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Stability Discrimination of Quadruped Robots by Using Tetrahedral Method

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ABSTRACT

Although the research of quadruped robot's stability has made great progress, most of the results are just local discriminant. However, there is no uniform standard for evaluating the stability of quadruped robots. In order to further study the static stability of quadruped robot and find a general method to describe the static stability of quadruped robots, a novel tetrahedron method is proposed to define the stability of quadruped robots. Firstly, this article describes the gait of the robot and obtains different duty cycle, which determines the form of the robot gait. Secondly, the tetrahedron method is briefly described, and the contact stability angle and diagonal stability angle are given. According to the relationship between the contact stability angle and diagonal stability angle that can obtain the minimum stable angle, which can be used to determine whether the quadruped robot is in a stable state. Thirdly, we analyzed the minimum tipping energy of the robot, and concluded that the centroid height and the minimum stable angle are the main factors that decide the minimum tipping energy of the robot. Finally, the influence of inclination angle, external force and external torque on the rollover performance coefficient is discussed, which provides a theoretical basis for robot design and control.

1. Introduction

Mobile robots are widely used in dangerous and unstructured environment, the moving ability and adaptability determine the performance of robots [1-2]. The stability analysis of quadruped robots is especially important in unstructured environment, so building reasonable quadruped robots stability performance evaluation index is the basis for robot design and control.

The judging method of static stability for the robot are the main focus of CG Projection Method [3], Static Stability Margin, SSM [4], Longitudinal Stability Margin, LSM [5], Crab Longitudinal Stability Margin, CLSM [6], Energy Stability Margin, ESM[7]. The dynamic stability criterion are the main focus of Center of Pressure Method, COP [8], Effective Mass Center, EMC [9], Zero Moment Point, ZMP [10], and Dynamic Stability Margin, DSM [11].However, for different backgrounds, we need to use different criteria to analyze the stability of robots, and all the criteria are only local discriminant methods, which makes the evaluation results unreliable [12].

2. The description of quadruped robot

2.1 Quadruped robot ontology

The quadruped robot's legs are made up of hip and knee joints. The hip joint has two degrees of freedom, so the whole mechanism has 12 degrees of freedom.

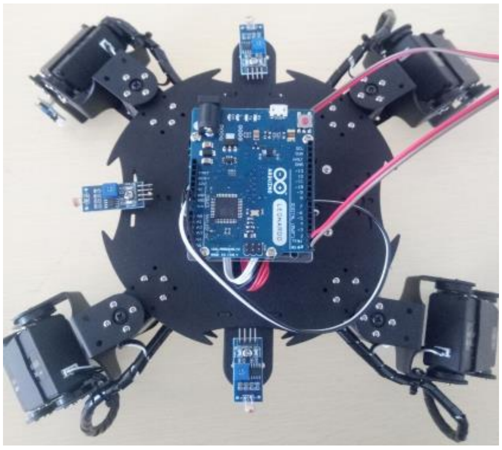

Fig. 1 Quadruped robot

According to the characteristics of the quadruped robot, its structural parameters can be measured. The specific parameters are shown in Tab.1.

Tab.1 Quadruped robot parameters

Body parameters	Unit（mm）

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Length	300
Width	300
Height	150
L1	60
L2	95
L3	65
Mass	2kg

2.2 Duty radio

The duty ratio refers to the ratio of the robot's support time to the period of motion, which determines the gait of the robot. Supposing that the support time of quadruped robot is T_{4leg}, the time taken by walking a cycle is T_{cycle}, and the air running time is T_{sw}, so that we can get the relationship between duty radio and time as shown in Fig.2[13]:

$$T_{cycle} = \frac{T_{sw}}{1-\beta} \tag{1}$$

$$T_{4leg} = T_{cycle} - 4T_{sw} \tag{2}$$

Tab.2 The relationship between duty radio and time

β	T_{sw}	T_{4leg}	T_{cycle}
0.75	1.00	0.00	4.00
0.80	1.00	1.00	5.00
0.85	1.00	2.67	6.67
0.90	1.00	6.00	10.00
0.95	1.00	16.00	20.00

