Design and Simulation Analysis of a Terrain Adaptable Wheeled Mobile Platform

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Abstract—This paper presents a novel obstacle-surmounting robot with eight big wheels, which is designed for searching and rescuing tasks. Four passive planetary swing wheel structures, each of which is composed of two wheels and a planetary structure, are installed into four corners of the vehicle symmetrically. The planet carrier performs as a swing arm to adjust the relative angle of the vehicle’s chassis and ground automatically and passively. As a consequence, the necessary actuators for the vehicle are reduced to four. For enhancing the stability and adaptability against complex uneven terrain, analysis and simulation experiments have been done to optimize dimensions of the vehicle, where the diameter of the wheel and the central distance of the neighbor planetary sets are modified to 460 mm and 560 mm in the end. Finally, experimental results demonstrate excellent stability and adaptability of the vehicle, and the vehicle is easy to control without any additional operations.

Keywords—Terrain Adaptable; mechanical design; planetary swing; simulation and optimization

I. INTRODUCTION

Many researches in the last few decades have focused on obstacle-surmounting robots, which play an important role in searching, rescuing, and planet exploring. In order to perform these challenging tasks with high performance, the mobile platform need to be stable, adaptable to various environments with robust structures and high energy efficiency. However, most of obstacle-surmounting robots do not match these requirements.

Obstacle-surmounting robots can be divided into three categories based on their mechanism: wheel-type robots, crawler-type robots and hybrid robots. As for the wheel-type robots, it may have simple but robust structure, fast movement. However, the wheel structure limits its adaptability to rough terrain, such as stairs, cobble stone and pipe areas.

As for the crawler-type robots, it presents high adaptability in various environments. The famous Helios series robots [1] and PackBot [2] are typical representatives of the crawler-type robots. Helios VII [3] and IX [4] have two independently actuated crawlers that can rotate 360 degrees relatively to the chassis, therefore improve the adaptability to uneven terrain. However, it needs skilled operation to adjust the relative angle of swings and obstacles when moving forward, which may be not easy for the manipulator. Meanwhile, the energy efficient and stability of this robot is not good.

As for the hybrid robots, there are various kinds of structures developed in recent decades, most of which are designed as wheel-leg type robots. For example, Charriot III [5], Wheeleg [6], Mantis [7] and Claw-Wheel hybrid robot [8] are designed to uses legs and wheels respectively in complex terrain and flat ground. These vehicles need additional operations to switch different modes for different environments. For instance, Claw-Wheel hybrid robot takes 10s or longer time in transformation. And for another category of wheel-leg robots, such as Octal Wheel [9], PAW [10], AZIMUT [11], RT-move [12], they utilize active or passive wheels installed on each leg. These vehicles keep excellent stability but require a number of actuators.

In order to incorporate advantages of the hybrid robots but have less actuators and simple manipulation, we had developed a novel terrain adaptable wheeled mobile platform with passive planetary swing structure. As a result, the vehicle uses only four actuators, keeps good stability and high energy efficiency in obstacle surpassing motion and is easy to control without additional operations [13]. In this paper, the latest version of the terrain adaptable wheeled mobile platform is described. Some novel features of the vehicle are discussed in Section II. In Section III and Section IV, the analysis and simulation of obstacle surpassing ability and stability are reported, which provides us the guidance for optimizing the diameter of the wheel and the central distance of the neighbor sets. Furthermore, the experiments reported in the final part prove that the vehicles were successfully developed in Section V.

II. MODEL DESIGN

A. The passive Planetary Swing Structure

Fig.1 describes the passive planetary swing structure. In this structure, the planet carrier supports five gears with hinged connection. These five gears are classified into sun gear, small planet gear and large planet gear. The sun gear is treated as power input, and the two same small planet gears are installed beside and contacting with the sun gear. Similarly, the two same large planet gears are fixed beside the small planet gear, and also keep contacting with the small planet gear, and also keep contacting with the small planet gear.
Therefore, all these gears and planet carrier are combined together as a planetary swing structure. Two wheels are fixed to the large planet gear. When the vehicle is moving, the input power from the sun gear will distributed into two planet gears, which actuate the wheels respectively.

This passive gear planetary structure shows excellent obstacle surpassing ability when facing obstacles. Consider two common situations. Fig. 2 (a) describes the scene that the vehicle is moving on a bumpy road. If the front wheel is lifted up by some reasons, while the rear wheel is trapped in the hollow on the road, the gravity force of the front wheel and the normal force from the ground to the landing wheel will form a torque on the planet carrier. Hence, the planet carrier will rotate inversely, and the lift-up wheel will land back while the rear wheel will be carried out from the hollow.

