Design and Analysis the Hybrid Linkage Walking Mechanism Based on the Variable Stiffness Active Flexibility Joint

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Abstract. Quadruped robots have been widely applied for the advantage of flexible mobile way. However, most of quadruped robots have large inertia and an impact load between the foot endpoint and ground in the process of movement because of series connection way. In order to solve the problems, a new mechanism of quadruped robot is designed and analyzed based on the active flexible joint with variable stiffness.

Introduction

High load, high mobility, high adaptability to environment has become the inevitable trend of quadruped robot technology development [1]. The performance of quadruped robot mainly depends on whether they have good driving characteristics, compact bionic mechanism and high robustness control system, and the top two because is based on performance of quadruped robot which has been the focus of the research on quadruped robot [1, 2].

In this paper, the bone structure and motion mechanism of the German Shepherd buffer is analyzed from the perspective of bionics, taking the five bar mechanism is put forward. A new series parallel hybrid mechanism and verified its feasibility as a quadruped robot single leg mechanism and rationality; According to the structural characteristics of the flexible joint with variable stiffness, this paper proposes and designs a single leg mechanism and the overall structure of the quadruped robot, and the quadruped robot kinematics and main performance analysis, planning a good foot trajectory using the co-simulation of MATLAB and ADAMS simulation and kinematics analysis of a quadruped robot based on the single leg.

Mechanism Design

Design of a new type of Single Leg based on Hybrid Linkage Mechanism

Based on the analysis of the structure of the German shepherd dog, a new series parallel hybrid mechanism that accord to the structural characteristics of the flexible joint with variable stiffness is designed as a single leg mechanism of the robot. The five bar mechanism is used to realize the pitching motion of the robot, and the hip joint which is connected in series with the five bar mechanism ensures the flexibility of the robot movement. The mechanism limits the attitude of the robot through the parallelogram mechanism, so it improves the adaptability of the robot in unstructured environment. The utility model has the advantages of simple control, small inertia, strong bearing capacity, etc. So it can effectively realize various motion of the robot.

Figure 1. Mechanism Form.
The single leg mechanism comprises three active joints (joint A, joint B and joint C) and a passive joint (joint K). The joint A is used to realize the swing motion and both the joint B and joint C is used to realize the *pitching motion* of the robot. When the foot’s end of the robot is vacated, the parallelogram mechanism of BEHG and GHLK can keep the end bar KL have a constant attitude. So it can ensure the foot’s end and ground have the *same ground pressure angle* each time when the robot has the yaw movement. It improves the adaptive ability on the unstructured environment for the robot. When the robot hit the ground, the spring rod HL on the parallelogram mechanism can effectively play the role of *energy storage* and *buffer*. Foot’s end is made of spring steel based on the arch structure design about the human body, which play a good buffer role and reduce the impact of the robot’s face.

### Analysis of the Mechanism Freedom

The mechanism is a series and parallel mechanism. The *freedom* of the planar mechanism is calculated that lever AD as the frame. The agency consists 8 components that is n=8. It consists 13 low side and 0 high side that is pl=13, ph=0. The mechanism introduces a virtual constraint because of the existence of two parallel four bar mechanisms. The mechanism has the repeated component n=4, low side pl’=8, high side ph’=0. Putting them into the virtual constraint formula (1) can be repeated part of virtual constraint number p’=4. Putting the above data into the freedom formula (2) to get the freedom of plane parallel mechanism F2=2. The freedom of the hybrid mechanism can be obtained according to the calculation method of degree of freedom for a series mechanism.

\[
p' = 2p_l' + p_h' - 3n' \tag{1}
\]

\[
F = 3n-(2p_l + p_h - p') \tag{2}
\]

### Kinematics Analysis

#### Forward Kinematics Analysis

The kinematics analysis of quadruped robot is the base of robot motion control and gait planning. Establishing the robot coordinate system reasonably can simplify the process of kinematics analysis. In this paper, we use the *D-H method* to analyze the kinematics of the robot, and the coordinate system is used to establish the global coordinate system of the robot single leg, as shown in Fig. 2.

![Figure 2. The Coordinate System of the Mechanism of the Single Leg.](image)

The parameters of the connecting rod of the quadruped robot in the D-H coordinate system are shown in Tab. 1:
Table 1. D-H Parameters of Quadruped Robot.

