Four-legged robot design and gait planning

R C Liu¹, G Y Ma¹, Y Chen¹, S Han¹, and J Gao¹

¹School of Mechanical, Electrical and Information Engineering, Shandong University at Weihai, China

Corresponding author and e-mail: J Gao, shdgj@sdu.edu.cn

Abstract. This paper proposes a new type of hybrid leg mechanism based on a five-bar mechanism. The single leg has three degrees of freedom. The positive and negative solutions of the leg mechanism are analyzed theoretically and solved with MATLAB. The gait planning choose diagonal gait. ADAMS is used to verify the centroid displacement and foot displacement of each leg of the gait planning. This model is proposed based on series-parallel mechanism. The mechanism not only increases the movement space and improves the carrying capacity, but also has the advantages of simple control and flexible movement. This research lays a theoretical foundation for later experiments.

1. Introduction

With the rapid development of robots, the substitution of robots has become a development trend, and robots have become a research hotspot today[1]. The foot robot is good at performing sports on various complex terrains, and its obstacle ability is strong, and it is easy to roll over. Therefore, foot robots are preferred in complex environments[2]. The foot robot can be divided into a series robot, a parallel robot, and a hybrid robot according to different leg structures. The existing serial-parallel hybrid robots have small working space, inconvenient control, interference of the arrangement position of the driver[3]. Therefore, it is necessary to provide a new configuration of series and hybrid robot leg to solve the above problems. This paper presents a new serial-parallel hybrid robot. The robot adopts a double-five-bar linkage in parallel and adds a freedom mechanism for hip rotation to solve the above problems.

2. Four-foot robot structure

Based on the mechanism of the five-bar linkage parallel legs, as shown in Figure 1. Figure 1 is a schematic structural diagram of a quadruped robot, and the whole robot is composed of four identical leg mechanisms and a fuselage. Four legs of the robot assigned to numbers 1, 2, 3, and 4, respectively. Three rotary drive motors are respectively added to the rotary pairs L, M and N.
3. Positive and inverse analysis of position

3.1. Analysis of the position Solution

Based on the parallel five-bar linkage leg mechanism, it is simplified into a flat five-bar, and its degree of freedom is analyzed. The single leg has three degrees of freedom and the whole machine has 12 degrees of freedom. The mechanism is simplified to a five-bar mechanism, as shown in Figure 3. AE as a rack, that is, static platform. CD as a foot, that is, moving platform. $\theta_1$, $\theta_4$ as an active input to the motor. Analyzing the planar five-bar mechanism. The lengths of the five bars are respectively $l_1=40\text{mm}$, $l_2=30\text{mm}$, $l_3=40\text{mm}$, $l_4=50\text{mm}$, $l_5=23\text{mm}$ and the angles between the five bars and the x-axis are respectively $\theta_1$, $\theta_2$, $\theta_3$, $\theta_4$ and the following relational expressions are obtained:
\[
\begin{align*}
\begin{cases}
x_b = l_1 \cos \theta_1 \\
y_b = l_1 \sin \theta_1 \\
x_d = l_3 + l_2 \cos \theta_2 \\
y_d = l_3 \sin \theta_2 \\
l_{cd} = \sqrt{(x_d - x_b)^2 + (y_d - y_b)^2}
\end{cases}
\end{align*}
\]
(1)
\[
\begin{align*}
\begin{cases}
x_c = x_b + l_2 \cos \theta_2 = x_3 + l_3 \cos \theta_3 \\
y_c = y_b + l_2 \sin \theta_2 = y_3 + l_3 \sin \theta_3
\end{cases}
\end{align*}
\]
(2)
\[
\theta_2 = 2 \arctan \left( \frac{B_0 + \sqrt{A_0^2 + B_0^2 - C_0^2}}{A_0 + C_0} \right)
\]
(3)

Among them, \( A_0 = 2l_1(x_2 - x_1) \), \( B_0 = 2l_1(y_2 - y_1) \), \( C_0 = l_1^2 + l_{cd}^2 - l_2^2 \).

MATLAB software analysis the model and get the result: \( x_c = 8.8080 \), \( y_c = -14.5763 \).

