Proceedings of CONF-MLA 2025 Symposium: Intelligent Systems and Automation: AI Models, IoT, and Robotic Algorithms
DOI: 10.54254/2755-2721/2025.LD28099

Bionic Optimisation Design and Analysis of Leg Structures for Bionic Mammalian Quadruped Robot

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Abstract. The inspiration for quadruped robots comes from quadrupeds, especially mammals, and is closely related to bionics. As one of the important components of quadruped robots, the leg structures have a significant impact on various capabilities, including payload capacity, running speed, stability, and agility. This paper starts from the perspective of bionics. On this basis, this paper focuses on the leg structures of bionic mammalian quadruped robots. The leg structures are divided into two parts: mechanical structures and actuation systems. Among them, mechanical structures are classified into three categories based on their connection methods, which are tandem mechanism, parallel or linkage mechanism, and mechanism with flexible tension elements. Actuation systems are classified into three categories based on their driving methods, which are motor-integrated gearbox drive, elastic actuation, and hydraulic actuation. Finally, the article also summarises the common methods for improving the leg structure of quadruped robots, including lightweight design and bionic optimisation.

Keywords: Bionics, mammalian, quadruped robots, leg structure

1. Introduction

Quadruped robots are a key type in the field of robots. It can cross different kinds of grounds and has been applied in transport, discovery and emergency rescue, etc. Quadruped robot Design Research primarily focuses on payload or Speed in both parameters when designing. Now, the problem we are facing is that there has not yet been a quadruped robot capable of meeting both criteria simultaneously: high-speed movement and sufficient load-bearing capacity; Therefore, this environment cannot be adapted to perfectly as expected.

Therefore, to solve this problem needs for quadruped robots' legs improvement. Due to the dependence of the payload and speed of a four-legged robot primarily on its legs. There are two parts of the stricture at the lower end: a mechanical part and an actuator; The mechanical structure determines the connection way of all parts that make up the Legs; Then it will affect its Leg motion trajectory and Stress status at this time. The actuation System outputs power in different modes to control the payload capacity and operating Speed of the quadruped robot.

Based on the biocidal perspective to improve the leg Structure in order to meet requirements more effectively, this paper will select various approaches and their examples for reference when

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designing a new Quadruped robot's Leg System. The reason why the bionic perspective is so significant is because quadruped animals in nature have already provided a reliable and high-efficiency blueprint for robot Design. Thousands of millions of years ago, quadruped animals have evolved leg structure and function that are highly fit for the need of moving. Through studies of these biological models, Engineers can modify the structures and functions of robot Legs.

Analyse the leg Structures of Bionic Mammalian Quadruped Robots in terms of mechanics and actuators separately. Compare various Designs in terms of Bionics' fidelity, Performance and their Applications Scenarios. In conclusion, the following optimisation methods combine structural design and actuator selection to enhance both the Speed and Payload Capacity simultaneously. To offer a systematic reference for subsequent generations of bionic quadruped robot systems that can perform generalised, high-efficiency work under actual conditions.

2. Analysis of bio-inspired leg

2.1.Analysis of the structures of legs

According to the mode of motion of the bionic mammals' quadrupeds in the field of bionic mammalian quadruped robots, they are typically digitigrade or unguligrade. Digitigrade animals such as cheetahs, Cats and Dogs come into contact with the ground at the tips of their toes during fast-running or pursuit-of-prey; Unguligrade animals, including goats, horses and deer, touch the ground with their hooves, have high running efficiency, and are suitable for long-distance migration. Due to their different leg structures and advantages, scholars choose different animals to simulate. For example, for quadruped robots designed to pursue speed, researchers simulate digitigrade animals, such as MIT's Mini Cheetah [1-4]. For quadruped robots aiming for payload capacity and jumping ability, researchers imitate unguligrade animals, such as Kawasaki Heavy Industries' BEX.

The leg structures of digitigrade and unguligrade animals are quite similar, but there are also differences. The leg structure of digitigrade animals can be divided into three segments [5]. By contrast, the leg structure of unguligrade animals should be divided into four parts [6]. However, most researchers did not consider the flexion that occurs at the footpads of digitigrade animals, regarding the foot as a unit [5]. What's more, they ignored the metatarsal of unguligrade animals, and the remaining small number of researchers use the spherical foot to adopt the metatarsal [7]. Therefore, they can simplify the leg structure and control model.

