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Design and Stability Analysis of the Hexapod Robot with Manipulator

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Abstract

Compared with other types of robots, legged robots are more adaptable to complex terrain, and have great application prospects for operation in natural scenes. At present, the legged robot does not consider the influence of the grasping operation status on its stability, and it is difficult to achieve grasping objects while adapting to the terrain. In this paper, a hexapod robot capable of grasping objects is designed. Taking the insect leg structure as a bionic object, the robot leg structure is designed, and the "skeleton" design principle is adopted to reduce the quality of the robot. Aiming at the force change of the robot on the flat ground and the slope, the stability of the robot is analyzed by the center of gravity projection method and the minimum stable distance method, the stability conditions are obtained, and the slope stability is simulated and analyzed. The simulation results show that when the center of gravity satisfies the stability condition, the robot can maintain balance, which provides a certain theoretical basis for the research on the stability of the legged robot.

Keywords

Hexapod robot, manipulator, center of gravity projection method, stability analysis.

1. Introduction

Mobility is the basis for other tasks of the robot. At present, scholars at home and abroad have developed various mobile robot platforms, such as wheeled, crawler, legged, and bionic motion. Among them, the legged robot has strong terrain adaptability compared to the wheeled robot, high mobility and strong load capacity compared to the crawler robot, and it has become one of the research hotspots of mobile robots, such as the ostrich-like biped robot Cassie of Oregon State University in the United States, Spot quadruped robots of Boston Dynamics, spider-like six-legged robots and multi-legged robots. Hexapod robots are favored by scholars among legged robots because of their good stability.

At present, the design of the hexapod robot is mainly based on the principle of bionics, imitating insects such as ants and spiders, and has achieved fruitful research results in its structural design, movement gait, and stability strategy [1]. However, the existing research mainly focuses on the non-operating state of the hexapod robot. The design of the operating mechanism of the robot as a mobile platform and the influence of the change of its center of gravity and posture during the operation on its motion performance have not been considered. Therefore, current research cannot meet the application requirements of robots under operating tasks.

Based on this, aiming at the characteristics of common work tasks that are mainly based on grasping, this paper designs a hexapod robot that integrates work manipulators.

Using multi-legged insects as a prototype, the overall structure of the robot is designed. The stability of the operation status in the plane and the inclined plane is analyzed respectively, and the feasibility of the stability operation is verified by simulation.

1.1. Structure Design of Hexapod Robot with Manipulator

In order to use the hexapod robot as the mobile platform to carry out the grasping mission, the robot mobile chassis is designed bionicly. According to the basic movement requirements of the grasping, a four-degree-of-freedom mechanical arm is designed. The overall structure of the robot is shown as Figure 1.

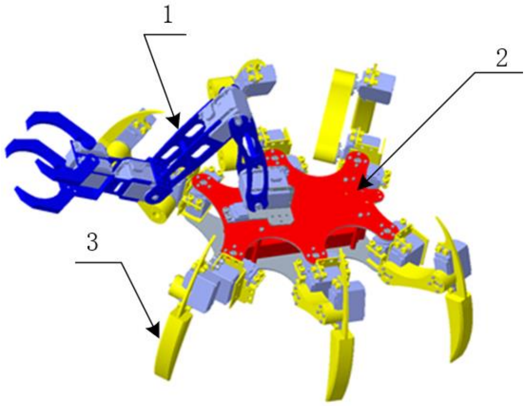

Figure 1: Schematic diagram of the overall structure of a hexapod robot with manipulator. 1- Manipulator. 2- Fuselage. 3- Leg.

1.1.1. Design of Robot Walking Structure

The leg structure is the main component of the legged robot, which has a huge impact on the robot's motion performance. This paper takes the multi-legged insect leg as the bionic object. It has multiple limbs and at least one kinematic pair at each joint. Taking into account the requirements of compact and light weight of the robot, the insect leg structure is simplified, and the leg structure is designed to be lightweight [2]. The leg structure is shown in Figure 2.

