Realization of A Deformable Wheel Adapting to Running Conditions

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Abstract. The problem of the aging society has become more serious, and the use rate of the mobile auxiliary equipment such as wheelchair has increased. Moreover, the situation of the ground on which such wheelchairs run becomes complicated by the urbanization progress, and especially, for the rough terrain and the obstacle, the elderly and the their caregivers meet difficulties to pass through due to such as the distance and the external force. According to this situation, a new mobility device adapted to various running environments is required. This research has proposed a deformable wheel to overcome these issues. The deformation wheel was designed to be able to run in the rough plane such as a step, and it runs only by the rotation motion of the wheel, with the expansion mechanism with the variable diameter hub added, while retaining the performance of the circular wheel which can run on the high efficiency and high speed in the plane.

1. Introduction

The purpose of this paper is to develop a deformable wheel which can move smoothly and stably like the typical circular wheel on the flat surface and move smoothly to climb the stairs with a function of deformation.

At present, the problem of the aging society becomes more serious. On the other hand, because of the urbanization, the land situation becomes complicated, and the steps and staircases are increasing. So, it's necessary to consider the efficient moving method for the elderly and their caregivers. Especially, the rough terrains such as stairs and steps are in everywhere, even in the urban area to pass these terrains, we must take the mean of a roundabout way or elevators.

As a vehicle which can move even such steps, Previous means such as wheel type, foot type, crawler type and so on have been studied. The wheel type is able to move in the plane in high efficiency, and the foot type can move at the rough terrain. The crawler type has their intermediate nature, and their merit and disadvantage respectively.

The merit of previous studies have been utilized well. Ohmichi et al.,who combine the foot and the crawler type, made the robot walk on the surface of the step like a spider [1]. Matsumoto et al. proposed the method to overcome the step with different vertical movement by combining the foot and the wheel type, changing the front and rear legs to move up and down[2]. Koyanagi et al., on the base of wheel type, proposed a method to overcome the step by controlling the relative position of the wheels with using a plurality of wheels[3]. However, as the above methods of overcoming the steps have poor efficiency and low stability. In order to run a step from a plane need a sensor detected the

step, then it can climb the step gradually and run continuously from plane to step. And the movement of the vehicle can't keep stable when running on the step. Especially the foot type, its vertical motion is very obvious.

In this paper, we aim at the realization of a new mobile device which combines these good properties. We propose a new deformable wheel, which can keep high efficiency and high speed in the plane by circular wheel mode and correspond to the rough terrain by a variable diameter hub. Then we will examine its practicality of running ability.

2. Pattern and walking condition

In contrast with previous researches[4], we propose a circular wheel using a variable hub which can be stretchable. And, based on the condition of running the steps with circular wheel as shown as figure 1, we will examine the rationality of this pattern.

Figure 1. The specifications of wheel

2.1 Choice of pattern

In this study, we propose a method that can maintain high speed and stability of running on a plane, and run smoothly on a stepped surface. Then, we choose the most suitable circular wheel as the base, and divide the tire parts, so they can be expanded and contracted.

In order to maintain the high speed and stability on the plane, all divided tires are accommodated to become one round tire, then this deformable wheel runs on the plane like the normal tire. When it runs on the stepped surface, the all tires parts are expanding to adopt to the shape of the step. So the running track on the step is close to the inclination of the step.Then this wheel can run on the step stably. And, the main motion of the running is the rotation motion of the whole wheel, and high-speed movement on the step is available.

2.2 Condition of overcoming steps

It is possible to calculate the condition in which a circular wheel runs over the steps by the resistance of the wheel's material and load as shown as figure 2. And the parameters are shown in table 1. The calculation model of circular wheel to overcome steps, when the component in the D direction of force Q is bigger than the component in the D negative direction of load W, the circular wheel can overcome steps. This condition is expressed as formula (1). Sorting out it, the condition of overcoming steps will been expressed as formula (2)[5].

$$Q \cdot \cos\theta > W \cdot \sin\theta \tag{1}$$

$$Q > W \cdot \tan\theta \tag{2}$$

From the formula (2), when load W has not been changed, the angle θ becomes smaller, the force Q will be small. On other word, the angle θ becomes smaller, the circular wheel will be easy to overcome steps.

