Research on the Walking Mechanism of Imitation Centipede based on Gait Simulation

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Abstract: In this paper, the authors analyze the walking gait of centipede, and propose the concept of imitating the centipede walking mechanism. Based on the planning of the bionic gait and the connection and movement of the centipede walking, we designed the motion scheme of the centipede walking mechanism, and carried on the kinematics simulation. Imitation centipede walking mechanism scheme proposed by this paper is just a simple imitation of the centipede arthropod movement. In order to fully simulate the movement of centipede, it is necessary to analyse the action mechanism of centipede foot and the supporting medium, the connection and movement mode of the centipede. The results of this study is significant for the research and development of new special vehicles.

Key words: Modularization, Bionics, Centipede, Walking mechanism

1. INTRODUCTION

The centipede belongs to the group of reptile, the body is composed of a plurality of sections, each section is flexible connection, the long body with the terrain (Adam, 2016). Every day there is a long centipede on both sides of the swinging group, rely on regular group, can be flexible in a variety of terrain quickly through. If the centipede is regarded as a large transport vehicle, the vehicle will have good terrain adaptability. Corresponding to the Centipede's multi body, it is a typical modular structure (Han, 2002; Ka, 2016). Through standard interfaces, each carriage can be conveniently combined. Therefore, imitation centipede walking mechanism may bring revolutionary changes to the development of special off-road vehicles.

2. GAIT ANALYSIS OF CENTIPEDE

The centipede has two legs in each section, relying on the connection with the adjacent section to maintain the stability of the sections. Each foot alternately complete support, movement, landing cycle action, to achieve forward, back and other walking action (Mohamed, 2014). The relative position between the sections can be adjusted, in order to complete the rise, bend, lateral bending and other attitude transformation, the flexibility to achieve vertical obstacle, turn around obstacles and other actions.

Figure 1. The centipede the marching gait

From the video data analysis on the road of centipede, centipede group in advance, although each group has its own sequence, but basically every 4 group, its action is consistent. In other words, each group of the phase difference of 4 (Fig. 1).

In order to facilitate the analysis, we put the figure 1 on the side of the group are numbered from right to left. The swing range of numbers for ③,④,⑤,⑥ as the 4 group as a group, ①-⑤,②-⑥,③-⑦,④-⑧ the swing direction in each group with the corresponding amplitude. We call the same phase group. Obviously, the motion law of the same group of the same phase. According to the observation group, the same group number at the same time, the phase difference is also different.
In summary, the centipede group of gait can be decomposed into: Lift - Swing - falling - swing back, group action similar to paddle. The centipede has the following characteristics: one is moving along the longitudinal amplitude is small, with low posture smooth flat driving characteristics; two is the relatively variable position, the internode of the change of the relative position, complete body lifting and bending, obtain better terrain adaptability. The three is a group of group exercise, alternating finish walking movements, the movement process is relatively stable; the four is the body weight distribution in multi group group, can adapt to the relatively soft ground; the five is according to the pavement soft, contact area and road adjustment group, to ensure adequate grip.

3. SINGLE FOOT MOVEMENT BIONIC MECHANISM

According to the group of centipede gait, we select the spatial crank rod mechanism to give a group of bionic mechanism " Lift up - forward swing - Fall - back swing ", the basic structure as shown in figure 2.

![Figure 2. Single foot bionic mechanism diagram](image)

The plot shows that the movement of the crank rod system with the single group (guide rod end track). And the link is a mirror image of the law. The layout of the crank guide bar system gives the mechanism a clear response. At the end of the connecting rod lift forward, no additional load, therefore, can use the quick return characteristics of mechanism, speed of swinging forward; at the end of the connecting rod falls, need to support the body forward, therefore, slow back swing can improve the load capacity of institutions.

