Design and Kinematic Analysis of a Wall-climbing Robot for Bridge appearance Inspection

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Abstract: In order to solve the maneuverability and safety of large bridge appearance inspection, a new type of hexapod wall-climbing robot is designed. As an important branch of mobile robot field, the organic combination of ground mobile robot technology and adsorption technology greatly expands the application range of robot. This paper introduces the mechanical structure of two self-designed legged wall-climbing robots, puts forward four problems on the quadruped robot and improves them on the hexapod robot. At the same time, in order to control the hexapod wall-climbing robot, the kinematics model of the hexapod wall-climbing robot must be established, and on this basis, the forward and inverse kinematics equations of the robot should be solved. The research results show that the two new robots meet the requirements of reliable adsorption and flexible movement, and have large application scenarios. The forward and inverse kinematics solved by the established kinematics model is proved to be effective by experiments.

1. Introduction
Due to the difficulty of large bridge appearance detection, the traditional detection method (bridge detection vehicle + manual) has been difficult to meet the needs of modern bridge detection. In recent years, robots have been widely used in various fields. It is a trend of social development that robots take the place of human beings to do all kinds of dangerous, onerous, repetitive, monotonous, toxic and harmful work. In the field of robot application, hexapod wall-climbing robot[1] has the advantages of flexibility, strong load-bearing capacity, good stability, good movement flexibility and environmental adaptability. At the same time, the structural characteristics of its limb redundancy ensure that the robot can complete a variety of tasks, such as detection, flaw detection, cleaning and rescue in the fields of nuclear industry, construction traffic, petrochemical and fire fighting. It has a good application prospect[2-4]. At present, the research on wall-climbing robot all over the world has achieved fruitful results. The United States, Britain, France, and other countries have successively developed anti-explosive robots and reconnaissance robots for some special fields. China has also
developed some robots for anti-terrorism, detection, wall cleaning and other aspects. In terms of bridge detection, with the increase of bridge operation mileage and operation time, the workload of bridge inspection is increasing, so there is an urgent need to develop a fast, safe and stable bridge appearance inspection robot.

Bridge appearance detection needs to control the detection robot equipped with high-definition cameras to complete the task of high-altitude work, of which the most difficult is to control its movement. Therefore, this paper develops a new type of hexapod robot, which is composed of six legs to form a parallel mechanism, and each leg is composed of multiple connecting rods through joints. Because of the multi-chain structure, time-varying motion topology and redundant drive system of hexapod walking robot, its kinematics is more complex than that of wheeled mobile robot\[^5\]. To control the motion of the robot is to control the relative position, velocity and acceleration between the connecting rods and joints of the robot. Therefore, the kinematics model of the hexapod robot is the basis for the motion control of the hexapod robot.

Therefore, this paper first introduces the mechanical structure design of two wall-climbing robots developed by ourselves. The difference between the two wall-climbing robots mainly lies in the number of feet. Increasing the number of feet in a certain range can improve the stability and adsorption capacity of the robot in the process of movement. Then the solutions to several problems encountered after the design and production of the first quadruped wall-climbing robot are proposed and applied to the second hexapod robot. Finally, through the derivation of the forward and inverse kinematics algorithm, the forward and inverse kinematics model of the hexapod wall-climbing robot is established and successfully tested on the prototype.

2. Robot structure design
This section mainly introduces the mechanical structure design of the wall-climbing robot. The wall-climbing robot is initially designed with a quadruped structure, which is mainly composed of three parts, namely the fuselage and the claws of the legs. The fuselage is responsible for connecting each leg and installing relevant control components; the leg is responsible for the movement of the robot; the claw is responsible for realizing the adsorption of the robot to the wall. Figure 1 below is a three-dimensional model of the robot.

