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Mobility evaluation of wheeled robots on soft terrain: Effect of internal force distribution

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ABSTRACT

Many applications of wheeled robots include operations in unstructured environments. Optimizing vehicle mobility is of key importance in these cases. Reduced mobility can limit the ability of the robot to achieve the mission goals and can even render it immobile in extreme cases. In this paper, some aspects of the effect of the wheel–ground interaction force distribution on mobility are investigated. A performance index based on the normal force distribution is used to compare different design layouts and vehicle configurations. The validity of this index was assessed using both multibody dynamics simulation and experimental results obtained with a six-wheeled rover prototype. Results confirmed that modifying the system configuration and employing active suspensions to alter the normal force distribution can lead to an increase of traction force available at the wheel–terrain interfaces, thus improving rover mobility. Finally, the study was extended to consider the change of soil properties during operation due to the multipass effect. Optimum load distributions were obtained as the solution of a constrained maximization problem.

1. Introduction

Optimizing vehicle mobility is an important goal in the design and operation of wheeled robots on soft soil. Degraded wheel–terrain interaction conditions can result in the vehicle not being able to develop the required traction to complete certain maneuvers. This may result in failure to achieve the mission goals and in some cases the loss of the robot. In spite of its importance, no general agreement exists in the literature about the precise meaning of mobility in the context of operations on soft terrain. The concept has a precise meaning for wheeled robots moving on rigid, flat ground [1], when it can be assumed that the robot wheels roll without slipping and no sinkage occurs. These conditions are commonly modeled with holonomic and nonholonomic kinematic constraints (e.g., [2]). However, such assumptions are often violated when the vehicle moves on soft terrain. In this case, mobility can be understood in the sense of the ability to move away from a certain configuration or to move with maximum speed. This definition is close to the *trafficability* concept introduced by Apostolopoulos [3], which points to the capacity of the vehicle to overcome terrain resistance and generate traction.

There is also a lack of consensus regarding which strategies are the best to enhance the mobility of wheeled robots operating on unstructured terrain. Reduction of the slip at the wheel–terrain contact area has been proposed in several works as a means

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to achieve this objective [4,5]. In these papers, the interaction of the wheels with hard ground is modeled using the assumption of Coulomb friction while the ratio of tangential to normal forces at the wheel–ground contact is minimized with the goal of reducing the risk of developing slip. While not directly dealing with soft soil modeling, these papers highlight the need for keeping wheel slip under control in order to improve the vehicle behavior. When soft terrain enters into the picture, the phenomena at the wheel–terrain interface become more complex and Coulomb friction models can no longer be used to describe them accurately. Then, two options are left to predict the effect of design and actuation parameters on robot mobility. The first one is turning to detailed models of the contact interface. These models are typically used in forward-dynamics simulation settings and require an accurate knowledge of the set of parameters that characterize the terrain properties, which are not always accessible. The second option consists in finding design and operation guidelines of general validity. These can offer simple means to compare alternative designs and can be used to define objective functions for design, operation, and control.

Based on results obtained from experiments with a four-wheeled rover, Ishigami stated that a variation in the normal force distribution does not change the drawbar pull developed by the vehicle [6]. However, it is acknowledged in the same work that a balanced load distribution helps reduce the resistant torque on some wheels and consequently improves the rover mobility. On the other hand, some researchers mention a uniform distribution of normal forces among the factors that enhance mobility. Grand et al. state that balancing the normal loads helps the vehicle to develop higher drawbar pull [7]. Along the same lines, Freitas et al. suggested that uniformly distributing the weight of the rover among the wheels is a valid strategy to achieve better mobility, when adequate information about contact forces is not available [8]. A similar conclusion was reported by Michaud et al. [9]: the load distribution among the wheels has to be even on flat ground to achieve the best performance. Kuroda et al. [10] and Kubota and Naiki [11] also reported that a relation exists between the performance of rovers on rigid ground and their normal force distribution. As a consequence, special attention must be paid to good adaptation to the terrain and the position of the center of mass (CoM) when deciding on the rover structure and configuration. The normal load and the motor torque applied to each wheel were computed by Iagnemma and Dubowsky [12] as the solution of an optimization problem to enhance mobility for quasi-static motion of the rover on rough terrain. In the work by Thueer and Siegwart the likelihood of incurring wheel slip was reduced by minimizing the virtual friction coefficient $\mu* = F_t/F_n$ for all the wheels, where F_t is the traction and F_n the normal force at the wheel–ground interface [13]. Following this approach on homogeneous soft terrain, traction is maximized if the normal forces are the same for all the wheels. An experimental confirmation of these statements for a particular rover design was reported by the authors in [14] and [15].

The level of slip must be considered together with the terrain reaction forces when studying mobility. Reaching higher slip values can be used as strategy to develop more traction, e.g., by applying a greater driving torque to the wheels. However, the total drawbar pull goes down when the slip ratio exceeds a certain value [16]. In the tests reported by Lindemann and Voorhees [17], the engineering models of *Spirit* and *Opportunity* were placed on a variable-slope-angle platform to measure the climbing ability for different slip ratios. It was found that the drawbar pull-slip curve is highly nonlinear. The actual shape of this plot depends on the nature of the terrain and the actions exerted on it by the wheels.

Some strategies exist to determine the climbing ability of a rover via estimation of the soil parameters and the slip ratio of the wheels [18]. The effect of chassis and wheel design on the climbing ability of rovers was investigated by several researchers such as Ding et al. [19] and Ani et al. [20]. However, despite being mentioned several times in the literature as a factor to consider during mobility evaluation, normal force distribution has only been studied in a systematic way by a scarcity of works, e.g., [21] with regard to its role in traction on soft soil. The purpose of the work reported here is to study the relation between the internal force distribution in a robot chassis, more specifically the normal force distribution among the wheels, and the robot mobility. This work is an extension of the one presented in [22] and describes the results in more detail, exploring the validity of the proposed approach with a broader scope. The relation between the normal force at a wheel and the drawbar pull that it can develop was used as a starting point for this study. Besides providing a justification for the effect of normal force distribution on mobility, the operation conditions under which this effect is most critical have been identified in this paper. A general framework, not limited to the study of a specific vehicle design or type of terrain, was adopted to ensure the general validity of the results. The structure of the paper follows: Section 2 describes the interaction between a single wheel and soft terrain, showing the relation between normal and tangential forces developed at the wheel–soil contact. Section 3 introduces a new indicator called Normal Force Dispersion and illustrates its effect on the performance of a six-wheeled rover via simulation studies. Section 4 describes the experimental test setup used in our study and the modifications that we introduced on the rover chassis in order to gain full control on the distribution of normal forces among its wheels. Section 5 provides simulation results to show that Normal Force Dispersion has a considerable effect on improving rover performance. Section 6 reports the results of a set of drawbar-pull tests on the rover prototype that confirms the effectiveness of the performance indicator defined in this work. Section 7 introduces the parameters that have the most relevant effect on the relation between the rover mobility and the load distribution among its wheels. Section 8 extends the study to more general scenarios and provides a methodology to achieve better mobility in those cases. Finally, the summary and conclusions of the work are provided in Section 9.

2. Analysis of single-wheel motion on soft soil

The interaction between a rigid wheel and soft soil under steady-state conditions is commonly modeled using terramechanics relations [23]. Following this approach, the forces at the wheel–terrain interface, shown in Fig. 1, can be obtained as functions of the vehicle state (generalized coordinates and velocities) and a set of parameters that defines the terrain physical properties.