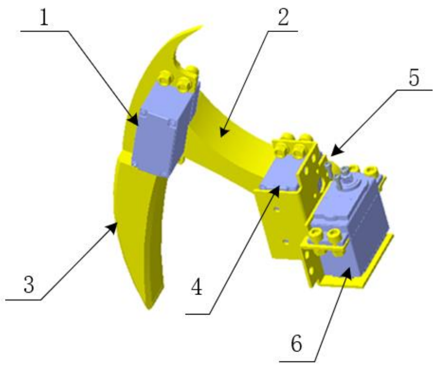

Figure 2: Leg structure. 1, 4, 6- Actuator. 2- Upper limb. 3- Lower limb. 5- Connector

The leg structure have three joints, which correspond to the waist, hip, and knee joints of insects. The actuator 6 drives the waist joint, has the function of connecting the legs and the fuselage. It can complete the swing of the fuselage, and maintain the stability of the fuselage. The connector 5 fixes the actuator 4 and 6 together, which saves space and increases the rigidity of the legs. The actuator 4 drives the hip joint and can raise and lower the entire leg. The actuator 1 drives the knee joint and can complete the posture adjustment of the foot [3, 4].

Based on the leg structure design, the robot body structure is designed. The body of the fuselage is designed to approximate a regular hexagonal shape, imitating a multi-legged insect, and the six legs are symmetrically arranged to increase the movement stability. Through reasonable configuration of the legs, the movement space of the legs is increased when the legs are moving, and at the same time, the mutual interference between the legs is avoided to a large extent[5]. The walking structure of the robot is shown in Figure 3.

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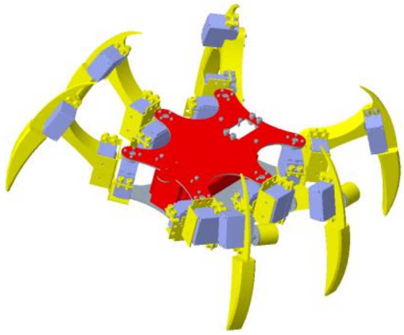

Figure 3: Robot walking mechanism

1.2. Structure Design of Manipulator

General industrial robots need 6 degrees of freedom(DOF) to achieve any posture operation in three-dimensional space. Since the robot walking mechanism can assist the flexible movement in two DOF, this paper only designs a four DOF manipulator. In order to ensure that the robot has a strong ability to overcome obstacles and can grasp objects at the same time, the manipulator is designed as a "skeleton" structure, which not only reduces the load on the fuselage body, but also ensures a larger working space. When the manipulator is in a non-operating state, it can save space by folding its own joints and enhance the stability of the fuselage [5].

The structure of the manipulator is shown in Figure 4, the first joint of the manipulator realizes yaw posture adjustment of gripper, and the second, third, and fourth joints realize the pitch posture adjustment. By cooperating with the body motion, it can realize the grasping operation in three-dimensional space [6].

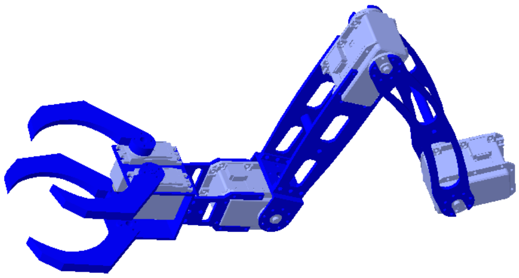

Figure 4: Manipulator structure

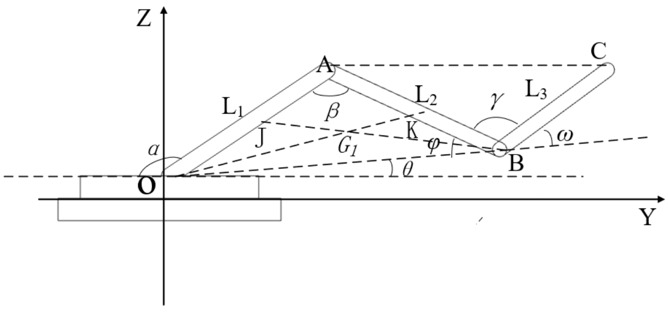

Figure 5: Two or more references

2. Stability Analysis of Hexapod Robot for Grasping

2.1. Analysis of the Position of the Center of Gravity of the Robot

Due to the existence of the manipulator, the position of the center of gravity (COG) of the robot is different from ordinary hexapod robot. The COG of evenly distributed objects is generally the geometric center, so we can superimpose the COG of the manipulator and the COG of the body to obtain the COG of the entire robot in this paper. In order to facilitate the analysis of the COG,

