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Parametric Study of Spherical Rovers Crossing a Valley

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I. Introduction

THE evidence of water on Mars and the idea of using the moon as a staging ground for future planetary missions has increased interest in Martian and lunar exploration. Future missions will require the exploration of large areas on these surfaces because areas of scientific interest may be far away from the landing sites. Because of the inherent dangers with manned missions, rovers provide a viable option for future investigations of these regions.

NASA currently employs wheeled rovers, including the Mars exploration rovers, to examine the Martian surface. These rovers are intricate and expensive, with limited ability to navigate rough terrain. This complicates gathering scientific data on Martian climate and geology and renders answering questions on the existence of water and life difficult.

A vehicle capable of exploring large areas of terrain is the tumbleweed rover. A tumbleweed is a spherical (wind driven or self-propelled) rover designed to provide superior mobility and greater accessibility on the surface of Mars and the moon. Compared with conventional wheeled rovers, a tumbleweed can cover vast distances faster and reach previously inaccessible areas of scientific interest, such as canyons and valleys. Because a tumbleweed is significantly less expensive than traditional rovers, multiple tumbleweeds can be deployed across the Martian or lunar surface for scientific surveys. The tumbleweed's design is also well suited for polar missions because the rover can seek out water sources beneath a surface desert or an ice sheet, a task that cannot be done accurately from orbit. For these reasons, parametric studies describing and predicting a tumbleweed's motion across the Martian or lunar terrain is valuable.

The tumbleweed rover is based on concepts going back to the 1970s, where Jacques Blamont of the National Center for Space Studies developed the notion for wind-driven rovers. The concept has been pursued by several investigators at the NASA Langley Research Center (LaRC) and at the Jet Propulsion Laboratory (JPL). LaRC is focusing on concepts based on lightweight deployable structures, while JPL is focusing on inflatable concepts based on airbag landing technology. Other organizations, including Texas Technical University (TTU), North Carolina State University (NCSU), and the Swiss Federal Institute of Technology, are also examining wind-driven rover concepts.

Research into the tumbleweed rover's dynamics, however, is in its early stages. Feasibility studies on wind-driven mobility on the surface of Mars have been examined [1–8] and other studies have presented dynamic models for particular tumbleweed concepts [9–14]. Several areas have been identified where the existing research can be expanded. Particularly, a numerical simulation model predicting a tumbleweed's motion for arbitrary terrains is needed. Also required are parametric studies describing the tumbleweed's behaviors on these terrains, which include flat planes, hills, ravines, and valleys.

This paper presents parametric studies of a tumbleweed (or spherical) rover as it moves across a valley. The model used covers the rover's bouncing, sliding, and rolling behaviors and its transitions between different terrain types. We present studies of the rover's motion for various sets of parameters and initial conditions. Theses parametric studies will provide an understanding of the range of tumbleweed design parameters essential for mobility over shallow and deep valleys on Mars.

II. Dynamic Modeling

For each study the tumbleweed is modeled as a sphere; it is assumed the tumbleweed is nonrigid during collisions with the terrain. It is also assumed the tumbleweed is sufficiently rigid while rolling so that elastic considerations may be ignored during rolling. Because of the thin Martian atmosphere, the effects of drag and the Magnus force are neglected. (Note the words *sphere* and *tumbleweed rover* are used interchangeably in this paper).

The numerical simulation model employs a collision model developed by Kane [15] for a sphere bouncing on a flat plane. The model provides a direct and efficient method for computing a sphere's generalized speeds after impact. Note that the sphere's angular velocity and translational velocity for the center of mass are expressed in terms of the generalized speeds $u_1, \ldots, u_6$ as

$$\boldsymbol{\omega} = u_1\boldsymbol{n}_1 + u_2\boldsymbol{n}_2 + u_3\boldsymbol{n}_3 \tag{1}$$

and

$$\boldsymbol{v} = u_4\boldsymbol{n}_1 + u_5\boldsymbol{n}_2 + u_6\boldsymbol{n}_3 \tag{2}$$

