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# Steering dynamic performance analysis of the tracked mobile robot

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**Abstract**. In order to obtain the relationship and the change regulation of dynamic parameters of the tracked mobile robot in the steering process, the dynamic models under the influence of slip and centrifugal force are established respectively. At the same time, the mathematical expressions of the deflection of the steering center and the pressure on the track are obtained. The relationship of parameters is analyzed by Simulink simulation software and the error of the slip model, the centrifugal force model and the ideal model and is compared.

## 1. Introduction

The tracked mobile robot has been widely used in military, agroforestry, industrial engineering and other fields because of its advantages such as large grounding area, low pressure per unit area, large carrying capacity and good grip performance. The excellent adaptability and stability for complex pavement make the tracked mobile robot occupy an irreplaceable position in the related fields. However, compared with the characteristics of wheeled robot, the tracked mobile robot is lack of maneuverability. How to improve the responsive speed and steering performance has become a key point in the research of the tracked mobile robot.

At present, a lot of researches on the steering process of the tracked mobile robot have been done. Wong et al. [1] studied the effect of slip on the steering performance, and verified the influence of slip on the steering performance by a large number of experiments. W.Y.Park et al. [2] established a prediction traction model of the steering process, and analyzed the influence of ground parameters on the steering. S. Al-Milli et al. [3] simulated the characteristics of the tracked steering by establishing a steering simulator with predictive function. Shi Lichen et al. [4] carried out the dynamic model and the simulation of the tracked steering, and analyzed the effects of various parameters on steering performance in the case of considering centrifugal force comprehensively. Chen Weijun et al. [5] considered the influence of the slip on steering performance and established practical steering model, the experimental results showed that the turning radius with considering the slip is approximately 1.5 times that of the ideal case. Based on the traditional steering model, Wang Hongyan et al. [6] established a more accurate steering model with the ground shear deformation.

This paper establishes the tracked mobile robot steering dynamics model under the condition of track slip and centrifugal force, and obtains the concrete steering center offset and the pressure on both sides of the track. The simulation analyzing is built, the error between that and the ideal model, and the influence of dynamic parameters on steering are attained.

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## 2. Dynamic model of the tracked mobile robot

### *2.1. The structure of the tracked mobile robot*

The tracked mobile robot consists of intelligent controller of power system, power supply, driving motor, drive pulley, driven pulley, tension pulley, body frame, and tracks. As shown in figure 1, the power supply, the intelligent controller of power system and the driving motors are placed on the body frame; the driving motors are powered by power supply under the control of the intelligent controller of power system; the drive pulleys are driven by the driving motors, and the tracks are driven by the drive pulleys. The analysis of the motion process of the tracked mobile robot is as follows in the paper.

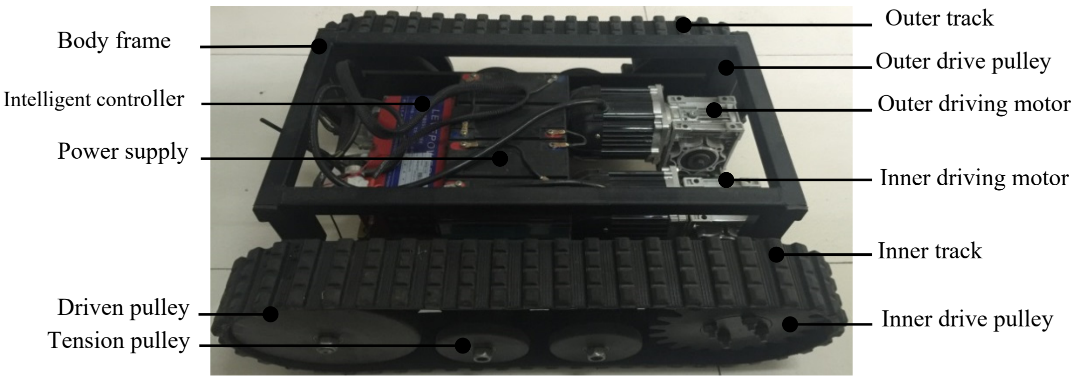


Figure 1. The schematic diagram of the structure of the tracked mobile robot.