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the manipulator is simplified and a three-dimensional coordinate system is established [7]. The simplified model is shown in Figure 5.

In the simplified model, the condition for the length of the three rods is: $L_1 \geq L_2 > L_3$ and the rotation angles between the joints are α、β and γ. When the robot move, the body is in motion, and the manipulator is in a relatively static state. When the manipulator is working, the fuselage is stationary, so the COG of the fuselage can be regarded as a fixed point, and the COG of the manipulator is a moving point, and the superimposed COG of the robot can be regarded as a moving point analysis.

In Figure 5, an auxiliary line is made to connect OB and AC to form triangle OAB and triangle ABC. The geometric center points G_1 and G_2 are respectively obtained. The midpoint between the two points is the geometric center G_3 of the entire mechanism, that is, the COG. In the triangle OAB, the length of OA is known to be L_1, so the coordinates of point A can be obtained as $(-L_1\cos\alpha, L_1\sin\alpha)$. According to the law of cosines, the length of OB is

$$L_{OB} = \sqrt{L_1^2 + L_2^2 - 2L_1L_2\cos\beta} \tag{1}$$

The expression of φ can be obtained by using the law of sine.

$$\varphi = \arcsin\frac{L_1\sin\beta}{OB} \tag{2}$$

Therefore, the angle between OB and X axis can be obtained $\theta=\beta+\varphi-\alpha$. Thus the coordinates of point B can be obtained as $(L_{OB}\cos\theta, L_{OB}\sin\theta)$. Take the midpoint K of AB, connect OK, take the midpoint J of OA, connect BJ, then the intersection of the straight line BJ and OK is the geometric center point G_1. In the same way, the geometric center G_2 of the triangle ABC can be obtained, and the midpoint of G_1 and G_2 is G_3, and the COG coordinates of the entire mechanism can be obtained as $(0, y_{G3}, z_{G3})$. Assuming that the YOZ plane rotates ε around the Z axis, the coordinate of the COG of the robot in space is G_3' $(y_{G3}\cos\varepsilon, y_{G3}\sin\varepsilon, z_{G3})$.

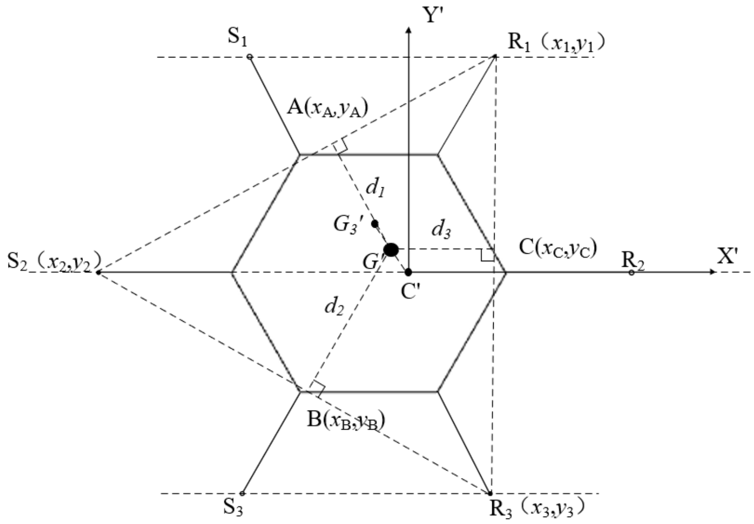

Figure 6: Diagram of COG projection analysis

2.2. Analysis of the Static Stability of the Robot on the Plane

The stability of the robot when walking on a flat ground can be analyzed by the COG projection method. Hexapod robots usually walk in a triangular gait. Projecting the COG of the robot on the plane composed of three legs, if the COG projection point is in the triangle, the robot maintains balance and has a certain anti-interference ability. If the COG projection point is not in the triangle, the robot is at risk of losing its balance [8].