3.1. Rod swing angle

The movement law of single group of bionic mechanism is one of the crank rod mechanism are given, therefore, the swing angle $\theta$ of the guide rod and the connecting rod size, determines the single group marching pace, as shown in figure 3.

set up Crank length $l_1$, Guide rod length $L_2$. The hinge between the distance of $h$, the guide rod swing angle $\theta$, there is:

$$q = 2 \arcsin \frac{l_1}{h}$$

![Figure 3. Rod swing angle](image)
In Figure 3, the condition of the entire cycle of the crank

\[ l_2 > l_1 + h \]

The turn of the crank 11 determines the direction of advance. Taking into account the overall size of the structure, when \( \theta = 60^\circ \sim 90^\circ \), The swing range is \( \pm 30^\circ \sim \pm 45^\circ \). This range is also valid for work. At this time, the swing amplitude of the rod end is \( S \):

\[ S = 2 \left[ l_2 - \sqrt{h^2 - l_1^2} \right] \sin \theta \]  \hspace{1cm} (1)

Accordingly, by adjusting the length of the connecting rod and the hinge seat position, design the corresponding group of step.

3.2. **Guide rod end of the amplitude**

Leader end of the ups and downs, determines the height of the bionic joint foot elevation \( H \), that is associated with its ability to cross obstacles, as shown in Figure 4.

![Figure 4. Guide rod end up and down](image)

The vertical amplitude of the guide bar in the range of the effective swing angle is \( H \):

\[ H = l_1 \left( 1 - \sin \frac{\theta}{2} \right) + l_2 \left( 1 - \cos \frac{\theta}{2} \right) \]  \hspace{1cm} (2)

Put the formula 1, 2 into the connecting rod motion equation can be obtained by single group of the actual stride length and height heels. Can also according to the specified length and foot height, calculate the corresponding crank guide mounting distance between the rod length and hinge.

4. **INFLUENCE OF CRANK SIZE ON MOTION**

Between the size of the crank and the installation of the hinge distance ratio, is directly related to the swing angle and the amplitude of landing guide rod, thereby affecting the efficiency of multi group simulation mechanism and moving obstacle capability.

In a single group of simulation model, the connection between the crank and the frame hinge center A and sliding countershaft center B distance is 50, when the crank length is 20, is for the short crank state, the trajectory of the end of the connecting rod as shown in figure 5.

![Figure 5. Trajectory of connecting rod end in short crank](image)
It can be seen from the figure, the rod end of the trajectory is relatively flat, that is, low lift heel height. At this point, the system along the longitudinal movement amplitude is small. When the terrain is not large, the use of this structure, you can get a good ride comfort. From the displacement-time curves in X and Y directions, it can be seen that the single-bodied foot-bionic mechanism has obvious quick-return characteristics (as shown in Fig.6 and Fig.7).

Figure 6. The X-direction Displacement Time Curve of Short Crank Connecting Rod End

Figure 7. Displacement Time Curve of Y-direction of Short Crank Connecting Rod End

The distance between the center A of the hinge connecting the crank and the frame is the same as the center B of the sliding axis. Take the crank length as 30, it is the long crank state. At this time, the trajectory of the connecting rod is shown in Fig.8.

Figure 8. Trajectory of Connecting Rod End in Long Crank

Can be seen in the figure, the relative motion of the rod end of the track, that is, the height of the lift foot is high. At this point, a single foot has a better obstacle clearance capacity.
As can be seen from the displacement-versus-time curves in the X and Y directions at the end of the long crank link, the two found acute-return characteristics also vary (Figure 9, 10). It can be seen from Fig. 10 that the slope of the Y-direction time-displacement curve increases, reflecting the increased velocity at the end of the connecting rod, and the resulting vibration is greater than the short-cranking scheme. However, due to single-foot enough to improve the ability to overcome obstacles, therefore, the long crank program is more suitable for flood road and other complex road.

5. COORDINATION OF THE SAME GROUP OF FOOT MOVEMENTS

Shown in Figure 11, can be seen as the four group of the same group of different attitude at the same time, can also be seen as a group of position at different time, namely in the crank clockwise case, guide rod lift (a), the highest point (b), fall (c), the lowest point (D).

When the crank for uniform circular motion, the length of the guide rod on both sides of the hinge with the rotation of the crank position changes, therefore, the end of the guide rod swing rate also changes. When the crank is transferred to the highest point, the swing rate of the end of the guide rod is the smallest; This is the aforementioned rapid-return characteristic.

