Novel Design of the Wheel-footed obstacle-surmounting Robot

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Abstract. In order to improve the mobile robot's movement efficiency, obstacle surmounting ability and stability in complex environments, a new wheel-footed obstacle surmounting robot is proposed. The robot wheels include semicircle arc and involute arc. Each group of wheels is complementary in phase to ensure that the contact point between the wheel and the ground is always the circumference of the wheel. This not only continues the high efficiency of the round wheel on the flat ground, but also enhances the ability of the wheel to cross obstacles. This paper studies the structure design and motion analysis of the wheel-footed obstacle-surmounting robot, and completes the robot of the physical prototype. At last, the experiment proves that the robot not only has simple structure, high moving efficiency, but also has good obstacle-surmounting ability, passing ability and stability.

1. Introduction
Multifunctional mobile robots in unstructured environments are one of the hot topics of robotics research area [1]. The Crusher designed by Carnegie-Mellon University is an unmanned ground mobile robot with 6-wheel independent drive and independent hydraulic active suspension. The turbo hybrid system provides strong power, but the infrared and noise levels are extremely low [2]. The chassis of ExoMar (Mars Concept Vehicle and designed by ESA) consists of a left suspension, a right suspension, and a rear suspension. It uses a wheel walking mode, but the control and structure are complicated [3]. Chinese "Yutu" lunar rover adopts a "six-wheel independent drive and four-wheel independent steering" mode, which has a 20-degree climbing, 20 cm obstacle surmounting capability, but has the disadvantages of abnormal control of the mechanism [4]. The University of Science and Technology of China has developed a six-wheeled legged mobile robot with high maneuverability to surmount obstacles. This robot can surmount obstacles with a height of about 1.5 times the wheel radius, but its trace is difficult to control [5].

A new wheel-footed obstacle-surmounting robot was designed by us. The robot has simple structure, high moving efficiency, strong obstacle surmounting ability, good terrain adaptability and great motion performance.

2. Structure design
2.1. Wheel structure design
The wheel structure designed in this paper consists of a semicircle arc and an involute arc, as shown in Figure 1. One section of this wheel is a semicircle arc, and the other is two symmetrical involute arcs. When the robot moves, the semicircle arc contacts the ground for plane motion, and the involute arc contacts the obstacle for obstacle-crossing motion.
When the robot moves, the two adjacent wheels rotate alternately. The ground is always the circumferential part, which is called the ground phase. There is a phase complementary relationship between adjacent wheels. Therefore, the two adjacent wheels need to form a complete circle through phase complementation, as shown in Figure 2. In this way, it is possible to ensure that the robot has a high efficiency of round wheel movement during the movement.

2.2. Body design

The overall three-dimensional structural model of the novel wheeled obstacle-crossing robot designed in this paper is shown in Figure 3. The robot is mainly composed of eight action wheels, six transmission chains, four motors and a robot body.
Action wheels are distributed on both sides of the body, four wheels on each side. The driving device uses four motors, and two motors on each side are facilitate to transmission efficiency and body layout. The wheels on the same side are interconnected in pairs through a transmission chain to ensure that the action wheels on the same side rotate and stop at the same time so that adjacent wheels can always touch the ground with a circumferential portion.

3. Movement analysis

3.1. Ground movement
When the robot is moving, generally, the point O of the center of gravity of the robot chassis is located at its geometric center. At any moment of the robot's movement, the four groups of wheels are complementary in phase, and there are two cases of wheel-ground contact surface, as shown in Figure 4 (a) (b).

When the left and right wheels rotate symmetrically, the contact points between the wheels and the ground form the surface ABCD; when the left and right wheels rotate asymmetrically, the contact points between the wheels and the ground form the surface ABEF. Because the point of contact between the wheel and the ground is always four points, and the plane formed by these four points is parallel to the ground, the center of gravity of the robot is more stable in the quadrilateral plane, so the robot has the high efficiency and stability of a round wheel when the robot is moving on the flat ground.
3.2. Motion of stair climbing

3.2.1. Mode of obstacles crossing. Generally, it is a discrete process when robots climb stairs. Therefore, large fluctuations occur and robots are not stable enough while moving. When discrete process is converted into a continuous process that enables objects moving along the inclined plane, robots can climb the stairs smoothly. If the inclination of the involute arc of the action wheel matches the stair’s slope, the involute of each group of wheels takes effect on the edge of the step. The robot’s body can climb up steadily and obliquely in that way, as shown in Figure 5.