![Figure 1. Quadruped wall climbing robot](image)

2.1 Introduction of leg structure
For the leg structure of the robot, the leg of the first generation wall-climbing robot adopts the structure of three rotary joints and one ball joint, which is composed of four parts, namely hip, thigh, calf and claw. The hip and the thigh are connected by the thigh steering engine and drive the joint between them (the hip joint), the thigh and the lower leg are connected by the calf steering engine, and drive the joint between them (knee joint), the calf and the claw are connected by the ball head rod end joint bearing, and the joint between them (ankle joint), which has no driving device. Because in some processes, the angle between the calf and the wall will change, and the claw is in fixed contact with the wall, it is unreasonable to use a rigid connection between the claw and the calf. To sum up, a set of ball pairs is added here, which is realized by ball head rod end joint bearings. Figure 2 below shows the structural model of the robot leg.

![Figure 2. Structural model of the robot leg](image)
2.2 Introduction of claw structure

The claw part adopts a three-layer structure, which is the pressing plate, the main body of the claw part and the nailboard. The function of the pressing plate is to press the sealing ring on the main body of the claw and fix it with self-tapping screws. In addition, in order to enhance the sealing effect of the sealing ring, a tooth structure is designed on the contact surface between the main body of the claw and the sealing ring. Finally, in order to increase the friction between the claw and the wall, a nailboard is designed on the lower surface of the claw. The structure of the claw is shown in figure 3 below.

\[ F = \Delta \rho \times \pi \times r^2 \]  

(1)

Bring the data \( \Delta \rho = 0.5 \) and \( r = 6 \) into the quadruped robot, it is obtained that \( F = 56 \) N, and the single leg can bear the pulling force of about 5 kg, that is, it can bear the mass of 15 kg when the three legs of the quadruped robot adsorb. After the completion of the design, the total weight of the quadruped robot is 4 kg, so the adsorption force of the claw can meet the requirements.
2.3 Robot structure optimization
In the debugging, it is found that the quadruped robot has the problem of insufficient motion stability in the process of motion, so the robot is changed from quadruped to hexapod structure, which will be explained in the next chapter.

In addition, in the actual debugging process, it is found that some movements of the first generation wall-climbing robot can not be realized, so the second generation wall-climbing robot is optimized in the form of four steering gear plus a ball joint, which divides the thigh into two parts. in order to achieve more flexible posture control. Figure 4 below shows the optimized structure model of the robot.

After the design is completed, the weight of the hexapod robot is about 9kg. According to the calculation in the previous section, the robot can bear the weight of 25kg when five legs are adsorbed, so the structure is reasonable.

![Figure 4. Wall-climbing robot after structure optimization](image)

3. Problems and optimization
After the completion of the adapting of the quadruped robot, some problems are found. By analyzing the problem, the corresponding solutions are put forward and applied in the design of the hexapod robot.

3.1 The robot is not stable enough
Due to the robot has the process of quadruped adsorption to tripod adsorption in the process of movement, the overall adsorption force suddenly decreases by 25% for the whole robot system. At this time, the dynamic load is too large, and the body has a large sloshing, which has a great impact on the motion of the robot.

The solution is also very simple, adding two legs to the whole fuselage and changing the quadruped type to the hexapod type, which can effectively reduce the dynamic load from hexapod adsorption to pentapod adsorption.

3.2 The movement of the claw cannot be limited
The ball joint bearing is used in the connecting mechanism between the claw and the leg of the robot, so there is a problem that the movement of the claw can not be limited when the claw is not adsorbed on the wall. The movement of the claw can not be limited, which has a great influence on the normal
adsorption of the claw.

The solution is to add a spring between the upper surface of the claw and the lower surface of the leg. The default relationship between the lower surface of the rear leg and the upper surface of the claw is parallel.

3.3 There is a situation that the leg is out of position during the movement of the leg
Due to the robot legs move into position and the claw negative pressure completion is an equivalent state, so use the pressure sensors to monitor the posture of the four-legged robots. However, in the actual process, it is found that when the robot moves into position, it takes a certain time to complete the negative pressure, so the robot will continue to move after it moves into position.

In order to solve this problem, a group of current sensors are added to the robot system. After the leg movement is in place, the steering gear stops rotating due to the blocking of the steering gear and the sudden change of the current, and the steering gear stops rotating after the sudden current is detected. Delay for a certain time until the negative pressure reaches the specified value, and then proceed to the next action.