Suppose the number of nodes in each group is n, and the motion phase difference $\Delta \theta$ between nodes is:
In order to ensure that the same group of nodes between the feet with more accurate phase difference, we use the chain gear transmission (Figure 12).

\[ \Delta \theta = \frac{2\pi}{n} \]

With 4 single blocks as a driving module group, that is, \( n = 4 \), can be calculated between the motion of the foot phase \( \Delta \theta \)

\[ \Delta \theta = \frac{2\pi}{4} = \frac{\pi}{2} \]

At this point, each section with the foot of the wheel rotation angle difference in turn ups and downs, alternating support of the body of travel (Figure 5). In the figure, four thick black lines represent the ipsilateral nodes respectively. \( t_1 \sim t_4 \) for a motion cycle.

In the multi-leg coordinated action, it is necessary to ensure that the motion of each joint does not interfere with each other. Thus, the maximum swing step size is limited by the pitch of the pitch. If the pitch is \( d \), then the maximum step size \( S_{\text{max}} \) is:

\[ S_{\text{max}} \leq d \]

If the crank length is \( l_1 \), the distance between the hinges a, b is h, the swing angle \( \theta_{\text{max}} \) of the guide bar, the relationship between the crank length \( l_1 \) and the hinge wheelbase h is:

\[ l_1 = h \sin \theta_{\text{max}} \]

There are two advantages: first, each section can rotate around the gear axis, so that the node group can change with the terrain and relative position, so as to get a better terrain adaptability; two-stage gear transmission program to simulate the movement of the node group; Is the use of gear transmission, can ensure that the same section of the section between the foot of the phase difference, to ensure that the group has coordinated gait; third section of foot control is relatively simple. But there are obvious shortcomings, such as stride length, heel height and other parameters difficult to flexibly adjust according to the actual road conditions, which to some extent, affecting the off-road performance of the prototype.

6. MOTION REALIZATION OF MODULAR CENTIPEDE BIONIC MECHANISM

In this paper, the prototype of the modular centipede bionic mechanism is designed according to the principle shown in Fig.2. The main design parameters are:

- The swing angle \( \theta = 90^\circ \)
- The swing range is \( \pm 45^\circ \)
Crank length \( l_2 = 10\text{mm} \)
Guide rod length \( l_2 = 3l_1 \)
Hinge spacing \( h = 1.5l_1 \)

Parts processing using 3D printer to complete, the principle prototype in Figure 10. The prototype is composed of six pairs of nodes, and the four nodes are set as one group, and the phase difference between the adjacent nodes is set to \( \pi / 2 \). To facilitate observation, the design of the W-foot structure, used to replace the pendulum part. Cylindrical helical spring was set up between the nodes to simulate the flexible connection between centipede internodes.

In the actual test, due to the accuracy of the 3D printer, making the machine running occasional Caton, after repair to be resolved.

In the experiment, using a DC motor as a driving force, while driving 6 on the 12 node movement.

![Figure 14. Centipede bionic mechanism prototype](image)

Principle prototype by 6 pairs of foot in turn followed by the floor and swing back, to achieve the whole machine to move forward. According to the prototype design parameters, the theoretical maximum step size can be obtained from the formula (1)

\[
S_{\text{max}} = 37.64
\]

Since the test is carried out on hard ground, the actual landing distance of each section is approximately \( H / 2 \). The corresponding step size also will be reduced, together with slippage and other factors caused by the step size loss, the actual step size of the prototype

\[
S \approx 16
\]

Let us take the second left foot as an example to illustrate its movement. The action sequence of each scale is determined by the phase difference, and the scale grasping action is as shown in Fig. 15, and the grip operation is completed as shown in Fig.16.

![Figure 15. Section II foot landing](image)

![Figure 16. The second section of the scale to complete the action](image)
7. MOTION STABILITY ANALYSIS

There are two factors that affect the stability of the movement: one is the impact vibration generated when the single foot falls to the ground, and the other is the fluctuation caused by the reaction force when the footrest is supported.

Each section foot landing, will have a certain impact vibration. Let crank rotation 1 cycle for 1 cycle, with time t, each cycle period, each section will fall on the ground 1 this, therefore, the node foot alternately caused by the vibration frequency f is:

\[ f = \frac{n}{t} \]

However, due to the movement of the foot section, there is the Y-direction of the rapid return characteristics, so the festival foot in the landing, the speed will slow down significantly. Therefore, the impact vibration caused by the landing foot can be adjusted by adjusting the length of the crank and the crankshaft and the guide rod support hinge center distance ratio to be alleviated.