2.2. Analysis of the gait of the animals

In the bionics of quadruped robots, gait is also an important component, like structure. To simplify the control system, many designers design the foot trajectory of quadruped robots into an ellipse or a circle [3,8,9]. However, the real foot trajectory of mammals is in the shape of a "broad bean" [5]. One of the most important states in this trajectory is the dead-point support [10]. In the dead-point support state, animals are the most energy efficient and relaxed. Therefore, rational utilisation of the dead point support state can enhance the payload of quadruped robots.

In addition to the movement trajectory of a single leg, the order in which the four feet of mammals touch the ground during movement is also worthy of attention. According to the movement speed of quadruped animals and the coordination mode of their limbs, the gaits of mammals can be divided into six types: walk, trot, canter, gallop, pace and bound.

DOI: 10.54254/2755-2721/2025.LD28099

3. Types of leg mechanical structures in bio-inspired quadruped robots

3.1. Tandem mechanism

The components and joints of the tandem mechanism are connected in sequence, without the need for complex closed-loop constraint design. Therefore, the structure is simple and easy to design and build. As one of the most used structures, prismatic legs not only inherit the advantages of the tandem mechanism but also have higher payload and stability. This is because the direction of the force is consistent with the leg axis, making it less likely to generate additional torque.

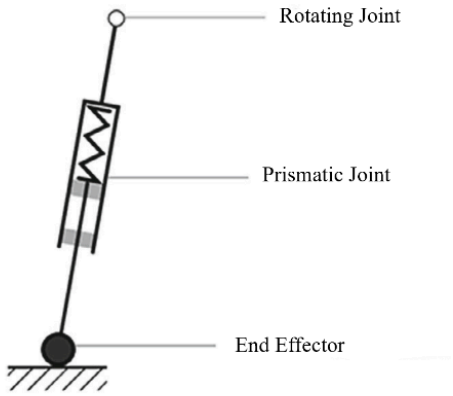


Figure 1. Topology of original prismatic leg

Figure 1 shows the first prismatic leg. Its structure can be divided into two parts: a rotating joint and a linearly moving prismatic joint, which becomes an initial model for further design. This structure imitates the tendons of animals. The moving of the prismatic joint is very similar to tendons, endowing the robot with strong jumping ability and payload capacity. However, this structure is unable to simulate the gait of mammals, so it cannot be flexible, and its application scenarios are limited.

A good example is the quadruped robot Kirin. It adopts prismatic legs to improve the problem of vertical force components in traditional articulated legs. Combined with dynamic control and online payload identification methods, it has a payload capacity of 125 kg and can trot at a speed of 0.7 m/s, which well demonstrates the advantage of prismatic legs in terms of high payload capacity [3].

3.2. Parallel or linkage mechanism

Since parallel mechanisms and linkage mechanisms are often combined in the leg design of quadruped robots, this article considers both mechanisms together. Compared with tandem mechanisms, parallel mechanism has more degrees of freedom and can walk in complex terrains. What's more, because the errors of multiple driving units can compensate for each other, parallel mechanisms can achieve more precise control. Therefore, parallel mechanisms are suitable for high-precision and complex motion scenarios.

DOI: 10.54254/2755-2721/2025.LD28099

3.2.1. Articulated legs

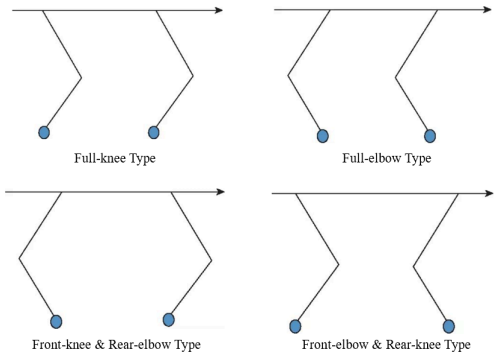


Figure 2. Topologies of four articulated legs

Compared with prismatic legs, articulated legs have several rotating joints instead of prismatic joints. These rotating joints are similar to animals' joints. Therefore, they can simulate the gait of animals well. Depending on the different animals that quadruped robots mimic, the topological models of articulated legs can be divided into four types. These four topologies are shown in Figure 2.

However, this structure has limited degrees of freedom and a relatively fixed movement trajectory. Therefore, scholars design the trajectory of such legs as circular or elliptical, which is different from the actual movement trajectory of mammalian legs. What's more, as mentioned above, researchers simplified the leg structure of the quadruped robot, ignoring the toes and metatarsals. This kind of simplification results in insufficient bionic capabilities of quadruped robots, failing to reach the motion capabilities of the prototype animals [5].

