Design of Flexible Feet for Legged Robots

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Abstract: Due to its unique body structure and movement mode, the legged robot has strong terrain adaptability and can move in many complex environments. However, the robot's feet will frequently contact with the ground during the movement, and will be subject to greater ground impact. The flexible foot structure can effectively reduce the ground impact. The leg and foot structures, and locomotor characteristics of cats and insects were analyzed based on bionic principles. Combined with the structural characteristics of the small-legged robot, the structure and function of the flexible foot end is analyzed.

Keywords: Legged Robot; Flexible Structure; Bionics Design

1. Introduction

The field of robotics covers a wide range of disciplines, including mechanical design, materials science, multi-sensor fusion, information science, and many other different disciplines, making it the most representative multidisciplinary field in contemporary times.As one of the important carriers for the implementation of artificial intelligence, robots have attracted more and more attention from researchers.In order to achieve different task requirements, researchers have also designed and manufactured various types of robots, whose body structure, movement mode, and control method are different.When a foot-type robot moves, the contact between the foot end and the environment is discrete. Compared with continuous contact robots such as wheeled and tracked robots, the former can better adapt to complex terrain and move in unstructured terrain, completing tasks that other robots cannot complete. Therefore, it has gained the favor of many researchers.Many experts and scholars have conducted extensive research on multi-legged robots and achieved excellent results.Currently, foot-type robots have been applied in many scenarios, including but not limited to disaster search and rescue, special rescue, military reconnaissance, resource exploration, etc.

However, it is precisely because of its unique motion characteristics that the foot end of the foot robot frequently contacts the ground in the process of motion, and will be impacted by the ground [1]. Excessive impact will not only affect the stability of the robot, but also damage the robot leg joint driver and sensor components. In order to reduce the impact force on the robot during its movement, many researchers choose to improve the traditional robot structure by adding flexible components to the robot joint driver and leg structure to achieve the purpose of reducing the impact [2]. However, the flexible joints and leg flexible mechanisms are complex and bulky, which are difficult to achieve on some small robots. At the same time, although adding flexible components to the robot structure can reduce the impact on the lower leg joints, due to the material and structural characteristics of the flexible mechanism itself, the robot will produce a certain degree of vibration in the process of movement, leading to the shaking of the robot body, the instability of posture, and even the tipping of the robot in some complex environments, reducing the control accuracy of the robot, It affects the stability and motion ability of the robot, and limits the application and development of flexible mechanism in foot robot.

Based on the above reasons, according to the structure and motion characteristics of the small foot robot, through the analysis of the leg foot structure and motion characteristics of two kinds of natural creatures with strong motion ability, a flexible foot end with composite structure is designed and manufactured, which can greatly reduce the impact force of the ground facing robot.

2. Analysis and Design of Flexible Foot Mechanism

In the process of motion, the legged robot will be subjected to a large impact force from the ground. A large instantaneous impact will not only reduce the stability of the robot, but also increase the load of the robot joint driver and affect the life of the robot. Therefore, this chapter will start with the structure and motion characteristics of the robot, analyze two kinds of natural creatures with excellent jumping ability by using the principle of bionics, and design the foot structure of the robot by imitating its foot structure and jumping buffer mechanism. At the same time, according to the structure and motion characteristics of the small robot platform used in the foot end, the materials and components of each part of the foot end are selected.

The concept of bionics appeared as early as the 1960s and 1970s. It was deduced from Latin by American scholar Steele. After thousands of years of evolution and selection, creatures in nature have complex body structure and superior movement ability. The core of bionics is to extract the abstract structure and functional characteristics from the specific organisms through targeted research, and combine them with the design functions to achieve the purpose of imitation and reference. From the early mechanical design, we can see the shadow of bionics. As a highly integrated multi-disciplinary and multi-disciplinary technology, robotics has been constantly imitating the creatures in nature since its birth. With the continuous extension of robot technology in various fields, various specific and complex task requirements lead to the development of robot Bionics for natural organisms from rough and rough shape imitation to fine and specific structure and function imitation.

In the field of robotics, the bionics of natural organisms is mainly divided into function, material, structure, behavior, control and other directions. In this paper, the design of foot mechanism is mainly based on the analysis of the body and motion characteristics of animals, and the bionics of materials and functions is carried out.

Material bionics is mainly through the research and analysis of the composition, structure, molecular characteristics and functional characteristics of biological body tissues, and the use of new bionic materials with similar characteristics to simulate the characteristics and functions of biological body [3]. In recent years, new bionic materials, such as artificial muscle and dielectric elastomer, have been continuously developed and more and more widely used in various robots with different body structure and functional characteristics. Adding flexible materials to the robot body structure to improve the performance of the robot has also become a hot issue in the field of research.

