Analysis of Obstacle-climbing Capability of Planetary Exploration Rover with Rocker-bogie Structure

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Abstract—Wheeled mobile robots are increasingly being utilized in unknown and dangerous situations such as planetary surface exploration. Based on force analysis of the differential joints and force analysis between the wheels and the ground, this paper established the quasi-static mathematical model of the 6-wheel mobile system of planetary exploration rover with rocker-bogie structure. Considering the constraint conditions, with the method of finding the wheels’ friction force solution space feasible region, obstacle-climbing capability of the mobile mechanism was analyzed. Given the same obstacle heights and contact angles of wheel-ground, the single side forward obstacle-climbing of the wheels was simulated respectively, and the results show that the rear wheel has the best obstacle-climbing capability, the middle wheel is the worst, and the front wheel is moderate.

Keywords—analysis of obstacle-climbing capability; planetary exploration rover; rocker-bogie; force analysis; solution space feasible region

I. INTRODUCTION

Many planetary exploration rovers have been developed since 1960s. According to the features of the mobile mechanism of robots, planetary exploration rovers have some types: wheeled, legged and tracked, etc [1-4]. Wheeled mobile mechanisms have some excellent features, such as high speed on a relatively flat terrain and easily control, so many researchers trended to design their exploration rovers with wheeled structure. Currently, wheeled structure planetary rovers have 4-wheeled, 6-wheeled and 8-wheeled, etc. Among them, the 6-wheel mobile system with rocker-bogie mechanism has superior adaptability and obstacle-climbing capability, which had been applied in Rocky series and Sojourner Mars Rover [5-7].

Taking the roll angle and pitch angle into consideration, this paper analyzed the force on the rover body with the method of quasi-statics, and established the force equation of the mobile mechanism of planetary rover with rocker-bogie under the constraint condition. When the wheels’ friction force solution space feasible region is inexistent, the mobile mechanism will not balance under the specified initial conditions, and has no obstacle-climbing capability. The right side forward obstacle-climbing of the wheels was simulated respectively.

II. FORCE ANALYSIS OF THE MOBILE MECHANISM

A. Introduce of the mobile mechanism

The principle of the 6-wheel mobile mechanism of planetary rover with rocker-bogie structure is shown in Fig. 1. Six independently driven wheels are mounted on an articulated frame. The frame has two rocker arms connected to the rover body. Each rocker has a rear wheel connected to one end and a bogie, connected to the other end. The bogie is connected to the rocker with a free pivoting joint and at each end of the bogie, there is a drive wheel. As in [8], the rockers are connected to the rover body with the differential joints so that the pitch angle of the body is the average of the pitch angles of the rockers.

B. Coordinate system

In Fig. 1, \( \theta_1 \), \( \theta_2 \), \( \theta_3 \) and \( \theta_4 \) define the configuration of the rocker-bogie mechanism, and can be calculated by using the method of inverse kinematics [8]. \( \psi \), \( \theta \) and \( \phi \) are the yaw, roll and pitch angles of the rover body. As the mobile mechanism of planetary rover is symmetrical, for convenient to force analysis of the mobile mechanism, we assumed that the yaw angle \( \psi = 0 \). \((x_0, y_0, z_0)\) are the center coordinates of the wheels, their subscript \# represents a (after), m (middle), f (front), r (right) and l (left). The other parameters of the mobile mechanism are shown in Fig. 1.
C. Force analysis of the differential joints

It is assumed that the rover body only subject to gravity, besides the force applied by the differential joints. Relative to the central coordinates of the two differential joints, the barycentric coordinates of the vehicle were \((x_b, y_b, z_b)\). Force analysis of the differential joints between the rover body and rockers is shown in Fig. 2. The rockers are connected to the rover body with the differential joints, thus can transfer the \(X\), \(Y\), \(Z\) axial forces and moments, which are defined as \(F_{y_b}, F_{y_l}, F_{z_b}, F_{z_l}, M_{y_b}, M_{y_l}, M_{z_b}, M_{z_l}, M_{sl}\) and \(M_{sr}\). \(G\) is gravity of the rover body. The force and moment balance equations of the rover body are written in the following:

\[
F_{y_r} + F_{y_l} = 0
\]
\[
F_{y_r} + F_{y_l} + G_y = 0 \quad (2)
\]
\[
F_{z_r} + F_{z_l} - G_z = 0 \quad (3)
\]
\[
G_z(y_b \cos \phi - x_b \sin \phi) - G_x y_b - M_{wr} - M_{zl} + (F_{z_r} - F_{z_l}) \frac{w}{2} = 0 \quad (4)
\]
\[
G_x(x_b \cos \phi + z_b \sin \phi) - M_{yr} - M_{zl} = 0 \quad (5)
\]
\[
(F_{z_r} - F_{z_l}) \frac{w}{2} + M_{wr} + M_{zl} - G_z(x_b \cos \phi + z_b \sin \phi) = 0 \quad (6)
\]
\[
M_{yr} = M_{zl} \quad (7)
\]

The forces applied on the wheels by ground only need to balance gravity and the horizontal driving force, so we assume that the forces applied on the wheels can be decomposed into three forces: the horizontal force \(F_{xx}\) along direction force \(F_{y} \) and the normal force \(F_{z}\), as shown in Fig. 2. The meaning of subscript ‘#’ is the same as above.

