Design and Simulation Analysis of Hexapod Bionic Spider Robot

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Abstract. According to the study of the physiological structure characteristics of hexapod insects, this paper proposes a design scheme of a hexapod bionic spider robot. According to the flexibility and stability requirements of the hexapod bionic spider robot, the body of the spider-like robot is designed from the perspective of bionics. The original model is further optimized by analyzing the structural proportion of the robot's legs and the defects of the original design. Finally, the static analysis of the hip and knee joints of the robot is carried out to verify the rationality of the hexapod bionic spider robot mechanism.

1.Introduction

Bionic robot is a robot designed to engage in biological characteristics works, which is based on biology in nature and imitates its physiological structure characteristics and behavior patterns [1]. In all kinds of bionic robots, bionic spider robots have the advantages of high flexibility and replicability, which enables it to adapt well to various harsh environments. In addition, bionic spider robot has the ability to avoid obstacles. With its advantages, it is widely used in industry, aerospace, military, emergency rescue and disaster relief and other fields, which fully shows its broad application prospect [2]. Foreign countries have joined the research of bionic multi-foot robots very early, and had very good research results. In 1968, American engineer Ralph Mosher successfully developed the quadruped robot named Walking Truck [1]. Although the overall operation of the robot has certain difficulty, it can well avoid obstacles when encountering obstruction during the crawling process. In the military field, the hexapod robot called Ariel [2] developed by the Massachusetts Institute of Technology is used for shoal demining. In 1989, the Massachusetts Institute of Technology developed Genghis [3,4], a robot used to detect the surface of outer space planets. In the early 21st century, Huazhong University of Science and Technology has designed a six-legged mobile robot [5,6]. When walking, its six legs are involved in walking. When working, two of the legs are switched to robots.

This paper mainly focuses on the structural design of the hexapod bionic spider robot, and optimizes and improves the original model. Finally, the key components of the hexapod bionic spider robot are checked.

2.Structural design of hexapod spider robot

The structure of the bionic spider robot is the carrier to realize the flexible motion, which determines the pros and cons of the robot's motion performance. From the perspective of mechanism, eight-legged spider robot is difficult to conduct bionics completely according to its physiological characteristics. Therefore, the arachnid robot designed in this paper is a hexapod structure. The mechanical structure
of a bionic spider robot is mainly composed of two parts: the trunk and the legs. And its structure diagram is shown in figure 1.

![Figure 1. The whole structure of the bionic spider robot.](image)

### 2.1 Trunk design of Hexapod Bionic Spider Robot
The trunk structure is the bearing platform of the robot walking mechanism, which directly affects the optimal stability of the robot when it moves. Kinematics simulation shows that the approximate rhombic robot structure is more advantageous than rectangle structure. The rhombic torso can effectively avoid contact collision between the legs of the robot, ensuring that it will not lose stability when walking. At the same time, it can also increase the orientation workspace of the legs. From the perspective of bionics, the torso of a bionic spider robot is shown in Figure 2. The upper and lower sides of the middle part of the body are inward to remove a circular groove, the upper groove is mainly used to arrange the operating platform and drive system hardware, in addition to reducing the body weight. The six circular holes connected with the coxae of legs on the trunk are distributed evenly in a circular array on a fan-shaped platform with a certain thickness. One end of the coxae is articulated to the trunk through bolts to form the base joint. The fan-shaped platforms at the edge of the trunk are also evenly distributed in a circular array, and are integrated with the trunk of the body, but the thickness is relatively small. On the one hand, this design can reduce the weight of the body and ensure sufficient strength, and on the other hand can restrain the rotation angle of the coxa during the movement.

![Figure 2. Trunk model of the bionic spider robot.](image)

### 2.2 Leg structure design of hexapod bionic spider robot
The arrangement pattern of the design’s leg is wraparound, which features that the six legs of the robot are evenly distributed around the circular body. At present, most of the legs of the hexapod robot adopt series mechanism, because it is easy to operate, and has a wide working range and fast reaction speed. After long-term research, the workspace of the six degrees of freedom parallel mechanism is relatively small, and the control process is extremely complicated. Based on all above factors and the previous research on spiders, the leg structure of the Hexapod spider-like robot is designed in series. Each leg contains three segments (coxa, femur and tibia) and three joints (base joint, hip joint and knee joint).