The angle θ is expressed as formula (3)(R is the radius of wheel.)

$$\tan\theta = \sqrt{\frac{R^2 - (R-s)^2}{(R-s)^2}} \tag{3}$$

In this paper, under the condition of expanding in its radius direction which we have proposed the wheel, the distance L becomes smaller, then the angle will become small.
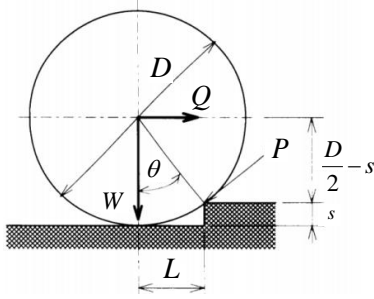

Figure 2. The mechanics analysis of wheel

Table 1: Name of parameters

W	Load on the wheel
Q	Force to push the wheel
D	Radius of the wheel
s	Height of the step
θ	The angle between the center of the wheel and the step
L	Horizontal distance between the center of the wheel and the step

Under the expansion of radius as ΔR, the calculation of the angle θ will become formula (4).

$$\tan \theta' = \sqrt{\frac{(R+\Delta R)^2 - (R+\Delta R - s)^2}{(R+\Delta R - s)^2}} \tag{4}$$

Above these, adding the function of expanding and contracting radius, the distance L becomes smaller then the angle θ will become smaller. Based on these, if considering the angle of running into the step and the length of expansion and contraction of the hub, we can find the movement rules under various running conditions.

2.3 Examination of stretching running

As the same as the Condition of overcoming steps, calculating the resultant force in the P direction of force Q and load W, expressing as formula (5).

$$F = W \cdot \cos\theta + Q \cdot \sin\theta \tag{5}$$

Here, we normalized formula (5) by the load W, the formula (5) is deformed, and it changes into formula (6).

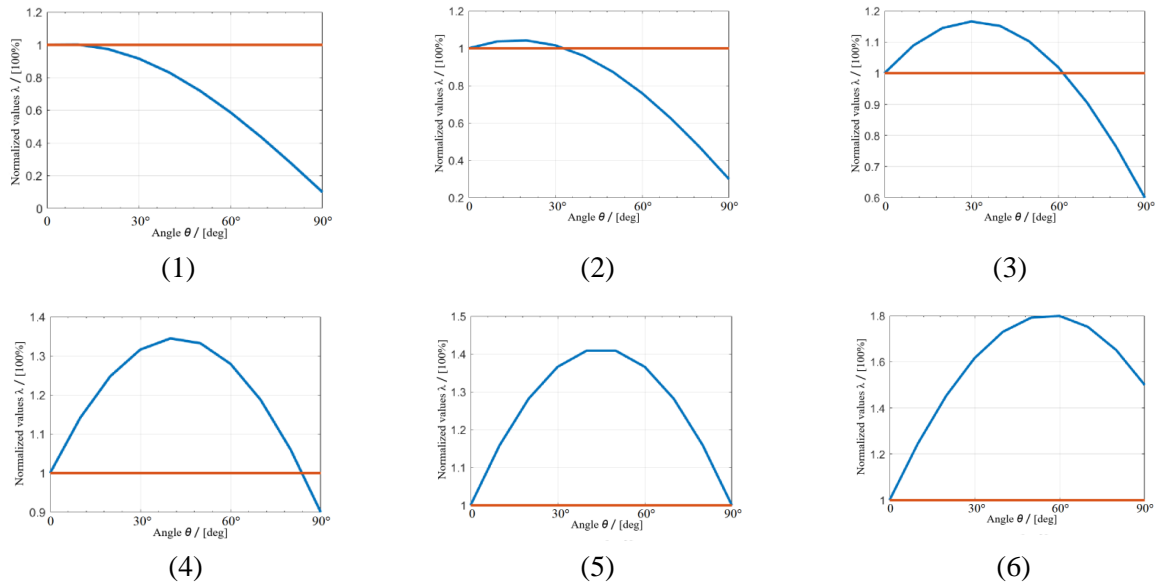$$\lambda = \frac{W \cdot \cos\theta + Q \cdot \sin\theta}{W} = \cos\theta + \eta \cdot \sin\theta \tag{6}$$

Figure 3. Relationship between pushing force and load

[(1):η=0.1，(2):η=0.3，(3):η=0.6，(4):η=0.9，(5):η=1.0，(6):η=1.5]

Base on the proportional coefficient of formula (6) (η= 0.1, 0.2, 0.3...), calculating the normalized values λ is showed in figure 3.

The angle θ of the deformable wheel is almost 30°～75°. From the figure 3, the value λ in this section is almost over 1. Since η=1.0, the overall value exceed 1. Therefore, the expansion and contraction of the tire becomes the basic operation under the situation of running steps.

