Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 4, No. 2, 2022

Design and Analysis of Transformable Wheel-legged Mobile Robot

Zhizhong Lv, Bao Yuan

School of Mechatronic Engineering, Southwest Petroleum University, Chengdu 610500, China

Abstract: Wheeled mobile robot has good ground motion ability, fast moving speed and low energy consumption, but poor obstacle surmounting performance. In order to make the mobile robot have the motion performance in complex environments, the wheel mechanism and the wheel-leg mechanism are coupled and designed, and a deformable wheel-leg structure is designed. The mobile robot can not only move in the wheel mode, but also switch to the wheel-leg mode to adapt to the complex motion environment. The deformable wheel-leg mechanism is composed of a four-bar linkage, and the static analysis of key components is carried out in ANSYS.

Keywords: Mobile robot, Deformable wheel-leg mechanism, Link mechanism, Finite element analysis.

1. Introduction

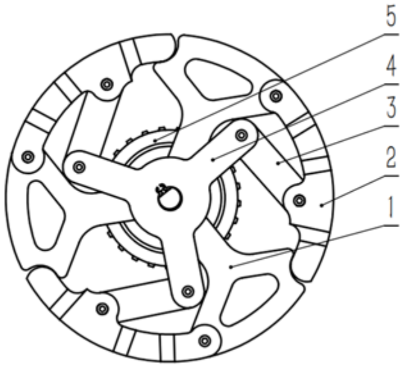
Small mobile robots have strong environmental adaptability and are widely used in information reconnaissance, disaster rescue and other places. Due to the complexity of the real environment, higher requirements are put forward for the size and environmental adaptability of mobile robots. Therefore, the design of mobile robots with adaptability to complex environments has important application value, and at the same time, the robots are required to have the advantages of light weight, small size, good maneuverability, and long working hours. The wheel mechanism has good ground movement ability, fast moving speed and low energy consumption, but its obstacle-surmounting ability is restricted by the radius of the wheel, and its maximum obstacle-breaking height is about one-third of the wheel diameter. The footed structure has excellent obstacle-crossing performance, but the control is more complicated, and the red energy consumption is relatively large during the movement process. In order to reduce the overall mass of the robot as much as possible, so that the robot has good ground motion performance, the wheel-leg coupling design is adopted, which can not only move in the wheel state, but also switch to foot movement for obstacle surmounting[1,2].

2. Structural Design and Force Analysis of Deformable Wheel Legs

2.1. Structure design of deformable wheel legs

The connecting rod mechanism is widely used in construction machinery. The kinematic pair of the connecting rod mechanism is generally a low pair, and its kinematic pair elements are in surface contact, which has the advantages of large bearing capacity, low pressure, small wear, and easy processing and manufacturing [3]. Combined with the existing research on deformable wheel-legged robots, a four-bar linkage mechanism is often used to realize the overall deformation of the roller arc, which improves the robot's ability to overcome obstacles, but the impact and vibration on the body during the obstacle course is relatively large. The mobile robot needs to have good environmental adaptability on the ground and minimize the impact and vibration during the movement. Therefore, the planar four-bar linkage mechanism is also used to realize the local deformation of the roller arc to improve the environmental adaptability of the robot.

The deformable wheel leg structure includes a driving wheel frame, an inner cage, an outer cage, a spoke connecting rod, and an extended arc leg. The driving wheel frame is located between the outer cages and the inner cage, and is installed on the D-shaped shaft to rotate together. One end of the stretched arc leg is connected with the driving wheel frame, one end of the spoke connecting rod is connected with the inner and outer cages, and the other end is connected with the stretched arc leg, forming a planar four-bar linkage mechanism together. The deformable wheel leg structure can be regarded as a deformable wheel leg composed of three groups of such planar four-bar linkages. The contraction direction of the stretching wheel legs can be limited by the driving wheel frame, and the direction of expansion of the stretching wheel legs can be limited by its own limit block to avoid excessive deformation [4].



