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Motion Simulation of Bionic Hexapod Robot Based on Virtual Prototyping Technology

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***Abstract*—Based on the principle of bionic hexapod, a 3D virtual prototype model of the bionic hexapod robot and the contact model between its feet and the ground are established by using MSC.ADAMS mechanical dynamics software to study the motion of the bionic hexapod robot on the horizontal ground. And then, the kinematics analysis of a single leg of the robot is made to realize the overall motion control of the robot. This paper analyzes the gait principle of the bionic hexapod robot and introduces the gait of the robot used. By simulating the straight motion of the robot, the angular velocity and angular acceleration in the legs of the virtual prototype model are obtained. The study is a theoretical foundation for the design of the physical model and motion planning of a bionic hexapod robot.**

Keywords-hexapod robot; bionic; virtual prototype; gait; simulation

I. INTRODUCTION

With the characteristics of high order, strong coupling, multivariable and non-linearity, the hexapod robot can adapt itself to the complex ground and dangerous operating environment, and can replace the human to fulfill some special tasks, thus liberating mankind and improving efficiency.

Because of these advantages, scientific research institutions in developed countries have been constantly improving and optimizing the structure and design of the hexapod robot. The Genghis[1] in the late 1980s and the Attila[2] in the early 1990s were autonomous planetary exploration robots developed by the Massachusetts Institute of Technology (MIT). They could walk on rough terrain. Scorpion[3,4], developed by the Fraunhofer autonomous Intelligence Institute of Germany in 2001, was able to perceive the external environment and had a strong ability to adapt itself to complex environment. The Silo-6[5] hexapod robot developed by the Spanish Association of industrial automation in 2009 could perform field clearance functions. In recent years, with the rapid development of high technology, especially intelligent technology in China, the research on robot has stepped into a new stage. For years, Nanjing Forestry University has developed a hexapod robot for disaster reduction[6,7], and a hexapod robot based on modular control unit has been developed by Harbin Institute of Technology.

Based on the biological prototype of the hexapod, the robot model and its walking gait were designed. In order to reduce research cost and time, we did our best to improve the quality of robot design. By using the simulation model established by the mechanical simulation software ADAMS, the model parameters of the robot can be adjusted easily, and the dynamics and kinematics simulation results of the robot motion process can be output directly. The study will provide some reference for the organization and motion control of the hexapod robot.

II. The Modeling Process of Hexapod Robot

A. Prototype Structure of Hexapod

Imitating the structure of six-legged insects in nature, the design of bionic hexapod robot is variable. Take beetles for example. A beetle generally has six legs which symmetrically distribute on its front, middle and rear sides of its body. Each leg consists of coxal, femur, tibia and foot. Coxal and the body are connected through the root joint. The coxal is connected to the femur through the hip joint. Femur and tibia are connected through the knee joint. A beetle is shown in Figure 1, and its leg structure is shown in Figure 2.

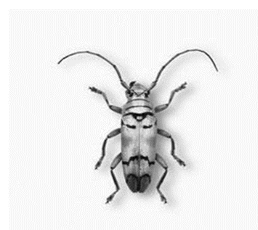


Figure 1. Beetle entity

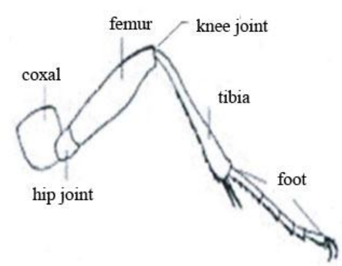


Figure 2. Schematic picture of leg structure

B. Modeling and Simulation Process

ADAMS, the automatic dynamics analysis of mechanical system, is the world famous virtual prototype analysis software. ADAMS was developed by Mechanical Dynamics Inc.company, which can complete the mechanical system modeling and solution operation. Simulation analysis of static mechanics, dynamics and kinematics can be done after the ADAMS virtual prototyping model is created. It can measure each joint's displacement, velocity, acceleration and torque curve. The conceptual design of the bionic hexapod robot using ADAMS can help to carry out the research on and improvement of the robot's performance. The whole work includes the layout design and parameter design of the model. After the construction of each component, it is necessary to establish the link and constraint relationship between the separate devices, and to add the corresponding motion pair to the constraint. The final step is to set the simulation time and to post-process the simulation results, completing the analysis of the simulation results and modifying the design. The main work flow of hexapod robot modeling is shown in Figure 3.

