WEP Warwick Evans Publishing

International Journal of Mechanical and Electrical Engineering

ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 2, Number 1, Year 2024
DOI: https://doi.org/10.62051/ijmee.v2n1.09
Journal homepage: https://wepub.org/index.php/IJMEE/index

Design and Research on the Mechanical Structure of a Heavy-Duty Hexapod Robot with Bouncing Characteristics

Zeyu Zhang *, Jiaju Wang, Shiyun Wang

College of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China
* Corresponding Author: Zeyu Zhang (Email: zhangzeyu990423@163.com)

ABSTRACT

Based on the lunar exploration project, a mechanical structure design scheme for a heavy-duty hexapod robot movement system with bounce characteristics was proposed. The materials used were determined by the robot's working environment and performance standards. The mechanical structure of a jumping heavy-duty hexapod robot was designed using SolidWorks 3D modeling software. Based on the analysis of the working modes of the root joint, hip joint, knee joint, and jumping energy storage mechanism, the main components of each joint and jumping energy storage mechanism were designed, and a single leg mechanism was obtained. Based on the special soil structure on the lunar surface, the foot end buffer mechanism was designed, and finite element stress analysis was conducted on the key components of the robot model, proving the rationality of the mechanical structure of a heavy-duty hexapod robot with bounce characteristics.

KEYWORDS

Hexapod Robot; Bounce Characteristics; Finite Element Stress Analysis.

1. INTRODUCTION

During lunar exploration, lunar exploration robots are essential as they can perform specific tasks in extreme lunar environments, such as lunar exploration and sample collection. Currently, among numerous lunar exploration mobile robots, wheeled and tracked robots have been extensively studied. They have a simple structure, good controllability, fast movement speed in flat terrain, and certain load-bearing capacity [1,3]. However, when facing rugged terrain such as trenches on the lunar surface, the obstacle crossing ability is insufficient, and the range of activity is limited, making it impossible to carry out exploration tasks more deeply. A novel and reliable exploration robot is essential for deeper exploration of the moon. Due to the low gravity environment of the moon, the robot's jumping ability is achieved, and it can jump over obstacles several times higher than itself [4]. In addition, compared to the tripod and quadruped, the stability and load capacity of the hexapod have been improved, making it better for carrying detection equipment for large-scale detection. Obviously, bouncing robots are very suitable in such low gravity environments, and their advantages are even more obvious.

The earliest bouncing robot was the single legged bouncing robot developed by Marc Raibert at the MIT Robotics Laboratory in 1980 [5]. It can complete continuous jumping movements in a plane, and the jumping direction, angle, and jumping state of the robot can be adjusted through control. However, due to the relatively simple structure of this robot, it cannot complete some complex jumping movements and cannot achieve all-round jumping movements. The Swiss LIS laboratory has successfully developed a miniature jumping robot. This R&D team is working on miniaturizing the jumping robot, with a body height of 5cm and a weight of only 7g. This robot has extremely strong jumping ability, and the experimental results show that its maximum jumping range is 1.3~1.4m, which can reach a height of 27 times its own size [6]. Researchers at the Massachusetts Institute of Technology in the United States have developed a robot called Cheetah, and based on this, have updated and optimized several generations of this series of robots [7].The control algorithm of this robot adopts advanced control algorithms at that time, and through its control algorithm, the robot's own motion state and its current state can be perceived. The research team of Northwestern Polytechnical University, led by Professor Ge Wenjie, has developed a bionic kangaroo jumping robot by studying the biological model of kangaroos and the biological structure of their legs during jumping. By utilizing the tail swing and unique back bending phenomenon during kangaroo jumping, springs were added to simulate the energy storage and release of kangaroo muscles, and a mixed model of rigid and flexible bodies was established for the kangaroo jumping process [8,9].

2. MECHANICAL STRUCTURE DESIGN OF HEXAPOD ROBOT

2.1. Material Selection

The materials commonly used in aerospace currently include titanium alloys and aluminum alloys. Titanium alloy has the characteristics of high strength, high corrosion resistance, low density, strong heat resistance, and low temperature resistance. In addition, titanium alloy has a good weight reduction effect. Aluminum alloy has the characteristics of low density, good corrosion resistance, and good thermal conductivity. Below is a comparative analysis of two commonly used titanium alloy and aluminum alloy materials for aerospace robots. As shown in Table 1.