1-driving wheel frame; 2- telescopic arc leg; 3- spoke link; 4- external frame; 5- internal frame

Figure 1. Deformable wheel leg structure

2.2. Active deformation mechanism of wheel legs

Commonly used switching methods for deformed wheels include passively triggering deformation through friction between the spokes and the ground, or switching between wheel and leg modes through active deformation devices. Since the conditions for passively triggering the wheel-leg deformation are unstable, the switching efficiency of the wheel-leg is not high, so this paper adopts the active deformation structure to realize the switching of the wheel-leg mode.

The key to whether the deformable wheel legs can switch between wheel and leg modes is to control the relative rotation state between the inner and outer frames and the active wheel frame. In the wheel mode and the wheel-leg mode, the inner and outer cages can be integrated with the driving wheel frame to perform overall rotation. When deformation is required, the inner and outer frames can rotate relative to the driving wheel frame.

In order to achieve the above actions, electromagnetic clutches are often used as actuators. Electromagnetic clutch is a widely used clutch. It is a friction clutch that generates a pressing force by electromagnetic force. It has two types: fixed coil and rotating coil, and has functions such as quick start, forward and reverse.

During the deformation process of the wheel leg, avoid driving the driven part to rotate during the rotation of the driving wheel frame or the inner and outer cages, so it is necessary to brake the driven part during the deformation process, or provide additional driving force for the driven part. The D-shaped shaft drives the driving wheel frame to rotate, the electromagnetic clutch and the D-shaft rotate coaxially, and the clutch friction plate is installed on the inner cage. When the electromagnetic clutch is energized and combined with the friction plate, the driving wheel frame and the inner and outer cages rotate as a whole. When the electromagnetic clutch is powered off and separated, the inner and outer cages and the driving wheel frame can rotate relatively, and the deformation of the wheel legs is realized through the gear meshing transmission on the inner cage. There are two ways to realize:

Method 1: The active rotation of the inner and outer cages is realized by adding an active motor with an encoder to drive the meshing gears to rotate, and the active wheel frame remains stationary during this process, as shown in Figure 2.

Method 2: The meshing gears are braked by the electromagnetic brake, so that the inner and outer cages are stationary, and the driving wheel rotates to realize the conversion of the wheel-leg mode, as shown in Figure 3.

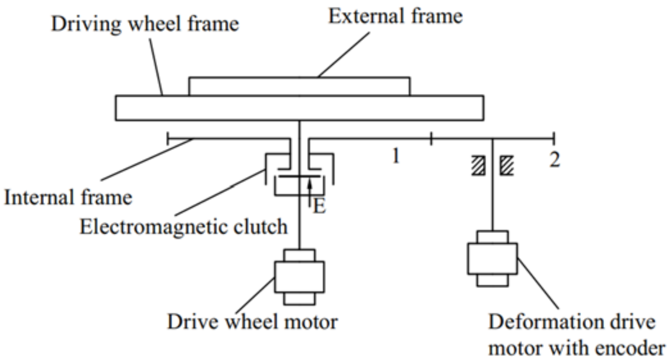


Figure 2. Additional deformation drive motor drive mode

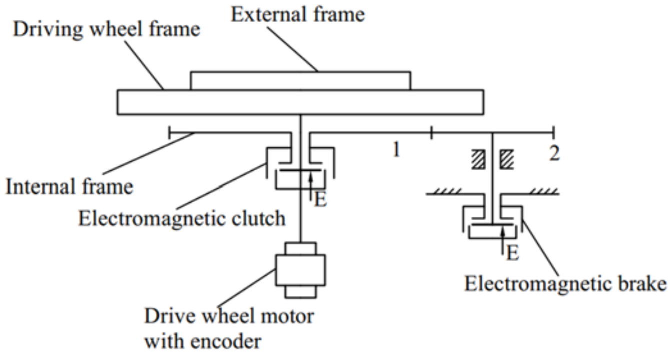


Figure 3. Electromagnetic brake braking deformation mode

In order to reduce the overall weight of the mobile robot and reduce the complexity of control, the second method is adopted as the deformation mechanism of the active wheel legs. In order to make the driving wheel leg rotate according to a certain angle during the rotation process and avoid damage to the wheel leg structure due to excessive rotation, the driving wheel motor is selected with an encoder.