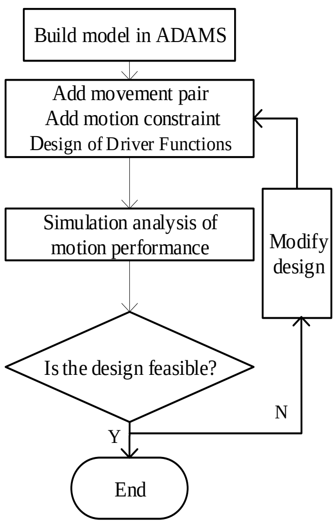


Figure 3. Modeling and simulation process

C. Construction of Bionic Hexapod Robot Model

In building the three-dimensional model in the mechanical dynamics simulation software ADAMS, in order to avoid too complex simulation model and difficult design, the model is simplified as follows:

1) The body of the robot is simplified into a uniform rectangular parallelepiped with the internal connection omitted. Keep the connection between the body and the root joint.
2) The coxal and the femur of the robot are simplified into a cylindrical structure, and the tibia into a truncated cone structure. The relative positional relationship between the joints in the leg structure is retained, and the connection between the coxal and the body is replaced by the revolute pair. The connection between the coxal, the femur and the tibia is also achieved by the revolute pair.
3) A cuboid is built at the bottom of the hexapod robot, Simulate the ground on which the robot walks, and establish the contact constraints between the foot and the ground.

Each leg of the hexapod robot has three degrees of freedom, and each degree of freedom needs rotational joints, so a total of eighteen revolute pairs are needed for the hexapod robot moving, swing and puting down its legs. The contact force creation dialog box is shown in Figure 4. Solid to Solid is selected as the Contact type, I solid as the robot's feet, and J solid as the ground. The various parameters are set as shown in Figure 4. The established model of a bionic hexapod robot is shown in Figure 5.

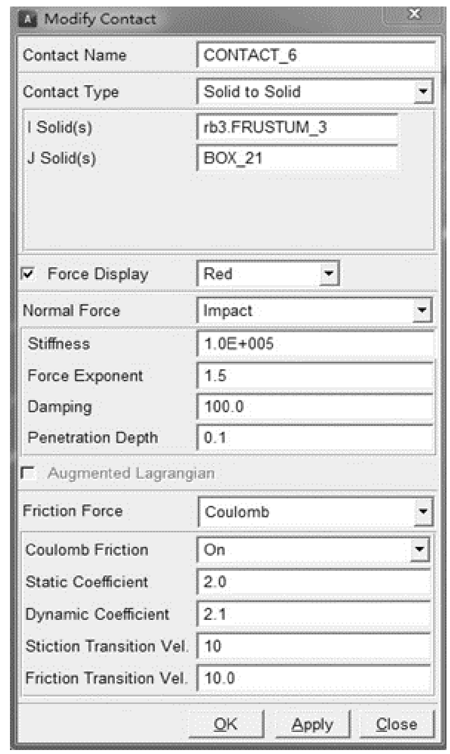


Figure 4. Creating a contact constraint dialog box

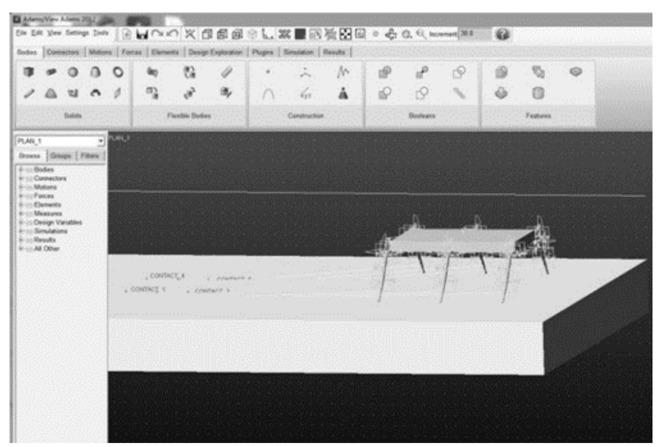


Figure 5. Bionic hexapod robot model

D. Kinematics Analysis of Hexapod Robot

The bionic hexapod robot is a multi-rigid body system, which satisfies the Newton-Euler equation, as in Formula (1).

$$m_i r^n = F_i^g - \sum_{i=1}^{n} T_{ij}(F_j^a + F_j^n) \quad (1)$$

$$J_i \bullet \omega + \omega_i \times (J_i \bullet \omega_i) = M_i^g - \sum_{j=1}^{n} [T_i^j (M_j^a + M_j^n) + C_{ij} \times (F_j^a + F_j^n)]$$

where $i = 1,2,\ldots,n$, C is the center of mass, force and moment are expressed in F, M, the association matrix is represented by T, the interaction between the external force of the superscript is indicated by g, the ideal effect of the hinge is represented by n and the interaction at the hinge is represented by a.

A forward kinematics analysis of a leg of a bionic hexapod robot is made. The single foot D-H parameters of the hexapod robot are shown in Table I. $\theta_1, \theta_2, \theta_3$ represent the rotation angles of the root joint, hip joint, and knee joint respectively. λ is the deflection angle of the root joint. The lengths of coxal, femur and tibia are represented by l_1, l_2, l_3. The distance between the common vertical lines is represented by d_i, α_i represents the twist angle of the joint axis, and the normal vertical length is a_i. The robot is shown in Figure 6.