MIT Cheetah 3 is one of the most well-known quadruped robots which adopted articulated legs. In experiments, the MIT Cheetah 3 can reach a speed of 0.7 m/s when tested in trot gait. When testing different gaits on flat ground, its maximum forward speed can reach 3 m/s, the maximum lateral speed is 1 m/s, and the maximum angular speed is 180 degrees/second [11]. However, the research did not mention the payload capacity of the MIT Cheetah 3.

3.2.2. Redundant articulated legs

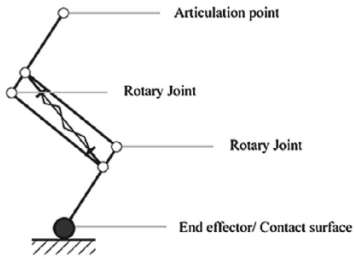


Figure 3. Topology of redundant articulated leg

The redundant articulated legs are an extension of the articulated legs. They have at least one more joint than articulated legs. The topology is shown in Figure 3. This structure highly simulates the limbs of mammals and can achieve a gait highly similar to that of mammals. As the redundant articulated legs have more joints than articulated legs, quadruped robots with redundant articulated

DOI: 10.54254/2755-2721/2025.LD28099

legs have stronger environmental adaptability. However, having more joints means having more actuators, which will increase the difficulty of control and result in an increase in the weight of the quadruped robot.

The BigDog, developed by Boston Dynamics, is a typical example of redundant articulated legs. It can move over rough terrain while carrying a 340-pound load and perform actions such as jumping. It is known as the world's most advanced robot for adapting to rugged terrain, showing the strong adaptability of redundant articulated legs to terrain [12].

3.3. Mechanism with flexible tension elements

In the above introduction, the paper shows three most classic quadruped robot leg structures, which are the prismatic leg, the articulated leg, and the redundant articulated leg. However, these traditional leg structures have some disadvantages which are difficult to overcome due to their characteristics. For example, the rigid link structure cannot undergo elastic deformation. Under this situation, Didier Papadopoulos and Martin Buehler clearly put forward the concept of compliant legs in 2000 and manufactured the first quadruped robot using flexible tension elements [13].

Joints that adopt flexible tension elements usually use cables or springs. By simulating the movement of animal tendons, quadruped robots with a mechanism incorporating flexible tension elements can often better mimic the walking patterns of animals, making themselves more agile. Quadruped robots driven by flexible tension elements usually adopt a hybrid control mode combining active control and passive compliance. Since forces and movements are transmitted by flexible elements, the actuations are usually placed at the rear, which greatly reduces the inertia of the legs [13].

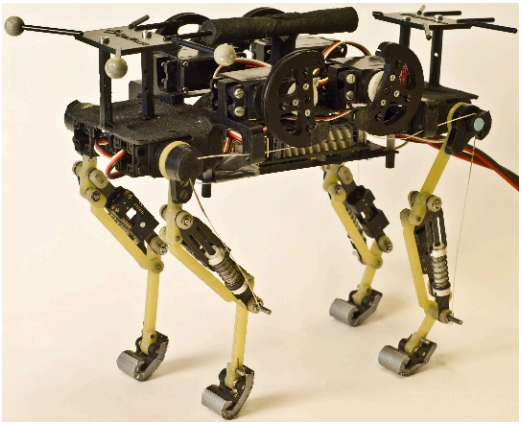


Figure 4. MIT Cheetah-cub

The flexible tension elements are usually used on two joints, the knee and the ankle. The MIT Cheetah-cub adopts a knee joint containing flexible tension elements. Its structure is shown in Figure 4. It exhibits self-stabilising behaviour with open-loop control and rapid movement [14]. For quadruped robots which adopt ankles with flexible tension elements, they not only have stronger stability, but also store energy during the foot's contact and increase the efficiency of the quadruped robots [15].

DOI: 10.54254/2755-2721/2025.LD28099

4. Actuation systems of bio-inspired quadruped robots

4.1. Motor-integrated gearbox drive

Instead of traditional driving mode, electromagnetic actuators are often combined with gearboxes. Having a high gear ratio, this type of drive can achieve high accuracy [16]. But although lowering the high gear ratio will increase friction losses and lower the system's overall mechanical strength, raising the gear ratio will increase impact loads and the system's overall mechanical impedance [16]. A very high impact load is created at the end actuator, and the force control capability is constrained when the mechanical leg rapidly interacts with the surroundings or is struck. The high mechanical impedance of the actuator system brought on by the high impact load is not lessened by conventional actuators with a high gear ratio. Therefore, this mode is often applied to small and medium-sized quadruped robots that do not need to carry heavy loads, such as the MIT Cheetah series.