The equations of motion are given as follows:

$$u_2(t_2) \approx u_2(t_1) \tag{3}$$

$$u_5(t_2) = -eu_5(t_1) \tag{4}$$

$$u_3(t_2) \approx \frac{Ju_3(t_1) - mbu_4(t_1)}{mb^2 + J} \tag{5}$$

$$u_4(t_2) = -bu_3(t_2) \tag{6}$$

$$u_1(t_2) \approx \frac{Ju_1(t_1) + mbu_6(t_1)}{mb^2 + J} \tag{7}$$

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$$u_6(t_2) = bu_1(t_2) \tag{8}$$

$$(S_1^2 + S_3^2)^{1/2} < \mu |S_2| \tag{9}$$

$$S_1 \approx m[u_4(t_2) - u_4(t_1)] \tag{10}$$

$$S_2 \approx m[u_5(t_2) - u_5(t_1)] \tag{11}$$

$$S_3 \approx m[u_6(t_2) - u_6(t_1)] \tag{12}$$

where u_i are the generalized speeds for $i = 1, \ldots, 6$, e is the coefficient of restitution, J is the principal moment of inertia, m is the mass, b is the radius, S_i are the impulses for $i = 1, 2, 3$, and μ is the coefficient of static friction. For no slipping, successive use of Eqs. (3–8) result in a set of values for $u_1, \ldots, u_6$ at time t_2. These values are valid if and only if inequality (9) is satisfied for values of S_1, S_2, and S_3 given by Eqs. (10–12).

Otherwise, if inequality (9) is violated, then the sphere is slipping at time t_2, and the quantities $u_1(t_2)$, $u_3(t_2)$, $u_4(t_2)$, $u_6(t_2)$, S_1, and S_3 must be recalculated using the relationships

$$\alpha_1 = u_4(t_1) + bu_3(t_1) \tag{13}$$

$$\gamma_1 = u_6(t_1) - bu_1(t_1) \tag{14}$$

$$k_1 = \frac{1}{m} + \frac{b^2}{J} \tag{15}$$

$$S_1 \approx -\mu' |S_2| \frac{\alpha_1 + k_1 S_1}{|\alpha_1 + k_1 S_1| [1 + (\gamma_1/\alpha_1)^2]^{1/2}} \tag{16}$$

$$S_3 \approx \frac{\gamma_1}{\alpha_1} S_1 \tag{17}$$

$$u_1(t_2) \approx u_1(t_1) - bS_3/J \tag{18}$$

$$u_3(t_2) \approx u_3(t_1) + bS_1/J \tag{19}$$

$$u_4(t_2) \approx u_4(t_1) + S_1/m \tag{20}$$

$$u_6(t_2) \approx u_6(t_1) + S_3/m \tag{21}$$

where α_1, γ_1, and k_1 are constants and μ' is the coefficient of kinetic friction. Note that $u_1(t_2)$, $u_5(t_2)$, and S_2 are given by Eqs. (3–5), respectively, regardless of whether or not the sphere experiences no slipping or slipping at time t_2.

The model is extended to include collisions on inclined and declined planes. Note that in adapting the equations used by Kane for sloping planes, subtle differences exist. For instance, the reinitialization of the sphere's generalized speeds after impact must now account for the gravity component acting along and normal to the plane. This task is most easily accomplished by introducing a trajectory model within the collision model, and this method is used in this study. The trajectory model numerically tracks the sphere's motion between bounces, detecting when a collision occurs and when the sphere transitions between different planes.

Now we numerically track a sphere's rolling and sliding motion on the horizontal, inclined, and declined planes. We list below the equations for a rolling/sliding sphere on the horizontal plane. For slipping, the equations for the normal force, angular, and translational velocities, respectively, are

$$N = mg \tag{22}$$

$$u_3(t) = \mp \frac{\mu' g b}{J/m} t + u_3(t_1) \tag{23}$$

$$u_4(t) = \mp \mu' g t + u_4(t_1) \tag{24}$$

Note that the signs of Eqs. (23) and (24) depend on the sense of the frictional force. Also, note that Eqs. (23) and (24) are equal to zero for the case of no slipping. The rolling/sliding model determines if the sphere is initially rolling without slipping or if the sphere is initially