When the fuselage moves, the manipulator is in a static state. Figure 6 shows the projection of the standing point and COG of the hexapod robot on the XOY plane. From the COG analysis, the coordinates of the COG of the manipulator on the XOY plane is G$_3$' ($y_{G3}\cos\varepsilon$, $y_{G3}\sin\varepsilon$). The COG of the fuselage can be determined as C' by the projection triangle, so the midpoint of the two points is the COG projection point G' of the robot.

When one set of legs S_1, R_2, S_3 of the robot is raised, the other set of legs R_1, S_2, R_3 supports the fuselage, so the COG of the fuselage will shift to the right. The coordinate system X'C'Y' is established with C' as the origin. Perpendicular to the three sides of the triangle through G', the vertical feet are A(x_A,y_A), B(x_B,y_B), C(x_C,y_C). Suppose the distances from G' to the three sides are d_1, d_2, d_3. The standing point of the foot supporting the fuselage is set to $R_1(x_1,y_1)$, $S_2(x_2,y_2)$, $R_3(x_3,y_3)$. Since G' is the midpoint of G$_3$' and C', therefore, the coordinates of G' are $(\frac{y_{G_3}\cos\varepsilon}{2},\frac{y_{G_3}\sin\varepsilon}{2})$. In order to facilitate analysis, set the coordinates of G' as ($x_{G'}$,$y_{G'}$). Therefore, the equation of the straight line R_1S_2 is:

$$y=\frac{y_1-y_2}{x_1-x_2}(x-x_1)+y_1 \tag{3}$$

So the equation of the perpendicular G'A is:

$$y=\frac{x_2-x_1}{y_1-y_2}(x-x_{G'})+y_{G'} \tag{4}$$

Combining the above equations (3) and (4) can obtain the coordinates of point A. So $d_1=\sqrt{{x_A}^2+{x_B}^2}$ can be obtained, and the expressions of d_2 and d_3 can be obtained in the same way. According to the concept of stability margin, the stability margin $D_m=\min\{d_1, d_2, d_3\}$ is defined. When $D_m\geq 0$, the COG of the robot falls within the projection area. At this time, the robot is stable and has certain immunity[8].

2.3. Stability Analysis on Inclined Plane

When walking on the inclined plane, compared to walking on flat plane, since the height of the COG is affected by the inclination of the inclined plane, the stability margin cannot reflect the influence of the height of the COG and the interference of external forces on the stability of the robot. To solve this problem, the minimum stable distance method is used to analyze the stability of the robot on the inclined plane [9].

There are two basic assumptions: (1) The bottom of the robot's foot is in point contact with the ground, that is, there is only force between the ground and the soles of the feet, and no torque is transmitted. (2) The stability analysis only considers the overturning balance of the robot and ignores the sliding of the sole relative to the ground, that is, it is assumed that the friction between the sole and the ground is infinite. The force analysis model of the hexapod robot is established, as shown in Figure 7.

Establish a global coordinate system f_1, with the XY plane parallel to the horizontal plane. f_2 is the reference coordinate system. The plane where the n_1n_2 axis is located is the plane where the robot is located, and the n_3 axis is perpendicular to the plane where the robot is located. The included angle between the Z axis and the n_3 axis is the included angle of the inclined plane. M_G and F_G are the external torque and force received by the robot, m is the mass of the robot, G is the COG of the robot, the projection in the n_1n_2 plane is G', and C is the center of pressure. K_1, K_2, and K_3 are the supporting force of the ground to the supporting leg. Draw a vertical line across G' to the R_1L_2 side, and the vertical foot is b. Establish e, t, a unit vectors with b as the origin, e is the unit vector along the edge of R_1L_2, t is the unit vector perpendicular to e, and a is the unit vector perpendicular to e and t. Assuming that the distance from G' to the edge of R_1L_2 is λ, the minimum value of λ is the stability margin of the robot. The larger the margin, the better the stability of the robot. Using the force analysis of the robot, the minimum stable distance of the robot can be derived. According to the definition of the pressure center, the vector sum of the supporting force of the ground reaction on the robot around a certain point is equal to the moment of the resultant force at the pressure center to a certain point.