3.4 The negative pressure cannot be recovered when the claw is lifted
The vacuum pump used by the robot is the diaphragm vacuum pump, which can not be reversed and has certain pressure retention, so the negative pressure of the claw can not be restored after the power loss of the vacuum pump. The concrete manifestation is that the claw can not be detached.

In order to solve this problem, a group of normally closed solenoid valves are added to the robot claw. When the negative pressure state needs to be relieved, the solenoid valve is electrically opened, so that the claw part can relieve the negative pressure more quickly.

4. Kinematics Analysis of Robot
Robot kinematics determines the position and posture of the foot end through the parameters of each connecting rod, which mainly studies the motion displacement relation, velocity relation and acceleration relation of each joint. Forward kinematics analysis refers to solving the position and attitude of the end actuator of the robot according to the given joint variables of the robot. Inverse kinematics refers to the inverse solution of each joint variable of the robot according to the position and attitude of the robot end actuator. The most commonly used modular robot kinematics modeling method is the D-H method, Among them, the generalized transformation matrix is the most widely used.

4.1 Forward kinematics analysis
Forward kinematics refers to the known parameters of each joint and the pose of the end effector relative to the base coordinate system. By discussing the forward problem of kinematics, we can judge whether the kinematic requirements are met one by one for the robots that have completed the kinematic design, and prepare for the discussion of the inverse kinematic problems. In this paper, the initial coordinate system is first set as the center of the robot's upper surface (suppose there is no error between the design size and the parts of the robot, and the weight is evenly distributed), and then set the coordinate system of each joint. Through the relationship between each joint, established the rotation translation matrix, and finally solve the homogeneous transformation matrix. At a certain time, the position of the right hind leg is shown in figure 5:
From the figure, the $\theta_1$, $\theta_2$, $\theta_3$, $\theta_4$ is the rotation angles of waist, hip, leg and ankle. $n$, $m$, $h$ is the width and length of the waist bracket. $l_1$, $l_2$, $l_3$, $l_4$ represent the length of the connecting rod at the waist, hip, leg and ankle.

Because the sucker of the defining robot is close to the ground, and the waist connecting rod must be in the same plane as the fuselage, and a spring (constraint) is added between the upper surface of the claw and the lower surface of the leg, so when the sucker plane is close to the ground, the ankle sucker connecting rod is perpendicular to the wall space. Therefore, there is a certain correlation between the rotation angle of the steering gear on the upper ankle of each leg $\theta_4$ and $\theta_2$ and $\theta_3$. According to the relationship, we can get:

$$\theta_4 = -\theta_2 - \theta_3 + \pi / 2 \quad (2)$$

Here we create the parameter table for the $i$ joint as shown in Table 1:

| Motion sequence | Joint variable | $\alpha$ | $d$ | $a$ |
|-----------------|----------------|--------|-----|-----|
| 1               | $\theta_1$     | 270°   | 0   | $l_1$|
| 2               | $\theta_2$     | 0°     | 0   | $l_2$|
| 3               | $\theta_3$     | 0°     | 0   | $l_3$|
| 4               | $\theta_4$     | 0°     | 0   | $l_4$|

According to the established rotating joint coordinate system, the generalized transformation matrix from the $(i-1)$ joint coordinate system to the $i$ joint coordinate system\cite{10} can be listed, and the generalized transformation matrix in the motion sequence can be multiplied at once. It can be known that the total homogeneous transformation matrix\cite{11} of the robot execution end and base reference coordinates is:

