Mechanism and Machine Theory 83 (2015) 137–151

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

A novel concept for analysis and performance evaluation of wheeled rovers

B. Ghotbi [*], F. González, J. Kövecses, J. Angeles

Department of Mechanical Engineering and Centre for Intelligent Machines, McGill University, 817 Sherbrooke St. West, Montréal, Québec H3A 0C3, Canada

ARTICLE INFO

Article history:
Received 26 March 2014
Received in revised form 27 August 2014
Accepted 29 August 2014
Available online 9 October 2014

Keywords:
Wheeled mobile robots
Planetary exploration rovers
Terramechanics models
Terrain interaction
Observative models

ABSTRACT

The analysis, design, and operation planning of rovers are often based on predictive dynamic simulation, where the multibody model of the vehicle is combined with terramechanics relations for the representation of the wheel–ground interaction. There are, however, limitations in terramechanics models that prevent their use in parametric analysis and simulation studies.

Increasing mobility is generally a primary objective for the design and operation of rovers. The models and assumptions used in the analysis phase should target this objective. In this paper we put forward a new concept for the analysis of wheeled rovers, particularly for applications in off-road environments on soft soil. We propose a novel view of the problem based on the development of models that are primarily intended to represent how parameter changes in the robot design can influence performance. These models allow for the definition of indicators, which gives information about the behavior of the system. We term such models observative.

In the reported work, a set of indicators for rover performance is formulated using such models. The ability of these indicators to characterize the behavior of a rover is assessed with a series of simulation tests and experiments. The indicators defined using observative models succeeded to capture the changes in rover performance due to variations in the system parameters. Results show that the proposed models can provide a useful tool for the design and operation of planetary exploration rovers.

1. Introduction

Mobile robots are among the best candidates for planetary surface exploration, due to their good performance in unstructured environments. Predictive dynamic simulation of mobile robots aims to anticipate the time response of the system and the representative forces as close to the real-life physical system as possible. Simulation includes the solution of an initial value problem of the governing dynamics equations. The mathematical model that forms the basis of such simulation studies must include all elements of the system as close to reality as possible. This is an extremely challenging task. The most problematic element is usually the wheel–soil interaction. The detailed study of the latter, known as terramechanics, plays a key role in the design, analysis, and simulation of wheeled mobile robots; significant advances have been made during recent years in this field [1,2]. Nonetheless, there are many open issues that can be mentioned. For example, robots are required to be robust to environmental uncertainties when it comes to semi-autonomous missions. However, terramechanics models can be very sensitive to the inaccuracies in the soil parameters [3]; the identification of these parameters is a major challenge [4]. Also, the fidelity of the terramechanics models can be questioned. The detailed modeling of the vehicle–terrain interaction may not be able to provide high-fidelity estimation of the forces involved in the interaction. The models are even less accurate when exact information on terrain properties is not available, which is particularly the case for

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[*] Corresponding author.

E-mail addresses: bahareh@cim.mcgill.ca (B. Ghotbi), franglez@cim.mcgill.ca (F. González), jozsef.kovecses@mcgill.ca (J. Kövecses), angeles@cim.mcgill.ca (J. Angeles).

http://dx.doi.org/10.1016/j.mechmachtheory.2014.08.017

planetary exploration rovers. Conventional terramechanics models, e.g. those of Bekker and Wong [5,6], have not really been developed for application in dynamic analysis and simulation. Furthermore, these models do not provide a full insight on how the variations of the system parameters can influence the reaction forces and performance. This is the motivation for proposing a new concept to capture the representative aspects of the behavior of the physical system, those that are important for performance evaluation and can result in parametric models for design analysis.

The experience of recent planetary exploration missions has brought to the limelight many challenges that must be faced in the autonomous operation of mobile robots in unstructured environments; these involve interaction with soft terrain and sloped and rocky surfaces. This brings the need for simulation and analysis tools that should provide a way of characterizing the mobility of the system under various terrain conditions. Recent efforts in this area have led to the development of several simulation toolboxes that include multibody dynamics models of mobile robots and wheel–soil interaction models. ROAMS [7] is a physics-based simulator that considers mechanical and electrical subsystems of robotic systems as well as vehicle–terrain interactions. Some other examples of simulation tools developed for performance optimization and chassis analysis are POT [8] and RCAST [9]. The analysis results provided by these simulation toolboxes can be useful in evaluating different design ideas and control strategies [10].