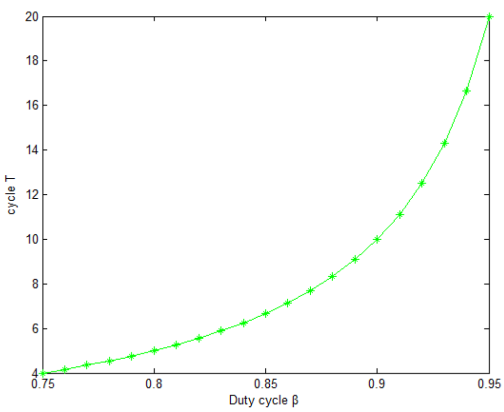

Fig.2 Cycle time of different duty radio

Tab.2 and Fig.2 show the relationship between duty radio β and cycle. When the duty ratio is $0.75 \le \beta < 1$, the walking gait of the quadruped robot is static gait, which indicates that the quadruped robot always has three legs or four legs on the ground.

3. The direct and inverse solution analysis

Position analysis is one of the core contents of the kinematics analysis, which is the basis of the mechanism velocity analysis, acceleration analysis, workspace analysis and mechanics analysis. *Denavit* and *Hartenberg* proposed the D-H method in 1955 and used it to model the robot. Since then, this method has become the standard method for robot modeling and kinematics analysis [14-15].

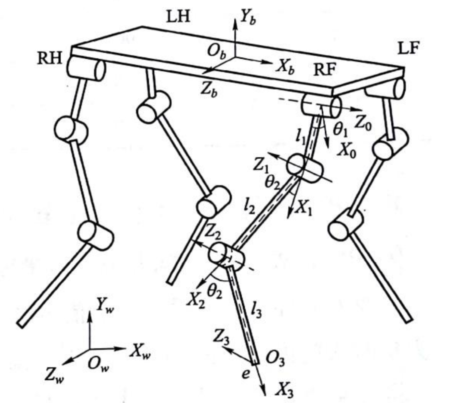

Fig.3 A brief description of robot

3.1 Direct solution analysis

Because the four legs of the robot are symmetrical, only one leg coordinate system needs to be established, as shown in Fig.3. According to the structure parameters and coordinate relations of the robot, we can get the D-H table, as shown in Tab.3.

Tab.3 Quadruped robot parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	90^0	L_1	0	θ_2
3	0	L_2	0	θ_3
4	0	L_3	0	0

The D-H parameters in Tab.3 can be taken into the general formula of the transformation matrix. General formula of transformation matrix T_i^{i-1} is given as follows.

$$ {}_0^1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, {}_2^1T = \begin{bmatrix} c_2 & -s_2 & 0 & L_1 \\ 0 & 0 & -1 & 0 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}_3^2T = \begin{bmatrix} c_3 & -s_3 & 0 & L_2 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, {}_w^3T = \begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Thus, we can have:

$$ T_w^0 = T_1^0 T_2^1 T_3^2 T_w^3 = \begin{bmatrix} c_1c_2c_3 - c_1s_2s_3 & -c_1c_2s_3 - c_1s_2c_3 & s_1 & p_1 \\ s_1c_2c_3 - s_1s_2s_3 & -c_2s_1c_3 - s_1s_2c_3 & -c_1 & p_2 \\ c_2c_3 + s_2c_3 & c_2c_3 - s_2s_3 & 1 & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

where:

$$p_1 = L_1c_1 + L_3(c_1c_2c_3 - c_1s_2s_3) + L_2c_1c_2 \quad (4)$$

$$p_2 = L_1s_1 + L_3(c_1c_2c_3 - c_1s_2s_3) + L_2s_1c_2 \quad (5)$$

$$p_3 = L_3(c_2s_3 - s_2c_3) + L_2s_2 \quad (6)$$

3.2 Inverse solution analysis

According to the geometric relationship of the mechanism, the foot position coordinates can be written as follows:

