Research on Bionic Foot Design and Climbing Strategy of Quadruped Robot

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Abstract. Aiming at the problem that it is difficult for a quadruped robot to climb a large angle slope, the bionics principle of goat climbing was analyzed. A bionic goat hoofs structure and a foot-to-ground coupling climbing model were designed. A climbing strategy of lateral sloping on a large slope was proposed, and foot trajectory planning under this model was studied. This design can assist the quadruped robot to climb the specific rugged surface with large slope. By building a single leg control model, combining with the Simulink and Simpack co-simulation technology, the single leg bench 60° slope simulation test, simulation results show that this design can effectively improve the quadruped bionic robot for rugged terrain with large slope stability of slope surface support.

1. Introduction
Legged robots have complex mechanical structure and high control difficulty, but they have better passability than wheeled or tracked robots in rugged terrain. They can use independent landing points to optimize support and traction, while wheeled robots need continuous support paths[1]. At present, the mobility efficiency of the legged robot is much lower than that of the wheeled robot, so it is very important to improve the adaptability of the legged robot to the complex terrain, such as steep slopes and rugged terrain, which are difficult for wheeled vehicles to pass.

In recent years, quadruped robots have gradually realized fast and agile movement. In order to maintain airframe stability in such extreme dynamic motion, the quadruped robot's feet should be firmly in contact with the ground. When performing extreme movements, such as jumping, sprinting and climbing, a quadruped robot must exert a force tangent to the contact surface to propel itself. In this case, the robot's ability to apply tangential forces to the ground is limited by the foot's coefficient of adhesion, a key indicator in the design of the robot's foot.

The feet of quadruped robots can be roughly divided into spherical feet, cylindrical feet, flat feet and irregular bionic feet[2]. Spherical feet are widely used because of their simple structure. SpaceClimber[3-4], a hexapod robot with spherical feet designed to probe the moon or craters, is designed to adapt to steep slopes ranging from 35° to 45° and complex terraces covered with loose gravel. The advantage of the cylindrical foot is that the leg can rotate around the axis of the cylindrical foot in the landing stage, which to some extent makes up for the lack of freedom of the ankle joint and facilitates the control of the leg. Boston Dynamics' BigDog, LS3, and Wildcat all adopted this design[5]. The flat foot can fully contact with the flat ground, and the interaction between the foot and the ground in a large area is conducive to the quadruped robot to carry a large load. However, flat foot is difficult to adapt to rugged terrain, so flat foot is mostly used for larger quadruped robots to walk on the structured road surface.
With the deepening of bionics research on biological structure and function, the field of robot design is increasingly looking for design inspiration from nature. Literature [6] studied the terrain adaptation mechanism of large ruminant feet from the perspective of kinematics, and literature [7] studied the contribution of goat hooves shape to smooth and rough surface to reduce slip. All these studies provide reference for the design of robot bionic feet. Literature [8] introduces a kind of anti-skid foot with main and secondary heterotypic foot pads imitating cat claw retractable toe. and the biped plane robot equipped with this new foot could attach to the surface of the concrete block with a slope of 50 degrees, but the dynamic walking test of the multi-legged robot on the slope surface has not been carried out. Moreover the foot to coupling model for complex terrain related research often focused on the foot end structure design, associated with the machine behavior planning less. Literature [9] for the stability of the quadruped robot motility and on the slope topography contradiction, we design a higher comprehensive properties of body posture and strong point location planning method, but only in a single plane xoz, no use of quadruped robot leg side show degrees of freedom.

Inspired by goat mountaineering, this paper designed a bionic foot based on goat hooves structure, established a foot ground coupling model with the characteristic ground, and proposed a lateral climbing strategy to solve the problem of limited climbing ability of quadruped robot at present, and planned the foot trajectory in space. Through the comparison of the forward posture and the side posture climbing of the simplified bionic foot model, the effectiveness of the bionic foot and climbing strategy was verified. It realizes the continuous and stable gait walking on the slope with large Angle.

2. DESIGN AND METHOD

2.1. Bionic principles and foot design

Oreamnos Americanus is a kind of alpine ungulate that can live at an altitude of more than 4000 meters and a gradient of more than 60 degrees[10]. From the perspective of bionics, goats have relatively developed shoulder and neck muscles, short and stout limbs, and low center of gravity. From the front, his body is rather thin, which helps him climb up the narrow ledge[11]. When goats walk at normal speed, the maximum vertical ground reaction on their forefoot and hindfoot accounts for 67.5% and 37.5% of their body weight[12]. Compared with sheep, the hooves of goats are larger[13]. In conclusion, the structure of goat foot can be used for reference in the study of quadruped robot climbing.

