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A mobile robot with a two-degree-of-freedom suspension for traversing uneven terrain with minimal slip: Modeling, simulation and experiments

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ABSTRACT

It is known in literature that a wheeled mobile robot (WMR) with fixed length axle will slip on an uneven terrain. One way to avoid wheel slip is to use a torus-shaped wheel with lateral tilt capability which allows the distance between the wheel-ground contact points to change even with a fixed length axle. Such an arrangement needs a two degree-of-freedom (DOF) suspension for the vertical and lateral tilting motion of the wheel. In this paper modeling, simulation, design and experimentation with a three-wheeled mobile robot, with torus-shaped wheels and a novel two DOF suspension allowing independent lateral tilt and vertical motion, is presented. The suspension is based on a four-bar mechanism and is called the double four-bar (D4Bar) suspension. Numerical simulations show that the three-wheeled mobile robot can traverse uneven terrain with low wheel slip. Experiments with a prototype three-wheeled mobile robot moving on a constructed uneven terrain along a straight line, a circular arc and a path representing a lane change, also illustrate the low slip capability of the three-wheeled mobile robot with the D4Bar suspension.

1. Introduction

An increasingly important new application of mobile robots is motion and navigation on uneven and rough terrains. Wheels in a wheeled mobile robot, moving on a plane surface, are often assumed to be undergoing pure rolling or slip-free motion. In general, two wheels joined by a common rigid axle cannot roll on an uneven terrain without slip since there is no instantaneous center compatible with both the wheels [1]. Slip at the wheel-ground contact points leads to localization errors when only on-board odometer is used and wastes power which is often at a premium in activities such as planetary exploration. To overcome wheel slip, the distance between the wheel-ground contact points needs to change so that a common instantaneous center exists. Researchers have proposed two approaches to avoid kinematic wheel slip — the variable axle length approach [2] allows the axle length to vary when the mobile robot moves on the uneven terrain and the wheel lateral tilt approach allows the wheel to tilt laterally while moving on the uneven terrain thereby effectively changing the wheel-ground contact distance without changing the axle length [3,4]. The lateral tilt changes the wheel camber angle and this has been termed as passive variable camber (PVC) [5]. However, in all the above mentioned works, experimental evidence is not presented. In this paper, we explore the wheel lateral tilt approach and provide numerical simulation and experimental results for a three-wheeled mobile robot traversing an uneven terrain.

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For wheel lateral tilt on uneven terrain, a two degree-of-freedom (DOF) suspension is required — one to accommodate the vertical motion of the wheel and a second to allow lateral tilting. There exists various suspension mechanism, developed by NASA and others (see, for example [6–11]) for traversing uneven terrain in planetary exploration and moving over rough terrain. All the suspension are for vehicles with several wheels — six wheels in Rover, Spirit and Opportunity, five wheels in Micro5 and four in the vehicle described in reference [10]. Moreover, the main goal of the developed suspensions is to navigate the rough and uneven terrain, maintain wheel-terrain contact in a stable manner and go over "small" obstacles and ditches. Avoiding or minimizing wheel slip is not the primary concern in these applications. In this paper, we present a three-wheeled mobile robot, with torus-shaped wheels and a novel two DOF suspension, capable of moving on uneven terrains with low slip.

Existing one DOF suspension systems accommodate the wheel vertical travel and ensure that the wheel-ground contact is maintained. Camber angle, equivalent to lateral tilt, provided in existing one-DOF suspension is fixed. Most one DOF suspension mechanisms presented in vehicle technology textbooks (see for example, Brandy [12] and Dixon [13]) use simple leaf springs for heavy duty vehicles and arrangements such as double wishbone, Macpherson suspension with springs, dampers and mechanism combinations for passenger cars. These suspension mechanisms do not allow lateral tilt required at the wheels. Sebe [14] and more recently Krajekian [15] present a suspension system for vehicles where variable camber can be obtained. In their design, camber control rods are united at the center of the vehicle on a plate which is articulated to the chassis and the embodiment formulates an approximate parallelogram linkage which can change the camber of both the wheels by an equal amount. Other researchers [16–18] have patented variable camber suspensions for vehicles by detecting the lateral force acting on the vehicle in turning. In these patents, a negative camber is set for the outer wheel and a positive camber is set for the inner wheel based on the measured force. In all the above mentioned patents and designs, the resulting camber angles for both the wheels, connected by the axle, are dependent making the mechanisms unsuitable for independent lateral tilting of the wheels. For a wheel with independent lateral tilt capability, a two DOF suspension mechanism is required — one for maintaining wheel contact with terrain in the vertical direction and other for the lateral tilting of the wheel. Tharakeshwar [19] proposed six possible two DOF suspension mechanisms and presented simulations of a three-wheeled mobile robot, with torus-shaped wheels equipped with the two DOF suspensions, traversing uneven terrains. In a recent publication [20], simulation and experimental results with a modified common trailing arm suspension mechanism is presented. In this work a significantly better and novel suspension system, in terms of decreased wheel slip and ease of manufacturability, named as the double four-bar (D4Bar) suspension mechanism is presented. This paper deals with modeling, simulation and experiments with a three-wheeled mobile robot equipped with two DOF D4Bar suspension mechanisms and moving on uneven terrain. Three representative paths, namely a straight line, a circular arc and a path representing a lane change are used for simulation and experiments. It is shown that the three-wheeled mobile robot can traverse uneven terrain with low slip and, furthermore, if the suspension is not used and the lateral tilting is not allowed, the slip is significantly larger. The simulation and experimental results presented in this paper proves the feasibility of reducing slip in WMR by using the wheel lateral tilt concept.

The paper is organized as follows: In Section 2, for the sake of completeness, the modeling a torus-shaped wheel moving on an uneven terrain and a three-wheeled mobile robot equipped with three torus-shaped wheels are presented. Section 2 also describes the two DOF D4Bar suspension used to enable lateral tilting of the torus-shaped wheel. In Section 3 the details of the uneven terrain

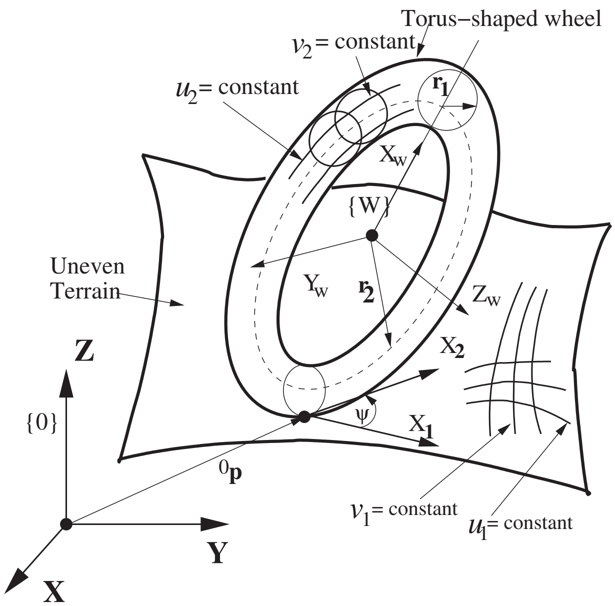

Fig. 1. Torus-shaped wheel on uneven terrain.