheeled vehicles may not be effective. There are several types of legged robots, including hexapods, quadrupeds, bipeds, and more. In this section, the different types of legged robots will be described, and their characteristics and performance will be compared.

2.1. Types of legged robots

Hexapod robots have six legs and are often used in research and industrial applications. They have a stable platform and are able to carry heavy loads. Hexapods are also highly maneuverable and can cross uneven terrains with ease [2].

Quadruped robots have four legs and are commonly used in search and rescue missions, military applications, and exploration [3]. They are highly adaptable and can operate in various environments. Quadrupeds are also known for their ability to climb stairs and cross through complex obstacles [4].

Biped robots have two legs and are often used for research purposes or as humanoid robots in the entertainment industry. They are highly advanced and capable of performing tasks that require dexterity and balance. Biped robots are also used in the medical field to assist with physical therapy and rehabilitation [5].

2.2. Comparison of legged robots

Stability: Hexapod robots are the most stable of the three types, due to their six legs, while biped robots are the least stable due to their two legs. Quadruped robots fall in the middle, with good stability but not as much as hexapods.

Mobility: Hexapod robots are highly maneuverable and can cross through uneven terrains with ease. Quadruped robots are also quite moveable, but they may not be as stable on rough terrains as hexapods. Biped robots are the least moveable due to their two legs, which limits their ability to cross complex terrains.

Payload Capacity: Hexapod robots have the highest payload capacity of the three types, due to their six legs and stable platform. Quadruped robots also have a high payload capacity, but not as much as hexapods. Biped robots have the lowest payload capacity, due to their two legs and less stable platform.

As shown in Table 1, legged robots come in different types, each with their own unique characteristics and performance. Hexapods are highly stable and can carry heavy loads, quadrupeds are highly adaptable and mobile, and bipeds are advanced and capable of performing dexterous tasks. When choosing a legged robot for a specific task or application, it is important to consider the characteristics of each type and their suitability for the task at hand.

Table 1. A simple Ranking table of various abilities of different multi-legged robots.

Robot type	Stability	Mobility	Payload Capacity
Hexapod	Most	Most	Most
Quadruped	Middle	Middle	Middle
Biped	Least	Least	Least

3. Technology and technical architecture

3.1. Technology

The field of multi-legged robots has seen significant progress in recent years, with numerous research achievements contributing to the development of more advanced and versatile robots. Here, some of the related works in this field are highlighted.

One of the major areas of research in multi-legged robots is locomotion control. Various approaches have been proposed to achieve stable and efficient locomotion, including gait generation and optimization techniques, adaptive control methods, and machine learning-based approaches. Bio-inspired gait generation algorithms have been developed based on the locomotion patterns of animals such as insects and spiders. Locomotion control parameters have been optimized by using reinforcement learning and other machine learning methods.

Another important area of research is perception and sensing. Multi-legged robots require advanced sensing capabilities to cross complex and dynamic environments. Researchers have explored various sensing modalities, including vision, force sensing, and proprioception, to enable robots to perceive and respond to their surroundings. Additionally, the use of distributed sensing and swarm intelligence techniques to enable multi-legged robots to cooperate and coordinate their actions has been explored by some researchers.

In addition to locomotion and perception, there has been significant research in the design and fabrication of multi-legged robots. Novel designs and materials to enhance the performance and efficiency of multi-legged robots have been explored by many researchers. For instance, the use of compliant and lightweight materials to reduce energy consumption and increase mobility has been investigated by some, while others have developed soft robots with flexible bodies that can adapt to various terrains.

Overall, related works have contributed to the development of more advanced and capable multi-legged robots. However, there are still many challenges to be addressed, including the development of more robust and efficient control algorithms, advanced sensing and perception capabilities, and improved design and fabrication techniques.

3.2. Technical architecture

The technical architecture of multi-legged robots requires the integration of various components, including sensors, controllers, and actuators. Here, a detailed overview of the technical architecture of multi-legged robots is provided.

3.2.1. Sensors. Multi-legged robots require advanced sensing capabilities to cross complex and dynamic environments. Various types of sensors are used to detect the robot's surrounding environment, including vision sensors, force sensors, and proprioceptive sensors [6].

Vision sensors, such as cameras and lidar, are used to provide information about the robot's surrounding environment. This information can be used for tasks such as steering clear of obstacles, path planning, and object recognition. Force sensors are used to measure the forces and torques applied to the robot's limbs and body, which can be utilized for estimate the robot's position and orientation.

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Proprioceptive sensors, such as encoders and gyroscopes, are used to measure the joint angles and angular velocities of the robot's limbs.

3.2.2. Controllers. Multi-legged robots require sophisticated controllers to generate stable and efficient locomotion. The controller is responsible for generating the commands that drive the robot's actuators and determine the robot's motion. Various control approaches have been proposed for multi-legged robots, including open-loop and closed-loop control methods [6].