The main characteristic of the goat foot structure is that there are two toes that can move independently. The toes are stiff at the tips, hollow in the middle of the foot, and soft underneath. When toes opened, they clamp firmly on the rock, and when closed, they get stuck in the crevices, providing grip and fine-tuning to hold steady. On hard pavement, the part that the sole of the goat foot contacts the ground is mainly the hard part of the edge and tip of the sheep's hooves. On soft ground and rough terrain, The sunken part of the sole is in contact with the irregular shape of the ground and bears the weight. Combined with the two movable toes, the entire sole is concave diagonally to cement the soil, limiting the flow of soil underneath, and increasing adhesion. In addition, the goat has a dewclaw structure suitable for rock and cliff terrain.
In the design of bionic foot, the bionic foot is divided into structural parts, elastic parts and coated parts. Among them, the bionic structure comes from the skeleton, which determines the movement direction of the mechanism. Bionic elastic parts come from the muscle, which reflects the passive degree of freedom; The bionics of the coated part are derived from the skin and it determines the contact surface and the direction of the force. The coated part will move along the direction of the structural part after being stressed.

Figure 2. Bionic goat hoof design

The left and right hooves of goat will produce a clamping effect, which changes the actual contact angle of the foot ground on the slope, and therefore changes the direction of the resultant force of friction. The foot ground binding force caused by the special macroscopic structure of the bionic hooves can also be counted as a part of the ground adhesion.

According to the different principles, foot adhesion can be divided into the friction force generated by the material surface, the structural force generated by the mechanical structure, the soil shear force generated by the subsidence action, the adsorption force generated by the special surface structures such as suction cup.

The geometric characteristics of the ground surface can be classified into hard ground and soft ground. Hard ground points to cement ground, rock surface and iron and steel ground to wait commonly. Soft ground is mainly represented by soil, according to the characteristics of the soil and the amount of water content can also be divided into sand, swamp and muddy land. In life, hard ground and soft ground are defined mainly on the basis of bearing characteristics. Under hard ground conditions, it is generally believed that the pressure deformation of such ground conditions is very small, so small that the naked eye can hardly see. However, the deformation of soft ground is very noticeable and can be easily measured.

This goat-like foot is made up of two hoof segments. Considering that the goat goes sideways up the hill while the general quadruped robot is designed to go up the hill by forward direction, the bionic toe is designed to be one front and one back. The contact surface is designed with small protrusions to increase friction. The toes have passive degrees of freedom and the Angle can be changed with the shape of the contact surface. On hard ground, the design can cover bumps, while on soft ground, the sand can be piled into bumps.

2.2. Hill-climbing strategy

Goat climbing is essentially a series of galloping jumps in which the animal pushes off the ground with its hind legs, grabs the top of the hill with its forelegs, lunges at the slope with its forelegs, and repeats the process[14]. Observation of the movement state of goats in the cliff climbing, we found that there are two characteristics of goat climbing, the first is that goats tend to oblique climbing, the second is that goats will choose some protruding points as landing points. The goats did not go straight up and down, but slanted upward along boulders on the cliffs. Similar to the road construction project in the face of large slope climbing operations, often zigzag roundabout road climbing. Although zigzag climbing lengthens the distance, it can effectively reduce the slope of the actual climb.

If the robot can stably stand on the inclined plane without skidding, it can reduce the actual climbing Angle by selecting the side climbing Angle. Therefore, the climbing problem can be decoupled into stable standing problem and walking planning problem.
Slope is the degree of steepness of surface units. The ratio of the vertical height $h$ and the horizontal distance $l$ of the slope surface is usually called the slope, namely the tangent value of the slope Angle. Slope calculation method is the percentage method, that is, the percentage of the elevation difference between two points and the horizontal distance. Its calculation formula is as follows: Slope = (elevation difference/horizontal distance) × 100%. As is shown in Fig.3. Take the inclined plane ABEO as an example, $\angle AOC = \theta$, Along the AO climbing on actual slope as $\tan \theta$. If the lateral uphill, Go uphill along a path OP with an $\alpha^\circ$ horizontal angle to the slope, boarded the slope as actual $\tan \beta$. The relationship between angles $\alpha$, $\beta$, and $\theta$ is as follows:

$$\sin \beta = \frac{h_s - h}{s \times \tan \theta} \quad (2)$$
$$\sin \alpha \sin \theta = \sin \alpha \sin \theta \quad (1)$$

$s$ represents the climbing distance, $h$ represents the elevation, $\alpha$ represents the slope Angle between slope and path, $\beta$ is the actual climbing Angle, and $\theta$ is the Angle of slope.