Functional bionics is based on the functions realized by the biological structure. By studying the functional characteristics and motion characteristics of the biological structure, the structure and motion characteristics of the specific functions are summarized. At the same time, the requirements of the specific tasks of the robot are analyzed, and the corresponding characteristics are integrated into the design of the robot mechanism to achieve the purpose of similar functions.

3. Foot Structure and Motion Analysis

Insects and mammals have been the main bionic objects of foot robots for a long time because of their excellent movement ability. Many researchers have developed many robots with different structures and functions based on them. This section mainly analyzes the body structure and motion characteristics of cats in mammals and crickets in insects, providing ideas and guidance for the design of flexible foot ends.

Insect animals are widely distributed in nature. In the process of long-term genetic selection, they have evolved different body structures and strengthened different motor functions according to different habitats and living habits. Crickets and other insects have super jumping ability and can jump several times or even dozens of times of their own height. When landing, they can slow down the impact of the ground and protect themselves from damage. This super cushioning ability is inseparable from its special leg and foot structure.

Figure 1 shows the body shape and leg structure of crickets. Insects have three pairs of thorax feet, each of which is composed of five joints, and the foot located in the lower thorax has the strongest movement ability. In the joints of the moving foot end, the basal segment connects the insect body and supports the leg movement; The rotation joint of triangle plays a role in controlling the direction and coordinating the movement of legs and feet; The femur contains developed muscles, which provide powerful power for the jumping movement of insects; The internal part of the tibia is connected with the tarsi, which can control the movement of the tarsi through contraction and adjust the range of motion of the legs and feet; The structure of the tarsal joint is relatively complex, which is composed of 3-5 sub segments. Each sub segment is connected with each other through a soft membrane structure, which can slow down the impact of the ground. As the part of the insect leg that directly contacts with the external environment during movement, the tarsi is very similar to the robot foot. Therefore, the structure and function of the tarsi will be mainly analyzed.

Figure 1. Cricket Body Shape and Leg Structure

The insect's tarsal claw end is distributed with a cystic claw pad. The surface of the claw pad can secrete elastic mucus, which can produce greater elasticity when stressed [4]. When the insect falls from a high place, the contraction of the tibial joint makes the tarsal joint fully open, which increases the contact area with the environment and reduces the instantaneous impact force of the environmental impact on the insect leg; At the same time, when the end of the tarsal is impacted by the ground, the impact force will be transmitted to each sub segment through the flexible membrane inside the tarsal, and the impact force will be reduced through the movement of the sub segment and the flexible membrane. In addition, there are rich receptors on the surface of the paw pad of the tarsal joint, which can enable insects to accurately feel the external environment and adjust the movement of their legs.

In nature, cats among mammals also have strong athletic ability, and can run and bounce at a very high speed for a long time without injury. During the movement of cats, the soles of their feet can play an excellent buffering role and reduce the damage caused by the ground impact on their bodies. The strong cushioning ability of the soles of cats' feet is inseparable from their unique structure. Figure 2 shows the typical claw morphology of cats.

Figure 2. Claws of Cats

The claws of cats have a unique structure, which can provide them with superior movement ability. The area of the soles of cats' feet is much larger than that of their legs, which not only increases the contact area with the environment, but also increases the stability of their movement. At the same time, the soles of its feet are elastic, and there are several thick meat pads on the surface, which can provide a strong buffer capacity when the cat is moving or bouncing at high speed. The meat pad is mainly composed of a very elastic fiber structure and a thick fat layer, which is evenly distributed on the surface of the claw, and can extremely slow down the impact force on the ground to adapt to long-term and high-speed movement. The legs of cats have developed muscles, which can constantly adjust the state of the legs in the process of movement and reduce the impact of ground impact on joint tissue.

When cats fall from a high place, the thick meat pad at the foot first absorbs the impact on the ground, then the cat's legs are bent, and the rich muscles in the legs move accordingly, further slowing down the impact on the ground, so as to minimize the impact on joints and body organs during the movement. In addition, there are rich sensory nerves on the surface of the sole of the foot, which can enable them to accurately perceive the changes of the external environment during the movement process and feed back the information to the brain, so as to change their movement state in real time to adapt to different environments.

