A Method for Modelling Normal Reaction Forces between Wheel and Soft Terrain for Planetary Exploration Rovers

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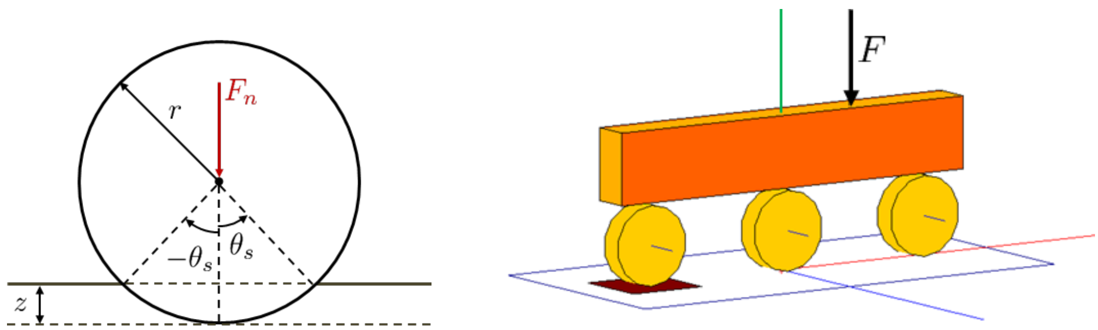
Abstract

The determination of the normal loads at the wheel-terrain interface is of key importance in the design, analysis, and operation of wheeled robots. The stability of these vehicles during certain manoeuvres, such as step climbing and slope negotiation, depends critically on the value of the terrain reaction forces. Moreover, the normal load distribution can also influence the maximum traction that a rover is able to develop.

The wheel-terrain interface can be modelled as a contact between two rigid bodies in certain situations when determining ground reaction forces [1]. This can provide useful information also in the case of operations on soft terrain [2]. This method assumes that the configuration of the system does not change considerably due to soil deformation. However, an additional difficulty arises if the consideration of the wheel contacts results in an indeterminate, i.e. overconstrained, model. In this case, an infinite set of solutions for the reactions is compatible with the dynamics equations of the system model. Information regarding the stiffness distribution at the wheel-terrain contacts needs to be considered to resolve the indeterminacy. In this work, the use of an augmented Lagrangian algorithm with scaled penalty factors [3] is proposed as a way to overcome this problem, to produce accurate values of the normal reaction forces.



(a) Static sinkage of a single wheel

(b) A three-axle model of a wheeled robot

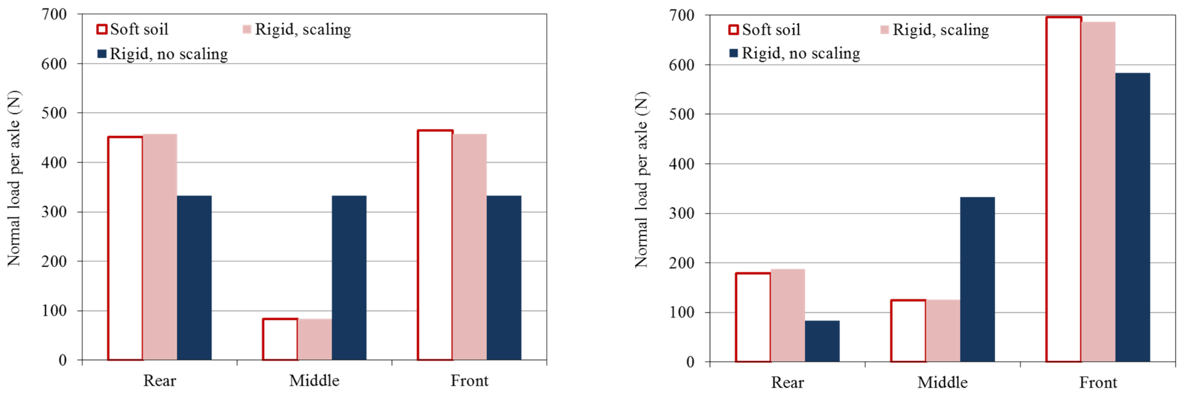
Figure 1: Simple examples subjected to static sinkage

The relation between the sinkage z and the static contact angle θ_s for a wheel in static equilibrium on soft terrain (Fig. 1a) is $z = r(1-\cos\theta_s)$. Based on semi-empirical models obtained with pressure-sinkage tests, the normal static load F_n can be expressed as a function of the static contact angle as [4]

$$F_n = \frac{r^{n+1}}{b^{n-1}}\left(ck'_c + \rho b k'_\phi\right)\int_{-\theta_s}^{\theta_s}(\cos\theta - \cos\theta_s)^n \cos\theta d\theta \tag{1}$$

where r and b are the wheel radius and width, ρ is the terrain density, and c, k'_c, k'_ϕ and n are parameters that describe the terramechanics properties of the soil. The load on each wheel results in a certain value of the sinkage, which in turn influences the stiffness of the soil under the wheel. From Eq. (1) it is possible to obtain the stiffness-vs.-normal force plot of the wheel-terrain interface, and to modify the penalty factors associated with each contact in order to represent the stiffness distribution at the wheel-terrain contacts.

The technique described above was used in the study of the model of a three-axle robot (Fig. 1b). The vehicle rests on non-homogeneous ground, with its rear wheel in contact with a hard surface (e.g. a rock) and the middle and front ones on soft soil. Initially, the sinkage of every wheel is zero. A vertically applied force $F = 1000$ N was used to represent the resultant of the gravity forces. Several values of the offset of this force with respect to the geometric centre of the vehicle were used, in order to represent different mass distributions of the same vehicle. The normal reactions at the wheel-terrain interfaces at the end of a forward-dynamics simulation can be considered the static equilibrium forces, provided that the velocities and accelerations of the system at this point are practically zero. Their values were first evaluated using the terramechanics relation in Eq. (1). With this representation, the wheels can undergo different sinkages and the final configuration of the robot is slightly different from the initial one. The reactions obtained were compared to the results obtained upon modelling the wheel-terrain interface as a contact between two rigid bodies, with and without scaling the penalty factors. Using this method, the sinkage remains zero for every wheel, without configuration changes during simulation. A comparison of the normal force distribution provided by each method is shown in Fig. 2.



(a) Force offset $x = 0$ m

(b) Force offset $x = 0.5$ m

Figure 2: Normal reaction on each wheel of the three-axle robot resting on non-homogeneous terrain, for a total applied load $F = 1000$ N

The small divergences between the reactions obtained with soft soil modelling and scaled penalty factors resulted from neglecting the changes in system configuration in the latter case. These changes are caused by the sinkage of the wheels in soft terrain, which is not considered if the ground is modelled as rigid. Results confirm that scaling of penalty factors can be used to enhance the normal reaction force values obtained with a rigid model of the wheel-terrain interface, thus describing the interaction with the terrain more realistically.

References

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