### 3.2. Analysis of the inverse solution

Known \( l_4, l_2, l_4, l_1, l_1 \). After \( x_c, y_c \) is taken in, solve \( \theta_1, \theta_2 \).

\[
\begin{align*}
\begin{cases}
x_b = x_c + l_4 \cos \theta_4 \\
y_b = y_c + l_4 \sin \theta_4
\end{cases}
\end{align*}
\]
(4)
\[
\begin{align*}
A_0 = (x_c - x_1)^2 + (y_c - y_1)^2 + l_1^2 - l_2^2 \\
B_0 = 2(x_c - x_1)l_1 \\
C_0 = -2(y_c - y_1)l_1 \\
A_0 + B_0 \cos \theta_4 + C_0 \sin \theta_4 = 0 \\
T = \tan(\theta_4 / 2) \\
\theta_4 = 2 \arctan T
\end{align*}
\]
(5)

Similarly, \( \theta_4 \) can be solved. Based on the above kinematic parameters, the model is solved and the leg parameters of the quadruped robot are worked out which laying the foundation for the next step of gait planning.

### 4. Four foot robot gait planning

Diagonal gait is a common gait for quadruped robots. According to research, diagonal gait is the most energy-saving gait in nature. For this model, we mainly study the diagonal gait, analyzing the stability of the robot during its advancement, and changing in the center of gravity[4]. The whole cycle time is 12s. Within 0-2s, legs 1 and 4 are raised, legs 2 and 3 are grounded, and within 2s-4s, legs 1 and 4 are rotated. Legs 2 and 3 Legs are still on the ground, 4s-6s, Legs 1 and 4 are on the ground. Within 6s-8s, Legs 2, 3 raise, 1,4 Legs on the ground, Within 8s-10s, Legs 2, 3 rotate, the legs 1 and 4 still touch the ground. within 10s-12s, the legs 2 and 3 land. At this time, all four legs are on the ground. as shown in Figure 4 for the timing diagram.
According to the analysis of the stability of the robot, it can be shown in Figure 5. In the a movement, the four feet are in the ground, and the center of gravity is at the intersection of the diagonal legs. In the b movement, legs 2 and 3 are lifted, legs 1 and 4 are on the ground. In the c movement, legs 2 and 3 rotate, and the center of gravity moves forward. In the d movement, the legs 2, 3 fall and the fuselage moves forward. In the e movement, the legs 1 and 4 lift, the center of gravity is at the intersection of the two legs. In the f movement, the legs 1 and 4 rotate, and the center of gravity moves forward. When the g moves, the four legs touch the ground and the body moves forward[5].

5. ADAMS software simulation results and analysis
According to the simulation result of Adams, as shown in Figure 6, the displacement of the centroid in the X, Y, Z directions can be easily seen. Displacement in the x-direction of the center of centroid represents the fluctuation of the left and right displacements. The maximum offset value less than 0.5 mm, indicating that the left and right offsets are small, and the forward movement is basically along the set trajectory. The Y-direction displacement of the center of centroid represents the stability of the upper and lower bumps. The maximum value of the upper and lower bump values is 0.03 mm, indicating that the machine is relatively stable and the fluctuation is small. The Z-direction displacement of the center of centroid represents the forward displacement, and the forward displacement in three cycles is approximately 20 mm.

The movements of the legs 1 and 4 in the Z and Y directions are the same, that is, the forward and downward movements of the two legs have the same tendency. The movement direction in the X
direction is opposite, that is, the left and right sides of the foot fluctuate in opposite directions. Therefore, it can be explained that the swaying of the body can just cancel. As shown in Figure 7 and Figure 8, the forward displacement in the three periods is about 20 mm. The maximum offset value of the left and right displacement fluctuations, it is less than 7.2 mm. After three cycles, the forward displacement of the four foot-ends is about 20 mm, which is basically consistent with the displacement of the center of mass of the body.

Figure 6. Displacement of centroid in three directions of XYZ

Figure 7. Foot direction displacement of legs 1,4
6. Conclusion
This paper studies the design and gait planning of a four-legged robot model based on a five-bar mechanism. By combining calculation with MATLAB software, the degree of freedom and the positive and inverse solution are analyzed theoretically. The simulation of the model by ADAMS software to obtain changes of each joint rotation, changes of centroid, changes of end of foot observation and analysis. Simulation results for verification which lays theoretical foundation for the next experiment.

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