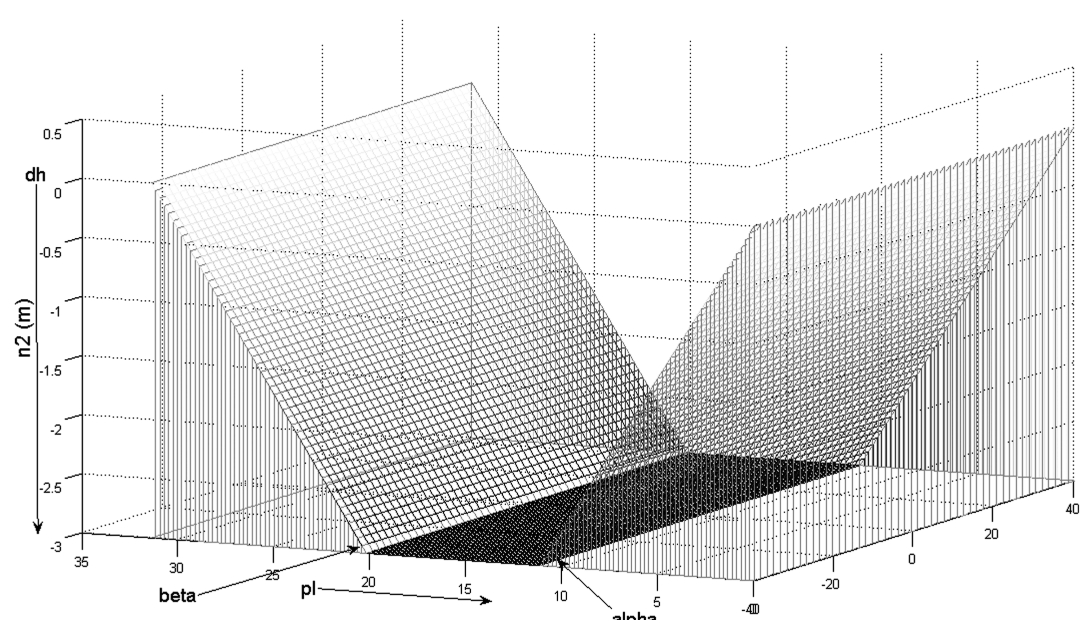

Fig. 1 A valley encountered by a tumbleweed rover.

sliding. If the sphere is initially rolling without slipping, then the motion will continue until the sphere impacts the terrain. If the sphere is initially sliding, then two potential cases arise. For the first case, the sphere impacts the terrain while sliding. For the second case, the sphere's motion will transition from sliding to rolling without slipping before impacting the terrain. The relevant equations of motion on the inclined and declined planes may be found in [16].

III. Parametric Studies

Here we generate parametric studies, which show tumbleweed design parameter values $[b, J/m, e]$ essential for mobility over shallow and deep valleys. For the parametric studies, the numerical simulation model is run for various sets of parameters and initial conditions. For all runs, we allow the design parameters to vary as follows: the radius b ranges from 1 to 6 m in increments of 1 m. The coefficient of restitution e ranges from 0.6 to 1.0 in increments of 0.01. Note that $e = 1$ represents the theoretical limit for perfectly elastic collisions. The principal moment of inertia divided by the mass (J/m) can take values of $J/m = 0.1b^2$ through $J/m = 0.67b^2$. Note that $J/m = 0.4b^2$ and $J/m = 0.67b^2$ correspond to a solid sphere and a thin spherical shell, respectively. Values of $J/m < 0.4b^2$ correspond to a sphere's density being concentrated more toward the sphere's center. Each simulation is run over a velocity range of 2–7 m/s or 5–10 m/s in increments of 0.1 m/s. Therefore, a completed parametric study has $6 \times 41 \times 7 \times 51 = 87,822$ runs. Note that for all simulations, we assume the nominal values of $\mu = 1.0$ and $\mu' = 0.8\mu$. We also assume $g = 3.71\ \mathrm{m/s^2}$ on Mars. For this paper we consider parametric studies only on Mars, although the methods employed could be applied to any planetary body.

A. Parametric Study 1: Shallow Valleys on Mars

Landing on Mars is hazardous because the planet is filled with rough terrain, steep slopes, and rocks that could damage the rover. Landing constraints imposed by 1) spacecraft and rover designs, 2) entry, descent, and landing, 3) scientific potential at various sites, and 4) safety are important considerations in landing site selection. Landing requires smooth, flat (low slope) areas with low-to-moderate rock distributions [17]. Consequently, regions of scientific interest are often far away from the landing sites, requiring tumbleweed rovers to travel substantial distances across varied

