Comparative Performance Analysis of Different Travelling Mechanisms Based on RecurDyn

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Abstract. According to the characteristics of different travelling mechanisms of the robot, the kinematic equations of wheeled mobile robot and tracked mobile robot are established by using the kinematic theory; the tire system and the triangle track system are established by using the multi-body dynamics simulation software RecurDyn, and the simulation analysis is carried out under the road conditions such as over the boss, according to the principle of single variable; manage the data, and we can get the difference of the robot's performance in obstacle surmounting, speed and stability. The results show that when the mobile robot adopts the travelling mechanisms of wheel shoe combination, it can improve the overall motion performance, and provide a new idea and direction for the future design of the travelling mechanism.

1. Introduction

With the progress of science and technology, the research of mobile inspection robot has also developed to a new height. Among them, the robot's travelling mechanism is no longer a single mechanism in the traditional sense, and various combinations are emerging. At present, the research in this field in China mainly includes: the triangle track climbing robot developed by Wang Rui and others can realize passive obstacle crossing [1]; Ma Peng and others use the new variant wheel shoe composite structure to realize the free transformation of the circular wheel and the triangle track through deformation [2]; and the variant planetary wheel structure developed by Huazhong University of science and technology [3]. Wang and others [4] made a deep research on the stable steering principle of tracked vehicle on hard ground based on the sliding friction theory between vehicle and ground. Thai and others [5] analyzed the characteristics of low-speed stable steering of tracked vehicles on soft ground. Therefore, it will be a new research angle in the future to optimize the robot structure and improve the robot motion performance if two different travelling mechanisms, wheel and track, can be integrated into a mobile inspection equipment.

In this paper, the kinematics equations are set up to compare and analyse the differences between different travelling mechanisms on the robot body in terms of motion track, pose equation, etc. The tire system and the track system are established by using the multi-body dynamics simulation software RecurDyn, and the differences in obstacle surmounting performance, travelling speed and travelling smoothness between the two mechanisms are verified according to the principle of one variable.
2. Comparative analysis of robot kinematic models

2.1. Kinematic model establishment and analysis of wheeled mobile robot

2.1.1. Global coordinate system and local coordinate system. Two kinds of coordinate systems, global coordinate system and local coordinate system, are often needed in mobile robot motion system. The global coordinate system is the coordinate system of the three-dimensional space object, and the vertex coordinates of the model are expressed based on this coordinate system. Instead, the local coordinate system is an imaginary coordinate system. The relative position of the coordinate system and the object is unchanged from the beginning to the end. The purpose of the imaginary coordinate system is to understand the "translation and rotation" operation of the object in the three-dimensional scene [6]. Therefore, in the kinematic analysis system of mobile robot, the global coordinate system is used to represent the global pose state information of mobile robot system, while the local coordinate system is used to represent the local pose state information of mobile robot system. What’s more, the conversion of two coordinate systems is an inevitable problem in the kinematic modelling of mobile robot.

As shown in Figure 1, the global coordinate system and the local coordinate system are established.

![Figure 1. Global coordinate system and local coordinate system](image)

It is easy to find that the pose state of the mobile robot can be described as a vector containing three elements. In the global coordinate system, the motion state can be expressed as:

$$\begin{bmatrix}
    X_1 \\
    Y_1 \\
    \dot{\theta}
\end{bmatrix}$$

(1)

In the local coordinate system, the motion state can be expressed as:

$$\begin{bmatrix}
    \dot{x}_2 \\
    \dot{y}_2 \\
    \dot{\theta}
\end{bmatrix}$$

(2)
It can be seen from the above formula that: \( \dot{x}_1 \) and \( \dot{y}_1 \) are the speeds of the wheeled mobile robot along the horizontal and vertical axes in the global coordinate system; \( \dot{x}_2 \) and \( \dot{y}_2 \) are the speeds of the wheeled mobile robot along the horizontal and vertical axes in the local coordinate system; \( \dot{\theta} \) is the yaw angular speed.

