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DRAFT: A PERFORMANCE INDICATOR FOR ROVER OBSTACLE NEGOTIATION

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ABSTRACT

A new indicator has been developed which looks at the velocity in the admissible subspace of motion to predict if a rover will tend to climb an obstacle after it initially contacts it. In conjunction with the effective pre-impact kinetic energy, which predicts the intensity of an impact [1], it can be used to select an appropriate speed at which to approach an obstacle. It can also be used in the design phase to quickly compare several rover designs.

INTRODUCTION

To reach scientifically rich sites on Mars, the Moon, or other celestial bodies, rovers often need to traverse obstacles. These can come in the form of steep slopes, rocks, craters or ledges. In previous work [1,2] it was shown that the intensity of the impact force when a rover contacts an obstacle, can be predicted from the pre-impact effective kinetic energy T_c^-. This indicator is obtained by decomposing the dynamics equations into the subspaces of admissible and constrained motion (SAM and SCM), and then calculating the portion of kinetic energy in the SCM at the instant just before the impact. Besides predicting the impact force we would also like to predict whether or not a rover can overcome an obstacle. One aspect of the obstacle negotiation manoeuvre is the tendency of the rover to climb after the contact is established. Contacting an obstacle with a certain speed is beneficial in cases when the rover tends to climb but it can be detrimental if it does not. An efficient way to predict the tendency of a rover to climb can be to look at the velocity in the SAM before the impact.

METHODOLOGY

The system is modelled using a set of n independent generalized velocities $\mathbf{v}$. A certain number, m, of modes of motion of the system are constrained when contacts are established. As shown in [3], it is possible to use projectors to decompose the velocities $\mathbf{v}$ into their SCM and SAM components, $\mathbf{v}_c$ and $\mathbf{v}_a$, as:

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

Where,

$$\mathbf{P}_a = \mathbf{I} - \mathbf{P}_c \tag{2}$$

$$\mathbf{P}_c = \mathbf{M}^{-1}\mathbf{A}^T(\mathbf{A}\mathbf{M}^{-1}\mathbf{A}^T)^{-1}\mathbf{A} \tag{3}$$

$\mathbf{M}$ is the $n \times n$ mass matrix, $\mathbf{A}$ is the $m \times n$ constraint Jacobian, and $\mathbf{P}_a$ and $\mathbf{P}_c$ are the $n \times n$ projectors into the SAM and SCM.

In the case of a six wheel rover that contacts a step with an angled side, four contacts are possible: the front wheels with the obstacle, the front wheels with the ground, the middle wheels

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with the ground and the rear wheels with the ground. Since each contact is unilateral, not all of the associated modes of motion should necessarily be constrained. The mode associated with the contact between the front wheels and the obstacle will always be included in the Jacobian $\mathbf{A}$ but the other three may or may not be. Thus, there are eight possible Jacobians to choose from. Since the total number of possible combinations is low, all of them can be tested to determine the correct one. Two conditions need to be satisfied to verify that the selected Jacobian is correct. The first is that the component of the admissible velocity, $\mathbf{v}_a$, in the directions normal to the ground or obstacle is not negative. The second is that the constraint forces are positive i.e. the ground can only push against the rover.

Once the admissible velocity has been determined, the velocity of the centre of the wheel contacting the obstacle in the direction parallel to the obstacle, w_a, can be used as an indicator of a positive or negative tendency of the rover to climb the obstacle after impact. The indicators, w_a and $\mathbf{T}_c^-$ are calculated in the following way:

$$w_a = \mathbf{B}\mathbf{v}_a \tag{4}$$

$$\mathbf{T}_c^- = \frac{1}{2}\mathbf{v}^T\mathbf{A}^T(\mathbf{A}\mathbf{M}^{-1}\mathbf{A}^T)^{-1}\mathbf{A}\mathbf{v} \tag{5}$$

where $\mathbf{B}$ is an $1 \times n$ matrix that gives the relation between the generalized velocities and the velocity of the centre of the wheel of interest.

EXAMPLES

In order to visualize the admissible velocity $\mathbf{v}_a$, forward-dynamics simulations were conducted with triple bogie rovers (port, starboard and rear) and step obstacles with different slope angles. Fig. 1 shows stills of two of the animations produced. In these simulations, the slope angle was 60° and gravity was neglected so that the visualization of the admissible velocity would be clearer. The rover was given an initial velocity, $\mathbf{v}_0$. No motor torque was supplied. Then, the simulation was paused when the front wheel contacted the obstacle. At this point, the admissible velocity was computed and the simulation was continued. The difference between rover A and rover B is the height of the front bogie joint. The admissible velocity shows that rover A, with the low bogie joint, tends to climb the obstacle after impact whereas rover B, with the high bogie joint, tends to tip forward and not climb the obstacle. This can be quantified by using the velocity of the front wheel as an indicator.

To verify if the assumption that the admissible velocity would give an indication of the motion after the impact, the results were compared to simulations using a Hertzian model of the ground and obstacle and the bristle friction model. Details of these models can be found in [4]. Comparing the two results, it was found that they were qualitatively similar. The principal difference was in the level of rebound which is determined mainly by the effective coefficient of restitution selected. Thus, the admissible velocity can be used as a computationally efficient alternative to contact force models.

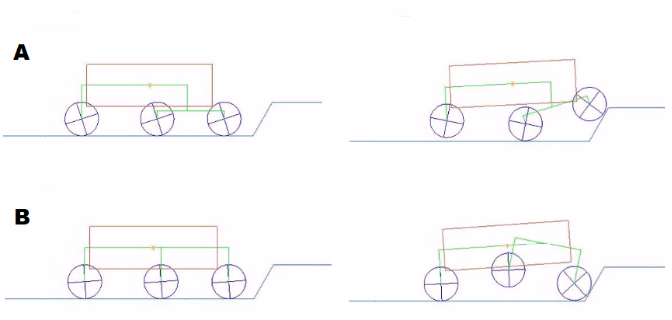

FIGURE 1. STILLS OF TWO TRIPLE BOGIE ROVERS BEFORE AND AFTER IMPACTING AN OBSTACLE.

The admissible velocity indicator can be useful to determine an optimum speed at which to approach the obstacle. In the cases shown in Fig. 1, rover A should approach the obstacle with a certain speed to use its momentum to climb the obstacle more easily. The preimpact effective kinetic energy, T_c^-, can be used in conjunction to give limits on speed to limit impact forces. On the other hand, the admissible velocity shows that rover B would not benefit from speed. This rover should be immobilized before climbing the obstacle.

In addition, these indicators could be used in the design phase to quickly run a parametric study of rovers with different dimensions to determine which configurations are optimal.

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