<table>
<thead>
<tr>
<th>NO</th>
<th>$\theta_i$</th>
<th>$d_i$</th>
<th>$a_i$</th>
<th>$\alpha_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-90°</td>
</tr>
<tr>
<td>2</td>
<td>$\theta_1$</td>
<td>$l_1$</td>
<td>0</td>
<td>-90°</td>
</tr>
<tr>
<td>3</td>
<td>$\theta_2$</td>
<td>0</td>
<td>$l_2$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$\theta_3$</td>
<td>0</td>
<td>$l_3$</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>$\theta_4$</td>
<td>0</td>
<td>$l_4$</td>
<td>0</td>
</tr>
</tbody>
</table>

The expression of transfer matrix between adjacent coordinate system:

$$T_{i+1}^i = T_{rot}(z_i, \theta_i) * T_{tra}(z_i, d_i) * T_{tra}(x_i, a_i) * T_{rot}(x_i, \alpha_i)$$

$$= \begin{bmatrix}
\cos \theta_i & -\lambda_i \sin \theta_i & \mu_i \sin \theta_i & a_i \cos \theta_i \\
\sin \theta_i & \lambda_i \cos \theta_i & -\mu_i \cos \theta_i & a_i \sin \theta_i \\
0 & \mu_i & \lambda_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(3)

Coordinate system with respect to the coordinate system transformation matrix:

$$T_{5}^0 = T_{1}^0 * T_{2}^1 * T_{3}^2 * T_{4}^3 * T_{5}^4 = \begin{bmatrix}
\frac{c_1 c_{234} - c_1 s_{234}}{-s_234} & -\frac{c_1 s_{234}}{-s_234} & -s_1 & l_2 c_1 c_2 + l_3 c_1 c_{23} + l_4 c_1 c_{234} \\
\frac{-s_234}{-s_234} & \frac{c_234}{-s_234} & 0 & l_1 - l_2 s_2 - l_3 s_{23} - l_4 s_{234} \\
\frac{-s_1 c_{234}}{-s_234} & \frac{s_1 s_{234}}{c_{234}} & -c_1 & l_2 s_1 c_2 - l_3 s_1 c_{23} - l_4 s_1 c_{234} \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(4)

Simplified the formula (4)

$$T_{5}^0 = \begin{bmatrix}
n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(5)

Put data `$\theta_1 = 0^\circ$, $\alpha = 150^\circ$, $\gamma = 30^\circ(\theta_2 = 120^\circ, \theta_3 = 120^\circ)$, $\theta_4 = -60^\circ$' into (5):

$$p_x = -\frac{1}{2} l_2 - \frac{1}{2} l_3 - l_4$$

(6)

$$p_y = l_1 - \frac{\sqrt{3}}{2} l_2 + \frac{\sqrt{3}}{2} l_3$$

(7)

$$p_z = 0$$

(8)

**Foot End of the Robot Jacobian Matrix**

After deriving quadruped robot kinematics equation to describe the single leg, in order to describe the transmission between the foot end of the robot work space and joint velocity ratio, we define the linear transformation between the robot end velocity and angular velocity for the foot end of the robot Jacobian matrix.

The motion equation of the quadruped robot:

$$x = x(q)$$

(9)

The relationship between the joint velocity and the velocity of the foot end is as follows:
\[ \dot{x} = J(q)\dot{q} \]  

(10)

The T transformation matrix between define the foot end of the robot coordinate system x5y5z5 and robot coordinate system is \( T^i_5 = [n_i \ a_i \ p_i] \), which can be constructed by law:

\[
J_{li} = \begin{bmatrix} (p_i \times n_i)_z \\ (p_i \times a_i)_z \\ (p_i \times o_i)_z \end{bmatrix}
\]  

(11)

\[
J_{oi} = \begin{bmatrix} (n_i)_z \\ (a_i)_z \\ (o_i)_z \end{bmatrix}
\]  

(12)

The quadruped robot single leg foot Jacobian matrix is:

\[
J(q) = \begin{bmatrix} 0 & l_2s_{34} + l_3s_{44} & l_3s_3 & 0 \\ 0 & l_2c_{34} + l_3c_{44} + l_4 & l_3c_4 + l_4 & l_4 \\ -s_{234} & 0 & 0 & 0 \\ -c_{234} & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \end{bmatrix}
\]  

(13)

Because \( q_2, q_3 \) and \( q_4 \) in the joint variable Q are an indirect variable related to the driving joint variables,

\[
\dot{x} = J_1q_1 + J_2q_2 + J_3q_3 + J_4q_4
\]  

(14)

\[
\begin{cases} q_2 = -\alpha \\ q_3 = \alpha - \gamma \\ q_4 = \gamma \end{cases}
\]  

(15)