TABLE I. SINGLE LEG D-H PARAMETER

连杆 i	变量 θ_i	扭角 α_i	距离 d_i	长度 a_i
1	θ_1	90°	$-l_1 \cos\lambda$	$l_1 \sin\lambda$
2	θ_2	0	0	l_2
3	θ_3	0	0	l_3

Each leg of the robot has 4 parameters $\theta_i, d_i, a_i, \alpha_i$, and they together determine the movement of each action. The $T = R(\theta)T(d_i)T(a_i)R(\alpha_i)$ represents the coordinate transformation, which is expressed by Formula(2).

$$T_{i-1}^{i} = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

c is a cosine transform, and s is sine transform. The bionic hexapod robot is transformed from the coxal coordinates to the femur and then to the tibia. The total shift of the foot (p_x, p_y, p_z) of the robot relative to the entire base coordinate is shown in Formula (3).

$$T_0^3 = T_0^1 T_1^2 T_2^3 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

thus, the position coordinates of the robot foot can be obtained, as expressed in Formula(4).

$$\begin{aligned} p_x &= c\theta_1 (l_3 c(\theta_2 + \theta_3) + l_2 c\theta_2 + l_1 s\lambda) \\ p_y &= s\theta_1 (l_3 c(\theta_2 + \theta_3) + l_2 c\theta_2 + l_1 s\lambda) \\ p_z &= l_3 s(\theta_2 + \theta_3) + l_2 c\theta_2 - l_1 c\lambda \end{aligned} \quad (4)$$

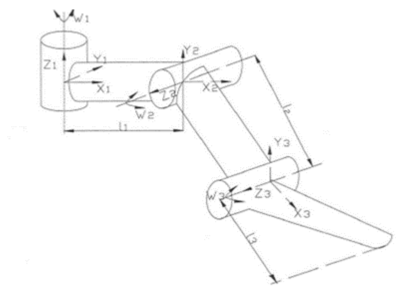


Figure 6. Single leg D-H coordinate system of bionic hexapod robot

III. Analysis of Gait Principle of Bionic Hexapod

A. *The basic concept of gait*

The swing phase is the position of the leg rising in the air from the ground. The support phase refers to the state of the leg landing. In the process of walking, the support phase and the swing phase alternate each other and the sequence of collections changing with time is called gait. Three-legged gait, four-legged gait and wave gait are three kinds of gait commonly used in the bionic hexapod robot. The time the hexapod robot takes to perform the whole gait during the moving process is called the gait cycle T. The duty factor β refers to the ratio of the support phase to the gait cycle in the period when the robot completes a gait cycle. The relationship between T and β is shown in Formula (5).

$$\beta = t / T \quad (5)$$

Step distance is the length of the center of gravity of a robot relative to the ground during moving, represented by λ. The foot travel refers to the distance the foot of a supporting phase moves forward or backward in the movement process of the bionic robot, which is represented by R.

The mathematical expression between the foot travel and the step distance is shown in Formula(6).

$$R = \lambda \bullet \beta \quad (6)$$

B. *Three-legged gait*

Because the three-legged gait is fast and stable, it is the most commonly used in the bionic hexapod robot movement. The walking mechanism of the three-legged gait is to divide the six legs of the robot into two parts, three legs into a part, and alternately move forward with a triangular support structure. The sketch map of the three-legged gait is shown in Figure 7.

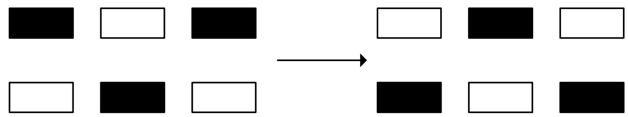


Figure 7. Three-legged gait sketch map

The black circle represents the support phase and the white circle represents the swing phase. The analysis of the movement of the hexapod robot is made as follows: 1,3,5 legs constitute a group, and 2,4,6 legs another group. When moving forward, 2,4,6 legs are in the swing phase and 1,3,5 legs in the support phase. First, the robot swings its 2,4,6 legs forward. And when the feet of the robot move down to the ground, 2,4,6 legs become the support phase while 1,3,5 legs become the swing phase. Such cycle repeats and the robot moves forward, which is shown in Figure 8.