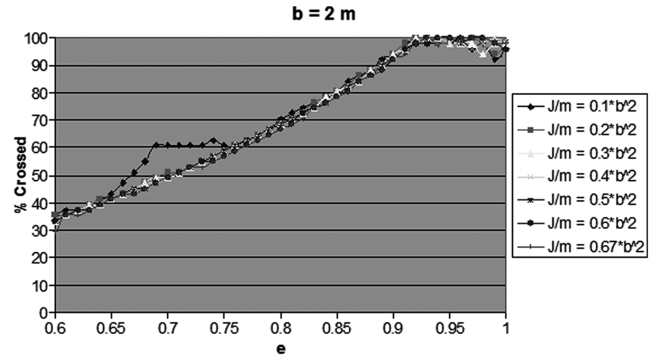

Fig. 2 Percentage crossed for varying design parameter sets and velocity range (2–7 m/s) on Mars.

terrain. During the tumbleweed's expedition, the rover is likely to encounter shallow valleys. This parametric study examines the range of tumbleweed design parameters required for the rover to cross such areas.

Picture a tumbleweed rover deployed on the Martian surface, where the terrain is flat except for areas populated with shallow valleys. Assume a characteristic valley is defined by the terrain parameters ($\beta = 15$ deg, $\theta = 15$ deg, $dh = -3$ m, $pl = 9$ m), where β and θ are the angles of the declined and inclined planes, respectively, dh is the height measured from the valley's floor, and pl is the distance between the declined and inclined planes (see Fig. 1). Also, assume the tumbleweed has a velocity ranging between 2 and 7 m/s. This velocity range is consistent with typical surface wind speeds during a Martian summer [1]. Suppose a mission is considered successful if the rover crosses the valley 80% of the time for a velocity range defined as before. Also, suppose the dimensions of the instrument payload dictate a rover with $b = 2$ m and $J/m = 0.3b^2$.

Motivated by this study, we generate a parametric plot, Fig. 2, around these parameters and initial conditions, which we employ when selecting tumbleweed design parameters. The plot determines the percentage crossed versus e for $b = 2$ m and for several values of J/m, where percentage crossed is defined as the probability that a rover with a randomly chosen wind velocity within the specified range will cross the valley.