In Fig. 2 (b), the mobile robot is to climb over obstacles. When the front wheel contacts an obstacle, a large part of power will be distributed from the sun gear and finally be transmitted to the contacted wheel, which forces the wheel rotate. Hence, the obstacle will generate a reaction normal force N and friction force F on the contacted wheel, which help form a torque on the planet carrier. This torque makes a tendency of the planetary structure to rotate around, and finally lifts the contacted wheel up. In a conclusion, when the wheel contacts an obstacle, the passive gear planetary performs as a simple swing structure to adjust the gear force disturbed from the sun gear, which enhances the adaptability of the vehicle against complex unstructured terrain.

B. The overview of whole platform

Fig. 3 describes the overview of the whole platform. Four sets of planetary gear structure are installed in the four corners of the chassis symmetrically. Therefore, the whole moving robot has four motors which actuate eight wheels. To keep the whole structure compact, the installation sites of the two wheels on the same planetary structure are kept parallel and partly overlapping with each other.

All eight wheels of the vehicle are kept landing on the ground during moving on the flat road, which is quite similar with the 4WD types. Hence, we can send different commands to the four actuators to drive the car move forward, backward and make a turn.

C. Motion of Climbing Stairs

As the proposal described above, the prototype of the vehicle is constructed. Fig. 4 describes the motion of climbing stairs of the vehicle clearly.

In Fig. 4 (a), the front wheel is contacting stairs. As mentioned above, a large torque will be transmitted from the sun gear to the contacted wheel, which forces the wheel to move relative to the stair. Therefore, the stair generates a normal force and a friction force on the planetary structure.
Since the planetary is not fixed but hinged with the vehicle, the planetary structure will rotate around the sun gear, which lifts the front wheel and chassis up. And when the wheel is lifted up, due to the gravity force of the wheel, the planetary structure rotates reversely, and lifts the rear wheel up, which is shown in Fig.4 (b). Fig.4 (c) and (d) shows the similar procedure. Thus, the motion of climbing stairs could be easily completed through the passive planetary swing structure.

III. Analysis

A. Evaluation metrics for the obstacle robot

There are kinds of vehicles that achieve appreciable performance in moving on complex unstructured terrain. However, there is not a universal evaluation criterion accessing and comparing their performance. To the author’s knowledge, most of these robots carry expensive experimental equipment, working in complex environments which is dangerous or even fatal for human. Therefore, a vehicle, which can move freely and stably and can be controlled with easy operations in such a complex environment, is indeed needed. Hence, in this paper, the adaptability and stability to various environments are treated as evaluation metrics for the obstacle robot.

This vehicle mostly works in the urban environment to do searching and rescuing tasks, where exists many obstacles and stairs. Therefore, to the vehicle, the most important part of adaptability is the obstacle surpassing ability, of which we define the maximum height of surmountable obstacle as the measurement.

Since this vehicle carries functional devices in missions, we need to be concerned about the stability of the vehicle and equipment both. To avoid the vehicle tipping over in stair climbing, the relationship of the height of gravitational center and horizontal travelling distance is needed to be focused on. Based on the smoothness of the vehicle in climbing stairs, the angle of inclination of the chassis to the ground shows the stability of equipment, which is defined as another measurement.

In order to get better performance of the vehicle with these evaluation metrics, we do the analysis of vehicle model in climbing against obstacles to find influence factors.

B. Analysis of the force model for the vehicle

In this part, some postures are chosen to analyze the mechanics of the vehicle, including front wheel and rear wheel climbing posture.

Fig.5 represents a force-balanced model of the vehicle when the front wheel is to climb over the obstacle.

Where, we define the center points of the planet gears are \( O_1, O_2, O_3, O_4 \) and center point of the sun gear is \( O \). Then, the center distance of the sun and planet gear is defined as \( l_1 \), and is half of the center distance of the two wheels. Also, we define center distance of the neighbor planetary sets is \( l_2 \), the horizontal distance between \( O \) and gravity force of the vehicle is \( l_3 \), the wheel radius is \( R \). And the height of the obstacle is defined as \( h \).

Also, we define \( F_1, F_2 \) and \( F_3 \) are reaction forces from the ground, \( f_1, f_2 \) and \( f_3 \) are traction forces to the three wheels respectively. \( F_g \) represents the normal force from the obstacle, and has an inclination angle \( \alpha \) with the horizontal line, which generates friction force \( F_f \) on the wheel. And \( G \) represents the gravity force of the vehicle.