Table 1. Various indicators of titanium alloy and 7079 aluminum alloy

attribute	7079 aluminum alloy	Ti-8al-1mo-1 titanium alloy	unit
Elastic modulus	7.2e+10	1.2e+11	N/m^2
Shear modulus	2.7e+10	4.6e+10	N/m^2
Poisson's ratio	0.33	0.32	—
Coefficient of thermal expansion	2.5e-05	8.5e-006	K
Mass density	2700	4370	Kg/m^3
yield strength	505	910	N/mm^2
Thermal conductivity	120	6	$W/(m{\bullet}K)$
specific heat	960	502	$J/(kg{\bullet}K)$

Based on the performance indicators in Table 1, after comparing and analyzing the two metals, it can be concluded that titanium alloy has higher performance indicators than aluminum alloy. However, due to the large temperature difference between day and night on the lunar surface, with a maximum temperature difference of up to 300 degrees Celsius, the robot body is prone to deformation and its performance is greatly reduced in this temperature environment. From the table, it can be seen that aluminum alloy has better low-temperature performance, but is not resistant to high temperatures. The thermal expansion coefficient of titanium alloy is much smaller than that of aluminum alloy, which can effectively prevent deformation of the robot body due to changes in lunar surface temperature. Therefore, TC6 titanium alloy was selected as the main material for the robot.

2.2. Airframe Structure Design

As shown in Figure 1, the main body is designed as a regular hexagonal structure with a side length of 300mm and a height of 200mm. The root joint installation joints of the robot legs are placed on each side of the hexagon. The main body is made of TC6 titanium alloy material, which provides sufficient strength and stiffness to ensure the performance of the robot main body.

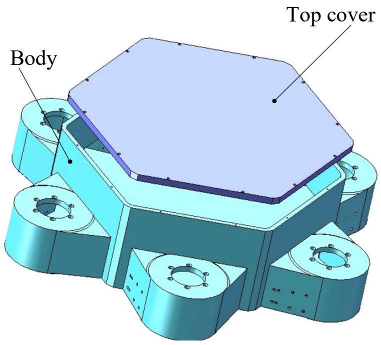
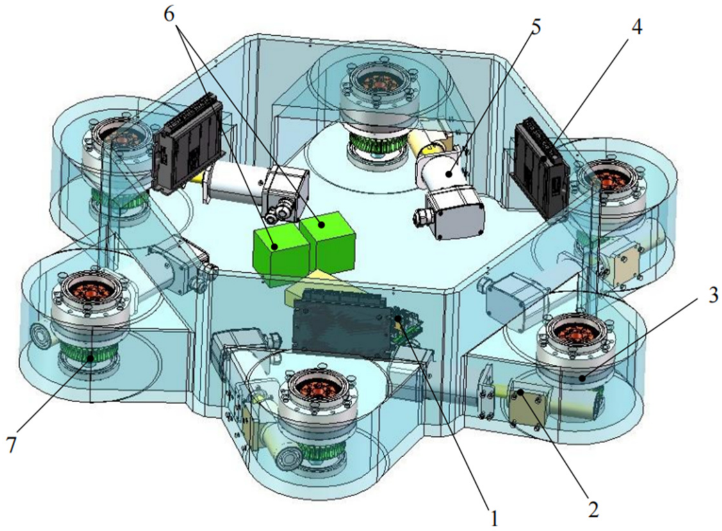


Figure 1. External configuration of heavy-duty hexapod robots with bounce characteristics

A series of accessories such as various motor control boards, onboard computer controllers, power supplies, and root joint drive motors are installed inside the body, and the installation layout of all accessories is basically symmetrical on both sides, which is conducive to maintaining the robot's center of gravity basically unchanged and preventing robot malfunctions caused by unstable center of gravity during jumping and walking, affecting the normal operation of the robot, In addition, there is still remaining space inside the robot body to install other components. The internal configuration of a heavy-duty hexapod robot with bounce characteristics is shown in Figure 2.