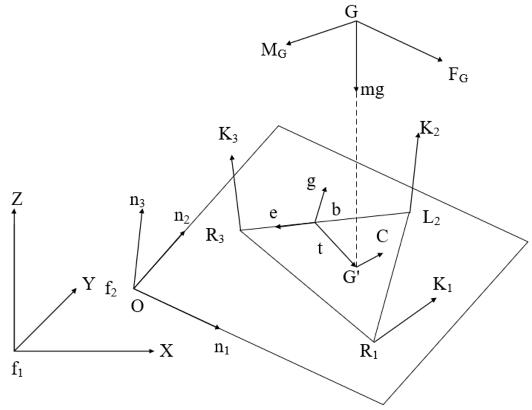

Figure 7: Robot force analysis diagram

$$r^{OC} \times \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} r_i^{OP} \times K_i \cdot \tag{5}$$

$$a \cdot r^{OC} = 0 \, . \tag{6}$$

Multiplying both sides of formula (5) by *a*, according to formula (6), we can get

$$r^{OC} = \frac{a \cdot \sum_{i=1}^{n} r_i^{OP} \times K_i}{(a \cdot \sum_{i=1}^{n} K_i)} \cdot \tag{7}$$

The torque balance equation around the reference coordinate system O is:

$$\sum_{i=1}^{n} r_i^{OP} \times K_i = -r^{OG} \times (F_G + mg) - M_G \cdot \tag{8}$$

The force balance equation in the a direction is:

$$a \cdot \sum_{i=1}^{n} K_i = -a \cdot (F_G + mg) \cdot \tag{9}$$

Combining the above formulas can be derived:

$$r^{OC} = r^{OG'} + \frac{a \times (M_G + r^{G'G} \times F_G)}{(a \cdot (F_G + mg))} \cdot \tag{10}$$

Multiply both sides of the above equation by the vector **t**. If we want to keep the robot balanced, we need to keep C within the polygon. Therefore, the following formula needs to be satisfied:

$$t \cdot r^{OC} = \lambda + \frac{a \times (M_G + r^{G'G} \times F_G)}{(a \cdot (F_G + mg))} > 0 \cdot \tag{11}$$

Among them, $t \cdot R^{OG'} = \lambda$, $t = a \times e$, $g = -a_G z$. a_G is the algebraic value of gravitational acceleration.

$$\lambda_{\min} = \frac{e \cdot (M_G + r^{G'G} \times F_G)}{-(a \cdot (F_G + mg))} \cdot \tag{12}$$

Then the minimum stable distance derived from $\lambda > \lambda_{\min}$ is:

$$\lambda_{\min} = \frac{e \cdot M_G + hX}{-(a \cdot (F_G + mg))} \cdot \tag{13}$$

Among them, $X = e \cdot (z \times F_G) = (t \cdot z)(a \cdot F_G) - (a \cdot z)(t \cdot F_G)$, and h is the height of the center of gravity. If the robot is to maintain balance, the minimum stable distance $\lambda_{\min}$ must be greater than or equal to zero, otherwise the robot will lose balance.

