Analysis of impact manoeuvres with planetary exploration rovers

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Abstract

Over the past four decades, autonomous wheeled rovers have been used for lunar and planetary exploration, with growing success. With the approach of new ventures such as the ESA's ExoMars mission scheduled for 2018, mobile rover tasks will increase, and so will the need for optimization of rover design. One such element of design which continually demands attention is the choice of the rover chassis and suspension system, which must reconfigure itself to achieve maximum stability for travel in a safe and effective manner. The design of this system will determine the rover's ability to negotiate unstructured terrain and to withstand any impact forces from collisions that may result if the stability of the rover is compromised. This paper focuses on contact and impact forces and how they are affected by the configuration of the mechanical systems involved in the collision. A new performance indicator for the analysis of impact intensity, termed "effective energy" is introduced and compared to indicators developed using established continuous force models.

Determining the value of the maximum normal force between two bodies during an impact requires the use of continuous force models. An alternative approach to dealing with the impact event consists of introducing kinematic constraints to represent the contact and using impulse-momentum equations to describe the dynamics. This second technique, however, does not provide any information about the impact forces. Nevertheless, it is possible to estimate the maximum normal contact force by evaluating the part of the total kinetic energy that the newly imposed contact constraint removes from the system. This portion of the kinetic energy is associated with the subspace of constrained motion (SCM), and is termed the effective energy, T_c. The effective energy can be used as an indicator of the maximum force developed during an impact that lies normal to the impact surface [1]. One way to express this effective kinetic energy is explained as follows. Let us consider that the motion of a system can be described with an $n \times 1$ array of generalized velocities $\mathbf{v}$, and the directions constrained by the impact are interpreted as $\mathbf{A}\mathbf{v} = \mathbf{u}_c$, with $\mathbf{A}$ an $m \times n$ matrix. The set of generalized velocities $\mathbf{v}$ can be decomposed into components associated with the SCM and its orthogonal complement, the subspace of admissible motion (SAM), as

$$\mathbf{v} = \mathbf{v}_c + \mathbf{v}_a = \mathbf{P}_c\mathbf{v} + \mathbf{P}_a\mathbf{v} \tag{1}$$

where $\mathbf{P}_c$ and $\mathbf{P}_a$ are projection matrices onto the SCM and the SAM, respectively. This decomposition allows for obtaining the kinetic energy associated with the SCM as

$$T_c = \frac{1}{2}\mathbf{v}_c^{\mathrm{T}}\mathbf{M}\mathbf{v}_c \tag{2}$$

where $\mathbf{M}$ is the $n \times n$ system mass matrix. The expression of the projection matrix $\mathbf{P}_c$ is given by [2]

$$\mathbf{P_c} = \mathbf{M}^{-1}\mathbf{A}^{\mathrm{T}}\left(\mathbf{A}\mathbf{M}^{-1}\mathbf{A}^{\mathrm{T}}\right)^{-1}\mathbf{A} \tag{3}$$

If we assume an elastic contact, all the kinetic energy associated with the SCM will be transformed into elastic potential energy at the end of the compression phase of the impact. Therefore, the value of T_c at the moment at which the impact begins, T_c^-, can be used to characterize the maximum value of the normal force during the impact, and the intensity of contact in general. This kinetic energy can be determined for a set of impact situations, where the impacts are identical except for one parameter. This parameter is varied over a range of values, and the effective kinetic energy values are recorded and compared. A 3-D model of a rover (Fig. 1) was used to demonstrate the relationship between T_c^- and the maximum impact force.

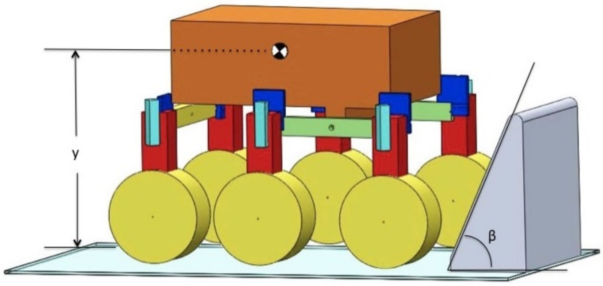
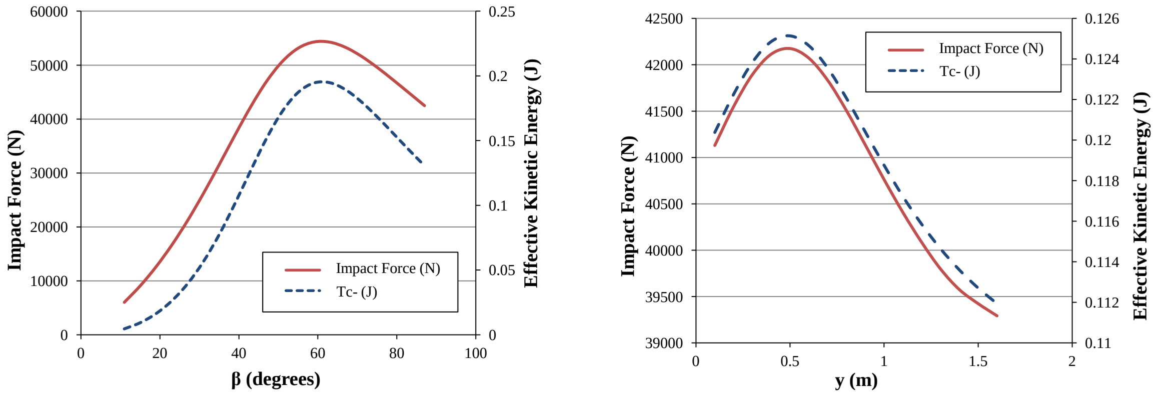


Figure 1: A 3-D model of a rover undergoing an impact with an obstacle

Simulations of the impact of the rover with an obstacle were carried out for different impact angles β and heights of the centre of mass (COM) of the vehicle with respect to the ground y. The effective kinetic energy was evaluated at the instant just before contact was established, and the maximum impact force was determined using the non linear spring-damper model proposed by Hunt and Crossley [3]

$$f_n = -k\delta^{3/2}\left[1 + \frac{3\,(1-e_{eff})}{2}\frac{\dot{\delta}}{v_i}\right] \tag{4}$$

where f_n is the normal force at the contact interface, k is the contact stiffness, δ is the indentation of contacting bodies, e_{eff} is the coefficient of restitution, and v_i is the initial penetration velocity.



(a) (b)

Figure 2: Maximum impact force and effective energy T_c^- for impact simulations with a coefficient of restitution of one. Impact parameters varied are: (a) impact angles β and (b) vertical displacements of the COM of the rover y.

Results in Fig. 2 show that the effect of modifying the impact configuration on the impact force f_n can be captured using T_c^-. This supports the validity of such an indicator in the estimation of the intensity of impact. An advantage to effective energy analysis is that it can be carried out without the need for detailed information about the constitution of the bodies involved in the impact.

References

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