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & r_{12} & r_{13} & p_x \\ 0 & r_{22} & r_{23} & p_y \\ 0 & r_{32} & r_{33} & p_z \\ \end{bmatrix}$$

$$r_{11} = -\cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_1 \sin \theta_2 \sin \theta_1 - \cos \theta_1 \cos \theta_2 \cos \theta_3)$$

$$r_{13} = -\sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_1 \sin \theta_2 \sin \theta_1 + \cos \theta_1 \cos \theta_2 \sin \theta_3)$$

$$r_{21} = -\cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_1 \sin \theta_2 \cos \theta_1 - \sin \theta_1 \cos \theta_2 \cos \theta_3)$$

$$r_{23} = -\sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_1 \sin \theta_2 \cos \theta_1 + \sin \theta_1 \cos \theta_2 \sin \theta_3)$$

$$r_{31} = -\cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_1 \cos \theta_2 \sin \theta_1 + \sin \theta_1 \cos \theta_2 \cos \theta_3)$$

$$r_{32} = -\sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_1 \cos \theta_2 \cos \theta_1 - \sin \theta_1 \sin \theta_2 \sin \theta_3)$$
\[ r_{13} = -\sin \theta_1 \]
\[ r_{23} = -\cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\sin \theta_2 \sin \theta_3 - \cos \theta_2 \cos \theta_3 \sin \theta_1) \]
\[ -\sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_2 \sin \theta_3 - \cos \theta_2 \cos \theta_3 \sin \theta_1) \]
\[ r_{22} = \sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\sin \theta_2 \sin \theta_3 - \cos \theta_2 \cos \theta_3 \sin \theta_1) \]
\[ -\cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_2 \sin \theta_3 - \cos \theta_2 \cos \theta_3 \sin \theta_1) \]
\[ r_{23} = \cos \theta_3 \]
\[ r_{33} = -\cos(\theta_3 - \theta_3 + \pi / 2) \cdot (\cos \theta_3 \sin \theta_3 + \cos \theta_3 \sin \theta_2) \]
\[ -\sin(\theta_3 - \theta_3 + \pi / 2) \cdot (\cos \theta_3 \cos \theta_3 - \sin \theta_3 \sin \theta_2) \]
\[ r_{32} = \sin(\theta_3 - \theta_3 + \pi / 2) \cdot (\cos \theta_3 \sin \theta_3 + \cos \theta_3 \sin \theta_2) \]
\[ -\cos(\theta_3 - \theta_3 + \pi / 2) \cdot (\cos \theta_3 \cos \theta_3 - \sin \theta_3 \sin \theta_2) \]
\[ r_{33} = 0 \]
\[ p_j = n / 2 + l_1 \cos \theta_1 - l_1 \sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_2 \cos \theta_3 + \sin \theta_2 \sin \theta_3) \]
\[ + \cos \theta_1 \cos \theta_2 \sin \theta_3 ) + l_1 \cos \theta_2 \cos \theta_1 \cos \theta_3 - l_1 \cos \theta_2 \sin \theta_3 \sin \theta_1 \]
\[ -l_1 \cos \theta_1 \sin \theta_3 \sin \theta_1 \]
\[ p_j = -m / 2 + l_1 \sin \theta_1 - l_1 \cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\sin \theta_2 \sin \theta_3 - \cos \theta_2 \cos \theta_3 \sin \theta_1 ) \]
\[ -\cos \theta_2 \cos \theta_3 \sin \theta_1 ) \]
\[ + l_1 \sin \theta_2 \sin \theta_1 + l_1 \cos \theta_3 \cos \theta_1 \sin \theta_3 \]
\[ -l_1 \sin \theta_1 \sin \theta_3 \sin \theta_1 \]
\[ p_j = -l \sin \theta_1 - l \cos(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_2 \sin \theta_3 + \cos \theta_3 \sin \theta_1 ) \]
\[ -l \sin \theta_3 \sin(\theta_2 - \theta_3 + \pi / 2) \cdot (\cos \theta_3 \cos \theta_1 - \sin \theta_3 \sin \theta_1 ) \]
\[ -l \cos \theta_1 \sin \theta_3 \sin \theta_1 \]

According to the formula (3), after determining the length and width of the waist support, the rod length of each part and the rotation angle, the coordinate position of the foot end can be determined.

### 4.2 Inverse kinematics analysis

The motion of the robot body can be realized by controlling all the driving joints of the standing leg, which leads to the inverse kinematics of the standing leg. The so-called inverse kinematics means that on the premise of determining the parameters of each joint and connecting rod of the mechanical leg, each joint variable of the mechanical leg is determined through the position and posture of the end effector of the mechanical leg, so that the end effector of the mechanical leg can achieve the desired position and posture\cite{12}. As shown in figure 6, the posture of the robot’s standing legs at a certain time is given.