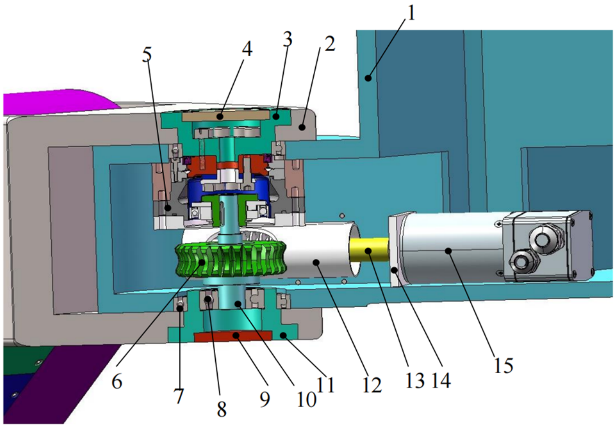
1- Lower leg motor controller; 2- Worm base; 3-joint harmonic reducer; 4-joint motor controller; 5-joint drive motor; 6- Power module; 7-Worm gear

Figure 2. Internal configuration of a heavy-duty hexapod robot with bounce characteristics

2.3. Mechanical Leg Structure Design

The root joint is an important part that connects the legs of the robot's moving system to the body, and its main function is to drive the legs to swing as a whole, thereby adjusting the overall posture of the robot's moving system. The main transmission components at the root joint, including the transmission shaft, worm gear, and harmonic reducer, are all installed inside the body. The root joint structure of the mechanical structure of the robot mobile system is shown in Figure 3.

The working principle of the root joint is as follows: by driving the worm gear to rotate, power is transmitted to the worm gear, causing the worm gear to rotate. The worm gear then transmits power to the harmonic reducer wave generator through the transmission shaft, and the wave generator begins to rotate. As the reducer at the root joint is fixed with a rigid wheel, according to the working principle of the harmonic reducer, the flexible wheel begins to rotate and outputs power to the external flange. The external flange will drive the rotation of the legs, thereby realizing the entire driving process. The mechanical structure of the hip joint, knee joint, and heel joint is similar, with the same working principle, and will not be elaborated.

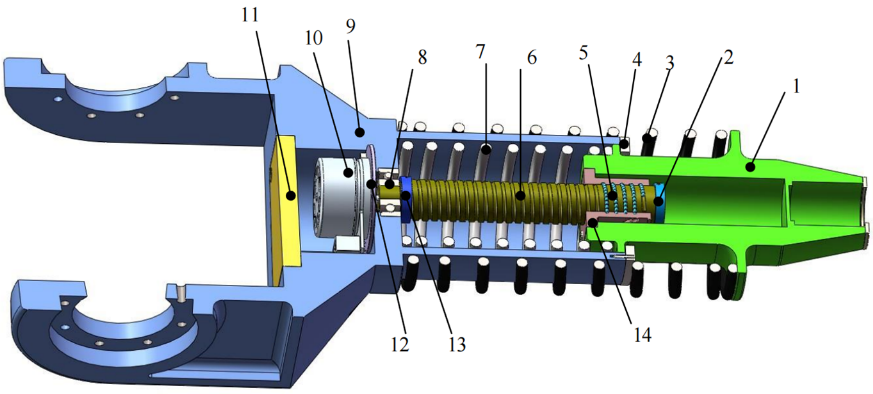


1- Body; 2- basal segment; 3- External flange; 4- Dust proof end cover; 5-harmonic reducer; 6-Worm gear; 7- 6203 deep groove ball bearing;8- 61811 deep groove ball bearing;

9- End cap; 10 joint drive shafts; 11- Connection components; 12- Worm mounting seat;13-Coupling; 14- Motor mounting base; 15- Motor

Figure 3. Mechanical Structure and Root Joint Structure of Robot Movement System

The main jumping energy storage mechanism of the robot is located on the lower leg, mainly realizing the energy storage jumping of the robot. The lower leg is a hollow configuration, and compression springs are installed inside and outside the robot's lower leg. At the same time, a screw rod is installed inside the lower leg, and one end of the screw rod is fixed with a nut and installed inside the compression rod, and the leg compression rod is installed inside the hollow part of the lower leg. The mechanical structure of the robot mobile system and the structure of the jumping energy storage mechanism are shown in Figure 4.



1. Compression rod; 2-Screw limit nut; 3- External spring; 4-Lower leg retaining ring;

5 ball bearings; 6-Ball screw; 7- Inner spring; 8-S7202 angular contact ball bearing; 9- calves;

10- Motor; 11- Motor cover plate; 12- Motor mounting plate; 13- Screw locking nut; 14- Screw Nut