3. Design of wheel
The wheel design is divided into two parts of mechanism design and drive design.

3.1 Design of mechanisms
From the functional requirements of the preface, almost two functions are required. The conversion of two running conditions and the expansion and the expansion of each tire part. Based on these two functions, we design the following mechanisms.
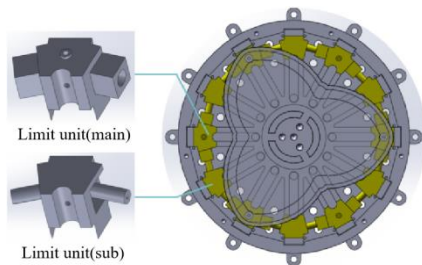

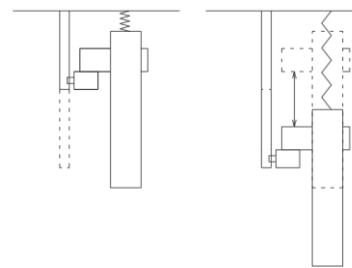**Figure 4.** Image model of deforming apparatus   **Figure 5.** Principle of deformation apparatus

3.1.1 deformation apparatus. By rotating motion of a star cam with the form of triangular star, Hub movement range is controlled by limit units as shown in the figure 4.

When the bearing connecting to the limit unit[main] hits the valley of the cam, the bearing is limited to the groove of the cam, and the spring is compressed. When the cam starts rotating, the limit unit[main] begins to move to the outside through the groove. By the interlocking apparatus of figure 6, the limit unit[sub] starts to move. The total limit unit moves along the rail, the lock on the hub is released, and the spring recovers, then the displacement unit start move and the part of the tire is expanded. When the bearing connecting to the limit unit[main] hits the hill of the cam, the bearing is pushed to the cam. Then the tire is expanded to the maximum. From the expansion and contraction of each spring, this wheel adopt to the shape of obstacles and overcome them. This is the process of wheel deployment as shown in the figure 5.

On the other hand, when the cam rotates further, and the bearing moves from the hill of the cam, the spring is pushed back, the limit unit is pressed to inside, and the part of the tire is converged. When the bearing moves to the valley of the cam, the tire is housed to the minimum and returns to the normal wheel .

3.1.2 interlocking apparatus. The quantity of limit units that can be directly controlled by the cam is limited, so that synchronizes the operation of all limit units through the mechanism between the limit units[main and sub] in the figure 6.

A ratchet mechanism is used to realize one-way rotation of the cam. The one-way rotation apparatus is connected by a rotating shaft to the opposite side of the cam. A part of the shaft is removed, and three helical gears are connected with the spring building in the shaft. The rotating shaft can be rotated only in the direction in which the helical gears overcomes against the spring. On the other hand, when the rotating shaft is rotated in the opposite direction, the helical gears will hit the side helical gears, so that the rotation is blocked as shown in figure 7. Therefore it possible to limit the rotation direction of the cam in one direction.
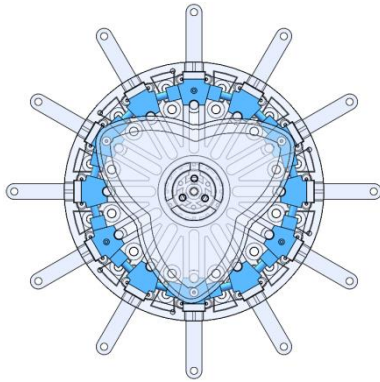
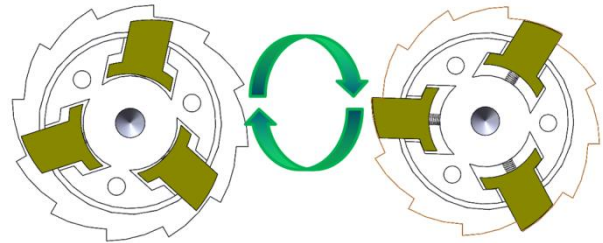**Figure 6.** Mechanism diagram of interlocking apparatus

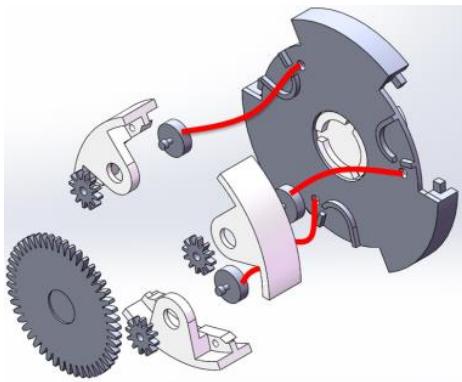**Figure 7.** Image model of one side rotator