$$p_x = [L_1 + L_2\cos\theta_2 + L_3\cos(\theta_2+\theta_3)]\cos\theta_1 \quad (7)$$

$$p_y = [L_1 + L_2\cos\theta_2 + L_3\cos(\theta_2+\theta_3)]\sin\theta_1 \quad (8)$$

$$p_z = L_2\sin\theta_2 + L_3\sin(\theta_2+\theta_3) \quad (9)$$

Based on the Eq.(8) and Eq.(9), the next result is follows.

$$\theta_1 = \arctan(\frac{p_x}{p_y}) \quad (10)$$

Supposing that:

$$m = \cos\theta_1 \quad (11)$$

According to Eq.(8) and Eq.(9), we can get:

$$L_3\sin(\theta_2+\theta_3) = p_z - L_2\sin\theta_2 \quad (12)$$

$$L_3\cos(\theta_2+\theta_3) = \frac{p_x}{m} - L_1 - L_2\cos\theta_2 \quad (13)$$

The following equations can be obtained by resolving Eqs.(12-13).

$$A\cos\theta_2 + B\sin\theta_2 = C \quad (14)$$

where:

$$A = 2L_1L_2 - \frac{2p_xL_2}{m}$$

$$B = 2L_2p_z$$

$$C = L_3^2 - p_z^2 - L_2^2 - (\frac{p_x}{m})^2 - l_1^2 + (\frac{2p_x}{m})L_1$$

Solving Eq.(14),we can get the next equation.

$$\theta_2 = 2*\arctan(\frac{B\pm\sqrt{A^2+B^2-C^2}}{A+C}) \quad (15)$$

Taking θ_2 into Eq.(12),we can obtain θ_3.

$$\theta_3 = \arctan(\frac{p_z - L_2\sin\theta_2}{L_3}) - \theta_2 \quad (16)$$

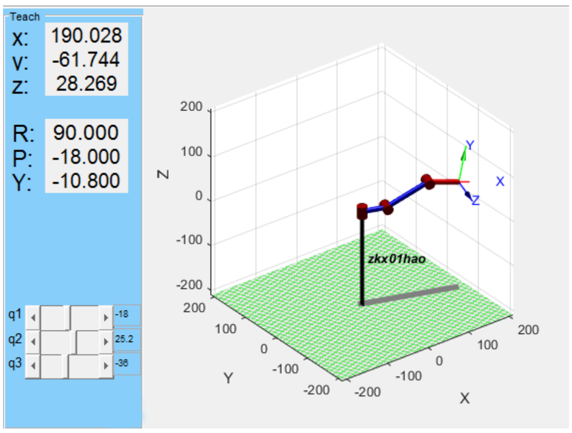

Fig.4 Direct simulation analysis

3.3 Direct and inverse solution verification

Given a set of parameters as follow: θ_1=-18^0, θ_2=25.2^0 θ_3=-36^0, according to Eqs.(4-6), we can obtain the position of the end point p_1=190.028, p_2=-61.744, p_3=28.269 .The specific simulation can be seen in Fig.4. Then, taking p_1=190.028, p_2=-61.744, p_3=28.269 into Eqs.(10,15,16), we can get θ_1=-18^0, θ_2=25.2^0 θ_3=-36^0.

Thus, the above analysis proves the effectiveness of the direct and inverse solutions, which provides necessary preparation for future analysis.

4. Tetrahedral method

On the basis of the force angular stability metric method [16] and the stable cone method [19], the stability of tetrahedron method is presented in this paper. This is a general method to judge the influence of various factors on the stability of the quadruped robot. The following assumptions are made when describing the method.

1) It is assumed that the mass distribution of the quadruped robot is uniform.
2) The contact of the quadruped robot to the ground is a point contact.
3) The foot and ground friction of the quadruped robot is infinite, and there is no skidding phenomenon.