If the mobile robot is placed in the two-dimensional plane \( \text{xoy} \) motion coordinate system, it can be seen that:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{y}_1 \\
\dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\dot{x}_2 \\
\dot{y}_2 \\
\dot{\theta}
\end{bmatrix}
\tag{3}
\]

That is to say, the transformation matrix from the motion state in the local coordinate system to the motion state in the global coordinate system is:

\[
T(\theta) =
\begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\tag{4}
\]

In the formula, \( \theta \) is the yaw angle, with the \( \text{ox} \) axis as the reference, and the counter clockwise direction is the positive direction.

2.1.2. Kinematic equation establishment of wheeled mobile robot. The kinematic equation mainly studies the relationship among the features of the object, such as position, velocity, angular velocity, acceleration, angular acceleration, etc. to carry out the mathematical model of the robot's motion track, pose analysis, etc. With the kinematic equation, we can easily derive some unknown quantities from some known quantities. For the wheeled mobile robot, it can be seen from Figure 1 that its kinematic equation in the local coordinate system is:

\[
v_L = w_L \cdot r 
\tag{5}
\]

\[
v_R = w_R \cdot r 
\tag{6}
\]

\[
w = \frac{v_R - v_L}{B} = \frac{rw_R - rw_L}{B} 
\tag{7}
\]

\[
v = \frac{v_R + v_L}{2} = \frac{rw_R + rw_L}{2} 
\tag{8}
\]

Among them, \( v_L \) is the left wheel speed, \( v_R \) is the right wheel speed, \( w_L \) is the left wheel speed, \( w_R \) is the right wheel speed, \( r \) is the wheel diameter, \( w \) is the yaw angle speed, \( L \) is the wheel spacing on the same side, and \( B \) is the wheel spacing on the different side.

It can also be seen from Figure 1 that its kinematic equation in the global coordinate system is:
\[
\begin{align*}
X(t) &= X(0) + \int_0^t v \cdot \cos \theta(t) \, dt \\
Y(t) &= Y(0) + \int_0^t v \cdot \sin \theta(t) \, dt \\
\theta &= \theta_0 + \int_0^t \frac{p}{B} (w_R - w_L) \, dt
\end{align*}
\]  

(9)

In the formula, \(X\) is the displacement of the robot along the \(X\) axis; \(Y\) is the displacement of the robot along the \(Y\) axis; \(v\) is the speed, \(w\) is the yaw rate, and \(\theta\) is the yaw angle.

2.2. Analysis of kinematic model of tracked mobile robot

For the kinematic analysis of the current mobile robot with track module, it is mainly considered that the difference between the track and the wheel type is that there is inevitable sliding friction between the track module and the ground in the process of travelling. That is to say, in the process of robot turning, it is very easy to produce slip phenomenon, so in order to simplify the complexity of analysis, it is necessary to simplify the stress and idealize the hypothesis [7].

Setting 1: the track and body of the tracked mobile robot are rigid bodies, ignoring deformation and other factors.

Setting 2: the tracked mobile robot moves at a low speed, and the track is evenly grounded.

On the whole, when the slip effect is not considered, the motion of the robot can be regarded as the combination of the translational motion of the base point and the rotation around the base point. Considering the slip effect, the ICR deviates, as shown in Figure 2.