#### 2.2.1 The design of coxa
The connection between the coxa of leg structure and the trunk structure is set as the revolute pair of horizontal direction, which is called the base joint. The other end of the coxa is connected to the femur,
forming a revolute pair in a vertical direction, called a hip joint. The three-dimensional model of the coxa is shown in figure 3. In this design, fillet edge processing at the edge of the coxa.

![Figure 3. The model of the coxa.](image)

### 2.2.2 The design of femur

The femur is located in the middle part of the coxa and the tibia, which acts as a connection and rotation. It has mentioned the end of the femur is connected with the coxa to form the revolute pair of vertical direction, which is called the hip joint in the previous section. The other end of the coxa is connected with the tibia to form the revolute pair of vertical direction, called the knee joint. The three-dimensional model of the femur’s model is shown in Fig 4. This design simplifies the structure of the femur, makes the structure of the assembly’s model more concise, and meets the strength requirements.

![Figure 4. The model of the femur.](image)

### 2.2.3 The design of tibia

The tibia is the last joint of the leg’s design. The end of the tibia is connected with the femur to form the revolute pair in the vertical direction, called knee joint. The other end of the tibia is in contact with the ground, forming a friction pair to assist the moving, turning and other movement of the bionic spider robot. The three-dimensional model of the tibia is shown in Fig 5. In this design, the area of the contact position between the tibia and the ground is relatively small. The effect of this design is that there is not enough friction between the robot and the ground, which brings certain difficulties to the movement of the robot. Therefore, we are going to do some detail on the selection of the tibia materials. And after the production is finished, the anti-slip mat is connected at the bottom of the tibia to increase the contact area and friction with the ground.

![Figure 5. The model of the tibia.](image)

### 3. The structural optimization of the bionic spider robot

#### 3.1. Optimization design of the trunk
The optimal design of the trunk is mainly reflected in the selection of materials. Since a large part of the robot's mass is on the trunk structure, the selection of trunk's material is particularly important. At the beginning of this paper, the choice of trunk’s material is alloy steel with a density of 7,700kg/m³. Since the body is designed with an integrated structure, the hollowing process is not performed. Therefore, the body weight is relatively large, and it is very important to change the material on this basis. After comparison, the material of the trunk was determined as ABS, and its density was 1020kg/m³. Such optimization make the bionic spider robot more portable and flexible.

3.2 Optimization design of the legs
Leg structure is not only an important part of the bionic spider robot, but also the key of the mechanical structure design. It is known that the legs of the bionic spider robot are mainly composed of three joints, so the optimization of leg structure mainly includes the length of each joint and the selection of materials. In the beginning, the design of the robot’s leg was mostly based on visual effect. Later, through the study of a large number of multi-legged walking robot's leg length ratio data, and referring to the leg structure of common insects and the mature cases of engineering machinery, the calculation results were analyzed and compared: when the ratio of the coxa segment is between 0 and 0.1, and the ratio of the femur segment and the tibia segment are both between 0.4 and 0.5, each indicator is reasonable [7]. However, the ratio of the coxa cannot be too small, otherwise the robot’s legs will have contact collision, and the direct result is that the robot’s flexibility is greatly reduced. When the ratio of the coxa is above 0.08 and the ratio of the femur is 0.45, the robot's flexibility will gradually stabilize. When the ratio of the femur segment and the tibia segment are both 0.45, the curve of workspace area reaches the highest point, This means that the robot has the highest flexibility [8].

According to the above reasons, the size of the leg joints was optimized, and the length ratio of the coxa segment, the femur segment and the tibia segment was 0.09:0.455:0.455. The total length of the leg is still 1000mm. According to the above ratio, the length of the coxa is 90mm, and the length of the femur segment and the tibia segment is 455mm.

For each leg joint material selection, all joint materials were alloy steel with a density of 7700kg/m³ at the beginning. After consideration, the material was changed to aluminum alloy with a density of 2,800kg/m³. The parameters of each part of the hexapod spider robot after optimization are shown in table 1.

| Name       | Length(mm) | Material          | Weight(kg) |
|------------|------------|-------------------|------------|
| The trunk  | 500        | ABS               | 13.69      |
| The coxa   | 90         | Aluminum alloy    | 0.425      |
| The femur  | 455        | Aluminum alloy    | 3.632      |
| The tibia  | 455        | Aluminum alloy    | 0.905      |

4. The check of the key components
The legs is the mainly key component of the bionic spider robot. Because the legs not only bear the weight of itself and trunk, but also bear the counterforce from the ground during the movement of the robot, the content of this section is mainly about the check analysis of the leg structure. The force analysis of one supporting leg of the robot is shown in Fig 6.
Figure 6. The force diagram of the supporting leg.