When a quadruped robot walks steadily, it has three legs or four legs to contact with the ground. When the quadruped support, the robot's geometric center is coincided with centroid, so the robot is stable. However, when the three legs of the robot are in the supporting phase, the stability of the robot needs to be judged.

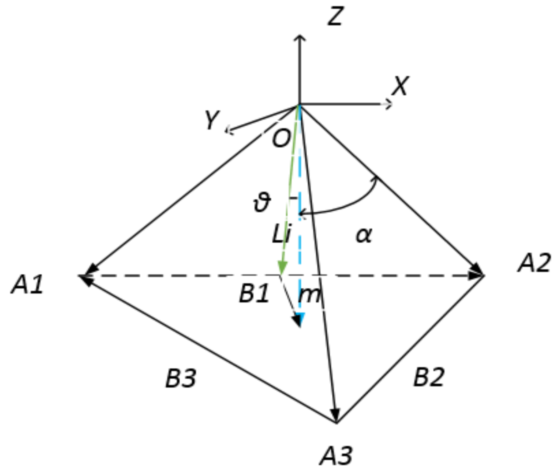

Fig.5 Tetrahedral stability expression

Fig.5 is the description of the robot stability by the tetrahedral method. $A_i(i=1,2,3)$ represent the contact point of the quadruped with the ground, the dynamic coordinate system $O-xyz$ is established at the centroid O. At this point, $O-A_1A_2A_3$ constitutes a tetrahedral structure. The vector m represents the direction of the centroid. $L_i(i=1,2,3)$ are the vector that perpendicular with B_i. We define the α_i as the contact stability angle, and the θ_i as diagonal stability angle.

The vector of the centroid O to the endpoints of each foot can be expressed as.

$$A_i = (A_x, A_y, A_z)(i=1,2,3) \quad (17)$$

According to the geometric relationship, we can get the following.

$$B_1 = A_2 - A_1 \tag{18}$$

$$B_2 = A_3 - A_2 \tag{19}$$

$$B_3 = A_1 - A_3 \tag{20}$$

$$L_i = (1 - e_{Bi} e_{Bi}{}^T) A_{i+1} (i = 1,2,3) \tag{21}$$

where, e_{Bi} represent the normal vector of B_i.

$$e_{Bi} = \frac{B_i}{\|B_i\|} (i = 1,2,3) \tag{22}$$

5. Stability discrimination

When the robot is tilting along the diagonal line, we use the angle θ_i between diagonal normal vector L_i and the vector m of the centroid as the criterion of stability. According to the mathematical relationship we can get.

$$\theta_i = \varepsilon_i \times arc\cos(e_m e_{Li}) \tag{23}$$

where,

$$\varepsilon_i = \begin{cases} +1, (e_m \times e_{Li}) e_{B_i} < 0 \\ -1, (e_m \times e_{Li}) e_{B_i} \ge 0 \end{cases} \tag{24}$$

When the robot is tilting along the foot end, we use the angle α_i between the vector of the centroid to the corner point A_i and the vector m of the centroid as the criterion of stability. According to the mathematical relationship we can get.

$$\alpha_i = g_i \times arc\cos(e_m e_{A_i})$$

where:

$$g_i = \begin{cases} +1, (e_m \times e_{Li}) e_{B_i} < 0 \\ -1, (e_m \times e_{Li}) e_{B_i} \ge 0 \end{cases} \tag{25}$$

In order to comprehensively evaluate the stability of quadruped robot, we will use the minimum value among the minimum contact stability angle α_i and its contiguous two diagonal stability angles θ_i as the stability criterion. Thus, the results can be obtained.

$$\sigma_1 = \min(\theta_3, \alpha_1, \theta_1) \tag{26}$$

$$\sigma_2 = \min(\theta_1, \alpha_2, \theta_2) \tag{27}$$

$$\sigma_3 = \min(\theta_2, \alpha_3, \theta_3) \tag{28}$$

The minimum value of the above three angles is taken as the stability evaluation index.

$$r = \min(\sigma_i) \tag{29}$$

From Eq. (29) we have the results, when $r < 0$, the robot is in a state of instability, when $r = 0$, the robot is in a critical state of stability, and when $r > 0$, the robot is stable. In general, the larger the r, the better the robot stability, and the robot will not tip-over.