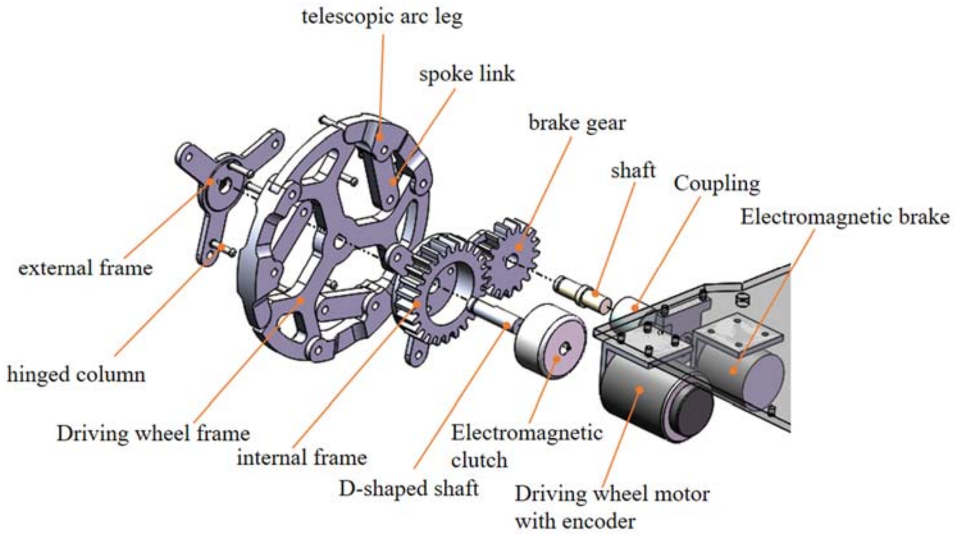


Figure 4. Schematic diagram of deformable wheel-leg structure

The extended arc legs are hinged to the drive wheel frame, and the drive wheel frame is located between the outer cage and the inner cage, and is connected together by hinge pins and spoke links. The other end of the spoke connecting rod is hinged with the extended arc leg, forming a circular roller when the spoke connecting rod shrinks. During the rolling process, the electromagnetic clutch is in the clutch state, the inner and outer cages and the driving wheel frame are integrated, and the friction plates of the electromagnetic brake are in a separated state. At this time, the brake gear can rotate with the gear teeth on the inner cage. When the wheel legs need to be deformed, the body is at rest first, the electromagnetic clutch is powered off and separated, and the inner and outer cages can rotate relative to the driving wheel frame. The driving wheel motor is reversed, and the rotation angle information of the motor can be obtained through the encoder. When the spoke connecting rod and the inner and outer cages are in the collinear position, the electromagnetic clutch is clutched at this moment, and the inner and outer cages and the driving wheel frame form a whole again. The electromagnetic brake is powered off, and the driving wheel motor drives the wheel leg structure to rotate, realizing the deformation from the wheel structure to the wheel leg structure. As show in Figure 4.

2.3. Force Analysis of Obstacle Crossing in the Wheel-leg Mode

The mobile robot has a stronger ability to overcome obstacles after switching from the wheel mode to the wheel-leg mode. It is assumed that the parts of the robot do not deform during the obstacle course, as shown in Figure 5. The obstacle model is simplified as a ladder with a certain vertical height, the vertical height of points A and B is the obstacle height h, the distance between the front and rear wheel centers is L_1, and the support force F_{NA} and friction force f_A are received at point A. After the front wheel is switched to the wheel-leg mode and contacts with obstacles, the moment the front wheel is about to leave the ground under the drive of the roller motor, the front wheel is only subjected to the force of the ground to extend the arc leg. Point B is not affected by the force exerted by the ground on the front wheel. Under the support force F_{NC} and friction force f_C at point C, the torque of the front and rear two-wheel drive motors is the same, that is, M1=M2, with point C as the reference point, there is a torque balance equation

$$\begin{aligned}&(F_{NA}\cos\gamma+f_A\sin\gamma)(R\cos\gamma+L_1\cos\alpha)+F_{NA}\sin\gamma(R\sin\gamma+L_1\sin\alpha+r)\\&=f_A\cos\gamma(R\sin\gamma+L_1\sin\alpha+r)+\frac{1}{2}GL_1\cos\alpha+2M_1\end{aligned}\qquad(1)$$

$$F_{NA}\cos\gamma+f_A\sin\gamma+F_{NC}=G\qquad(2)$$

$$f_A+f_C=F_{NA}\sin\gamma\qquad(3)$$

In the formula, R is the maximum radius when switching to wheel-leg mode. r is the wheel radius of the robot in wheeled mode. α is the angle between the line connecting the front and rear wheel centers and the horizontal direction. γ is the line between the contact point of the extended arc leg and the obstacle and the center of the front wheel in the wheel-leg mode. L_1 is the distance between the front and rear wheel centers.