The robot single leg velocity Jacobian matrix:

\[
J = \begin{bmatrix} 0 & l_3(s_3 - s_4) + \frac{l_2l_3s_3 \sin(\alpha - \lambda)}{l_5 \sin(\gamma - \lambda)} - \frac{l_2l_3s_3 \sin(\beta - \lambda)}{l_5 \sin(\gamma - \lambda)} \\ 0 & \frac{l_2l_3c_3 \sin(\alpha - \lambda)}{l_5 \sin(\gamma - \lambda)} - \frac{l_2l_3c_3 \sin(\beta - \lambda)}{l_5 \sin(\gamma - \lambda)} \\ l_2c_2 + l_3c_{23} + l_4c_{234} & 0 \\ -s_{234} & 0 & 0 \\ -c_{234} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\]  

(16)

Performance Analysis of a Quadruped Robot

Summarize

The performance analysis of quadruped robot is an important link in the design process of the robot. The performance of the quadruped robot directly determines the overall performance of the robot. This chapter will mainly from the toe of the reachable workspace of the robot single leg performance analysis.
Analysis of Single Leg Toe Reachable Workspace

For quadruped robot, toe reachable workspace represents the collection of robot toe all reachable position, on behalf of the robot motion range of toe size reflects the maximum step size and the maximum robot leg height is an important indicator to measure the motion parameters, motion performance of quadruped robot.

We can see from Fig.3, the main structure parameters including the length of the connecting rod of L₁~L₈, the joint angle θ₁~θ₄ and α, β. By formula did not affect the length of the connecting rod mechanism of L₁ foot size end movement space L₁=0; joint angle is θ₃ and θ₄ are the joint angle θ₂ and β, and the length of the connecting rod joint decision parameters; therefore influence the mechanism parameters of the reachable workspace of the foot end of the connecting rod length of L₂~L₈, joint θ₁, θ₂ and β.

![Coordinate Diagram of Five Bar Mechanism](image)

In the 3D model of the robot, the rotation of the joint can be obtained quickly, and the rotation angle of the joint angle without interference is satisfied. Joint angle limit of theta 1 range -14.73°<θ₁<21.24°; joint angle 2 and β limit range of 122.69°<θ₂<161.4° and 33.25°<β<79.35°.

In order to facilitate the programming of the joint angle range of -14°<θ₁<20°, 125°<θ₂<160°; by formula can be calculated and rounding 40°<θ₃<115°, for forelimb φ=90°, θ₄=180°-θ₂-θ₃.

Quadruped robot single leg mechanism is designed in this paper is due to the series of five bar mechanism, the numerical method is chosen to solve the reachable workspace of toe.

According to the given link parameters and obtain the upper section of the joint angle range, application MATLAB programming can be obtained by robot shown in Fig. 3 coordinates on reachable workspace, as shown in Fig. 4.

![Toe 3D Workspace](image)

From the above figure can be seen the biggest step for 440mm robot; the highest lift height is 300mm; the maximum yaw adjustment of -150mm~200mm. A large range of motion in the robot pitch direction; a small range of motion in the transverse direction; have better ability of obstacle capability and lateral adjustment.
Simulation

In the single leg straight movement of the main movement of the robot for the two active rotation joints are defined as joint A and B, the other three driven joints are defined as joint C, B, D, E, F.

In the ADAMS simulation post-processing module can get the angular velocity and angular acceleration curve of the joint of the single leg, the angular velocity and angular acceleration curve of the joint is shown in Fig. 5 and Fig. 6. Through the analysis of single leg active joints of the whole movement process, On the basis of the above parameters, the model of single leg can be built in ADAMS, the moving-track curve of toe is obtained after setting the driving function and running the simulation.

![Figure 5. Curve of Active Joint Angular Velocity.](image1)

![Figure 6. Curve of Active Joint Angular Acceleration.](image2)

![Figure 7. Curve of Angular Velocity of Driven Joint.](image3)

![Figure 8. Curves of Angular Acceleration of Driven Joints.](image4)

In order to verify the kinematic performance of the single leg mechanism, the angular velocity and acceleration curves of the C, D, E, and F of the driven joints are derived respectively, as shown in Fig. 7 and Fig. 8.

According to the above motion curve that single leg joint in the process of the movement of the angular velocity curve is smooth, from lots of lots and touch movement process is basically the same, the swing segment and the support section of each joint movement for uniform motion, joint angular velocity was 150deg/s, the angular acceleration are 2400deg/s², all without overall joint movement obviously the speed mutation and impact load in the process of the whole movement, the movement is more stable state.

Conclusions

In this paper, according to the structural characteristics of the flexible joint with variable stiffness, a new type of single leg based on hybrid linkage mechanism is proposed and its freedom is analyzed based on the structure and motion buffering mechanism of German Shepherd Dog. At the same time, we also verify the rationality and feasibility of the organization. We also analyze the kinematics and the main performance and have the kinematics simulation. Finally, our study
provides a strong basis for the further optimization of the variable stiffness active flexible joint and structure design of Quadruped Robot.

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References