Figure 5. Trajectory of the center of gravity

The Gait shown in Figure 6 (a)-(d) indicates its motion process when climbing stairs. When the robot moves to the stairs, the motor continues to rotate until the involute of the frontmost action wheels touches the step edge, as shown in Figure 6 (a). At this time, the action wheels are continuously driven. With the rotation of action wheels, the involute of the frontmost wheels gradually rolls off the step edge, and then involute of the other group of wheels succeeds to touch the step edge, as shown in Figure 6 (b). It is through such a cycle that the robot can achieve stair climbing movement with no fluctuation and non-stop, as shown in Figure 6 (c) (d).
3.2.2. Static analysis for obstacle crossing. When the robot encounters an obstacle, its force analysis is shown as Figure 7.

Equations (1) and (2) are obtained from the mechanical equilibrium relationship:

\begin{align}
    f_1 \cos \alpha + f_2 + f_4 &= N_1 \sin \alpha \\
    N_1 \cos \alpha + N_2 + N_4 &= Mg
\end{align}

Where \( f_1, f_2, \) and \( f_4 \) are the friction forces from the ground for wheel 1, wheel 2, and wheel 4, respectively, and \( N_1, N_2, \) and \( N_4 \) are the supporting forces for ground wheel 1, wheel 2, and wheel 4, respectively, and \( M \) is the mass of the entire robot. \( \alpha \) is the inclination of wheel 1 to the obstacle, and \( l \) is the distance from the contact point to the center of the wheel 1.

At this moment, the torque analysis of the wheels are shown in equations (3), (4) and (5).

\begin{align}
    T_1 &= N_1 l (0 < l < R) \\
    T_2 &= N_2 R \\
    T_4 &= N_4 R
\end{align}

Because the action wheels are driven synchronously on the same side, the motor output torque is:

\[ T_m = \text{MAX}(T_1, T_2, T_4) \]

From the trigonometric function, we can get the \( h \) in equation (7):

\[ h = l \sin \beta \]

The obstacle clearance height of the robot can be calculated according to the geometric relationship:
6

\[ H = h + R = l \sin \beta + R \]  

(8)

4. Experiment
In order to verify the performance of the robot, a physical prototype of the eight-wheeled foot robot has been developed. The robot is 560mm long, 400mm wide, 180mm high and the wheel diameter is 180mm. After testing on flat terrain, it is found that the motion performance of the robot is as efficient as the one with round wheel, and that the phase coordination between each group of wheels is very good, as shown in Figure 8.

Figure 8. Test on the flat ground

Unstructured terrain is selected to be tested on the stairs, as shown in Figure 9. The stair size is 15 cm height, the step width is 28.5 cm, and the slope is 27 degrees. The experiment shows that the robot climbs up the stairs smoothly without fluctuation and any pause.

Figure 9. Test on the stairs
5. Conclusions

It was found some conclusions:

1. Based on the defects of the existing obstacle crossing robot, this paper designs a novel obstacle crossing robot that combines the function of smooth and efficient together, or more specifically, which not only move quickly like a round wheel robot in flat terrain, but also cross the obstacles smoothly in non-structural terrain.

2. The robot's wheels are composed of a semicircle arc and an involute arc, and the semicircle arc is conducive to flat movement while an involute arc is beneficial for crossing the obstacles. The two wheels complement each other in phase to increase stability.

3. The action wheels are driven by the way “same side and same phase”, which makes it easier to control the robot.

4. The experimental results show that the robot has better obstacle crossing ability and stability. It can provide an adaptive mobile platform for tasks such as security inspection and environmental monitoring in non-structural environment.

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