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Drawbar pull of a wheel with an actively actuated lug on sandy terrain

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Abstract

Sandy terrains are widely distributed across terrestrial, lunar and Martian surfaces. These surfaces are difficult to traverse, and their access presents an ongoing challenge for mobile robots. This paper introduces a novel wheeled mechanism integrated with an actively actuated lug. The drawbar pull characteristics are measured on a prototype mechanism affixed to the fabricated testbed undergoing a complete lug–soil interaction process. By tuning the sinkage length of the active lug, the developed wheeled mechanism can dampen the fluctuations of the drawbar pull that arise when using a fixed lugged wheel. The performance of the developed wheeled mechanism is highlighted by comparing its generated drawbar pull with that generated by a smooth wheel and a fixed lugged wheel.

Keywords: Terramechanics; Sandy terrain; Lug trajectory; Wheeled robot; Active lug; Drawbar pull

1. Introduction

Wheeled robots have been deployed across sandy environments in planetary explorations and geological investigations. Under such conditions, they easily slip and become trapped, which may result in mission failure. Significant efforts have been made to improve the traveling performance of wheeled robots, and thereby undertake complex scientific exploration tasks on challenging terrains [1,2].

Lugs are attached to the wheel surface to improve the drawbar performance of wheeled robots. The wheels of the Apollo lunar rover were studded with titanium chevrons to provide traction [3]. For easy turning, the microplanetary rover Micro5 was outfitted with special tires with spiral fins [4]. Ding et al. reported that lug height and lug inclination angle influence the performance of the driving wheel [5]. They found that, while increasing the lug height increases the drawbar pull amplitude of the wheel, it also magnifies unwanted fluctuations. These fluctuations can be reduced by increasing the lug inclination angle, similar to the engagement of helical gears, but may generate lateral force, thereby introducing mechanical performance differences between the forward and backward motions of the wheel. Sutoh et al. proposed a linear traveling speed model of a wheel rover with grousers, and determined the suitable lug interval on the wheel that achieves stable linear velocity [6].

Many new mechanisms try to overcome the limitations of conventional wheels studded with fixed lugs. Chen et al. proposed movable lugs for the driving wheels of boat tractors [7]. In this concept, the pull and lift forces produced by the lugs are maximized by setting the lug plates at an appropriate angle. The lug forces acting on single and multi-movable lugs were measured in [8,9]. The Intelligent Vehicle Group of Jilin University, China, has developed a compound walking wheel with retractile laminas that can be extended and withdrawn [10]. Adopting a terramechanics model, Chen et al. concluded that this walking wheel can improve the mobility of a rover on loose lunar

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terrain. Because they allow tuning of the inclination angle or sinkage length of the lug, these new types of wheels enhance the traveling performance of the device. However, the lug trajectories achieved by these wheels are limited by the few degrees of freedom of the mechanisms.

In performance evaluations of locomotion mechanisms traversing soft terrains, an important prediction is the wheel–soil interaction. Its principle was previously investigated by Bekker [11] and Wong [12]. However, the hypothesis of terramechanics models is frequently inconsistent with existing conditions [13]. Moreover, because these models assume on smooth wheeled mechanisms, they cannot inherently capture the fluctuations caused by lugs. To solve this problem, researchers have estimated the effect of lugs using passive pressure theory [14,15] and discrete element methods (DEM) [16,17]. In addition, Irani et al. proposed a dynamic model to capture the dynamic oscillations introduced by a wheel with lugs [18]. To date, there exists no theory that is well supported pertaining to the soil failure characteristics generated by wheel operations with grousers.

The objective of our research is to develop a new wheel mechanism with better drawbar performance than conventional wheels. This paper performs an experimental investigation and analysis based on the measured drawbar pull of the developed mechanism. The paper is organized as follows. Section 2 demonstrates the developed wheel for accessing the soft terrains. The experimental setup for measuring drawbar pull of the wheels is discussed in Section 3. The measured characteristics of the drawbar pull are analyzed and compared in Section 4. In Section 5, a strategy is proposed for adjusting the lug sinkage length to reduce drawbar pull fluctuations. Conclusions and plans for future studies are presented in Section 6.

2. Active Lugged Wheel

2.1. Prototype mechanism

An Active Lugged Wheel (ALW) has been developed to improve the drawbar performance of mobile robots. The idea was inspired from our previous study on ePaddle mechanism, in which paddle trajectories were generated for accessing soft terrains [19]. The mechanism, consisting of a set of lugs and a wheeled shell, has three degrees of freedoms (Fig. 1(a)).

It is essential to observe and evaluate the drawbar pull generated by the wheel with a single active lug before investigating the drawbar performance of the ALW. For this purpose, the drawbar pulls generated by the ALW mechanism with a single active lug adopting different lug trajectories were measured in this study. The main components of the ALW are as follows.

i. An active rotational joint for rotating the wheeled shell. The hinge passively rotates around its shaft affixed to the wheel rim, allowing free retraction or protrusion of the lug through the hinge.

ii. A planetary gear mechanism with a sun gear and carrier actuated by different motors. This mechanism drives the lug shaft contacted to the planetary gear. The center distance between two gears, L_A, is equal to the center distance between the planetary gear and lug shaft L_B; thus, the lug shaft can arrive at any position within a circle of radius $R_W = L_A + L_B$ denoted in Fig. 1(b).

According to three joint angles (wheel rotation angle θ, carrier rotation angle θ_A and planetary gear rotation angle θ_B), the posture of the lug can be derived by a kinematic model [20]. The wheel, carrier, and sun gear are separately driven by three DC brushed motors via timing belts and their angular positions are measured by three absolute encoders. As the wheel rolls forward, the lug is actively protruded or retracted through the hinge by changing the position of the lug shaft. The specifications of the ALW are listed in Table 1.

Most of the ALW components employed in this study were fabricated from polyoxymethylene (POM) by using a laser cutter. Being lightweight and self-lubricating, POM is ideally suitable for fabricating the components of the developed modules. Consequently, the complexity, weight, and fabrication time and cost of prototyping are significantly reduced. Fig. 1(c) shows a prototype of the fabricated wheel.

2.2. Inclination angle and sinkage length

The world coordinate system is shown in Fig. 2, in which a wheel is rolling forward on soft terrain with constant wheel sinkage h. The horizontal and vertical directions are denoted by x_w and y_w, respectively. As the wheel rolls forward, the inclination angle and sinkage length of the lug can be adjusted by changing the position of the lug shaft. The inclination angle α is defined as the angle between the lug and the horizontal direction. The sinkage length l_s is defined as the distance from the lug tip to the interaction point of the lug and the ground surface. It determines the contact area between the lug and the soil.

2.3. lug–soil interaction process

Based on the above description, it is possible that the lug motion corresponding to rotation of the wheel can be controlled to enhance the drawbar pull on sandy terrain. An example of the lug–soil interaction process is shown in Fig. 3. The process passes through three phases as the wheel rotates from 0° to 180°. In phase I, the lug contacts and penetrates the soil. At the switch point where $\theta = \theta_1$, the lug enters the initial state of phase II. As the wheel rotates through θ_1 to θ_2 in phase II, the drawbar performance is enhanced by driving the lug shaft along a desired trajectory S_1S_2. Finally, the lug is retracted from the soil during phase III.