We set up a simulation time of 30s and take a discrete point per 5s, and we can get the minimum stability angle at different times through the previous formula. In order to conveniently observe the relationship between the minimum stability angle and the time change, we have done the curve fitting. Here, three times polynomial, five degree polynomial, ten polynomial and thirteen polynomial are applied to curve fitting respectively. The fitting results show that the thirteen polynomial fitting result is not very different from the simulation value, so this paper adopts thirteen polynomial to do the curve fitting.

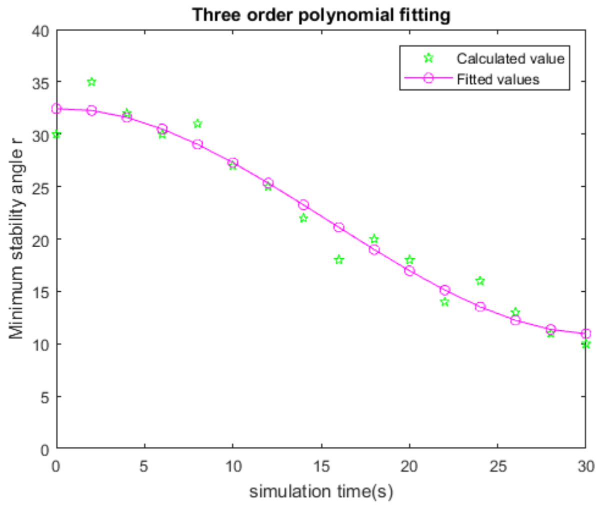

Fig.6 Three order polynomial fitting

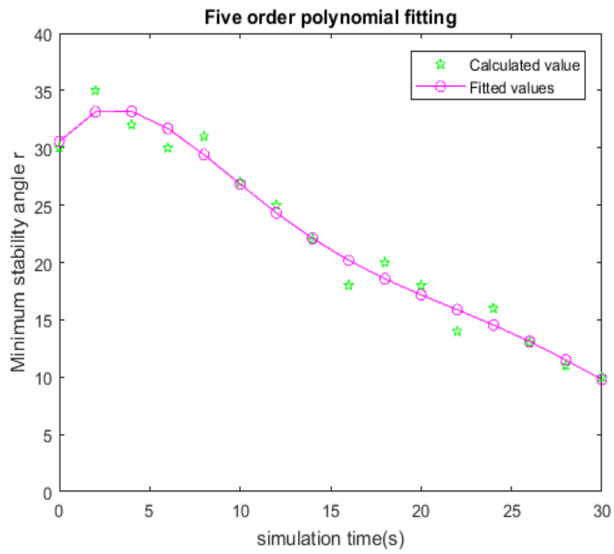

Fig.7 Five order polynomial fitting

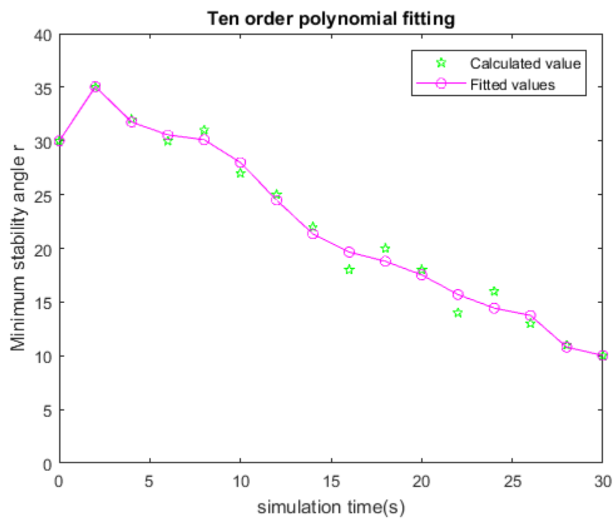

Fig.8 Ten order polynomial fitting

It can be seen from the fitting results of Fig.(6-9) that the robot has good stability under the initial state, and when the robot on uneven ground, because the environment is incompatible with each leg, it will cause the minimum stability angle changing. At the same time, we can understand from Fig.(6-9) that the initial minimum stability angle of the robot is 35°, and the tilting phenomenon is issued when the minimum stability angle is 10°.