During each cycle, at least one node of each segment is grounded, resulting in fluctuations in reaction forces caused by the landing support, the number of nodal segments, the number of nodes per segment, the spacing between nodes, Connection. In the simulation model described in this article, the joints are connected by means of flexible connections, each section has a relative independence, in the test, the reverse support caused by the ups and downs of each section, will be flexible connection block or absorption. For the smoothness of the whole little effect.

8. INTERCONNECTION MODE

The centipede pitch climbing and obstacle avoidance steering, are asymmetric contraction of the muscles between the implementation rely on. To facilitate the analysis, we assume that there are 4 relatively independent muscles between the two adjacent sections of the centipede, which are denoted as \( L_1, L_2, L_3, \) and \( L_4 \) (as shown in Figure 17).

![Figure 17. Centipede internode connection model](image)

When \( L_1, L_2, L_3, \) and \( L_4 \) in length when the internode is actually 4 parallelogram mechanism of cube connected, the internode can freely swing and torsion in a certain range, to meet the demand with the terrain elevation.

When \( L_1, L_2, L_3, \) and \( L_4, \) respectively, the same distance between the contraction and relaxation, you can achieve the imitation of the lateral bending device centipede (Figure 18).

![Figure 18. Transverse bending of Centipede](image)

At this time, the relationship between the bending angle of the centipede internode and internode expansion
amount of $\Delta L$ for muscle:

$$\Delta L_i = w \cdot \tan \theta_i$$

Where, $\Delta L_i$ for the first section of the internode expansion and contraction, $\theta_i$ for the $i$th node angle. When the first section in the course of the movement of the need for lateral bending $\theta_i$, the relationship can be obtained through the formula (1) the corresponding amount of muscle stretch $\Delta L_i$, to determine the corresponding inter-section muscle movement.

When the $L_1$, $L_2$, $L_3$, and $L_4$, respectively, simultaneously synchronized contraction and relaxation, you can achieve imitation centipede model of longitudinal bending (Figure 19).

![Figure 19. Centipede vertical bending](image19)

At this time, the centipede model of longitudinal bending angle between the internode $\psi$ and the amount of muscle stretch between $\Delta L$ relationship between the

$$\Delta L_i = w \cdot \tan \psi_i$$

Where, $\Delta L_i$ for the first section of the internode muscle stretch, $\psi_i$ for the $i$th node angle. When the $i$-th section needs longitudinal bending $\psi_i$ during the movement, the corresponding inter-node expansion and contraction amount $\Delta L_i$ can be obtained by formula (2) to determine the movement of the corresponding internode.

![Figure 20. Adjacent internode bending any direction](image20)

As shown in Fig. 16, a space rectangular coordinate system was established by using one of the four intercostal muscle simulating guide rods as the OX axis and the plane defined by the OX axis and the adjacent guide rod as the XOY and XOZ planes. The abcd coplanarity of the four guide rods of the simulated centipede internode muscle is given, and the space bending angle of the centipede can be expressed by the normal vector $\mathbf{n}$ (A, B, C) of the plane abcd. At this time, the plane equation is:

$$Ax + By + Cz + D = 0 \quad (3)$$

If the abcd in any point as a reference point, denoted by $P_i (x_i, y_i, z_i)$, into the equation (3), can be obtained

$$D = -Ax_i - By_i - Cz_i$$

Back to the plane equation:
Ax+By+Cz-Ax_i-By_i-Cz_i=0 \hspace{1cm} (4)

As shown in Fig. 8, in the established Cartesian coordinate system OXYZ, the Y and Z coordinates of each point of abcd are constant. Therefore, the expansion and contraction amount X of each guide rod can be obtained from equation (4).

Therefore, by adjusting the telescopic quantity of the four guide rods of the centipede model, the angle of the centipede model can be bent at any angle.

9. CONCLUSION

To centipedes as the representative of the multi-foot class reptiles, terrain adaptability and off-road capability, has obvious advantages. In this paper, the imitation of the centipede walking mechanism is only a simple imitation of the movement of the centipede, in order to fully mimic the centipede's progress, also need to centipede foot and supporting medium mechanism, centipede internode connection and movement mode Detailed analysis and research. This has the demonstration and the instruction significance to the research and development new special vehicles.

REFERENCES