When switching to the wheel-leg mode to overcome obstacles, the front wheels rotate around the obstacle contact point A, and the torque of the drive motor mainly overcomes the torque generated between the gravity of the robot and the obstacle contact point. Therefore, it can be obtained that the driving torque of the roller motor when the robot surmounts obstacles in the wheel-leg mode is

$$M_{\mathrm{tr}}=\frac{1}{4}GR\cos\gamma\qquad(4)$$

When γ=0°, Mtr takes the maximum value at this time, and the support force of the extended leggings is the largest, that is,$F_{NAmax}=G/4$.

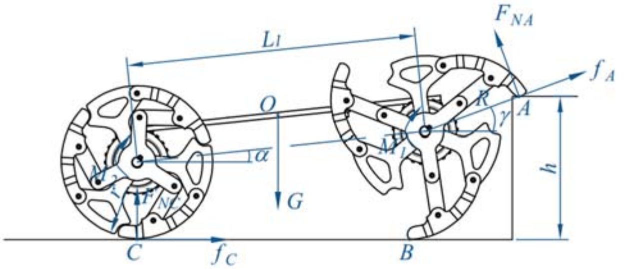


Figure 5. Force Analysis of obstacle crossing in wheel-leg mode

When it is transformed into a wheel-leg mode, the maximum wheel diameter R_{max}=1.35r, the maximum height that the deformed wheel-leg theory can span is

$$h^*=R_{\max}\sin\gamma_0+R_{\max}\qquad(5)$$

$$r\geq R_{\max}\cos\gamma_0\qquad(6)$$

$$h^*=R_{\max}[\sin(\arccos\frac{r}{R})+1]\qquad(7)$$

When in wheel-leg mode, the deformation wheel can span a maximum height of h^*=135mm, and γ_0=42° at this time.

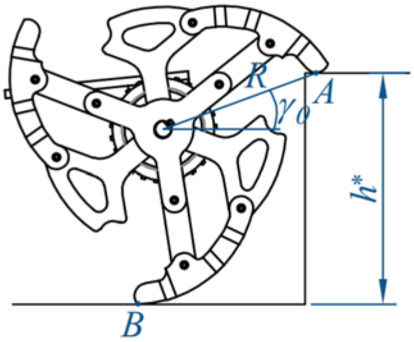


Figure 5. Wheel-leg mode maximum spanning height

3. Finite Element Analysis of Key Parts

3.1. Static analysis of driving wheel frame

After establishing the 3D model of the part in Solidworks, save the part as a Parasolid file format so that the model can be imported into ANSYS. The Parasolid geometric core system can provide precise geometric boundary expression, and can reliably transfer model geometric information between CAD/CAE systems that use it as the core. *.x_t represents the text format of the part model, and *.x_b represents the binary format of the part model [5]. In order to meet the requirements of the lightweight design of land-air amphibious robots, the active wheel frame is manufactured by 3D printing, and PA material is selected as the printing material of the active wheel frame. The material performance parameters are shown in the following table.

Table 1. Physical properties of PA materials

Material	Density	Poisson's ratio	Young's modulus	Yield Strength
PA	$1.15\times10^3\ kg/m^3$	0.3	$1.0\times10^9\ N/m^2$	$54.88MPa$

Assign material properties to the imported 3D model, mesh the model, and set the mesh size to 1mm. The meshing results are shown in Figure 6. The number of divided grid units is 27041, and the number of nodes is 129047. The driving wheel frame receives the driving torque of the motor and exerts a load on the parts. The schematic diagram of the force is shown in Figure 7.

