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Push–pull locomotion for vehicle extrication

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Abstract

For applications in which unmanned vehicles must traverse unfamiliar terrain, there often exists the risk of vehicle entrapment. Typically, this risk can be reduced by using feedback from on-board sensors that assess the terrain. This work addressed the situations where a vehicle has already become immobilized or the desired route cannot be traversed using conventional rolling. Specifically, the focus was on using push–pull locomotion in high sinkage granular material. Push–pull locomotion is an alternative mode of travel that generates thrust through articulated motion, using vehicle components as anchors to push or pull against. It has been revealed through previous research that push–pull locomotion has the capacity for generating higher net traction forces than rolling, and a unique optical flow technique indicated that this is the result of a more efficient soil shearing method. It has now been found that push–pull locomotion results in less sinkage, lower travel reduction, and better power efficiency in high sinkage material as compared to rolling. Even when starting from an "entrapped" condition, push–pull locomotion was able to extricate the test vehicle. It is the authors' recommendation that push–pull locomotion be considered as a reliable back-up mode of travel for applications where terrain entrapment is a possibility.
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1. Introduction

One of the most difficult challenges faced when driving unmanned vehicles through unfamiliar terrain is preventing immobilization. Manned vehicle operations have the benefit of using the driver's observations to survey the terrain conditions; whereas autonomous or remotely operated vehicles rely on either sensor feedback or previous knowledge of the terrain to determine whether an area is safe to traverse. Situations where a vehicle could potentially become entrapped can be difficult to assess, especially in extraterrestrial locations.

Robotic vehicles with on-board sensors can be a useful method for determining the traversability of an area. However, it may not become apparent that the terrain is too difficult or unsafe to drive through until the vehicle has already become immobilized, such as in the case of robotic exploration. For example, in 2009 the Mars Exploration Rover, Spirit, became embedded in a soft sandy material on Mars, a terrain condition that was not anticipated and could not have been predicted (NASA Jet Propulsion

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Laboratory, 2013). Typically the drivers for the Spirit rover would assess its wheel slip by taking photos of its tracks and observing how often certain tread patterns appeared in the terrain. However, this assessment could only be conducted after the commanded movements were completed and the photos were sent back to Earth. This challenge, coupled with a broken drive motor on one of the wheels, resulted in a case where the rover had become entrapped in a high sinkage material before the drivers on Earth were aware of the situation. Alternative modes of locomotion could provide a greater likelihood of extrication in extreme situations such as this.

This paper addresses the challenge of traversing terrain that generally results in high sinkage and high wheel slip under normal all-wheel drive modes. The authors demonstrate how adding additional degrees of freedom to a robot significantly helps not only traverse difficult terrain, but extricate the robot from an immobile state. Though there are other alternative modes of locomotion that can be used to improve a robot's extrication abilities, the focus of this paper is on one specific mode, referred to here as "push–pull locomotion".

2. Push–pull locomotion

The term push–pull locomotion is used to describe a general mode of generating thrust. Unlike conventional rolling where thrust is produced by a rotating implement, the thrust force for push–pull locomotion is generated by keeping a portion of the vehicle stationary relative to the ground and re-positioning another portion of the vehicle to a different location by active articulation (Creager et al., 2012). The stationary portion is then re-positioned while the previously moved portion remains planted to the terrain. This alternating process continues resulting in a translation of the entire vehicle. During this cycle, the stationary implements in contact with the terrain are essentially "pushing" or "pulling" the vehicle while gripping the ground. Walking, which the NASA ATHLETE robot is capable of (Wilcox et al., 2007), is a familiar form of push–pull locomotion; however systems that implement walking are typically complex and inefficient due to the requirement of many active degrees of freedom.

2.1. Scarab and "inch-worming"

The specific variation of push–pull locomotion that is the focus of this research is often called "inching" (or "inch-worming"). It is visually similar to the method an inch-worm uses to propel itself forward and uses a combination of rolling wheels and vehicle articulation. The Scarab roving vehicle (Wettergreen et al., 2010), developed at Carnegie Mellon University, is a four wheel drive robotic vehicle with the ability to move by conventional rolling or by inching (Fig. 1). On each side, each wheel is attached to the end of an arm that extends out from the center of the chassis at a shoulder joint. An actuator controls the angle between these arms, thus creating the ability to vary the wheel base (distance between the front and rear wheels). When inching, the rear wheels are first held in place relative to the ground while the wheel base is increased and the front wheels are driven forward. Once the front wheels are in place, the back wheels are driven forward while the wheel base is reduced. Fig. 1 shows Scarab undergoing the inching process starting with the largest wheel base. During this cycle, two wheels (either front or rear) are always stationary, relative to the ground acting as anchors from which the rest of the vehicle can push or pull itself into position.

2.2. Previous research using this technique

The concept of inching is not unique and has been investigated in the past. At the Army Land Locomotion Laboratory (Czako et al., 1963) the concept of a segmented vehicle with the ability to inch was introduced. It was determined through theoretical analysis that by keeping one axle stationary and propelling the other forward, the thrust generated by the stationary wheels would be transferred to the rolling wheels allowing them to better overcome the resistance on the moving axle. The stationary wheels would not encounter rolling resistance, thus the net resistance on the vehicle as a whole decreased while the thrust remained the same. In theory this would allow an inching vehicle to generate more net tractive force than a pure rolling vehicle, but only by an amount equal to the rolling resistance on one axle.

2.2.1. Drawbar pull testing

More recently, a series of drawbar pull tests were conducted at the NASA Glenn Research Center (GRC) that quantitatively compared the net tractive forces of inching to rolling (Creager et al., 2012). It should be noted that the terms "rolling" or "conventional rolling" in this paper refer to the case where all four wheels are being driven at the same rotational speed.

For these tests, the Scarab rover was driven through a simulated lunar terrain consisting of a granular material called GRC-1 (Oravec et al., 2010) while a drawbar pull test apparatus applied a controlled pull force to the vehicle in the direction opposite of travel. For both modes of travel, rigid and compliant tires were tested over multiple levels of pull force. A relationship between pull force and the reduction in forward speed was developed. It was found that inching was able to generate approximately 37% of the vehicle's weight in drawbar pull force with the pneumatic tires, compared to only 27% when rolling. For rigid tires, the maximum pull forces were approximately 33% for inching and 25% for rolling.

The drawbar pull force, or net tractive force, is equal to the thrust generated by the wheels minus any rolling resistance in the system. Therefore, if inching requires less rolling resistance as theorized by Czako et al. (1963), this could account for a higher maximum drawbar pull force as