4.2. Elastic actuation

Reducing mechanical impedance is essential for a quadruped robot to walk steadily and interact with the ground dynamically in an unstructured environment [16]. Motor-integrated gearbox drive has a disadvantage in this regard. In contrast, elastic actuation contains elastic components, so it can absorb the impact when landing, thereby reducing mechanical impedance. According to the different connection modes of elastic components, elastic actuation can be divided into two types, namely series elastic actuation (SEA) and parallel elastic actuation (PEA).

In SEA, springs serialise the output shaft and payload [17]. By contrast, in PEA, the springs are aligned with the transmission in a way that preserves the original mechanism's integrity [17]. Their advantages and disadvantages are mainly reflected in three core dimensions, which are energy efficiency, load adaptability, and frequency sensitivity.

SEA has a comparative advantage under the condition of small operating Position's Offset Angle. Due to dynamic compensation from the SEA through a motor adjustment of the equivalent equilibrium point to offset static torque due to small deviations; At this time, a low-speed/high-torque loss peak appears near 20 Hz. PEA is more effective than PEAs in terms of the operating position offset Angle; It can automatically correct the static torque of gravity, which is not dependent on extra power consumption in the motor [18]. PEA can withstand longer periods of a fixed load-bearing condition; However, SEA offers greater flexibility in terms of motion dynamics and cannot be used to bear static forces directly with elastic elements. Because the series-parallel elastic components in SEA have been incorporated into the direct force transmission system, they can reduce dynamic impact [16]. Finally, because the elastic elements in SEA have been connected in series, a feedback linearisation algorithm must be added to this problem, thus increasing the degree of control difficulty. On the other hand, the load Angle of PEA is in agreement with that of the gear box; Thus, exhibiting Second-order Dynamic Properties; Its Control Is Simpler. [18].

4.3. Hydraulic actuation

Hydraulic actuators have a higher output power, stronger power Density; wider Bandwidth; faster Response Speeds than the other three types described above; and are more robust against Interference. Thus, as an advantage for using it is to improve the payload capacity of the robot and

DOI: 10.54254/2755-2721/2025.LD28099

expand its working area. Due to the features of hydraulic systems, such a drive is usually not as accurate or energy efficient as other forms.

According to the different movement modes, hydraulic actuators can be divided into two versions, which are linear and rotary. These two different versions can be applied to the knee joints and hip joints, respectively. Rotational hydraulic actuators can stably output torque symmetrically and have a larger range of motion. Linear hydraulic actuators can deliver high torque and meet the demand for highly asymmetric torque of the knee joint during movement. Meanwhile, linear hydraulic actuators are lightweight, which can reduce the inertia of the robot's legs [19]. The HyQ2Max is a good example which contains both linear and rotary versions.

5. Optimisation design methods for bio-inspired structures

5.1. Lightweight design

The weight given to the quadruped robot is low and thus less efficient. Based on biomechanical models, it has been shown that there is a negative relationship between the total mass of a quadruped robot and its stride rate [20]. In addition, with an increased weighting factor for a quadruped robot, it will have more in-actuation lag; This may severely burden the motors or reduce the robot's dexterity [21]. In addition, a greater weight may promote faster Material Fatigue (MB), reduce the service Life of equipment, lead to Structure deformation or Failure. Therefore, a light-weight Design for quadruped Robots is urgently needed at present.

Lightweight Design is realised through the employment of the Lattice Link Units, or LLUs. Translates lightening targets into manufactured topological optimisation Structures that have minimized weight while ensuring mechanical performance, presenting important applications to enhance the Agility, Energy Efficiency and Robustness of Quadruped Robots. [22]

Traditional LLU design is limited by the engineers' thinking capacity and experience; therefore, it has a relatively low-efficiency Design Process. Thus, Researchers have proposed generative Design (GD) as a method for developing LLU [22]. Integrating artificial intelligence technology, GD can autonomously solve the conflict of objectives among lightweighting, stiffness, strength and vibration frequency during LLU design. In addition, it can replicate the micro-structures of bones and plants to fabricate robust biomimetic lattices.