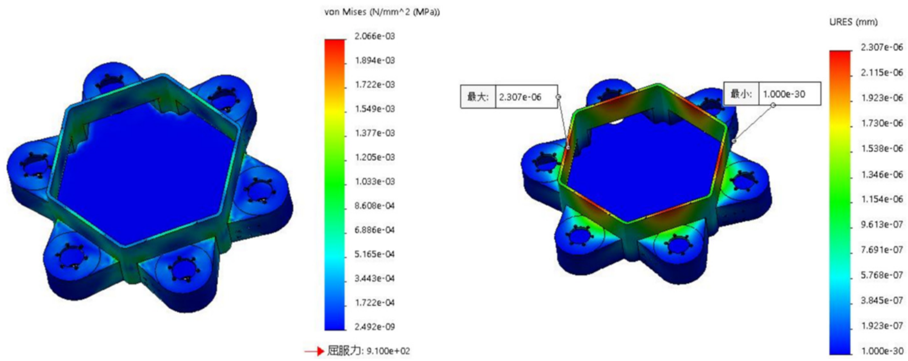
Figure 4. Mechanical Structure of Robot Mobile System Jumping Energy Storage Mechanism Structure

When the robot needs to jump, it is driven by a screw to move its legs downwards. At the same time, the robot body begins to press down. At this time, both the internal and external springs of the calf will be compressed. In addition, the spring in the elastic component at the knee joint will also be compressed. At this time, the mechanism begins to store energy. When the jumping condition is reached, the screw stops rotating. At this time, the spring compression stops and begins to return to its original state. At the same time, the energy is released, and the robot body begins to rise, thereby achieving the jumping effect of the robot.

3. FINITE ELEMENT ANALYSIS OF A HEAVY-DUTY HEXAPOD ROBOT MODEL WITH BOUNCING CHARACTERISTICS

3.1. Stress Analysis of the Main Components of the Body Module

To ensure the safety and reliability of various components of the robot during overload or normal operation, and to prevent malfunctions during task execution, this section conducts finite element stress analysis on the hazardous points of the robot body based on the parameters designed in the previous section. The finite element stress analysis of the body is shown in Figure 5.

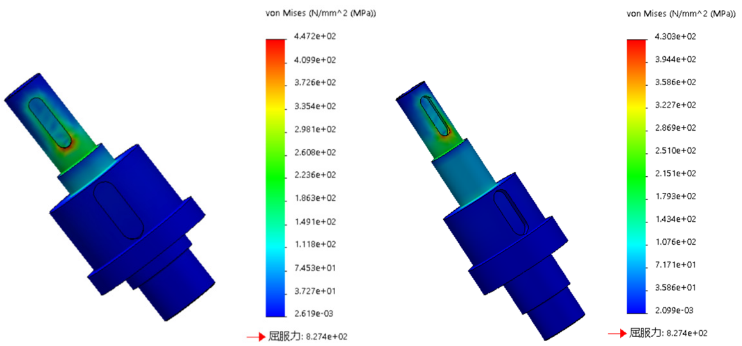


(a) Body finite element stress analysis diagram (b) Body displacement diagram

Figure 5. Body finite element analysis diagram

From the finite element stress analysis results of Figure 5, it can be seen that the maximum stress of the robot body is 0.25Mpa, which is less than the maximum yield stress of the material. Therefore, the designed robot body structure is a safety structure. According to Figure 5, the displacement diagram of the robot body shows that during the process of reloading, the maximum displacement of the robot body is 2.3×10^{-6}. Due to the small displacement of the robot body, it can be ignored and will not cause damage to the robot movement system.

3.2. Stress Analysis of Leg Mechanical Structure



(a) Stress Analysis of Joint Transmission Shafts (b) Stress Analysis of Hip Joint Transmission Worm

Figure 6. Stress analysis of joint transmission mechanism

According to the working mode of the leg mechanism, finite element stress analysis will be conducted on the robot base, thighs, calves, worms, transmission shafts, ball screws, and internal and external compression springs of the legs. According to Figure 6, it can be seen that the maximum stress on the root joint drive shaft is 4.4×10^2 Mpa, and the maximum stress on the hip joint drive shaft is 4.3×10^2 Mpa. The maximum yield stress of both drive shafts is smaller than the yield stress of the material, so the designed drive shaft is a safety component.

According to Figures 7 and 8, it can be seen that the maximum stress on the worm is 2.1×10^2 Mpa, the maximum stress on the lead screw is 68 Mpa, and the yield stress of the material is 8.3×10^2 Mpa. The maximum stress on the worm and lead screw are both smaller than the yield stress of the material. The designed worm and lead screw are safety components.