Suppose the moving velocity is slow, then the vehicle can be treated as a force-balanced model. Meanwhile, to simplify this model, we suppose the coefficient of rolling friction is small and can be omitted, and two wheels of the rear planetary structure set can be treated as one wheel, hence, \( F_2 \) and \( F_3 \) are replaced by \( F \).

Therefore, the force-balanced and torque-balanced equations for the vehicle can be obtained and shown in Eq. (1) ~ Eq. (3). The torque-balanced equation for the planetary set can be written as Eq. (4):

\[
F_g \cdot \sin \alpha - F_v \cdot \cos \alpha = 0
\]  
\[
F_v \cdot \cos \alpha + F_v \cdot \sin \alpha + F_t + F - G = 0
\]  
\[
F_1 \cdot 2l_1 + F \cdot (l_1 + l_2) = F_h \cdot R + G \cdot (l_1 + l_2)
\]  
\[
(F_h \cdot \cos \alpha + F_v \cdot \sin \alpha) \cdot (R \cdot \cos \alpha + l_1) = F_1 \cdot l_1
\]  

From Eq. (1) ~ Eq. (4), the relationship between \( \cos \alpha \) and \( F_h \) is shown in Eq. (5):

\[
\cos \alpha = 2\left(\frac{(G/F_h) \cdot (1 - l_1/l_2) - R/l_1}{1 - 4/F_h \cdot (G/F_h) \cdot (1 - l_1/l_2) - R/l_1}\right)
\]  

Meanwhile, from the geometry relationship, we can know:

\[
\sin \alpha = 1 - h/R
\]  

Hence, from Eq. (5) and (6), the relationship between \( h \) and \( R \) is obtained as the result:

\[
h/R = 1 - \sqrt{1 - 4\left(\frac{(G/F_h) \cdot (1 - l_1/l_2) - R/l_1}{1 - 4/F_h \cdot (G/F_h) \cdot (1 - l_1/l_2) - R/l_1}\right)^2}
\]  

Since \( l_1 \) is approximately half of \( l_2 \), the conclusion that the height of obstacle can be larger with bigger diameter size of the wheel and smaller center distance of the wheels on the same set, is obtained.

In Fig.6, it is shown that the rear wheel of the vehicle is moving against the obstacle. Similarly, we can obtain the force-balanced and torque-balanced equations:
\[ F_R \cdot \sin \alpha - F_N \cdot \cos \alpha = 0 \]  
(8)

\[ F_R \cdot \cos \alpha + F_N \cdot \sin \alpha + F \cdot R - G = 0 \]  
(9)

\[ F_R \cdot R + F \cdot (l_2 - l_1) = F_1 \cdot 2l_1 + G \cdot (l_2 - l_1) \]  
(10)

\[ (F_R \cdot \cos \alpha + F_N \cdot \sin \alpha) \cdot (R \cdot \cos \alpha + l_1) = F_1 \cdot l_1 \]  
(11)

From Eq. (8) ~ (11), relationship of h and R is generated:

\[ h/R = 1 - \sqrt{1 - 4\left(\left(G/F_R\right) \cdot (l_1/l_2 - l_1/l_2) - R/l_1\right)^2} \]  
(12)

From Eq. (12), we can draw the conclusion that the obstacle-surpassing ability can increase with smaller center distance of the neighbor planetary sets, bigger diameter size of the wheel and smaller center distance of the wheels.

However, stability is largely influenced by the center distance of the neighbor planetary sets. It is considered that the separated landing points will increase the stable zone and the stability.

Due to the analysis above, the optimization of the wheel radius and the center distance of the neighbor planetary sets is described below.

### IV. SIMULATION AND OPTIMIZATION

In this section, a series of simulation experiments are conducted to explore the relationship between the two variables and the performance. Specifically, the model of the vehicle is created using Creo and imported to V-REP. In V-REP, dimensions and specifications of the vehicle are defined in Table I, and the friction coefficient of the obstacle and the wheel is 0.4.

<table>
<thead>
<tr>
<th>TABLE I. DIMENSION OF THE VEHICLE</th>
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<tbody>
<tr>
<td>Dimensions of the whole vehicle</td>
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<tr>
<td>Dimensions of the vehicle body</td>
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<tr>
<td>Diameter size of the wheel</td>
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<tr>
<td>CD of the neighbor planetary sets</td>
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<tr>
<td>CD of the wheels on the same set</td>
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<tr>
<td>Weight</td>
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<tr>
<td>Motors</td>
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<tr>
<td>Payload ability</td>
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A. Obstacle surpassing ability in simulation

Due to the ordinary size of stairs, with numerical computing, the diameter size of the wheel must equal or larger than 400 mm, and the center distance of the neighbor planetary sets is equal or smaller than 800 mm. Meanwhile, to avoid mechanical interference, the limits of these two dimensions are 520 mm and 500 mm. Here, the simulation describes the motion of obstacle traversing with these two variables.