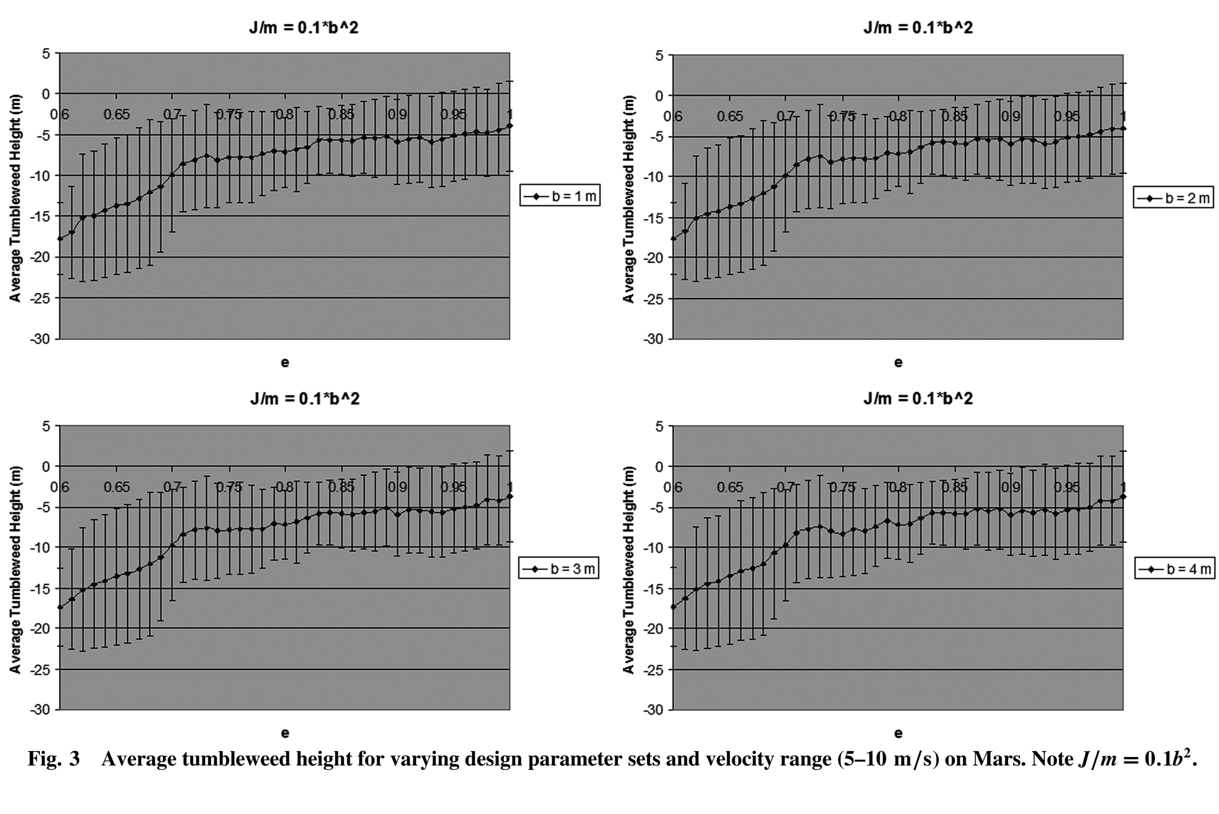

Fig. 3 Average tumbleweed height for varying design parameter sets and velocity range (5–10 m/s) on Mars. Note $J/m = 0.1b^2$.

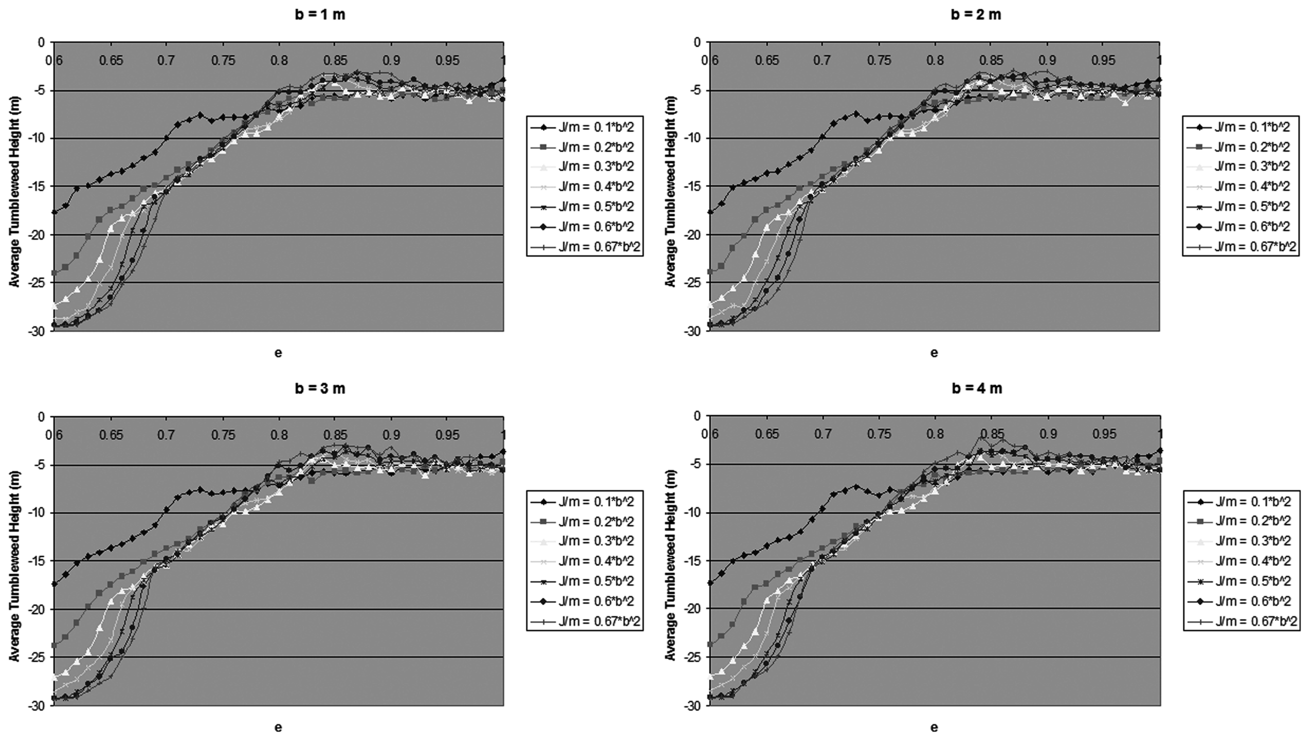

Fig. 4 Average tumbleweed height for varying design parameter sets and velocity range (5–10 m/s) on Mars.