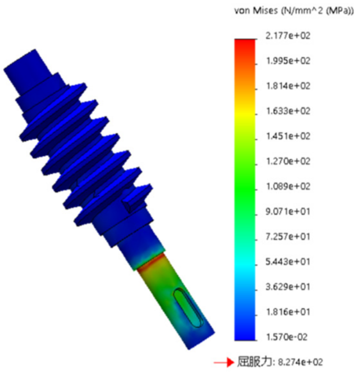


Figure 7. Worm Stress Analys

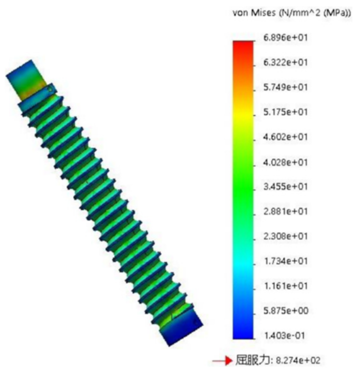
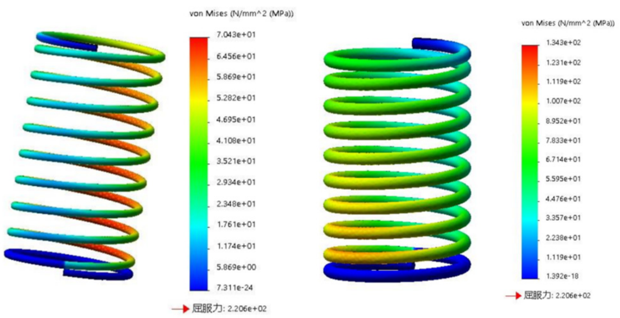


Figure 8. Ball Screw Stress Analysis

The stress analysis of the internal and external springs of the jump energy storage mechanism is shown in Figure 9. From Figure 9, it can be seen that the maximum yield stress of the outer spring is 70 Mpa, and the maximum stress borne by the inner spring is 1.3×10^2 Mpa. The maximum stress of the inner and outer springs is smaller than the yield stress of the material, so the compression spring is safe.



(a) Outer spring (b) Inner spring

Figure 9. Stress Analysis of Inner and Outer Springs

4. SUMMARY

Completed the design of the overall leg configuration of the robot movement system, analyzed the working modes of the root joint, hip joint, knee joint, and jump energy storage mechanism, and designed the components of each mechanism. The three joints of the leg were designed to be transmitted in the form of worm gear and worm gear accelerators to ensure the normal rotation of each joint. Select a spring with appropriate stiffness and use a ball screw to compress the spring to achieve robot jumping. And finite element stress analysis was conducted on the robot transmission shaft, worm, ball screw, and compression spring. Based on the analysis results, it was determined that all the designed components were safety components.

REFERENCES

[1] Chongfeng, Z., Liangliang, H. Preliminary Study on Lunar Robot for Manned Lunar Exploration [J]. Manned spaceflight, 2019, 25(05): 561-571. DOI:10.16329/j.cnki.zrht.2019.05.001.

[2] Yaao, Z. Research on Design Method of Wheeled Jumping Robot for Lunar Environment [D]. Chongqing University, 2021. DOI: 10.27670/d.cnki.gcqdu.2021.001938.

[3] Xiaolong, L. RESEARCH ON A BOUNCING ROBOT FOR MARS EXPLORATION [D]. Harbin Institute of Technology, 2019.

[4] Fei, Y. DESIGN OF MARS HOPPING ROBOT [D]. Harbin Institute of Technology, 2018.

[5] Fiorini P, Burdick J. The development of hopping capabilities for small robots [J]. Autonomous robots, 2003, 14(2): 239-254.

[6] Park H W, Wensing P M, Kim S. Online planning for autonomous running jumps over obstacles in high-speed quadrupeds [J]. 2015.

[7] Hui, C., Jianhua, L., Wenjie, G. Gait Analysis on Bionic Kangaroo-hopping Robot Based on Adjustable Geared Five-linkage Mechanism [J]. Robot, 2009, 31(06): 487-492.

[8] Long, B., Wenjie, G., Xiaohong, C., Ming, Z. Research on Hopping Robot for Planetary Exploration [J].Robot,2009, 31(04): 311-319.DOI:10.13973/j.cnki.robot.2009.04.009.

[9] Yiyang, L., Wenjie, G., Lixia, G. Characteristics of a Bionic Kangaroo-hopping Robot with Variable Transmission Ratio of Geared Five-bar Mechanism [J]. Mechanical Science and Technology for Aerospace Engineering,2011, 30 (05): 722-726. DOI:10.13433/j.cnki.1003-8728.2011.05.015.