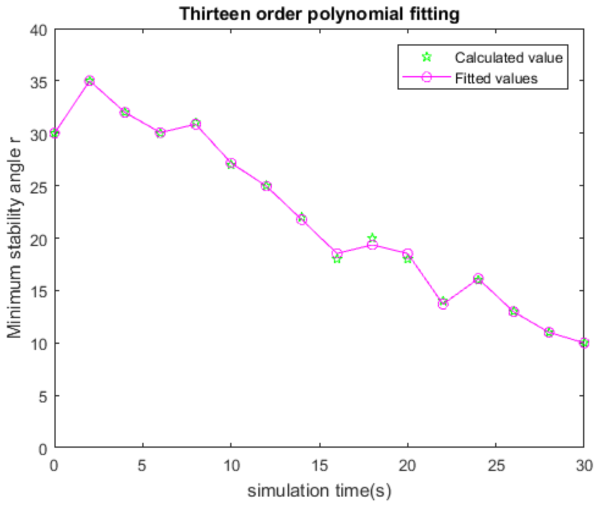

Fig.9 Thirteen order polynomial fitting

In the analysis of the dynamic stability, the minimum tipping energy consumed by the tilting axis and the flipping of the foot point must be considered in the dynamic condition. According to literature [16], the minimum tipping energy calculation formula is as follows.

$$E = \frac{mgh(1-\cos r)}{\cos r} \tag{30}$$

As we can see from Eq. (30) that the change of the centroid height and the minimum stability angle will affect the minimum tipping energy.

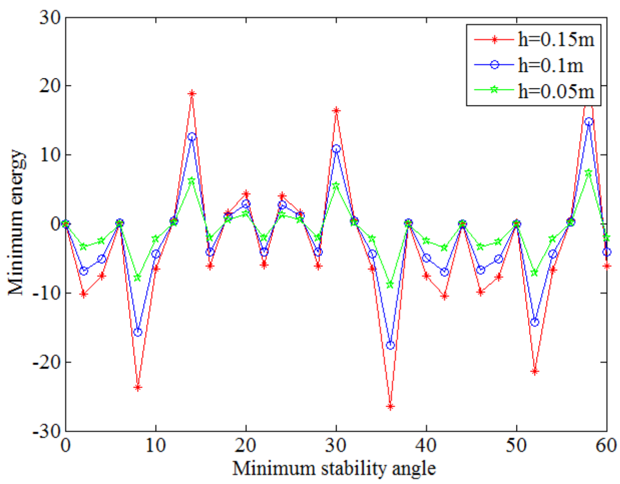

Fig.10 The relationship between energy and stability angle

It can be obtained from Fig.10, as the centroid height increases, the greater the minimum tipping energy is needed. At the same time, we can see that the minimum tipping energy with the increase of the minimum stability angle shows certain regularity, but the minimum tipping energy at some points is mutated, this is because the robot's legs are complicated with the contact environment. At this time, the robot is easy to lose stability, so that the robot needs more energy to make it not rollover.