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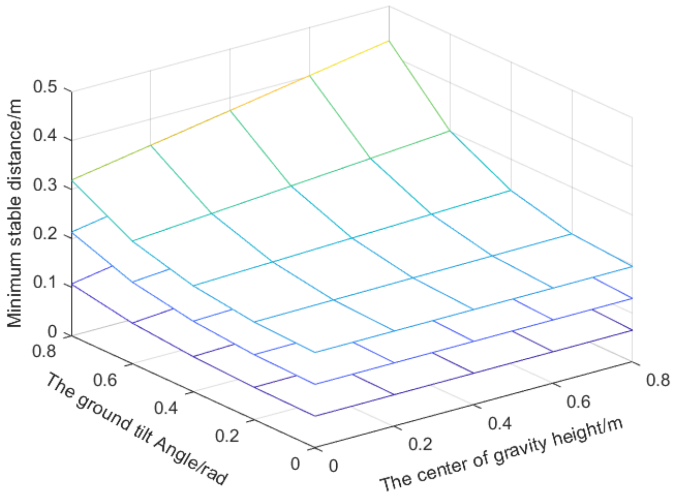
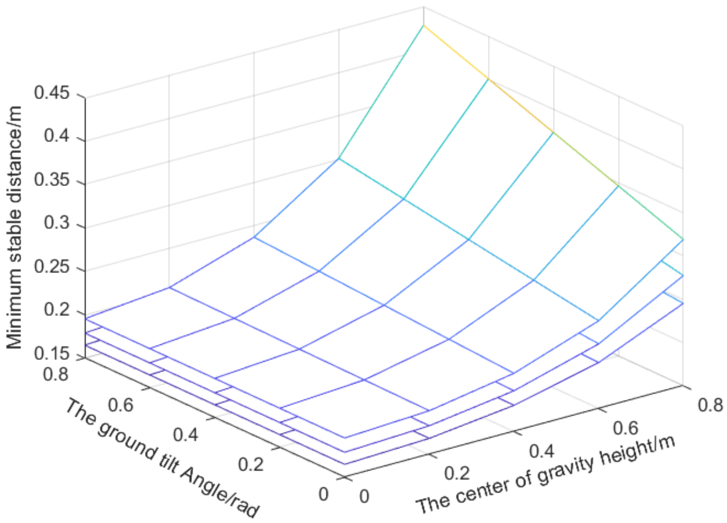
3. Simulation Analysis

In order to verify the formula (13),the corresponding mathematical model is established in MATLAB, and the initial conditions are given to the models respectively.The initial conditions are as follows:

The total mass of the robot is 3 kg. The acting force F_G is 3 N, 6 N, 9N. The acting moment M_G is 1.5(N·m), 3(N·m), 4.5(N·m). The height of the center of mass h is 0~0.8m. The ground inclination is 0~π/4, where F_G acts in the plane of vector n_3t, F_G and n_3 form 45°, and the direction is upward. The M_G direction is the same as the direction of the vector e. The direction of the ground inclination is along the direction of rotation with the R_1R_3 side as the axis. Different external forces and moments are controlled, and the curved surfaces obtained by different curves. The simulation results are shown in Figure 8.



(a)The relationship between the minimum stable distance λmin and the inclination of the ground and the height of the COG under different external moments.



(b)The relationship between the minimum stable distance λmin and the ground inclination angle and the height of the COG under different external forces.

Figure 8: Simulation diagram of minimum stable distance

It can be observed from the simulation graph that when the height of the COG or the inclination of the ground increases, the minimum stable distance λ_{min} will also increase, indicating that the stability margin of the robot decreases and the stability of the robot decreases[9]. From Figure 8 (a) and (b), it can be seen that the external moment has little effect on the ground inclination

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and the height of the COG, while the external force has a greater influence on the ground inclination and the height of the COG. Therefore, it is concluded that when the robot is moving on an inclined plane, try to avoid the interference of external force. At the same time, it can be concluded that the method of minimum stable distance is suitable for the analysis of the stability of the robot on the slope, and more accurate data can be obtained.

4. Conclusion

Aiming at the robot's requirement for stable grasping operations, this paper uses multi-legged insects as a prototype, combined with a manipulator bionic design of a hexapod robot capable of grasping objects. It retains the strong adaptability of the legged robot to complex terrain, while increasing the function of grasping objects. The COG projection method is used to analyze the stability of the robot on the horizontal plane. Using the method of minimum stable distance, the stability of the robot on the inclined plane is analyzed. Through these two methods, the stability of the robot on different roads can be accurately analyzed, which provides a certain theoretical reference for the future research on the stability of other types of robots.

Acknowledgements

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