At present, the body of the most quadruped robots are parallel to the horizontal plane in the process of climbing, and the working space of the front and back legs is small under this climbing posture, which limits the stride length. In the case of steep climbing, it will exceed the working space of one leg, so this posture is not conducive to slope walking. As shown in Fig. 4, the height of front and hind legs of the main supporting edge, $h_F$ and $h_H$, are respectively:

$$h_F = h_B - 0.5l_B \tan \theta \quad (2)$$
$$h_H = h_B + 0.5l_B \tan \theta \quad (3)$$

Where, the slope is $\theta$, the length of the body is $l_B$, and the projection height of the centroid of the body on the ground is $h_B$.

If the slope is climbed in a lateral attitude, as shown in Fig. 4, $h_F$ and $h_H$ can be obtained from Equations 1-3:

$$h_F = h_B - 0.5l_B \tan [\sin^{-1}(\sin \alpha \sin \theta)] \quad (4)$$
$$h_H = h_B + 0.5l_B \tan [\sin^{-1}(\sin \alpha \sin \theta)] \quad (5)$$

Figure 3. Mathematical model of climbing slope

Figure 4. Slope climbing diagram of robot with two postures

Figure 5. Comparison of the size of foreleg workspace in two climbing postures
It is assumed that the projection height of the torso centroid on the ground $h_B$ is a constant value, the ratio of the height of the front and hind legs $h_F/h_B$ to $h_B$ can be used to measure the size of the leg workspace of the quadruped robot. The ratio of body length and height $l_B/h_B = 0.7$ is taken to compare the foreleg workspace of forward attitude and lateral attitude climbing. As shown in Fig. 5, when the climbing Angle $\theta$ is greater than $40^\circ$, the foreleg workspace in the forward attitude (red) decreases sharply, but the foreleg workspace in the lateral attitude (blue) is still large when climbing at a small Angle. The foreleg workspace of the quadruped robot is close to each other only when the side attitude (blue) is large, i.e., $\alpha$ is close to $90^\circ$, which also conforms to the definition of the side climbing Angle $\alpha$. It can be seen that the leg workspace of the quadruped robot can be improved significantly when climbing in the side attitude.

2.3. Coupling model
In order to verify the effect of this design in the climbing and walking of the foot robot, on the basis of the variable Angle, a kind of bionic foot with fixed Angle and the matching terrain coupled with it are simplified.

![Mathematical model of bionic foot size design](image)

In the Fig. 6, $\theta$ is the Angle between the leg and the normal of the inclined plane, $R$ is the bionic foot radius, $r$ is the distance from slot P to ankle point, $\alpha$ is the included Angle between the line from the point P to the ankle point and the foot end face, and $\beta$ is the relative inclination of the groove PAB. The quadruped bionic robot has two joints in one leg. Thigh length 250mm, The length of the mounting surface from calf to foot is 310mm. Feet and calf are fixed, no degree of freedom. Simplify it into a mathematical model and establish the coordinate system as shown in the Fig.6, We get: $P(r \cos \alpha, r \sin \alpha)$, $A(x_A, y_A)$, $B(x_B, y_B)$.

Equation of line AP:
$$\frac{y_A - r\sin \alpha}{x_A - r\cos \alpha} = \tan(\alpha + \beta - \pi) = \tan \Delta$$

(6)

The equation of circle:
$$x_A^2 + y_A^2 = R^2 \ (x_A \geq 0 \ y_A \geq 0)$$

(7)

The simultaneous solution is as follows:
$$x_A = (1 + \tan \Delta^2)^{-1}[r^2(\tan \Delta^2 \cos \alpha - \sin \alpha \tan \Delta) \pm \tau]$$
$$y_A = (\tan \Delta + \cot \Delta)^{-1}[r^2(\tan \Delta^2 \cos \alpha - \sin \alpha \tan \Delta) \pm \tau] - r(\tan \Delta \cos \alpha - \sin \alpha)$$

(8)

$$\{ \tau = [r^2(\tan \Delta^2 \cos \alpha - \sin \alpha \tan \Delta)^2 - (1 + \tan \Delta^2)(\tan \Delta^2 r^2 \cos \alpha^2 + r^2 \sin \alpha^2 - R^2 - 2r^2 \sin \alpha \tan \Delta \cos \alpha)]^{-1} \}$$