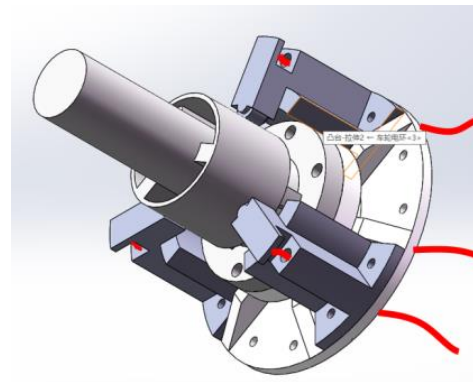**Figure 8.** Steering device of planetary wagon

Figure 9. Slip ring apparatus

3.2 drive and power design
In order to drive and control mechanisms at 3.1 chapter, the transmission devices of power and signal are necessary by the planetary wagon as shown in the figure 8.

3.2.1 slip ring power system. Due to the problem that the wire is cut with the rotation of the wheel, we used the slip ring apparatus to solve it. The slip ring apparatus is arranged at the axle side. It has a fixed ring penetrated by the axle and three rotating brushes which connect the outer surface of the fixed ring. The brush contacts the ring while rotating, then it connects to each small flat motor with wires. So power delivery from the ring can be supplied to each small flat motor through each rotation brush as shown in the figure 9.

4. Mechanics analysis
Based on the preface design, according to the running situation, its strength is required. Especially, the friction between the apparatuses gives a considerable load to the drive system. So we analyse these friction.

4.1 Friction
The friction of the cam rotates and hub slides is large. It is difficult to operate the motion of the deformation apparatus smoothly. In this paper, we analyzed kinds of friction, and found their corresponding solution to reduce the friction.

   The cam unit provides the force F to move the limit unit. Its effective component is F_y and another component F_x and will make the friction large. The force F is provided from the torque τ of the motor

and is related to the position of the contact point. The friction f_1 with cam pressure angle is expressed as formula (7). The dynamic analysis such as figure 10.

$$f_1 = \frac{\tau}{s} \cdot \sin \alpha \cdot \mu_1 \tag{7}$$

The moving unit of the deformable wheel has limit units and hubs. The friction f_2 of the unit movement is composed of the rotation of the cam, and the moving friction of hubs with the expansion and contraction of the spring.

The friction F_μ between the limit units is caused by pressure $F_{y\mu}$ generated by the effective component F_y from the rotation of cam. The moving direction of the friction f_3 is between the interlocking apparatus. The dynamic analysis such as figure 11.

$$F_{y\mu} = F_y \cdot \cos \beta \tag{8}$$

$$F_\mu = F_{y\mu} \cdot \mu_2 \tag{9}$$

$$f_3 = F_\mu \cdot \sin \beta \tag{10}$$

The balance of of whole wheel consists of the above three frictions. The effective component F_y, the resistance of spring N and the balance of whole wheel is expressed as formula (11)(12)(13).

$$F = \frac{\tau}{s} \cdot \cos \alpha \tag{11}$$

$$N = k \cdot x \tag{12}$$

$$\frac{\tau}{s} \cdot \cos \alpha = k \cdot x + \frac{\tau}{s} \sin \alpha \cdot \mu_1 + f_2 + \frac{\tau}{s} \cdot \cos \alpha \cdot \cos \beta \cdot \mu_3 \cdot \sin \beta \tag{13}$$
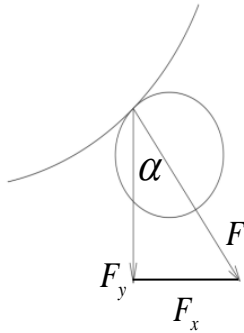

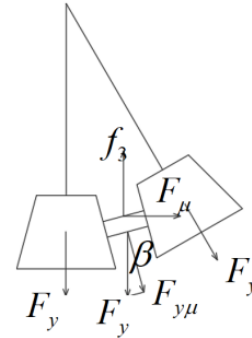**Figure. 10** Dynamic analysis of cam   **Figure. 11** Dynamic analysis of mechanisms

5. Conclusion

In this paper, on the basis of the restriction of dual-purpose with wheel type, foot type, crawler type, etc. A deformable hub was installed on the base of the wheel type, and design and analyze the deformable wheel. So it is possible that run both the plane and the stepped surface. In the future, quantitative evaluation of the performance is examined.

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