### *2.2. Straight-line analysis*

In order to carry out theoretical analysis more conveniently on the steering process in the movement of the tracked mobile robot, some assumptions are made for the complicated and changeable road conditions: the ground is ideal, and the conditions everywhere are identical, and the track's bandwidth is not considered, and the pressure of track is distributed uniformly.

When the tracked mobile robot is moving along a straight line, it is subjected to the driving force of motor, the friction resistance between the track and the ground and the air resistance. Generally, when the tracked mobile robot runs at a low velocity less than 30 km/h, the influence of the air resistance can be ignored. In the paper, the tracked mobile robot moves at low velocity, therefore, the resultant force of the tracked mobile robot is the following

$$\sum F = \frac{T_{\mathrm{l}} i\eta}{r} + \frac{T_{\mathrm{r}} i\eta}{r} - f_{\mathrm{l}} - f_{\mathrm{r}} \tag{1}$$

where $T_{\mathrm{l}}$ , $T_{\mathrm{r}}$ are the output torques provided by the inner and outer motors respectively, $\mathrm{N} \cdot \mathrm{m}$ ; $i$ is the gearbox's transmission ratio; $\eta$ is transmission efficiency from the motor to the tracked wheel; $r$ is the radius of the wheel, m; $f_{\mathrm{l}}$ , $f_{\mathrm{r}}$ are the friction between the inner and outer tracks with the ground, N.

### *2.3. Ideal steering process*

The steering motion of the tracked mobile robot can be divided into rotation mode, differential steering mode and independent steering mode. In the rotation mode, the driving force of the left and right side of the track are equal but opposite in the direction and the robot takes the barycenter as the center of rotation. In the differential steering mode, the track's velocity of one side is reduced while of the other side is increased, which makes the robot keeps its original velocity. In the independent steering mode, the track's velocity of one side is unchanged and the other side reduces. In this paper, differential mode is used as the steering mode of the tracked mobile robot. The force and velocity diagram of the tracked mobile robot in ideal steering process is shown in figure 2.

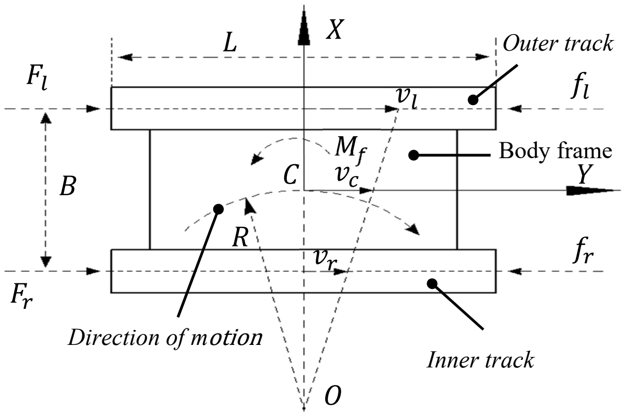


Figure 2. The force and velocity diagram of the tracked mobile robot in ideal steering process.

In figure 2, $L$ is the length of the connected part between track and ground, m; $M_{\mathrm{f}}$ stands for the steering resistance moment, $\mathrm{N}\cdot\mathrm{m}$ ; $B$ is the central distance of the two tracks, m; $R$ is the steering radius, m; $C$ is the barycenter of the robot; $O$ is the steering center; $F_{\mathrm{l}}$ , $F_{\mathrm{r}}$ are the active wheel traction respectively, N; $f_{\mathrm{l}}$ , $f_{\mathrm{r}}$ are the friction between tracks and the ground respectively, N.

The pressure of the track is distributed evenly when the influence of the slip and centrifugal force are not considered, so the steering resistance torque on both tracks can be got by integral

$$M_{\mathrm{f}} = 2\int_0^{\frac{L}{2}} fQ\cdot x\mathrm{d}x + 2\int_0^{\frac{L}{2}} fQ\cdot x\mathrm{d}x = \frac{fGL}{4} \tag{2}$$

where $f$ is the steering resistance coefficient, which is determined by the ground condition and relative steering radius; $Q$ is the unit load of the track. The dynamic equilibrium equation of the tracked mobile robot is established and the driving force of both tracks can be attained

$$F_{\mathrm{l}} = f_{\mathrm{l}} + \frac{fGL}{4B} \qquad F_{\mathrm{r}} = f_{\mathrm{r}} - \frac{fGL}{4B} \tag{3}$$

*2.4. The influence of slip on steering of the robot*

In the actual situation, the slip of the track has an important influence on the steering motion of the robot, and it is inevitable that the slip will occur in the steering process of the robot. In differential steering mode, the slip will cause that the velocity of the outer track cannot reach its theoretical velocity, while of the inner track is higher than its theoretical velocity. A slip diagram of the tracked mobile robot is shown in figure 3.