Since the rotate axis of the base joint is perpendicular to that of the other joints, the bolt bears most of the torque of the joint. Therefore, only the torque analysis of the hip joint and the knee joint are required. According to the principle of virtual work, the generalized equilibrium equation of the support leg is established as follows:

\[ M_1 + \frac{1}{2} m_1 g l_1 \cos \theta_1 + m_2 g[l_1 \cos \theta_1 + \frac{1}{2} l_2 \cos(\theta_2 - \theta_1)] = N[l_1 \cos \theta_1 + \frac{1}{2} l_2 \cos(\theta_2 - \theta_1)] \]

\[ M_2 + \frac{1}{2} m_2 g l_1 \cos(\theta_2 - \theta_1) = N l_2 \cos(\theta_2 - \theta_1) \]  

(1)

Where \( l_1 \) and \( l_2 \) is the length of the femur and the tibia respectively; \( m_1 \) and \( m_2 \) is the mass of the femur and the tibia respectively; \( M_1 \) and \( M_2 \) is the torque received by the hip and knee joint respectively; and \( \theta_1 \) is the angle between the femur and the horizontal, \( \theta_2 \) is the angle between the tibia and the extension of the femur; and \( N \) is the counterforce of the ground to the foot end.

While the minimum support of a hexapod robot is no less than three legs. Or to be more precise, when the robot walks in a typical tripod gait, the load will be evenly distributed on the support foot, the supporting force of the foot is:

\[ N = \frac{1}{3} mg \]  

(3)

By the parameters of table 1 can calculate the total weight of hexapod bionic spider robot is about 52.1kg. \( \theta_1 \) is the angle of the initial state of the robot, set at 30°, \( \theta_2 - \theta_1 \) is 60°. Based on the conditions of robot motion and position control, the range of the joint's rotation is limited here: 25° ≤ \( \theta_1 \) ≤ 60°. Then when \( \theta_1 = 25° \), the torque of the joint is the large: \( N = 170.193 \) \( N \), \( M_1 \approx 29.273 \) \( N\cdot m \), \( M_2 \approx 18.778 \) \( N\cdot m \).

The finite element analysis results of hip joint are shown in Fig 7. The stress diagram of the finite element analysis of the hip joint is shown on the left and the displacement diagram on the right. It can be seen from the figure that the maximum force bearing position of the hip joint is on the inner surface of the bolt hole, which is in line with the actual situation. And the maximum stress of hip joint is 2.245×10^7 \( N\cdot m^2 \). It less than the yield strength of the material, the yield strength of the material is 3.171×10^8 \( N\cdot m^2 \). Therefore, it can be considered that the selection of this material can basically satisfy the normal movement of the bionic spider robot.

Figure 7. The force diagram of the supporting leg.

The finite element analysis results of knee joints are shown in Fig 8. The diagram on the left is the stress diagram of the finite element analysis of the knee joint, and the displacement diagram on the right. It can be seen from the figure that the maximum stress position of the knee joint is on the surface of the bolt hole, which is in line with the actual situation. And the maximum stress of the hip joint is
2.942×10⁶N·m², it less than the yield strength of the material, and the yield strength is 3.171×10⁸N·m². Therefore, it can be considered that the material is qualified in the process of the bionic spider robot’s movement and meets the strength requirements.

5. Conclusions
Based on the analysis of the characteristics of spider's physiological structure, this paper presents a design scheme of a hexapod bionic spider robot. Then, according to the characteristics of the bionic spider robot, the trunk and leg structure of the hexapod bionic spider robot are designed from the perspective of bionics. Next, according to the defects of the structure proportion of the leg and the material of the original design, the mechanical structure of the robot is improved and optimized. Finally, the simulation module in SolidWorks is used to complete the check and analysis of key parts, which verifies the rationality of the design. The research in this paper provides some theoretical references for the development of the prototype of the hexapod bionic spider robot.

Acknowledgment
This work was supported by the Special Fund of Sany under Grant number 17B011-18(Sany), the Soft Science Research Foundation in Jiangsu Province under Grant number BR2018011, the Open Fund of Key Laboratory of Special Robot Technology in Jiangsu Province under Grant number 2017JSJQR03, the Fundamental Research Funds for the Central Universities under Grant number 2018B793X14, Postgraduate Research & Practice Innovation Program of Jiangsu Province under Grant number SJCX18_0208.

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