Figure 2 reveals $e \geq 0.85$ results in mission success. Let us define e_{cr} as the critical value of e, where the additional benefit of increasing e stops. Then, Fig. 2 shows $e_{cr} = 0.92$, indicating values of e of 0.92 or greater maximize the rover's ability to cross the valley for any mission. However, because it is often easier to achieve a material with $e = 0.85$ rather than $e = 0.92$, we select $e = 0.85$ for this mission, because based on Fig. 2 this is an adequate value. Based on this information, we have that a design parameter set satisfying the conditions of the mission is $b = 2$ m, $J/m = 0.3b^2$, and $e = 0.85$.

B. Parametric Study 2: Deep Valleys on Mars

On Mars, science considerations regarding Martian climate and geology favor highland sites, areas covered with dark unoxidized materials, and at the mouths of outflow channels. Science considerations also favor sites suspected of housing underground water sources. Regions exhibiting scientific potential include Ares Vallis, Tritonis Lacus, and Isidis [17–19]. These regions are valleys possibly carved by large water flows billions of years ago. Tumbleweed rovers, equipped with packages of scientific instruments, are designed to explore such areas, and future missions will require these rovers to examine specific regions within the valleys. This parametric study examines the range of tumbleweed design parameters required for the rover to reach a specified height on the other side of a deep valley.

Consider a tumbleweed rover encountering a deep (30 m) valley on the Martian surface. Assume the valley is defined by the terrain parameters ($\beta = 25$ deg, $\theta = 25$ deg, $dh = -30$ m, $pl = 90$ m). Also, assume the tumbleweed has a velocity ranging between 5 and 10 m/s. This velocity range is consistent with typical surface wind speeds during a Martian fall [1]. Suppose the tumbleweed rover identifies an area of interest on the valley's adjacent wall at a height of -15 m and above. Given the above conditions, we generate a series of parametric plots (see Figs. 3 and 4), which we will use when selecting tumbleweed design parameters. These plots determine the average height or position that the rover reaches up the valley versus e for selected values of b and J/m. Note the average height is determined for each design parameter set and velocity range. Also, note that the vertical bars on Fig. 3 represent the variability of the rover's position up the valley from its average height.

Before selecting tumbleweed design parameters, several comments about the parametric figures are in order. Figure 3 reveals that the average height is nearly level for initial values of e (region 1), then increases monotonically for increasing e (region 2) before leveling off (region 3). This result suggests a critical value of e exists, namely, e_{cr}, where the additional benefit of increasing e stops. For $e \geq e_{cr}$ (region 3), the rover will approximately attain its maximum position traveling up the valley. Generally, we see the vertical bars are larger in region 2, while they show the smallest variability in region 3.

Notice from the figures that different values of b produce relatively minor changes in the average height. This is not the case, however, for values of J/m (see Fig. 4). For clarity, the error bars have been omitted. Initially, the average height drops off for increasing values of J/m before leveling off. Moreover, larger values of J/m show the greatest variability in the rover's maximum position up the valley.

Returning to the study, Figs. 3 and 4 suggest that to maximize the average height while minimizing the variability in the height range, the rover should be constructed with its density concentrated toward its center. Hence, we select $J/m = 0.1b^2$. From Fig. 3 different values of b produce relatively minor changes in the average height and size of the vertical bars. Suppose a rover with a radius of 2 m is chosen to satisfy certain mission criteria. For this radius Fig. 3 shows that e ranging from 0.71–1 provides an average height greater than -15 m (recall that the valley has a height of -30 m), while minimizing the length of the vertical bars. For this e range, the average height and its corresponding vertical bars are above -15 m. Financial and material constraints, however, are inclined toward rovers with lower e values. Thus, based on Fig. 3, we select $e = 0.71$, and have determined that a design parameter set which satisfies the conditions of the mission is $b = 2$ m, $J/m = 0.1b^2$, $e = 0.71$.

IV. Summary

This paper has presented parametric studies illustrating how spherical rovers maneuver across shallow and deep valleys and uses these studies to outline a design method for creating tumbleweed rovers to match various terrain challenges. The paper demonstrates how a researcher can identify a collection of design parameter values satisfying specific mission conditions, thereby aiding in the initial design of the rover. We have shown how the parametric studies can be used to determine the range of e values (coefficient of elasticity) which will result in mission success, thus aiding in the selection of appropriate materials early in the design process.

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