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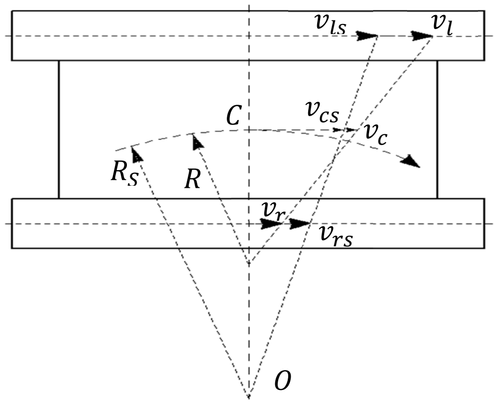

Figure 3. The schematic slip diagram of the tracked mobile robot.

The following equation can be obtained by figure 3

$$R_s = \frac{B}{2} \cdot \frac{v_{ls} + v_{rs}}{v_{ls} - v_{rs}} \qquad v_{cs} = \frac{v_{ls} + v_{rs}}{2} \qquad \omega_s = \frac{v_{cs}}{R_s} \tag{4}$$

where $v_{ls}$ is the slide velocity of outer track, m/s; $v_{rs}$ is the slip velocity of the inner track, m/s; $R_s$ is the actual radius, m; $v_{cs}$ is the slip steering velocity of the tracked mobile robot, m/s; $\omega_s$ is the slip steering angular velocity of the tracked mobile robot, rad/s. According to Wong's definition of slip coefficient, the slip coefficient is the ratio between the error of track velocity and the target velocity, the slip coefficients of two tracks are as followings

$$i_l = \frac{v_l - v_{ls}}{v_l} \qquad i_r = \frac{v_{rs} - v_r}{v_r} \tag{5}$$

At the same time, the following equation is attained by theory of Bekker [7]

$$i = \frac{K / L}{\ln(F / F_{max})} \tag{6}$$

where $K$ is the ground shear deformation coefficient, cm; $L$ is the length of the connected part between track and ground, m; $F$ is the actual traction of the track, N; $F_{max}$ is the maximum traction for the track, N. $F_{max}$ is determined by the area of the tracked area, the adhesion coefficient of the ground, the self-weight of the vehicle and the internal friction angle.

### *2.5. The effect of centrifugal force on steering*

With the weight of the tracked mobile robot, when the steering velocity reaches a certain value, the centrifugal force cannot be ignored. Under the action of the centrifugal force, the bearings of two tracks are no longer equal and the pressure of the track is no longer an average distribution. Ignoring the deviation of the barycenter of the robot, the steering center of the tracked mobile robot slips forward under the action of $F_R$. The force of the robot is shown in figure 4 and figure 5.

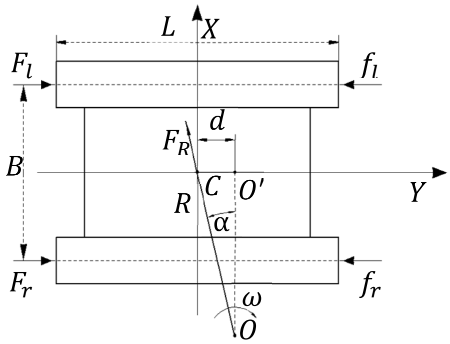


Figure 4. The force diagram of the robot in the horizontal direction under the centrifugal force.