Figure 6. Mesh division results of the active wheel frame

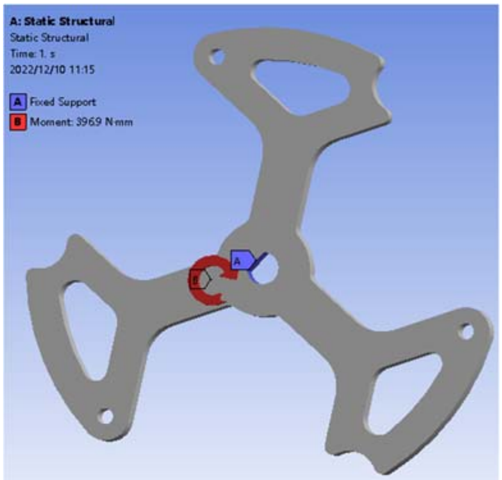


Figure 7. Force diagram of the wheel frame

Add the items to be solved to the analysis structure tree to analyze and solve, as shown in Figure 8 and Figure 9. It can be seen from the figure that after the driving wheel frame is stressed, the maximum deformation is 0.15616mm, and the maximum equivalent stress is 1.6704MPa, which is much smaller than the material yield strength of 54.88MPa. The analysis results show the composite design requirements of the active wheel frame.

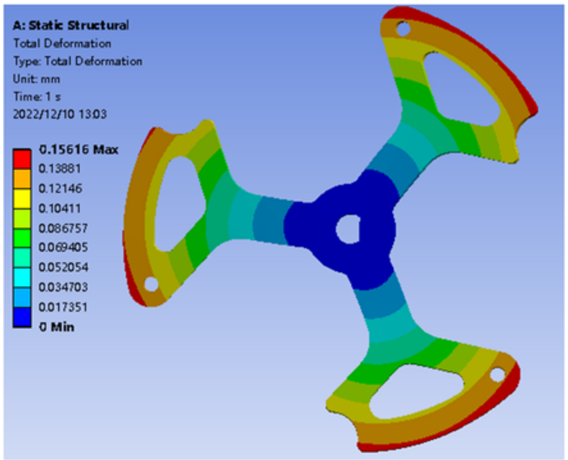


Figure 8. Overall deformation diagram

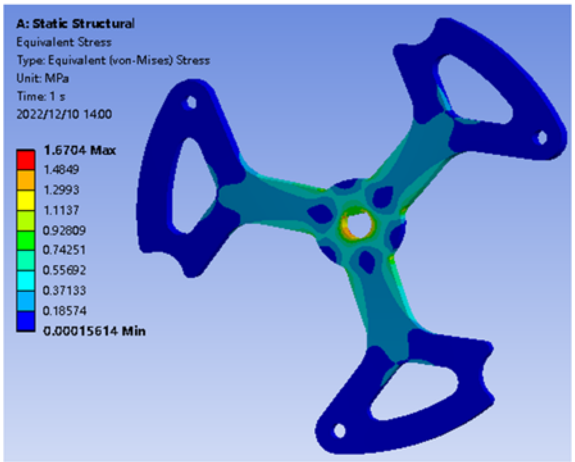


Figure 9. Equivalent stress diagram of parts

3.2. Static analysis of stretched arc legs

The extended arc legs are also made of PA material. When the roller is in the wheel-leg mode, the force on the stretched arc leg is the largest at this time, so the force on the stretched arc leg when the wheel leg crosses obstacles is used for analysis. The maximum force at the end of the stretched arc leg is its own gravity, and the force of the stretched arc leg at the hinge position and support position is obtained by analyzing the vector drawing method in Solidworks. In the middle of the extended arc leg, the hinge is subjected to a horizontal component force of 7.370N to the right and a vertical component force of 2.510N. Set the unit size to 1mm, and divide the arc legs into meshes. The number of meshes is 12265, the number of nodes is 22142, and the load is applied, as shown in Figure 10 and Figure 11.