The two typical industrialisation pathways for the LRU process are selective laser fusion (SLM) and direct-metal-fusion-sited (DMLS). SLS can also be used to manufacture joints subjected to heavy loads that require a long service life and have excellent fatigue resistance. However, compared with DMLS, DMLS often works on ceramic-metal composites materials or parts, such as hydraulically operated arms' hydraulic-leg integrated manifolds.

5.2. Bionic optimisation

Bionics optimisation is essential for the Design of Quadruped Robotic Legs. Due to this, there will be a direct solution for its own weaknesses at present; Also, through maximum application of optimised movements found by nature in countless million-year periods of evolutionary adaptation. Obviously, it is necessary to introduce bionics further.

Based on observations of mammals, it has been found that there is a considerable difference in function and movement Pattern among the forelimbs and hind legs [5]. Foreleg functions include support and turning; After-leg functions include driving force and jumping height in the human body. Many quadruped robots use the same structure and control mode for their front and back legs

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at present. Although it is simpler in terms of System design and improves Performance. Therefore, Designing the forelegs and hind legs of quadruped Robots in different ways based on mammals may help improve their performance.

In addition, due to their relatively weak and flexible nature, many bio-inspired designs feature such components. Researchers developed a legged robot that mimics the performance of a two-jointed muscle-tendon unit structure located in the thigh [21]. In a state of rest, the mechanisms of both legs were able to facilitate torque transmission among multiple joints; as such, about fifty per cent less energy was required for the robots' motors to oppose gravity. A dynamically increased vertical jump exceedingly twice the length of the robot's legs by the action of its thigh device. Some researchers have found the best Spring Stiffness in specific situations. The torque-saving ratio for the hind legs was 19%, and that of energy-saving reached up to 13%; thus, this design has achieved good effect in reducing energy consumption [23].

6. Conclusion

Based on summarizing previous studies, this paper presents the typical bionics mammalian quadruped robot leg structures. Taking a bionics perspective in this study to explore how mammalian legs are structured and move. Based on these analyses, the research findings in previous studies have often been relatively simple in terms of designing leg structures and gait for quadruped robots. These bionics-based analyses provide the basis for subsequent research.

The Leg Structure of bionic Mammalian Quadruped Robots is divided into Mechanism Structure and Actuation System in this paper. Based on an analysis of the mechanism's Structure in this paper concludes that it will have some deficiencies including poor Flexibility and not being adaptable enough for Complex terrain. The redundant articulated leg can be said to have better bionics in terms of geometric topology; however, it also has a complicated shape and difficult control. The performance of the articulated leg is in-between these two kinds of leg structure. It is less rigid than the prismatic leg and simpler to control compared with the redundant articulated leg. Therefore, many applications can be realised under these conditions. As a new concept proposed after 2000, the mechanism with flexible tension elements has better bionic characteristics, and is more flexible and stable, but its development is not mature yet.

Through the analysis of actuators Systems, it was found that Motor-integrated gearbox Drive was relatively flexible and elastic actuation reduced Mechanical Impedance, thereby affecting the Performance of motor-Integrated Gearbox Drive; And Hydraulic Actuation had a load-carrying capacity much greater than that of the previous two types.

The proposed methods for improving the leg Performance of bionic mammalian-quadruped robots in this paper include both weight reduction Design and Bionics Optimisation from two sides. Among these, the suggestions listed under bionic optimisation provide directions to address issues arising from simple bionics; those raised at the outset of this article pertain to such matters.

There are still some issues with the development of the leg area now. In terms of Structure, the leg must withstand the Body Weight and generate powerful Explosion Force; Therefore, It Is necessary for Drives Units to Have Extremely High-Power Density. But the weight of the Legs is very significant in terms of energy consumption and dynamic performance. Therefore, there is not an obvious equilibrium of these two opposite demands at all. Actuation in a four-legged animal is relatively high-energy consumption. Some scholars are now using the tendon system to store energy, but it is not yet perfect for mechanical systems as well.

To deal with these problems, we can conduct further study from the aspects below in the future. Firstly, we should develop some new type of actuators like hydraulic artificial muscle (HAM), high-

DOI: 10.54254/2755-2721/2025.LD28099

performance servo motor and piezoelectric ceramic motor that can achieve more power density and efficiency. And as well the replication of this biological tendon passive dynamical attributes can be made, hence good energy recyclers will exist within any outside structure.

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