![Figure 2. Global coordinate system and local coordinate system 2](image)

As shown in Figure 2, the motion of the robot's center of mass is also composed of translational speed \(v_c\) and angular speed \(w\). \(v_c\) can be divided into \(v_x\) in \(X\) direction and \(v_y\) in \(Y\) direction, \(v_x\) in forward direction and \(v_y\) in vertical direction. In order to describe the slip effect, the coefficient of slip ratio is introduced. \(i_x\) and \(i_y\) are used to represent the sliding ratio of the left and right main drive tracks.

\[
i_L = \frac{v_L - v_x}{v_L} = \frac{rW_L - v_x}{rW_L}
\]

(10)
The kinematic equation of the mobile robot with track module in local coordinate system is as follows:

\[ i_R = \frac{v_R - v_x}{v_R} = \frac{rw_R - v_x}{rw_R} \]  

(11)

The kinematic equation of the mobile robot with track module in global coordinate system is as follows:

\[ w_C = \frac{v_Rx - v_Lx}{B} = \frac{rw_R(1 - i_R) - rw_L(1 - i_L)}{B} \]  

(12)

\[ v_C = \frac{v_Rx + v_Lx}{2} = \frac{rw_R(1 - i_R) + rw_L(1 - i_L)}{2} \]  

(13)

It can be seen from Figure 2 that the kinematic equation in the global coordinate system is:

\[
\begin{align*}
X(t) &= X(0) + \int_{0}^{t} r \left( \frac{w_R + w_L}{2} \right) \cdot \cos \theta(t) dt \\
Y(t) &= Y(0) + \int_{0}^{t} r \left( \frac{w_R + w_L}{2} \right) \cdot \sin \theta(t) dt \\
\theta &= \theta_0 + \int_{0}^{t} \frac{r}{B} (w_R - w_L) dt
\end{align*}
\]  

(14)

In the formula, \( X \) is the displacement of the robot along the \( X \) axis; \( Y \) is the displacement of the robot along the \( Y \) axis; \( v \) is the speed, \( w \) is the yaw rate, and \( \theta \) is the yaw angle.

3. Comparative simulation analysis of running mechanism

In recent years, with the development of multi-body dynamics, RecurDyn is more and more applied to the complexity of tracked vehicles. There are many composite modeling modules in RecurDyn software, including track module (HM), track module (LM), gear train module Gtire, etc [8]. It can not only build three-dimensional model for the track module, but also carry out more complex dynamic analysis and simulation research by setting the road parameters and driving parameters, so as to provide a reliable simulation model for the later experimental platform construction, and contribute to the later in-depth research [9].

3.1. Establish dynamic model

3.1.1. Wheeled mobile robot

(1) Model import and establishment

For the wheeled mobile robot, its body can be built by Creo parametric saved as a x_t. format and imported into RecurDyn; the wheel model is modeled by the internal Gtire subsystem. Figure 3 and Figure 4 show the modeling parameters and model of the wheel.
In order to study the motion and dynamic characteristics of the robot, it is necessary to define the constraints and driving elements among the components. The specific values are shown in Table 1.

**Table 1.** Types and quantity of motion pairs between components

| Base     | Action              | Joint                | Amount |
|----------|---------------------|----------------------|--------|
| body     | rear axle           | Revolute 1           | 1      |
| body     | Rear drive system   | Revolute(motion)2    | 1      |
| body     | front axle          | Revolute(motion)4    | 1      |
| body     | Front drive system(L)| Revolute 5           | 1      |
| body     | Front drive system(R)| Revolute 3           | 1      |
| rear axle| GTire 1             | Fixed 1              | 1      |
| rear axle| GTire 2             | Fixed 2              | 1      |
| front axle| GTire 3            | Fixed 3              | 1      |
| front axle| GTire 4            | Fixed 4              | 1      |
| Revolute 1| Revolute 2         | Coupling 1           | 1      |
| Revolute 3| Revolute 4         | Coupling 2           | 1      |
| Revolute 5| Revolute 4         | Coupling 3           | 1      |

It can be seen from Table 1 that both Revolute 2 and 4 are driven. The driving definition is completed by applying motion on the Revolute. The functions are shown in Table 2.