Quadruped robots are easily affected by external loads when they walk in irregular terrain. If F and M are the resultant forces and resultant moments respectively, which acting to the robot centroid respectively. The resultant force of the external load and gravity is $(F+mg)$, so the resultant force of robot tipping is as follows.

$$F_i = (1-e_{Bi}e_{Bi}{}^T)(F+mg) \tag{31}$$

If there is the existence of M , the force of the robot is equivalent to Eq.(32).

$$F_e = F_i + \frac{L_i(e_{Bi}e_{Bi}{}^T)M}{\|L_i\|} \tag{32}$$

According to the geometric relationship, we can get the following relation.

$$h = L_i \cos\theta_i = A_{i+1}\cos\alpha_{i+1} \tag{33}$$

Taking Eq. (21) into Eq. (33), we can gain the result.

$$(1-e_{Bi}e_{Bi}{}^T)\cos\theta_i = \cos\alpha_{i+1} \tag{34}$$

According to Eq. (31) and Eq. (34).

$$F_i = \frac{(\cos\alpha_{i+1})}{\cos\theta_i}(F+mg) \tag{35}$$

$$F_e = F_i + e_{Li}\frac{\cos\theta_i - \cos\alpha_{i+1}}{\cos\theta_i}M \tag{36}$$

The analysis shows that when the robot walks on the inclined plane, the angle of change in the direction of the centroid equals the inclination angle χ of the inclined plane. At this time, the diagonal stability angle θ_i will take place change, where, we introduce a relational factor K .

$$\chi = \frac{K}{\theta_i} \tag{37}$$

$$F_i = (F+mg)\cos\chi \tag{38}$$

Combined Eq.(35) and Eq.(38), we can obtain the next conclusion.

$$\cos\chi = \frac{(\cos\alpha_{i+1})}{\cos\theta_i} \tag{39}$$

In order to evaluate the robot stability comprehensively, the rollover performance coefficient η is used as the criterion to determine the comprehensive influence of other components on robots [18].

$$\eta = \max(\frac{\varphi}{\theta_i} + \frac{\psi}{\alpha_{i+1}} + \phi\sqrt{\frac{\cos r_i}{1-\cos r_i}})(i=1,2,3) \quad (40)$$

where: r_i is the minimum stability angle, ϕ is the weight stability coefficient, ψ is the weight influence coefficient, φ is the energy stability coefficient, φ/θ_i represent the weight value of the axis tilting stability angle, ψ/α_i represent the weight value of the foot point tilting stability angle, $\phi\sqrt{\frac{\cos r_i}{1-\cos r_i}}$ represent the weight value of the tilting energy, η indicates the danger of the robot tilting during a movement, The larger the η is, the more easy for the robot is to lose stability, so that it can be used as a comprehensive criterion for the stability analysis of the robot.

When the robot is in a triangular stable gait, the weight coefficient ϕ , ψ and φ can be obtained by Tab.4. In general, $\phi=0.5$, $\psi=0.5$ and $\varphi=0.5$ are selected when there is no special requirement on the terrain, so that Eq. (40) becomes as follows.

$$\eta = \max(\frac{0.5}{\theta_i} + \frac{0.5}{\alpha_{i+1}} + 0.5\sqrt{\frac{\cos r_i}{1-\cos r_i}})(i=1,2,3) \quad (41)$$

Tab.4 Weight coefficient table [19]

weight coefficient	tripod gait		
ϕ	1	0.5	0.5
ψ	1	1	0.5
φ	1	0.5	0.5

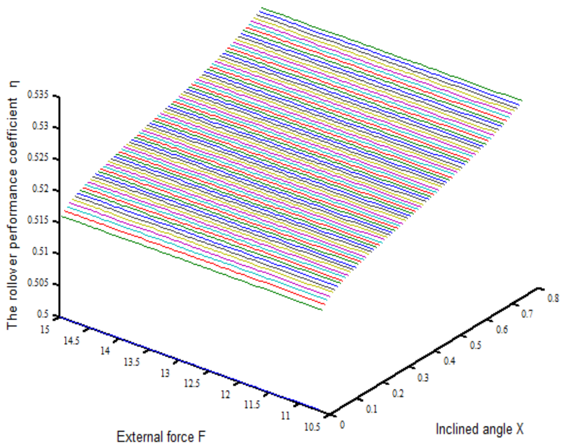

Fig.11 Response surface for the rollover performance coefficient (a)

According to Eqs. (35-41), we can have the result.