In Fig.7, lines of distinct colors represent different diameter size of the wheel. It is shown in graph that the obstacle surpassing ability increases with larger diameter size of the wheel, and smaller center distance. Meanwhile, when diameter size of the wheel is between 460 mm to 520 mm, the height of the obstacle does not change much.

![Fig.6. Moving against obstacle on the rear wheel](image)

![Fig.7. The relationship of center distance of neighbour planetary sets and the height of obstacle](image)

![Fig.8. The relationship of curve change rates and the height of obstacle](image)

In conclusion, when the diameter size of the wheel is between 460 mm to 520 mm, and the center distance of the
neighbor sets is between 500 mm to 525 mm, the obstacle surpassing capacity is better.

B. Stability in simulation

Here, the stair climbing stability is optimized by the simulation experiment. The height of stairs is defined as 170mm, and the width of stairs is 300mm.

In Fig.9, the height of gravity changes smoothly with the horizontal travelling distance, which shows excellent stability of the vehicle. Furthermore, we are also concerned about the stability of the equipment carried by the vehicle that can be measured by the change of the relative angle between chassis and ground during moving.

In Fig.10, it is shown that the inclination angle changes periodically during climbing procedure. Therefore, stability can be measured by the angle conversion amplitude of one period. To be more accurately, we define the average of the angle change amplitude in all periods as the measurement.

When the center distance of neighbor planetary sets is smaller than 620 mm, the vehicle performs better in stability with larger center distance of the neighbor planetary sets, otherwise the stability changes little.

C. Result analysis

From the conclusions, to get better stability, the diameter size of the wheel is 455 mm. And simulation A guides us to modify the center the center distance of the neighbor planetary sets to 500 mm ~ 520 mm, meanwhile simulation B leads us to optimize this dimension to larger than 620 mm. To balance these, the center distance of the neighbor planetary sets is modified to 560 mm.

V. EXPERIMENTAL VERIFICATION

The analysis and simulation results provide guidance for the optimization of the vehicle. The dimension of the vehicle is 1200 x 800 x 500 mm, the diameter size of the wheel is 460 mm, and the center distance of the neighbor planetary sets is 560 mm. With these parameters, the vehicle is constructed and the verification experiment is described below.

Fig.11. The relationship of the diameter size of wheels and the relative angle between chassis and ground

- When the center distance of neighbor planetary sets is smaller than 620 mm, the vehicle performs better in stability with larger center distance of the neighbor planetary sets, otherwise the stability changes little.
In future work, more details and more utilizations of this useful structure are to be researched and developed. When two wheels of the same size on the planetary swing structure are replaced by a bigger wheel and a smaller wheel, we obtain a similar mechanism that may perform better in obstacle surpassing ability. For complex tasks, a snake-like-integrated robot can be obtained by serially linking serial these structures.

REFERENCES


VI. CONCLUSIONS AND FUTURE WORK

This paper outlines a design of novel terrain adaptable cascading wheeled mobile platform with passive planetary swing structure in the first part. Due to the analysis and simulation experiments about obstacle crossing procedure, which is reported in the later part, we draw the relationships between the vehicle’s performance and dimensions. From the relationships, the diameter size of the wheel and the center distance of the neighbor planetary sets are optimized to 460 mm and 600 mm. Furthermore, the experiments reported in the final part prove the vehicles was successfully developed.

However, the vehicle is only an ordinary utilization of the planetary swing structure that is proved to have excellent terrain adaptability by theoretical and experimental methods.

The experiment was done in ordinary building-house staircases environment, the height and the width of which is 170 mm and 300 mm.

In Fig.12 (a) ~ (d), the passive gear planetary performed as a swing structure to adjust the relative angle between chassis and planet carrier passively, which did not need any manual operations. Since there were always eight wheels keeping landing on the ground, the vehicle performs high stability. Fig.12 (e) ~ (h) describe the stair descending process, which is a similar but inverse process with the stairs ascending motion.

The electronic gradierter installed on the vehicle showed that angle conversion amplitude was average 5 degrees during this procedure, which shows excellent stability.