Rover performance can be analyzed considering different aspects. One of them is mobility, which is specially important in applications on unknown and soft terrain. Due to the autonomous nature of planetary applications, it is critical to identify possible strategies to enhance the mobility of the rover and the modes of failure. Mobility is not rigorously defined in the literature for wheeled vehicles operating on soft soil. The concept is clearly defined for mechanism models where the connections between the links are given with holonomic or nonholonomic kinematic constraints, e.g. for linkages or wheeled robots operating on hard surfaces [11]. However, for rovers operating on soft terrain, generally such kinematic constraints cannot be given a priori for the modeling of wheel–ground interaction. Also, for wheeled rovers mobility is often meant in a different sense: *the ability to move from a certain configuration or to move with maximum speed*. Apostolopoulos [12] categorized the mobility performance of wheeled robots under three terms: *maneuverability*, *terrainability*, and *trafficability*. Maneuverability refers to the steering capabilities of the robot and its ability to navigate through obstacles in cluttered environments. Based on this definition, locomotion parameters such as the robot length to width ratio can then be calculated as functions of traction forces and total motion resistance developed at the wheel–terrain contact. Terrainability is the ability to negotiate uneven terrain without losing stability, while providing enough traction for forward motion. A parametric relation between the maximum slope the robot can climb and stability requirements, traction-force limits, and power limitations of the robot is obtained. Trafficability is defined as the ability of the robot to generate traction and overcome resistance, which is the primary focus in the context of robot mobility. In [12], the dependency of sinkage, soil traction, and motion resistance forces on wheel parameters, diameter, and width, are represented by parametric expressions. All of the above expressions are obtained based on assumptions such as uniform normal stress distribution, which greatly simplifies the terramechanics relations. Some of the existing mobility indicators were studied along with novel concepts to quantify mobility, as proposed and applied to exploration rovers on hard ground [13]. These indices include minimum friction requirement at wheel–ground contact for forward motion, maximum actuation torque requirement, total slip distance over the course of a run, and average violation of pure rolling constraint among all wheels of the vehicle. In fact, slip plays a key role in the determination of the mobility of a wheeled rover on soft soil, as pure rolling cannot always be guaranteed during motion. Moreover, Iagnemma et al. [14] showed using simulation results that, due to the slip–sinkage effect, increased slippage causes additional sinkage of the wheel, which will result in increased motion resistance. The concept of maximum mobility for wheeled robots on soft soil is thus related to minimizing the slip of the wheels. In order to improve the behavior of a rover it is necessary to identify the influential parameters at the design and operation levels. In different designs of planetary rovers the parameters that can be tuned during the operation vary. In some designs it is possible to control the distribution of input power among the wheels. In several studies [15–17] improvement of the wheel traction through proper selection of input torques to the wheels is discussed. Lamon et al. considered quasi-static modeling, as the dynamic effects are assumed to be negligible within the range of robot speed, while the calculation of the friction requirement is based on the Coulomb friction model [17]. However, in practice, the value of the friction coefficient is not known. According to the foregoing approach it is first assumed that the wheel does not slip and the ratio of traction to normal force falls below the actual friction coefficient. With this assumption it is possible to calculate normal and traction forces as functions of torque applied to the wheel. Next, in an optimization process an input torque that minimizes the ratio of traction to normal force is calculated. By doing this, the chance that this ratio can be smaller than the friction coefficient increases.

Previous work by the authors showed that similar simplified models can generally be used to characterize the behavior of the system [18]. Such models are not intended to replace their terramechanics counterparts. However, they can be used to predict the way in which a change in the design, actuation, or configuration of the rover will affect its ability to operate. At the design and control stages it is very important to foresee all the challenging situations in which the rover would face mobility problems, to provide tools and algorithms to avoid those situations or to overcome them. In reconfigurable robots it is possible, for instance, to change the position of the center of mass (COM) and other effective inertial properties, which can provide an important means to improve the mobility of the system and its stability [19]. The effect of changes in other parameters such as distribution of input torque and wheel radius is also discussed in this paper.

2. Dynamics modeling

2.1. General formulation

A key element in wheeled mobile robots is the characterization of their interaction with the ground via the wheels. The wheel–ground contact usually involves a complex geometry and a finite contact area. However, the forces exchanged between the wheel