Open-loop control methods involve predefining a sequence of limb movements, or gaits, for the robot to follow. Closed-loop control methods, on the other hand, rely on feedback from sensors to adjust the robot's motion in real-time. These methods are often used in combination to generate stable and efficient locomotion [7].

3.2.3. Actuators. Multi-legged robots use a variety of actuators to move their limbs and body. These include electric motors, hydraulic systems, and pneumatic systems. Electric motors are commonly used for their high efficiency and precision, while hydraulic systems are used for their high power-to-weight ratio. Pneumatic systems are also used in some cases due to their simplicity and fast response [8].

3.2.4. Robot Body. The body of a multi-legged robot is typically designed to be lightweight and durable, with a modular architecture that allows for easy replacement and repair of components. The body is also designed to accommodate the sensors, controllers, and actuators required for locomotion and perception [9].

3.3. Challenges

The design and control of multi-legged robots is challenging due to the complex interactions between the robot's limbs and the environment. Stability and coordination issues can arise when the robot encounters uneven terrain or unexpected obstacles. Additionally, the high number of degrees of freedom and the large amount of sensory data generated by the robot can make control and perception challenging.

Despite these challenges, multi-legged robots have the potential to revolutionize a wide range of applications, from industrial automation to search and rescue operations. Continuing advancements in sensing, control, and design are likely to further enhance the capabilities of multi-legged robots in the future.

4. Application

Multi-legged robots have been extensively studied and developed due to their high mobility and adaptability in various applications. The design of multi-legged robots' legs allows them to traverse uneven terrain, climb stairs, and access difficult-to-reach areas that are inaccessible for conventional wheeled robots. So, multi-legged robots have been widely used in a variety of fields, including rescue missions and disaster response, military operations, exploration and entertainment.

One of the most promising applications of multi-legged robots is in search and rescue missions. During natural disasters, such as earthquakes, floods, or landslides, the environment can be highly unpredictable. These obstacles can affect the movement of wheeled robots. Multi-legged robots can move across rough terrain, climb over debris, and cross through limited spaces to locate and rescue survivors. In addition, multi-legged robots equipped with sensors can detect and identify gas leaks or other hazardous materials, providing valuable information to first responders [10].

Another important application of multi-legged robots is in military operations. Multi-legged robots can be used in reconnaissance and surveillance missions. They can move stealthily and gather intelligence in hostile environments. Moreover, multi-legged robots can also be used to transport heavy equipment and supplies in rugged terrain or harsh weather conditions, reducing the risk to human soldiers. The ability of multi-legged robots to carry out tasks in dangerous or difficult environments makes them an ideal tool for military applications.

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Multi-legged robots are also being developed for exploration purposes. For example, NASA is currently developing a six-legged robot called ATHLETE that will be used to explore the Moon and Mars. The robot's legs are designed to be adaptable to different types of terrain, enabling it to traverse rough and rocky surfaces. Furthermore, the robot's ability to carry out tasks remotely makes it a valuable asset for space exploration missions.

In the entertainment industry, multi-legged robots are being used in various performances, such as in theme parks and circuses. The robots' unique design and movement abilities make them an interesting and engaging attraction for visitors. In addition, the robots can be programmed to perform complex routines, adding to their entertainment value [3].

Multi-legged robots have a wide range of applications in various fields. They will be the best choice for working in complex and dangerous environments. With continued research and development, the potential applications of multi-legged robots are likely to expand, making them an increasingly important tool for a variety of industries.

5. Conclusion

Multi-legged robots have become an increasingly important area of research in robotics due to their high adaptability to complex terrains and their ability to perform various tasks in a versatile and efficient way. A comprehensive overview of the current development of multi-legged robots has been provided in this paper.

The different types of multi-legged robots, such as quadrupeds, hexapods, and octopods, have different structural designs and locomotion capabilities. With their respective strengths and weaknesses, they are able to play different roles in different environments.

From the Technology and Architecture, it can be observed that significant progress has been made in the development of multi-legged robots in recent years, particularly in the areas of structural design and control strategies. The technical architecture of multi-legged robots is complex and includes a wide range of components, such as sensors, controllers, actuators, and communication systems. However, there are still some technical challenges that need to be addressed, such as achieving stable and efficient locomotion, dealing with uncertainties in complex environments, and developing robust and scalable control algorithms.

Multi-legged robots have found applications in various fields such as search and rescue, and manufacturing, where they are used to complete tasks that are difficult or dangerous for humans. They can also be used in research areas such as biomechanics, control theory, and artificial intelligence to study complex locomotion and behavior of animals and insects.

Advances in control strategies, structural design, and applications will continue to drive progress and enable new applications. However, there are also potential challenges, such as developing robust and scalable control algorithms, addressing ethical and safety concerns, and ensuring that the benefits of multi-legged robots are distributed fairly. In conclusion, multi-legged robots have the potential to revolutionize various industries and research fields, and their development will continue to be an active area of research in the coming years.

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