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Research paper

Design and analysis of a compliant variable-diameter mechanism used in variable-diameter wheels for lunar rover

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Variable-diameter wheels have two limited working statuses: the unfolded limit rimless wheel and the folded rigid circular wheel. These can solve the contradiction between tractive performance and the limited spacecraft volume of the lunar rover. The variable-diameter mechanism proposed here is the most critical part. It allows the wheel to transform its structure using expansion-retraction motion and to possess excellent running performance. A novel compliant mechanism configuration with helical torsion springs is introduced, along with its mechanism principles. Based on two extreme wheel statuses, a two-position motion generation using nonlinear optimization synthesis is used to determine the dimensional parameters of the mechanism. The load-deflection behavior is derived by developing a pseudo-rigid-body model for the mechanism. Load-deflection relationships obtained from the pseudo-rigid-body model are compared with the results of finite element analysis (FEA) simulations. The results show that the predictions made by the pseudo-rigid-body model (PRBM) are in good agreement. Overall, the design and analysis approaches proposed here are applicable for variable-diameter mechanisms. In addition, the load-deflection relationships presented can provide theoretical references for the variable control of the wheel diameter.

1. Introduction

Rover performance can be analyzed considering different aspects. One of them is mobility, which is particularly important in applications on unknown and soft terrain [1]. Optimizing mobility is an important goal in the design and operation of wheeled rovers on soft soil [2]. Wheels play a significant role in improving the mobility of wheeled rovers. The lunar surface is typically covered with soft soil, and its gravity is only 1/6th that of the earth, which leads to the poor mobility of the rover [3]. On soft soil, a vehicle with conventional circular wheels can easily slip. Moreover, slipping causes the wheels to sink into the soft soil, which means that vehicles can easily become stuck [4]. Therefore, to improve the tractive capability of wheeled rovers on soft soil, researchers have developed various unconventional wheels [5]. Rigid circular wheels with grousers are usually used in unmanned planetary exploration rovers [3,5,6]. The rigid rim wire mesh wheels for Lunokhod, made in the former Soviet Union, and the Chinese wheels of the Jade Rabbit are examples of such wheels. However, their tractive performance was still not sufficient.

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Increasing the length of the contact patch by deflection of the wheel carcass without increasing the dimensions of the wheel is an approach that can be used to improve thrust [7]. The wire mesh metal-elastic wheels of the Apollo lunar roving vehicles (LRVs) are one example of an alternative.

Additionally, increasing the diameter of a rover wheel can allow the wheel to achieve optimal tractive performance by reducing sinkage [8,9]. However, this approach is restricted because of spacecraft volume. Therefore, an expandable wheel prototype, which is designed to fold during launch and then unfold to a larger diameter when the rover is first deployed, was developed. The expandable wheel mechanism plays the most important role in allowing the wheel to change its diameter. Thus, various expandable mechanisms for expandable wheels have been researched.

An inflatable tire changes its shape between a small stowed volume and a large deployed size by a special inflation system [10]. However, this system is complicated. Additionally, several expandable planar mechanisms have been introduced. Based on distinct mechanism types, they may be classified into rigid-body mechanisms and compliant mechanisms. Many mechanisms (Fig. 1(a)–(d)) belong to rigid-body mechanisms. Two mechanisms (Fig. 1(e) and (f)) are compliant mechanisms. Unlike rigid-body mechanisms, compliant mechanisms gain their mobility from the deflection of flexible elements rather than from kinematic pairs [11]. Their potential advantages including reduced weight, friction, and backlash, and also the possible elimination of assembly.

According to different mechanism motion planes, these planar mechanisms can be categorized into expandable mechanisms in the lateral plane of the wheels and expandable mechanisms in the longitudinal plane of the wheels. Some expandable mechanisms (Fig. 1(a)–(c)) place the mechanisms in the lateral plane of the wheels. Other expandable mechanisms (Fig. 1(d)–(f)) place the mechanisms in the longitudinal plane of the wheels.