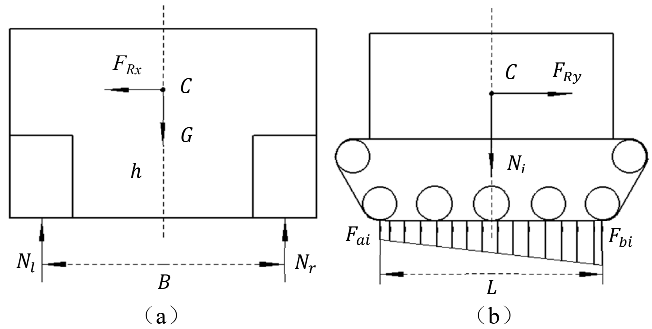


Figure 5. The force diagram of the robot in the vertical direction under the centrifugal force.

In figure 4, the positive velocity direction of the robot is the Y-axis, and the X-axis is perpendicular to the Y-axis. $d$ is the offset distance of the steering center, , $F_R$ is the centrifugal force. In figure 5, $F_{\mathrm{Rx}}$ and $F_{\mathrm{Ry}}$ are the component of the centrifugal force; $N_{\mathrm{l}}$, $N_{\mathrm{r}}$ are the pressures on the inner and outer tracks respectively, N; $h$ is the distance from the barycenter to the ground, m. The centrifugal forces on the X-axis and Y-axis direction can be found from figure 4. If the pressure on the front of the track is $F_{\mathrm{a}i}$ , the opposite is $F_{\mathrm{b}i}$ , $i$=l, r which represents the outer and inner tracks respectively. Because the pressure distribution on the track is increased uniformly in the length of track, from the force balance and torque balance of figure 5 (a) and figure 5 (b), the pressure of the track can be expressed under the action point of $F_{\mathrm{a}i}$ as the origin

$$F(y)_i = \frac{N_i}{L} - \frac{6h}{L^2}F_{\mathrm{Ry}} + \frac{12hy}{L^2}F_{\mathrm{Ry}} \quad (i = \mathrm{l,r}) \tag{7}$$

The steering resistance moment generated by the steering resistance can be obtained

$$M_{\mathrm{f}}' = f\int_0^{\frac{L}{2}}(F(y)_{\mathrm{l}} + F(y)_{\mathrm{r}})\left(\frac{L}{2} - d - y\right)dy + f\int_{\frac{L}{2}-d}^{L}(F(y)_{\mathrm{l}} + F(y)_{\mathrm{r}})(y - \frac{L}{2} + d)dy \tag{8}$$

According to Newton-Euler equation, the dynamic equilibrium equation of the robot is established, and $F_{\mathrm{l}}$, $F_{\mathrm{r}}$ under the centrifugal force can be obtained

$$F_{\mathrm{l}} = f_{\mathrm{l}} + \frac{F_{\mathrm{Ry}}}{2} + \frac{M_{\mathrm{f}}'}{B} \qquad F_{\mathrm{r}} = f_{\mathrm{r}} + \frac{F_{\mathrm{Ry}}}{2} - \frac{M_{\mathrm{f}}'}{B} \tag{9}$$

## 3. Modeling and simulation by Simulink

The parameters are found and the Simulink models of the tracked mobile robot are established. The line velocity of the robot is set at 1 m/s, a steering signal as a ramp signal with the slope of 0.5 and an upper limit of 0.2 rad/s at 5 s. The slip's influence performs on the steering angular velocity and steering radius mainly, as shown in figure 6 and figure 7.

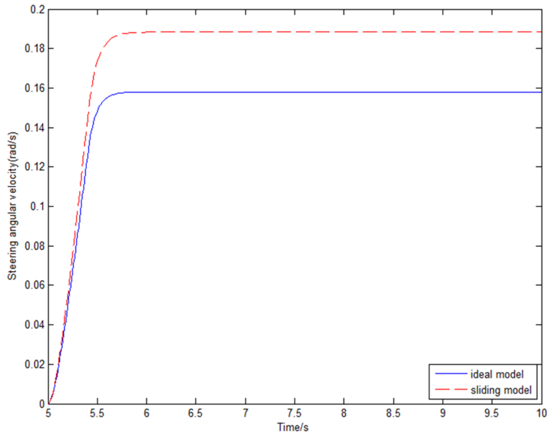


Figure 6. Contrastive diagram of the angular velocity.