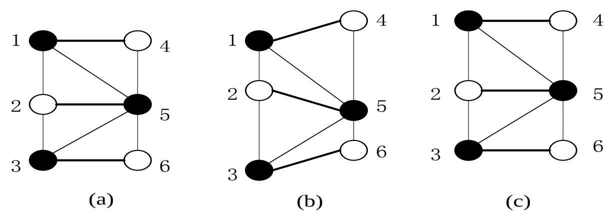
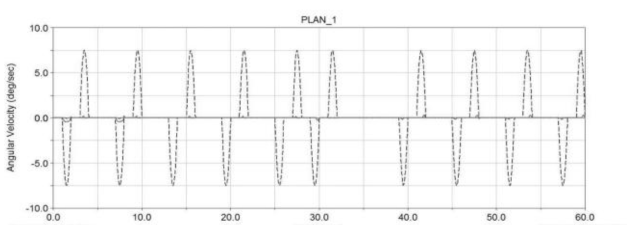


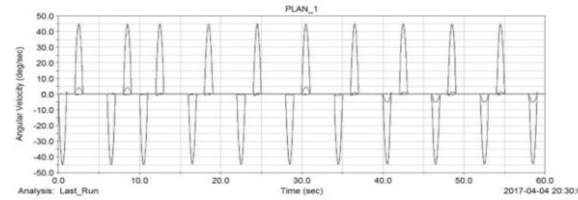
Figure 8. Sketch of three-legged gait in forward movement

IV. Motion Simulation of Bionic Hexapod Robot

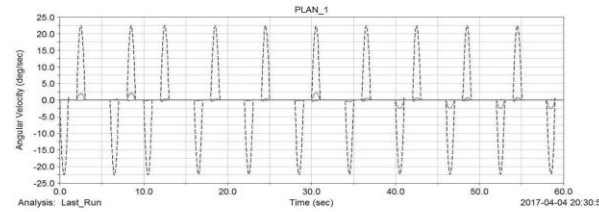
After the model of the bionic six-legged robot is created and the corresponding revolute pairs and constraints are added, the corresponding drive is added to the root joint, hip joint and knee joint of the robot. The *step* function in ADAMS is adopted as the drive function. The format is $step(x, x_0, h_0, x_1, h_1)$, where x stands for argument time, x_0, x_1 represents the start time and end time respectively, and h_0, h_1 represents the initial value and final value of the function. Finally, after adding the corresponding drive function, a group of curves of each joint of the robot are measured. The angular velocity curve of the root joint is shown in the Figure9 (a), the angular velocity curve of the hip joint is shown in Figure9 (b), and the angular velocity curve of the knee joint is shown in Figure9 (c).



(a) angular velocity curve of the root joint



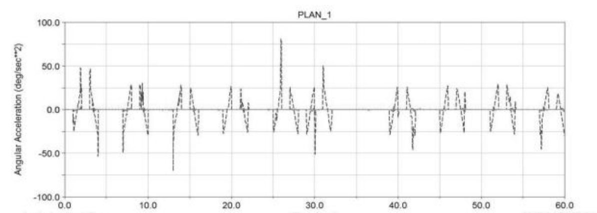
(b) angular velocity curve of the hip joint



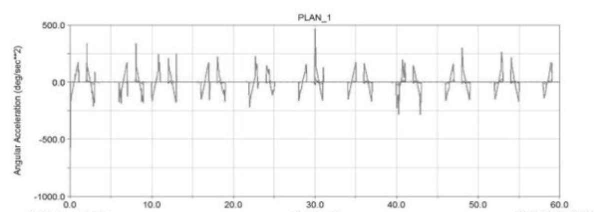
(c) angular velocity curve of the knee joint

Figure 9. Angular velocity curve of each joint

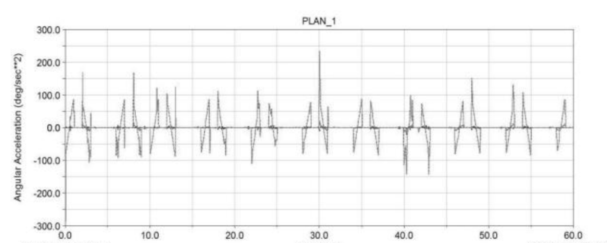
And the angular acceleration curve of this set is obtainded. The angular acceleration curve of the root joint is shown in Figure10 (a), the angular acceleration curve of the hip joint is shown in Figure10 (b), and the angular acceleration curve of the knee joint is shown in Figure10 (c).



(a) angular acceleration curve of the root joint



(b) angular acceleration curve of the hip joint



(c) angular acceleration curve of the knee joint

Figure 10 Angular acceleration curve of each joint

V. Conclusion

The experimental results show that the bionic hexapod robot prototype created by ADAMS is reasonable in layout, and the hexapod robot walks well under the driving function based on the three-legged gait. However, it can be seen from the simulation that the angular acceleration of the robot changes greatly at some time, indicating that the feet are subjected to greater impact. Therefore, when designing a physical prototype, it is advisable to add a damping equipment under the feet. The kinematic analysis obtained from the experiment provides a theoretical basis for the development of the physical prototype.

Acknowledgment

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