The forces applied on the two sides articulated frames are defined in (8), (9), and their sum equal gravity, as in (10).

\[
F_r = F_{y_r} + F_{mr} + F_{wr} \quad (8)
\]
\[
F_t = F_{y_t} + F_{mt} + F_{at} \quad (9)
\]
\[
F_r + F_t = G \quad (10)
\]

For convenience, it is assumed that the origin of force \(F_r\)

and \(F_t\) are the center of the triangle, which vertexes are the center of the wheels. The \(Y\) axial forces of \(F_r\) and \(F_t\) can be obtained as in (11) and (12). The \(X\) axial moment balance equations can be described as (13) and (14). Subscript ‘A’ means the center of differential joint.

\[
F_{y_r} = F_r \sin \theta \quad (11)
\]
\[
F_{y_t} = F_t \sin \theta \quad (12)
\]
\[
\frac{F_{x_r}}{\sin \theta} \left(\frac{y_{fr} + y_{mr} + y_{wr}}{3} - y_{dr}\right) - M_{wr} = 0 \quad (13)
\]
\[
\frac{F_{x_t}}{\sin \theta} \left(\frac{y_{fr} + y_{mt} + y_{at}}{3} - y_{al}\right) - M_{al} = 0 \quad (14)
\]

Equation (15) is written according to the \(X\) axial moment balance of the mobile mechanism.

\[
\frac{G}{3} \left(\frac{y_{fr} + y_{mr} + y_{wr}}{3} - y_{dr}\right) + \frac{F_{x_r}}{\sin \theta} \left(\frac{y_{fr} + y_{mr} + y_{wr}}{3} - y_{dr}\right) = 0 \quad (15)
\]

Where, \(y_{fr}\) is the \(y\)-coordinate value of the mass centre of the rover body in the reference coordinate system \(F\).

By solving (2), (13), (14) and (15), the values of \(F_{y_r}, F_{y_t}, M_{wr}, M_{al}\) can be obtained.

For simplified calculation, the tangential forces, which are caused by the directional control error of the wheels, are taken no account of, i.e., without regarding to the \(Z\) axial moments applied by the ground friction forces to the two side rocker-bogie planes. Therefore, \(M_{fr} = M_{ar} = 0\). \(F_{fr}, F_{ar}\) can be calculated by solving (1), (6) and (16), \(M_{fr}, M_{ar}\) can be obtained by solving (5), (7), \(F_{sr}, F_{sr}\) can be calculated according to (3), (4). Thus, the twelve unknown parameters of force analysis of the differential joints can be worked out.

D. Force analysis between the wheels and the ground

Without regard to the normal friction forces, we take the rocker-bogie planes as research object for the force analysis. The two side rocker-bogie mechanisms are selfsame except the displacements and forces at the joints, so their mechanical models are selfsame too. This paper only analyzes the right side rocker-bogie mechanism.

For convenience, it is assumed that they are point-contact between the wheels and the ground. \(\alpha_1, \alpha_2, \alpha_3\) are the included angles between the tangents at contact points and the ground, \(r\) is the radius of the wheel, \(N_1, N_2, N_3\) are the normal forces of the wheels. \(T_1, T_2, T_3\) are the tangential friction forces, as in Fig. 3.

According to the force balance principles, (16) and (17) can be established.

\[
F_r - N_1 \sin \alpha_1 - N_2 \sin \alpha_2 - N_3 \sin \alpha_3 + T_1 \cos \alpha_1 + T_2 \cos \alpha_2 + T_3 \cos \alpha_3 = 0 \quad (16)
\]
\[
-F_r + N_1 \cos \alpha_1 + N_2 \cos \alpha_2 + N_3 \cos \alpha_3 + T_1 \sin \alpha_1 + T_2 \sin \alpha_2 + T_3 \sin \alpha_3 = 0 \quad (17)
\]
NALYSIS OF OBSTACLE

The mechanical model as in Fig. 3 has six unknown parameters, but there only have four balance equations, therefore, the solution is not unique.