The sliding state of the bionic quadruped robot on the slope can be decomposed into the single leg rotating sliding with the joint as the center of the circle and the whole machine sliding. If all four legs contact the inclined plane but can not maintain stability, the whole machine sliding and the path is parallel sliding along the inclined plane; If the three legs stand firm, the whole machine remains motionless, and the sliding foot moves in a circle with the joints as the center. All motions of descent can be thought of as a combination of these two states.
Figure 7. Slip motion model of inclined plane

The single leg rotates and slips as shown in the Fig. 7, H is the radius of rotation, s is the step error, H is the height of the bulge.

\[
H = L \cos \theta \\
R - x_A \geq h \\
N(R - h, s) \\
\frac{BM}{NM} \geq \frac{AM}{AN}
\]

\[(x_B - 0)^2 + (y_B + L \cos \theta - R)^2 \geq (R - h - 0)^2 + (s + L \cos \theta - R)^2 \geq (x_A - 0)^2 + (y_A + L \cos \theta - R)^2 \]

Equation (13) builds the relationship among the design parameters \(x_A, y_A, R\) (The radius of curvature of the foot), \(\alpha, \beta, r\) (Locating parameters of grooves), \(L\) (The length of the leg), control parameters \(s\) (The step error), \(\theta\) (Leg Angle), and terrain parameters (the height of the bulge, Slope of the terrain and the convex shape, The distance between the bulges greater than \(s\), etc.) of the foot-ground coupling model. It provides the basis for the construction of simulated terrain and the selection of key parameters of bionic foot design.

2.4. Foot trajectory planning

The commonly used foot trajectory of quadruped robot is programmed according to sinusoidal curve[15]. It is difficult to limit the velocity in the middle of the trajectory. Moreover, when walking on non-ideal road surface, it is difficult to carry out complex curve fitting with piecewise changes, thus increasing the instability of the robot. Bezier curve can generate complex smooth curve with only a few control points, and it can plan the foot velocity and acceleration at the same time. It is simple to control but has a strong description ability, and is suitable for the planning of complex segmentation path in space.

The trajectory planning of the swing phase foot is segmenting fitted by third-order Bezier curve, which is divided into lifting section and descending section. The Bezier curve defined by control points \(P_0, P_1, ... P_n\) has the following equation:

\[
C(u) = \sum_{i=0}^{n} B_{n,i}(u)P_i
\]

\[
\frac{d}{du} C(u) = C'(u) = \sum_{i=0}^{n-1} B_{n-1,i}(u)\{n(P_{i+1} - P_i)\}
\]

\[
B_{n,i}(u) = \frac{n!}{i!(n-i)!} u^i (1-u)^{n-i}
\]

Therefore, the trajectory of the third-order Bezier curve is:

\[
C(u) = (1-u)^3 P_0 + 3u(1-u)^2 P_1 + 3u^2(1 - u)^1 P_2 + u^3 P_3
\]

Foot movement speed:
\[ C(u) = 2(1 - u)^2(P_1 - P_0) + 4u(1 - u)(P_2 - P_1) + 2u^2(P_3 - P_2) \]  

(17)

The fitting result is expressed in the world coordinate system as follows:

Forward climbing attitude:

\[
\begin{align*}
    x(t) &= \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3\right] \frac{s \cos \theta}{2} - 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} \\
y(t) &= 0 \\
z(t) &= \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3\right] \left(\frac{s \sin \theta}{2} + h\right) - 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} 
\end{align*}
\]

(18)

\[
\begin{align*}
    x(t) &= \frac{s \cos \theta}{2} \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3 + 1\right] + 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} \\
y(t) &= 0 \\
z(t) &= 2\left(\frac{2t}{T}\right)^3 - 3\left(\frac{2t}{T}\right)^2 + 1\right] h + \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3 + 1\right] \frac{s \sin \theta}{2} + 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2}
\end{align*}
\]

(19)

Lateral climbing attitude:

\[
\begin{align*}
    x(t) &= \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3\right] \frac{s \cos \alpha}{2} - 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} \\
y(t) &= \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3\right] \left(\frac{s \sin \alpha \cos \theta}{2} - 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} \\
z(t) &= \left[3\left(\frac{2t}{T}\right)^2 - 2\left(\frac{2t}{T}\right)^3\right] h - 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2}
\end{align*}
\]