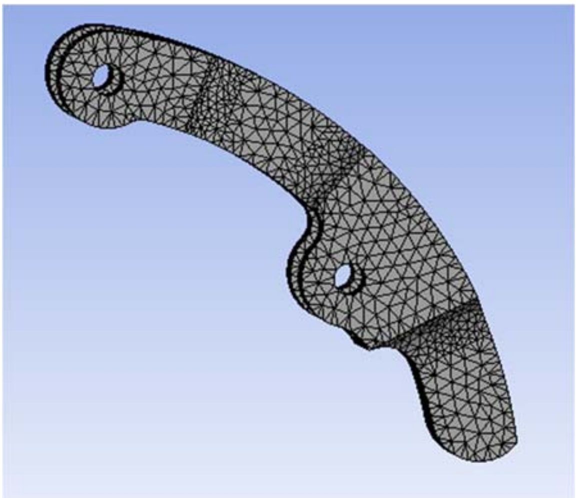


Figure 10. Stretched arc leg meshing

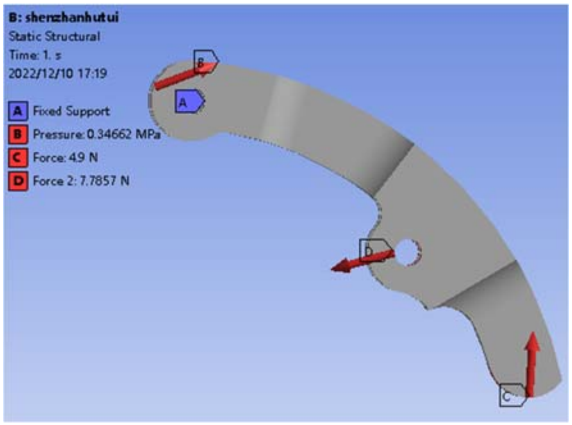


Figure 11. Applied load

Through ANSYS analysis, the overall displacement cloud diagram and equivalent stress cloud diagram of the arc leg can be obtained, as shown in Fig. 3-5 below. The maximum overall displacement of the extended arc leg is 0.00799mm, the deformation is very small, and the maximum equivalent stress is 1.068Mpa, which is less than the yield strength of PA material, so it meets the design requirements.

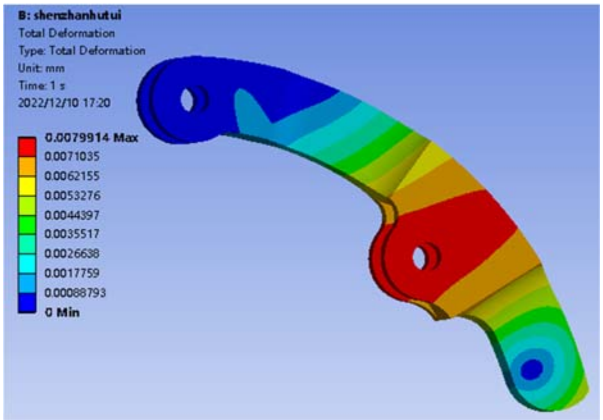


Figure 12. Overall displacement diagram of stretched

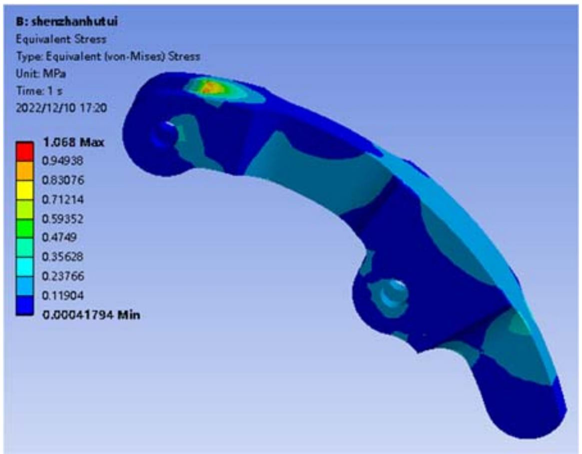


Figure 13. Equivalent stress diagram of extended arc leg

4. Summary

In this paper, a deformable wheel-legged mobile robot is designed, and the wheel-leg deformation mechanism is realized by a four-bar linkage. It can not only make the robot move in the wheeled mode, but also switch the robot to the wheel-legged mode to have better obstacle surmounting performance. The force analysis of different working conditions of the mobile robot is carried out, and the calculation and selection of the roller drive motor is carried out. The force analysis of the key parts of the mobile robot is carried out by using ANSYS. The analysis results show that the structure of the parts meets the design requirements.

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