III. ANALYSIS OF OBSTACLE-CLIMBING CAPABILITY

A. The constraint of obstacle-climbing

When the planetary rover is climbing the obstacle, the driving torque of the wheel cannot exceed the maximum torque allowed by the motor, written as in (20).

\[ Tr \leq M^m \]  

(20)

Where, \( T_r \) is the driving torque of the wheel, \( M^m \) is the maximum torque allowed by the motor.

Due to the limitation of the friction coefficient, the friction force has a maximum value and the corresponding torque is the maximum torque. If the driving motor is designed according to the maximum torque, then we can take no account of the limitation of the torque of the motor.

The constraint conditions of the normal forces and the tangential friction forces are written as in (21), (22). Where, \( \mu \) is the friction coefficient.

\[ -\mu N \leq T \leq \mu N \]  

(21)

\[ N \geq 0 \]  

(22)

B. Obstacle-climbing capability

If (16)-(19) meet the constraint condition written as in (20)-(22) and have a rational solution, then the wheels have the obstacle-climbing capability. Equations (16)-(19) constitute a nonhomogeneous linear system of equations, which can be written as matrix form, as in (23).

\[ \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ T_1 \\ T_2 \\ T_3 \end{bmatrix} = \mathbf{B}_{\text{inv}} \]  

(23)

When the rank of matrix \( A \) is four, (23) has a two-dimensional solution space. Taking the two friction forces as the variable of the solution space, the solution space feasible region can be found out by the constraint condition. Whether the right or the left wheels’ friction force feasible region is inexistent, the rocker-bogie mechanism will not balance under the specified initial conditions and have no obstacle-climbing capability.

C. Examples of simulation

The Obstacle-climbing capability can be simulated by Matlab program. The parameters of the mobile mechanism are given: \( l_1=79.41 \text{cm}, l_2=22.36 \text{cm}, l_3=40.70 \text{cm}, l_4=40.70 \text{cm}, \alpha=125.26^\circ, \beta=94.98^\circ, w=90 \text{cm}, x_b=5 \text{cm}, y_b=0, z_b=10 \text{cm}. \)

As the mobile mechanism is symmetrical, for convenience, it is assumed that the yaw angle \( \psi=0 \) and the pitch angle \( \phi = \gamma - (\theta_1 + \theta_2)/2 \). Where, \( \gamma \) is the initial value of \( \theta_1 \) and \( \theta_2 \).

1) Right-front-wheel obstacle-climbing

According to the order of right to left and real to front, the \( Z \) coordinates of the wheels are defined as: \([0 \ 0 \ 25 \ 0 \ 0 \ 0] \) cm, the contact angles between the wheels and the ground are defined as: \([0 \ 0 \ 45^\circ \ 0 \ 0 \ 0] \), the relationship of the friction forces \( T_{1z}, T_{2z}, T_{3z} \) and \( T_{1r}, T_{2r}, T_{3r} \) are shown in Fig. 4. As shown in Fig. 4, the right wheels’ friction force feasible region is reduced, and is shifting to the positive direction.

2) Right-middle-wheel obstacle-climbing

According to the order of right to left and real to front, the \( Z \) coordinates of the wheels are defined as: \([0 \ 25 \ 0 \ 0 \ 0 \ 0] \) cm, the contact angles between the wheels and the ground are defined as: \([0 \ 45^\circ \ 0 \ 0 \ 0 \ 0] \), the relationship of the friction forces \( T_{1z}, T_{2z}, T_{3z} \) and \( T_{1r}, T_{2r}, T_{3r} \) are shown in Fig. 5. As shown in Fig. 5, the right wheels’ friction force feasible region is reduced, and is shifting to the positive direction.

3) Right-real-wheel obstacle-climbing

According to the order of right to left and real to front, the \( Z \) coordinates of the wheels are defined as: \([25 \ 0 \ 0 \ 0 \ 0 \ 0] \) cm, the contact angles between the wheels and the ground
are defined as: $[45^\circ 0 0 0 0 0]$, the relationship of the friction forces $T_{r1}$, $T_{r2}$, $T_{r3}$ and $T_{l1}$, $T_{l2}$, $T_{l3}$ are shown in Fig. 6.

IV. Conclusions

Under the constraint condition, the wheels’ friction force solution space feasible regions are founded by using the method of quasi-statics, and the obstacle-climbing capability of the mobile mechanism is analyzed based on the solution space feasible region. When the feasible region is inexistent, the mobile mechanism will not balance under the specified initial conditions and have no obstacle-climbing capability. The simulation showed that when the mobile mechanism goes forward, with the same obstacle heights and contact angles between the wheels and the ground, the rear wheel have the best obstacle-climbing capability, which solution space feasible region is the best, the middle wheel is the worst, and the front wheel is moderate.

Figure 4. Right-front-wheel obstacle-climbing

Figure 5. Right-middle-wheel obstacle-climbing

Figure 6. Right-real-wheel obstacle-climbing

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