![Fig. 6 the posture of the robot’s standing legs at a certain time](image)

For a robot with 6 degrees of freedom, the inverse kinematics solution is very complex, and there is generally no closed solution. For the position and direction of the end effector of a given robot, the joint angle of the connecting rod is required. This problem is sometimes unsolved or there is a phenomenon of multiple solutions\cite{13}.
First of all, determine the known conditions, and the parameters calculated here represent the same meaning as the parameters in forward kinematics above, and not repeat them here. Inverse kinematics is to calculate the joint angle variable from the given foothold, so we can get the coordinates \([a^o_x Ai, a^o_y Ai, a^o_z Ai]\) of foothold A relative to the base coordinate system O. Because the O center of the fuselage is considered when choosing the base coordinate system, so point \(\sum B\) is in the same plane as the coordinate system \(\sum O\), according to the length and width of the fuselage bracket and the height relative to the foothold, the coordinate \([a^o_x Bi, a^o_y Bi, a^o_z Bi]\) of point B can be obtained. Among them, \(a^o_z Bi = a^o_z Ai\).

First calculate \(\theta_1\), as shown in figure 7:

![Fig. 7 Top view of different positions of right hind leg](image)

We can calculate that:

\[
\theta_1 = A \tan 2(a^o_y Ai + m/2, a^o_x Ai - n/2)
\]

(4)

In the formula, \(A \tan 2(y, x)\) is a two-parameter inverse tangent function for calculating \(\arctan(y/x)\), which determines the quadrant of the angle by the symbols of \(x\) and \(y\).

At the same time, because the adsorption device in contact with the wall in this design is a vacuum sucker, in order to ensure its tightness, set the vacuum sucker in vertical contact with the wall. According to figure 7:

\[
\begin{align*}
L_i &= l_1 + l_2 \cos \theta_2 + l_3 \sin \theta_4 \\
H_i &= l_2 \sin \theta_2 + l_3 \cos \theta_4 + l_4
\end{align*}
\]

(5)

The \(\theta_2\) and \(\theta_3\) contain the magnitude and direction of the angle. According to formula (2), we can get the relation of \(\theta_4\) with respect to \(\theta_2\) and \(\theta_3\). But here we bring in \(\theta_4\) to participate in the
calculation to simplify the formula, and after finding \( \theta_4 \), we naturally find \( \theta_3 \).

In formula (5), we have obtained the parameter relationship of a standing leg of the robot on the vertical Y-z plane. Here, let’s find the relationship between the standing legs in the X-y plane. As shown in figure 8:

![Fig. 8 projection of standing leg on X-y plane](image)

According to the geometric relationship shown in figures 6 and 8, we can get:

\[
\begin{align*}
L_i &= \sqrt{(x_{Ai} - n / 2)^2 + (y_{Ai} + m / 2)^2} \\
H_i &= \frac{b_{z_{Ai}}}{z_{Ai}}
\end{align*}
\]  

(6)

According to formula (5) and formula (6), the equation of driving joint parameters expressed by known parameters can be obtained:

\[
\begin{align*}
l_2 \cos \theta_2 + l_3 \sin \theta_3 &= \sqrt{(x_{Ai} - n / 2)^2 + (y_{Ai} + m / 2)^2} - l_i \\
-l_2 \sin \theta_2 + l_3 \cos \theta_3 + l_4 &= -\frac{b_{z_{Ai}}}{z_{Ai}}
\end{align*}
\]  

(7)

The two equations in the simultaneous formula (7) are transformed into

\[
\begin{align*}
a_1 \sin \theta_2 + a_2 \cos \theta_2 &= a_3 \\
b_1 \sin \theta_4 + b_2 \cos \theta_4 &= b_3
\end{align*}
\]  

(8)