(20)

\[
\begin{align*}
    x(t) &= \left[1 - 2\left(\frac{2t}{T}\right)^3 + 3\left(\frac{2t}{T}\right)^2\right] \left(\frac{s \cos \alpha}{2}\right) + 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} \\
y(t) &= \left[1 - 2\left(\frac{2t}{T}\right)^3 + 3\left(\frac{2t}{T}\right)^2\right] \left(\frac{s \sin \alpha \cos \theta}{2}\right) + 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2} \\
z(t) &= h\left[2\left(\frac{2t}{T}\right)^3 - 3\left(\frac{2t}{T}^2 + 1\right\right] + \left[1 - 2\left(\frac{2t}{T}\right)^3 + 3\left(\frac{2t}{T}\right)^2\right] \left(\frac{s \sin \alpha \sin \theta}{2}\right) + 3\left(\frac{2t}{T}\right)^2 \left[1 - \left(\frac{2t}{T}\right)^2\right] \frac{v}{2}
\end{align*}
\]

(21)

Where, S is the step length, H is the step height, V is the step speed, T is the swing period, and T is the time variable. Taking s=1, h=1 and v=1, foot trajectories of the two climbing strategies are shown in Fig. 8.

![Figure 8. Foot trajectory diagram](image-url)
\[ \theta_3 = \pm \frac{L_2 + L_3}{L_3} \varphi \]  

\[ \varphi = \cos^{-1} \left( \frac{L_2^2 + (x-x_0)^2 + (y-y_0 - L_1 \sin \theta_1)^2 + (z-z_0 + L_1 \cos \theta_1)^2 - L_1^2}{2L_2(x-x_0)^2 + (y-y_0 - L_1 \sin \theta_1)^2 + (z-z_0 + L_1 \cos \theta_1)^2} \right)^{1/2} \]  

Where, \( L_1, L_2, L_3 \) are the lengths of the rods between the motor joints respectively, \( \theta_1, \theta_2, \theta_3 \) are the rotation angles of the motor in turn, and \( P(x_0, y_0, z_0) \) are the coordinates of the connection point between the single leg and the fuselage relative to the centroid coordinate system.

3. The simulation

A single leg 60° slope bench model was designed for simulation. The design slope is 60°, each 100mm interval has a raised wooden strip with a cross section of 32mm×18mm. Take the foot radius \( R=43.65mm \). The Angle \( \theta \) between the leg and the normal line of the inclined plane is 30° when the foot ends are completely fitted to the inclined plane. The coordinate system is constructed with the center of the cross section semicircle of the foot as the origin and the forward direction of the horizontal radius as the positive direction of the X axis. Shown as Fig.6. Groove PAB three anchor point coordinate \( P (2.57, 28.1), A (10.77, 42.3), B (17.8, 39.86) \) respectively.

The co-simulation technology of Matlab2020A and Simpack2018 is used to carry out the simulation. A simple single-leg control algorithm is built for single-leg bench test. Firstly, foot trajectory planning is carried out according to geometric relations. Then, the rotation Angle of each joint is calculated by inverse kinematics, and the joint torque is controlled by PID to build the control model from foot trajectory to single leg movement. Finally, the data of foot contact force and peak joint moment are measured and analyzed.

![Figure 9. Simplified foot design model](image)

![Figure 10. Control program](image)

The simulation results are as follows: Fig. 11 shows that the single leg of the swing phase moves according to the plan and can be coupled with the inclined plane. The single leg is set to move downward and contact the inclined plane. Fig.12 shows the change of the interground force of the foot. The contact force of the foot is the resultant force of the supporting force and the friction force. The stable support force of one leg is greater than half of the gravity of quadruped robot, which can meet the requirements of stable support.
4. Conclusion

A bionic goat hooves is designed and a corresponding foot-ground coupling model is proposed, which can meet the requirements of stable standing of quadruped robot on large slope.

The bionics principle of mountain climbing is analyzed. Aiming at the slope climbing problem of the quadruped robot, a lateral climbing strategy is proposed. Combined with the bionic foot design, the movement trajectory of the quadruped robot is planned, so that the comprehensive performance of the quadruped robot under the climbing condition can be maximized in two aspects of movement space and movement stability.

In order to adapt to the slope terrain, control the landing speed and reduce the impact when the swing leg lands, the foot trajectory planning method is improved. The experimental results show that...
the experimental prototype can support and travel stably in the environment with large slope under the control of the proposed algorithm, which proves the feasibility and effectiveness of the method, and indicates that the strategy has certain practical value. However, due to the restriction of the strong coupling relationship between the foot structure design and the ground environment, the generality of robot walking planning is poor. Therefore, the following research will be carried out in combination with terrain perception and recognition module, aiming at self-seeking of suitable landing points for the robot, so as to improve the intelligent level of the robot.

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