**Table 2.** Driving function

| Kinematic pair | Driving function               |
|----------------|--------------------------------|
| Revolute 2     | Step(time,0,0,0.5,1)           |
| Revolute 4     | Step(time,0,0,0.5,-1)          |
3.1.2. Triangle-tracked mobile robot

(1) Model import and establishment

For the triangle-tracked mobile robot, its body can be built by Creo parametric saved as a x_t. format and imported into RecurDyn; the track model is modeled by the internal track (LM) subsystem. Figure 5 and Figure 6 show the modeling parameters and model of the track.

(2) Add constraints and drivers

In order to study the motion and dynamic characteristics of the robot, it is necessary to define the constraints and driving elements among the components. The values are shown in Table 3.

![Figure 5](image1.png) The modelling parameters of the track

![Figure 6](image2.png) The model of the track

| Base          | Action                | Joint             | Amount |
|---------------|-----------------------|-------------------|--------|
| body          | rear axle             | Revolute 1        | 1      |
| body          | Rear drive system     | Revolute 2        | 1      |
| body          | front axle            | Revolute 3        | 1      |
| body          | Front drive system(L) | Revolute 4        | 1      |
| body          | Front drive system(R) | Revolute 5        | 1      |
| rear axle     | GTire 1               | Fixed 1           | 1      |
| rear axle     | GTire 2               | Fixed 2           | 1      |
| Revolute 1    | Revolute 2            | Coupling 1        | 1      |
| Revolute 3    | Revolute 4            | Coupling 2        | 1      |
| Revolute 5    | Revolute 4            | Coupling 3        | 1      |
| Revolute 3(LTrack) | Revolute 3      | Coupling 4        | 1      |
| Revolute 3(RTrack) | Revolute 5       | Coupling 5        | 1      |

Since the driving function of tracked robot is the same as those of wheeled robot, it will not be discussed here.
3.2. Simulation analysis of running mechanism

Due to the different characteristics and advantages of wheeled robot and triangle-tracked robot in the process of travelling, it is proposed to adopt a variable principle to compare and analyze the differences of two different mechanisms under different working conditions. It is proposed to verify from three aspects: boss height, travelling speed and travelling smoothness.

In order to objectively compare the characteristics of two different road structures, it is necessary to unify the setting of road information. The terrain of lean clay is selected for the road in this analysis, and its parameters are shown in the Table 4.

| Parameter                      | Data         |
|--------------------------------|--------------|
| Terrain Stiffness(k_c)         | 1            |
| Terrain Stiffness(k_phi)       | 0.4          |
| Cohesion(c)                    | 6.895e-002   |
| Shearing Resistance Angle      | 20           |
| Sinkage Ratio                  | 5e-002       |

3.2.1. Boss height. According to a variable principle, set the boss height to 50mm.

From Figure. 7 (a) - (d), it can be seen that the wheeled mobile robot cannot climb over the 50 mm boss obstacle, while the triangle-tracked mobile robot can climb over the 50 mm boss obstacle, which is also reflected in the change of the center of mass, as shown in Figure. 9 (a) and (b).
The center of mass displacement curve of the wheeled mobile robot passing through the boss is shown in Figure 9(a). It is not difficult to see that the vehicle center of mass displacement fluctuates slightly in 1.8s, which means that the front wheel of the wheeled mobile robot starts to touch the boss, and the vehicle center of mass displacement no longer increases after 5.6s, which means that the rear wheel cannot pass through the boss normally, so the wheeled mobile robot cannot pass through the 50 mm boss.

As shown in Figure 9(b), the displacement curve of the center of mass of the triangle-tracked mobile robot passing through the boss is easy to see that the displacement of the vehicle's center of mass fluctuates slightly in 3.1s, indicating that the center of mass has a slight improvement, and the displacement level of the vehicle's center of mass remains unchanged after 5.8s, indicating that the rear wheel begins to encounter the boss, and the displacement of the vehicle's center of mass begins to rise again after 10s, indicating that the triangle-tracked mobile robot can pass through over 50 mm boss.