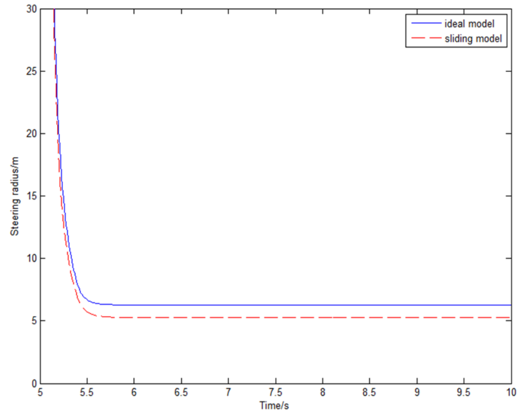


Figure 7. Contrastive diagram of the radius.

It is known from figure 6 that the steering angular velocity of the robot reaches equilibrium and approaches the desired angular velocity of 0.2 rad/s in a period time after receiving the steering signal without considering the effect of slip. Under the influence of slip, the steering angle velocity is lower than the ideal model when it reaches equilibrium. From figure 7, it can be seen that when the steering signal is received, the slip and the ideal models both approach the steady steering radius from the infinite, and the steering radius of the slip model is larger than the ideal steering radius.

Similarly, compared the ideal and centrifugal force model without considering the slip, the torque of the two driving wheels and the offset of steering center are shown in figure 8 and figure 9.

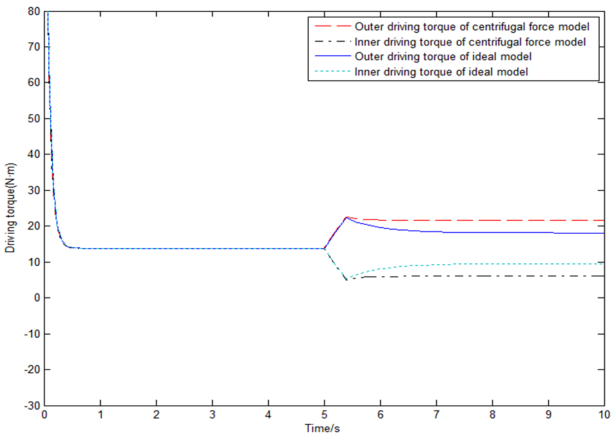


Figure 8. Contrastive diagram of the driving torque.

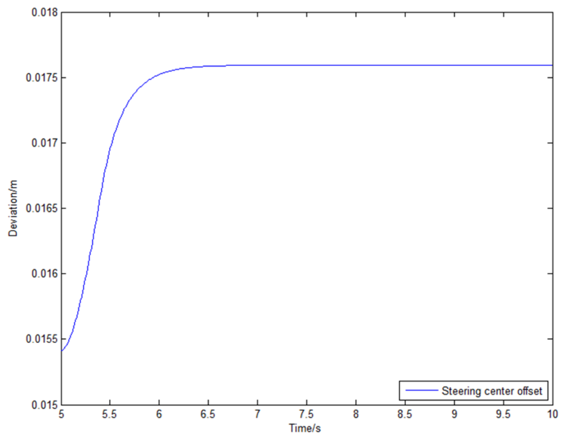


Figure 9. The offset of steering center.

From figure 8, it can be seen that the driving moment of the inner track increases while the outer decreases after receiving the steering signal. However, due to the change of the steering resisting moment caused by the centrifugal force, the change of the pressure on both sides and the change of the driving torque on both sides of the centrifugal force model is smaller than the ideal model. In addition, the steering center offset is stable at about 0.0176 m as shown in figure 9.

## 4. Conclusions

The models of the ideal, slip and centrifugal force of the tracked mobile robot are established without considering the offset of centroid, theoretical expressions of the steering center offset and the driving force of the two sides are derived, which provide the theoretical reference for the study of the steering dynamics and the optimization design of control law of the tracked mobile robot.

The effect of the slip and the centrifugal force on the steering process of the tracked mobile robot is analyzed by Simulink, and the relationship between the parameters is obtained. The error of the slip model, the centrifugal force model and the ideal model are compared. The slip decreases the velocity of outer flank and the steering angular velocity, and increases the inner velocity and the steering radius. The centrifugal force will increase the outer driving torque and reduce the inner driving torque.

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