In terms of expandable mechanisms in the lateral plane of the wheels, the ratio between the wheel width and diameter is constrained. By contrast, expandable mechanisms in the longitudinal plane of the wheels are interesting because the global shape of the wheel can be freely chosen. In addition, a number of expandable mechanisms (Fig. 1(a), (c)–(f)) can expand only once to the largest wheel diameter, as the mechanisms can only lock in the largest unfolded status. A repeatedly expandable and foldable mechanism (Fig. 1(b)) is characterized by a real-time adjusting radial size according to different terrain conditions, owing to real-time self-locking of the mechanism. Principle diagrams for these expandable mechanisms are shown in Fig. 1. In Fig. 1(a), the expandable mechanism of an expandable paddle wheel is a crank-slider mechanism in the lateral plane of the wheel, and the wheel diameter changes when a secondary plate (the slider) is pushed along the shaft [12].

The unfoldable mechanism of a variable-topology repeated foldable wheel is a double-slider mechanism in the lateral plane of the wheel. The mechanism adjusts the radial dimensions by a screw transmission, as shown in Fig. 1(b), and the wheel diameter can always be locked by screw pairs of the screw transmission [13]. The expandable mechanism of a rover wheel for deployment is a parallel mechanism whose each chain is imbricated four-bar mechanisms (consisting of a crank-slider mechanism and a four-bar mechanism) in the lateral plane of the wheel [14], as described in Fig. 1(c). The inputs of the mechanism are the same linear motions of two sliders. Stable unfolding conditions are achieved using a singular-mechanism configuration; thus, the mechanism can only lock in the largest radial size. However, this concept is complex in terms of fabrication, and presents some difficulties for assembly. The radial expansion mechanism [Fig. 1(d)] is a special four-bar mechanism for an unfoldable wheel. This mechanism is actuated by the rotation of each arc-shaped rod in the longitudinal plane of the wheel. The arc-shaped rods are in contact in the compact form (the smallest wheel diameter) [15]. The mechanism also uses a singular configuration to stay in an unfolded situation.

Moreover, expandable compliant mechanisms have been investigated. In Fig. 1(e), the expandable spring wheel consists of flexible spokes, a hub, an expansion ring, and outer rims. A single flexible spoke for expansion action is constructed of left leaf spring A and right leaf spring B, which wind around the hub inverse to each other [16]. One end of leaf spring A is fixed on an outer rim, and the other end of the spring is fixed on the expansion ring that covers the hub. One end of leaf spring B is fixed on the same outer rim, and the other end of the spring is fixed on the hub. Then, the wheel can expand in the longitudinal plane of the wheel because of the bending deflection of leaf springs A and B, which are wound in inverse directions, when the expansion ring is rotated around the hub. After expansion (only once), the wheel size is fixed by pins [17].

In Fig. 1(f), the spoke of the expandable flexible wheel is constructed of six leaf springs that wind around the hub. One end of a single leaf spring is fixed on one wheel foot, and the other end of the spring is fixed on the hub. Note that the leaf spring section between the two ends is clamped by the spring clips in the next wheel foot. The wheel can be expanded only once to its largest diameter in the longitudinal plane of the wheel. This is accomplished with bending deformations of the flexible spokes, which are wound around the hub, owing to the torque acting on the hub and the reaction forces from the ground when the hub is rotated [18]. After expansion, the wheel structure is fixed when the spring clips are inserted into the grooves on the leaf springs.

Based on the above research, the variable-diameter mechanism of a variable-diameter wheel for a lunar rover (which is also an expandable wheel) is introduced, as shown in Fig. 2. This mechanism, which integrates the advantages of the above mechanisms, is a compliant expansion mechanism in the longitudinal plane of the wheel. In addition, the novel variable-diameter mechanism of the wheel can change the wheel diameter continuously and repeatedly from a folded rigid circular wheel (storage size) to an unfolded rimless wheel (working size), and vice versa. Moreover, the mechanism is compliant, which prevents wear, backlash, and lubrication [19].

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