According to the previous known parameters, the solution can be obtained:

\[
\begin{align*}
a_1 &= -2l_5(l_4 + b_{z_{Ai}}) \\
a_2 &= 2l_5(l_1 - \sqrt{(x_{Ai} - n / 2)^2 + (y_{Ai} + m / 2)^2}) \\
a_3 &= l_1^2 - l_2^2 - (\sqrt{(x_{Ai} - n / 2)^2 + (y_{Ai} + m / 2)^2} - l_1)^2 - (l_4 + b_{z_{Ai}})^2 \\
b_1 &= 2l_5(l_1 - \sqrt{(x_{Ai} - n / 2)^2 + (y_{Ai} + m / 2)^2}) \\
b_2 &= 2l_5(l_4 + b_{z_{Ai}}) \\
b_3 &= l_1^2 - l_2^2 - (\sqrt{(x_{Ai} - n / 2)^2 + (y_{Ai} + m / 2)^2} - l_1)^2 - (l_4 + b_{z_{Ai}})^2
\end{align*}
\]  

(9)

Since any \( \theta \) angle is uniquely determined by \( \tan(\theta / 2) \) on interval \( 0 \leq \theta \leq 360^\circ \), so ordered that:

\[
l_1 = \tan(\theta_4 / 2) \\
l_2 = \tan(\theta_4 / 2)
\]  

(10)
\[
\sin \theta_2 = \frac{2t_1}{(1 + t_1^2)} \quad \cos \theta_2 = \frac{(1 - t_1^2)}{(1 + t_1^2)} \quad \sin \theta_4 = \frac{2t_2}{(1 + t_2^2)} \quad \cos \theta_4 = \frac{(1 - t_2^2)}{(1 + t_2^2)}
\]

By substituting the simultaneous formula (7), can get:

\[
\begin{cases}
(a_2 + a_3)t_1^2 - 2a_1t_1 - a_2 + a_3 = 0 \\
(b_2 + b_3)t_2^2 - 2b_1t_2 - b_2 + b_3 = 0
\end{cases}
\]

By solving the two equations of formula (12), can obtain:

\[
\begin{align*}
t_1 &= \frac{a_1 \pm \sqrt{a_1^2 + a_2^2 - a_3^2}}{a_2 + a_3} \\
t_2 &= \frac{b_1 \pm \sqrt{b_1^2 + b_2^2 - b_3^2}}{b_2 + b_3}
\end{align*}
\]

Therefore, the solution of the joint angle can be obtained finally:

\[
\begin{cases}
\theta_1 = A \tan \left(2 \left(\frac{\gamma_{,ii}}{y_{,ii} + m/2}, x_{,ii} - n/2\right)\right) \\
\theta_2 = 2 \arctan t_1 \\
\theta_4 = 2 \arctan t_2 \\
\theta_3 = \theta_2 - \theta_4 + \pi/2
\end{cases}
\]

So far, we have solved the inverse kinematics solution of the robot model in this design. The inverse kinematics itself has multiple groups of solutions, and multiple sets of joint angle values can make the end manipulator reach the desired position. The number of solutions depends on the number of joints and parameters of the manipulator [13]. However, as shown in figure 7, when the initial gait of the robot is specified, the angle value of \( \theta_2 \) can be determined that between -90~0 degrees, set the clockwise direction is the positive direction, so the corresponding optimal solution in accordance with the characteristics of the human body can be obtained by taking the corresponding solution in the corresponding angle range.

5. Conclusion

1) In this paper, the body structure of the designed quadruped wall-climbing robot is described, and under the experimental condition of building a quadruped robot prototype, aiming at the problems of insufficient adsorption force, poor stability and weak anti-overturning ability of the quadruped robot, design a new type of hexapod wall-climbing robot body structure, and the kinematics model of hexapod robot is built according to its mechanical body structure.

2) Based on the experiment on the prototype of the hexapod robot, it is verified that the adsorption capacity and stability of the sucker on the body structure of the new hexapod robot are higher than that of the quadruped robot, and the accuracy of the kinematics model built by the hexapod robot is also verified.

3) The detection robot can be applied to the appearance detection of large bridges, which can detect the appearance of bridges quickly and safely, and provide an intelligent detection scheme for bridge detection.
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