Assuming parameters are: $M = 0 \sim 20N\cdot m$, $\chi = 0 \sim 50^0$ $m = 2kg$, $F = 0 \sim 15N$, $K = 1$, $h_{\max} = 150mm$, it is can be obtained from Figs.(11-12) that how the parameters affect the stability of the quadruped robot.

$$\eta = \max\left(\begin{array}{l} \dfrac{0.5 ar\cos\dfrac{F_i}{(F+mg)}}{k} \\ + \dfrac{0.5}{\arccos\left(\cos\chi\cos\dfrac{k}{\chi}\right)} \\ +0.5\sqrt{\dfrac{\cos r_i}{1-\cos r_i}} \end{array}\right) \quad (42)$$

$(i=1,2,3)$

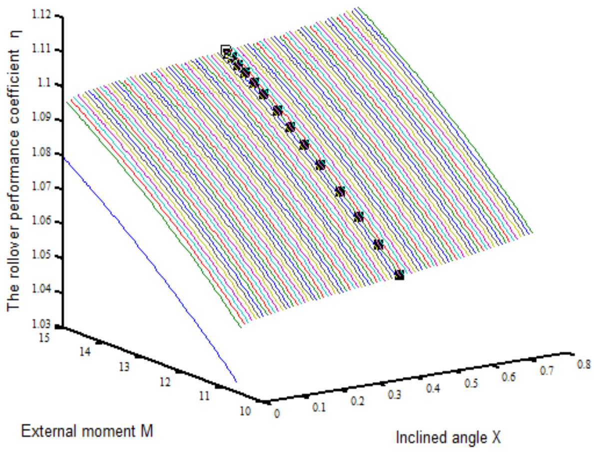

Fig.12 Response surface for the rollover performance coefficient (b)

It can be obtained from Fig.11 that the relationship between the rollover performance coefficient and the external force and the inclined angle when external moment is zero. The results show that the inclined angle has great effect on the rollover performance coefficient, and the force had little influence on the rollover performance coefficient, so the inclined angle is the main factor, which lead to the robot tip-over. As we can see from Fig.12 that the relationship between the rollover performance coefficient and external moment and inclined angle when external force is zero. The inclined angle and the external moment have a significant impact on the robot rollover performance coefficient, which indicates that the external moment and the inclined angle are the main factors leading to the tilting of the robot. In general, the robot should avoid in the steep road walking, and ensure that the external moment is as small as possible.

6. Summary

1) The gait of quadruped robots is briefly introduced. By analysis, it can be found that when the duty ratio is greater than 0.75, the robot is in a static gait. Then, the structure parameters of the quadruped robot are given, which lays the foundation for the robot analysis.

2) The D-H model of the quadruped robot is established, and the forward and inverse kinematics algorithm of the quadruped robot is given. The effectiveness of the forward and inverse kinematics algorithm is verified by simulation.

3) On the basis of the force angular stability metric method and the stable cone method, a novel tetrahedral method was introduced in this paper. We defined the contact stability angle α_i and the

diagonal stability angle θ_i , and regard the minimum stability angle r as the stability discriminant standard. In order to clearly show the relationship between the minimum stability angle and time, we have done the curve fitting. Three times polynomial, five degree polynomial, ten polynomial and thirteen polynomial are applied to curve fitting respectively. The fitting results show that thirteen times polynomial fitting can satisfy the requirement of precision.

4) The influence of the centroid height and the minimum stability angle on the minimum tipping energy for the robot is analyzed. The analysis results show that the higher the centroid height, the worse the stability of the robot.

5) In order to synthetically evaluate the stability of the robot, the rollover performance coefficient η is proposed. The analysis results indicate that the inclined angle and external moment are the main factors that decide the tip-over of quadruped robot. These theories provide important reference values for robot engineering practice.

Acknowledgements

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