Many experts and scholars at home and abroad have designed and applied the flexible leg foot structure to the foot robot based on the

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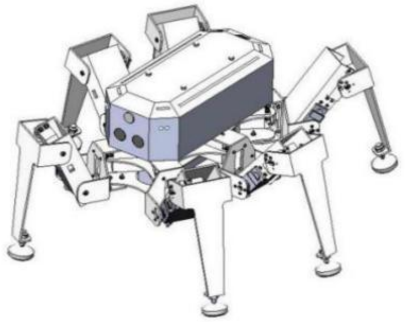
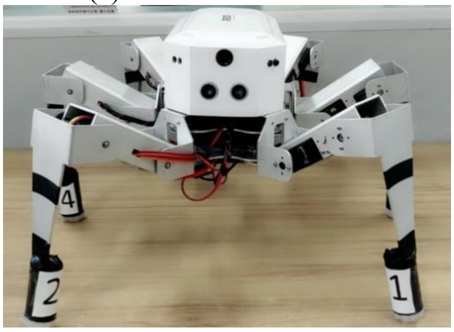
principle of bionics. Experiments show that the introduction of flexible mechanisms into the robot leg and foot structure can significantly improve the impact resistance of the robot leg and foot [5-6]. Therefore, this paper combines the body structure and motion characteristics of two kinds of animals to design the flexible foot end: the elastomer or muscle of the foot end is equivalent to a spring mechanism, the flexible material is used to imitate the insect claw pad or meat pad, and the pressure sensor is installed in the foot end to simulate the sensory nerve of animals.

4. Flexible Foot End Design and Working Mechanism Analysis

Aiming at the problem that the traditional point contact hexapod robot has limited movement ability in smooth, rugged and other unstructured terrain, a universal foot end with surface contact is designed, which effectively increases the contact area and friction between the robot legs and the ground, and the top can rotate within 30 degrees to adapt to more unstructured terrain; In order to solve the problem of large foot impact, a flexible foot end prototype was designed to reduce the impact on the ground. The universal foot robot and flexible foot robot are shown in Figure 3.



(a) Universal foot robot



(b) flexible foot robot

Figure 3. Leg Structure of Hexapod Robot

By analyzing the motion characteristics of the biped robot and the structural characteristics of the small hexapod robot, the flexible foot end is designed according to the design requirements of absorbing the impact force of the ground and improving the environmental adaptability. The design of flexible foot end shall meet the following requirements:

(1) Effectiveness: the designed flexible foot end should be able to meet the requirements of improving the buffering capacity and terrain adaptability, as well as the motion characteristics of the foot robot. The overall structure of the foot end shall also be lightweight and simple as far as possible to facilitate installation and replacement.

(2) Biomimetic: according to the structure, functional characteristics and motion characteristics of the foot end of natural organisms, and the design principles of material bionics and functional bionics, the designed foot end can achieve the function similar to the leg foot structure of insects and cats.

(3) Flexibility: the designed flexible foot has certain adaptability to complex terrain environment, and can carry out stable and efficient movement in different environments.

(4) Versatility: the designed flexible foot end should be able to be loaded on a general small foot robot, and different foot robots can adjust some structural parameters of the foot end according to the needs of their own tasks to meet their own needs.

In the previous paper, the structural morphology and individual motion mode of insects and cats' foot ends were analyzed through bionics theory. Combined with the structural motion characteristics of the hexapod robot itself and the foot end design requirements, the flexible foot end of the composite structure as shown in Figure 4 was designed. The foot end of this model imitates the foot end structure of insects and cats and the motion characteristics of multiple buffering during movement, and divides the impact force of the robot into two stages to slow down, so as to minimize the impact of falling foot impact on the robot body. The foot end design is derived from the leg foot structure and movement process of insects and cats. By adding flexible materials to the foot end to simulate the meat pad of cats and the elastic claw pad of insects, the impact force can be absorbed directly through deformation; The internal spring connected to the flexible top imitates the process of the second absorption of the ground impact by the movement of the tarsal and leg muscles when the cat and insect touch the ground. At the same time, a force sensor is installed inside the foot tip, which can sense the force changes of the foot tip in real time during the whole touchdown process, which is equivalent to the sensory nerve of the animal foot tip, and can make judgments on the external environment to adjust the movement.

Figure 4. Structural Diagram of Flexible Foot End

The flexible foot end is mainly composed of six parts: the top end made of flexible materials, the lightweight foot end shell, the internal spring of the foot end, the push-pull rod connecting the flexible top end and the internal spring, the sensor installed inside the foot end, and the foot end bottom plate connected with the robot leg through bolts for easy disassembly and assembly. The flexible top is made of silicone rubber cured in the mold. The shell, push rod and foot base are made of photosensitive resin by 3D printing technology, and the printing accuracy is 0.1mm. The inside of the push-pull rod and the shell are polished and coated with lubricating oil to reduce the friction of the foot end during movement. Holes are punched on the base plate of the flexible foot end to facilitate the disassembly and assembly of the robot leg. The flexible top is hemispherical, and the outer surface has granular bulges, which can increase the friction between the foot end and the ground, and improve the environmental adaptability of the robot.