Because the wheeled mobile inspection robot cannot pass through the 50 mm boss, the height of the boss is reduced. Through simulation, it is found that the wheeled mobile robot can only pass through the 37 mm boss. Therefore, the advantages of the mobile robot with track module are obvious in the condition of turning over the boss.

3.2.2. Travelling speed. According to a variable principle, the boss height is set to 30mm.

When the set height of the boss can make the two kinds of travelling mechanisms cross over, it can measure the difference of the travelling speed of the robot with different travelling mechanisms.
As shown in Figure 10 (a), in 2s, the speed starts to drop rapidly, indicating that the front wheel begins to contact the boss; in 5.5s, the speed starts to drop rapidly again, indicating that the rear wheel begins to contact the boss; in 7.5s, the wheeled mobile robot successfully completes the obstacle crossing, and the speed of stable operation is about 75mm / s.

As shown in Figure 10 (b), at 3s, the speed starts to rise rapidly, indicating that the front triangle-tracked mobile robot begins to contact the boss; at 5.8s, the speed starts to drop rapidly again, indicating that the rear wheel begins to contact the boss; at 11s, the speed of the triangle-tracked mobile robot tends to be stable indicating that the vehicle body has successfully completed the obstacle, and the speed of stable operation is about 65mm / s.

Therefore, it is not difficult to find that the wheel module helps to speed up the overall travelling speed of the robot.

3.2.3. Travelling smoothness. According to a variable principle, the boss height is set to 30mm.

When the set height of the boss can make the two kinds of travelling mechanisms cross over, it can also measure the difference in the stability of the robot in different travelling mechanisms.
As shown in Figure 11 (a) and (b), the peak value of the contact force between the triangle-tracked wheeled mobile robot and the ground is about 29N, while the peak value of the contact force between the wheeled mobile robot and the ground is about 83N. Especially when the robot is used in a non-structural environment, the large contact area between the track and the ground is used to reduce the vibration of the upper platform of the car body and improve the stability and stability of the whole robot.

4. Conclusion

In view of the difference of the travelling mechanisms of the ground mobile robot, this paper analyzes the kinematics of the wheeled mobile robot and the triangle-track mobile robot respectively, and establishes the global coordinate system and the local coordinate system. According to whether there is slippage or not, the kinematics equations are established respectively, and then the pose equations of the robot in each coordinate system are solved. Then, the solid wheel and triangle-track module are established to add constraints and drives, set the road parameters, and follow the principle of single variable in RecurDyn. The characteristics of two different travelling mechanisms are compared and analyzed from the height of the over boss, the travel speed of the robot and the travel stability of the robot. The results show that:

(1) When the boss height is the only variable, the maximum boss height that the triangle-track mobile robot can cross is 50mm, while the wheel mobile inspection robot can cross is 37mm. Therefore, when
the robot faces the vertical obstacle of the boss in front, the triangle-track can improve the robot's ability to cross the obstacle by 35%.

(2) When the travelling mechanism is the only variable, the average speed of the triangle-track mobile robot in the stable moving stage is 65mm, while the wheel mobile robot entering the stable moving stage is 75mm, so when the robot has the travelling mechanism of the wheel module, its travelling speed will be increased by 15%.

(3) When the travelling mechanism is the only variable, the contact force between the triangle crawler mobile robot and the ground fluctuates in the range of 0-30N, while the contact force between the wheel mobile robot and the ground fluctuates in the range of 0-80N, so the triangle-track module can reduce the collision between the robot body and the ground due to its large grounding area and other characteristics, especially for the mobile equipment working in the non-structural environment, it is more suitable to apply the track module.

To sum up, if the robot's travelling mechanism includes both wheel and track, it will coexist the advantages of two different mechanisms, which not only improves the obstacle surmounting ability and moving stability of the robot, but also speeds up the speed, which is the future research idea and direction of the new mobile robot in mechanism design.

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