In the design of flexible top, bionics is the main consideration. The size, size and weight of the foot should conform to the foot shape of creatures in nature, and should not be too large to affect movement; It should not be too small to affect the balance of the body. Therefore, when designing the size of the foot end, the diameter of the foot end is designed to be slightly larger than the diameter of the robot leg with reference to mammals with strong movement ability such as cats. In the design of foot end shape, there are mainly three kinds of foot end structures which are more common: flat bottom type, cylindrical type and hemispherical type. The foot ends of these three shapes have their own advantages, which should be selected according to the actual design requirements. The planar foot tip has a large contact area with the ground, strong friction, and strong stability ability, which can help the robot maintain stability when moving. At the same time, the large contact area can effectively disperse the body mass, which is mostly used in some heavy robots or humanoid robots; The cylindrical foot end can make the robot leg rotate in the process of support, improve the flexibility of movement, and complete the task in some narrow space; The foot end of the hemispherical structure can flexibly adapt to different terrains and has a certain absorptive capacity to terrains. The design purpose of the flexible foot end studied in this paper is to improve the absorption ability of the robot legs and feet to the impact force on the ground and strengthen the adaptability of the robot to the unstructured environment. Therefore, the flexible foot end in this paper adopts the combination of cylindrical and hemispherical form, and the upper shell of the foot end adopts the cylindrical structure, which can flexibly deal with many task scenarios requiring steering, and can reduce the lateral impact to a certain extent; The flexible top adopts a hemispherical structure, which can absorb irregular terrain protrusions through deformation while buffering the impact force of the ground. At the same time, the flexible deformation can increase the contact area between the robot legs and the ground, and improve the adaptability of the robot to the complex environment.

5. Foot End Flexibility Parameter Analysis

For the robot, when the flexible foot touches the ground, the first part that contacts the ground is the flexible part at the top. Therefore, the performance of the flexible tip is very important for the buffering capacity of the overall flexible foot end. Different materials of the flexible tip will affect the overall stability and environmental adaptability of the flexible foot end.

With the progress of science and technology, robot technology is more and more extended to the field of bionics, and all kinds of flexible materials with different functional characteristics and structural forms are also widely used. Compared with traditional rigid materials, flexible materials can still maintain their original characteristics after deformation such as expansion and bending. However, the molecular structure, functional characteristics and use environment of different flexible materials are very different. When selecting flexible materials, the flexible materials should be selected according to the task requirements of the robot. Common flexible materials include silicone rubber, dielectric elastomer, shape memory alloy, hydrogel, ionic polymer.

Among many flexible materials, silicone rubber is widely used in robot leg mechanism, end gripper and other aspects because of its good characteristics of high controllability, strong stability and easy access. Combined with the characteristics of the hexapod robot platform used in this paper, silicone rubber is selected as the top material of the flexible foot.

Silicone rubber materials have different manufacturers and series, and their main characteristics are generally similar. With different models, the strength, viscosity and transparency will differ. In order to make the designed foot end more convenient to transplant to the common foot robot, this paper selects the common silicone rubber in the market to make the flexible top. In this paper, HC90 series additive liquid silicone rubber produced by shinbon is selected to manufacture the flexible top. HC90 series silicone rubber has the advantages of good elasticity, strong stability, low price and easy preparation. In this paper, three different types of silicone rubber hc9000, hc9008 and hc9015 under HC90 series are selected for comparison. The hardness of the three types of silicone rubber is 0 degrees, 8 degrees and 15 degrees respectively. The lower the hardness of silicone rubber, the softer the silicone rubber is. For HC90 series silicone rubber, the silicone rubber with hardness below 15 degrees has better elasticity and deformation characteristics within the stress range, while the silicone rubber with hardness above 15 degrees has higher hardness, which is generally used in the production of mold, and is not suitable for the production of flexible foot end in this paper. This series of silicone rubber materials have good physical properties and are very stable at room temperature.

6. Summary

In order to reduce the impact of the ground on the robot legs and feet, the flexible foot end is designed from the perspective of bionics. Through bionics analysis, the natural biological structure and functional characteristics are summarized. Combined with the body structure and motion characteristics of the small foot robot, the structure of the flexible foot end is designed. According to the actual movement demand of the foot end, the mechanical characteristics of different materials were compared and analyzed, and the selection of flexible materials was completed.

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