Design of a Biologically Inspired Martian Rover based upon the Russian Thistle (*Salsola tragus*)

Richard M. Kolacinski\textsuperscript{a}, Roger D. Quinn\textsuperscript{b}
\textsuperscript{a}Orbital Research, Inc., Cleveland, Ohio, USA
\textsuperscript{b}Dept. of Mech. and Aero. Eng., Case Western Reserve University, Cleveland, Ohio, USA

Abstract

In this paper, we investigate the mechanical design of a wind driven Martian Rover whose physical design is based upon the Russian Thistle (*Salsola tragus*) and is intended for use within a collective of wind driven rovers whose behaviours are coordinated via swarm intelligence-based algorithms. Specifically, we examine the physical attributes and capabilities necessary for a wind driven rover to effectively navigate the Martian environment under the directives produced by decentralized group behaviour algorithms for the exploration of the Martian atmosphere as well as biologically inspired mechanisms for providing these attributes and capabilities.

Introduction

The recent discovery of evidence of water on Mars and the attendant possibility of extra-terrestrial life has resurrected interest in the exploration of the Red Planet. Future missions must be able to explore large areas of the Martian surface, far from the landing sites, as the regions of scientific interest (i.e. areas where evidence of water has been found) are not close to suitable landing sites. Due to the tremendous risks associated with manned missions, the use of autonomous rovers is the obvious choice for near term exploration.

The challenges associated with space exploration necessitate unique solutions that maximize the effectiveness, robustness, functionality and adaptability of all systems and techniques used while satisfying severe restrictions on size, weight and operational envelopes. Planetary exploration places additional restrictions upon any systems due to the addition of environmental considerations such as the ubiquitous presence of dust, radiation and corrosive elements [1], [2]. Any rover design must accommodate these and other challenges in addition to navigating the Martian terrain.

Much of the current research on the design of planetary rovers centres on wheeled vehicles [3] and does not adequately address the difficulties described above. Recent work at NASA Langley Research Center [4] and JPL [5] has focused on novel methods for traversing the Martian terrain including wind driven dirigibles and “tumbleweed” rovers. The use of ambient wind as a propulsive force is one of the oldest technologies in use today but its latest incarnation, as a propulsive force to drive rovers is clearly rooted in biology.

The strategy of using biological inspiration to solve engineering problems was described by Beer et al. [6]. First, the engineering problem is well defined.
Second, research is conducted to determine what natural system might provide a good solution to that problem. Third, modelling is performed and the biological solutions are evaluated in the context of the engineering problem. Finally, the biologically inspired solutions are implemented in an engineering system.

As described by Quinn et al. [7], biological inspiration can be applied in varying degrees from the direct to the abstracted. In a direct approach the biological mechanisms important for the behaviour of interest are implemented in the engineering system. This sometimes requires that new technology first be developed and this can be a long term approach. In an indirect approach, the biological mechanisms are abstracted and applied with current technology resulting in a near term solution.

The problem addressed in this paper is the movement of unmanned science vehicles over large distances on the surface of Mars for the purpose of exploration. Energy sources and active locomotive mechanisms can be the most massive, complex and least robust systems on such a vehicle, which leads to the conclusion that locomotion via environmental forces can have many advantages. To this end, Martian winds, at 2-10 m/s, can provide a readily available motive force.

With a well defined engineering problem in hand, the next step in the strategy described in [6] is to ask what natural systems on Earth locomote via wind? There are many examples. Wind enables birds to travel distances otherwise not possible. For example, in 2001 a Baltimore Oriole was apparently carried across the Atlantic Ocean to Ireland by a storm. Wind is not an uncommon way for spiderlings (baby spiders) to disperse into the environment after hatching. They walk to the top of a plant and spin silk into the wind until there is enough drag to pull them off of the plant. Some species of caterpillars do the same thing. Plants such as dandelions propagate by way of airborne seeds that can be carried long distances by the wind. Maple tree seeds rotate as they fall, which produces lift so that they can be carried further by the wind.

The Russian Thistle (Salsola tragus) also casts winged seeds, which are carried by the wind, but what distinguishes it from other plants is that the plant itself moves by wind propulsion resulting in a dispersion of its seeds over a much larger region. It is a bushy summer annual (Figure 1a) with numerous slender ascending stems 8 to 36 inches in length that become woody at maturity. The overall shape of the mature plant is oval to round and it may attain a diameter of 18 inches to 6 feet. After it dries, the base of the stem becomes brittle and breaks off at the soil level in fall and early winter (Figure 1b). These round, thorny plants are capable of travelling miles as they tumble along in the wind.

Planetary exploration also poses unique challenges for guidance and navigation systems, most notably, the absence of a Martian Global Positioning System. The rovers must possess a high level of autonomy as teleoperation is not feasible [8] due to communication lags and black outs. Traditional approaches are map-based [9] and, as such, are computationally expensive, often require sophisticated sensors, assume a priori knowledge of the environment and lack flexibility. An alternative strategy is to use a behavioural approach to direct the rover [10].
In the behavioural approach, a combination of simple, often biologically inspired, behaviours can allow the rover to operate autonomously even in the absence of a specific goal. In some cases, much of the behavioural algorithm can, in essence, be embedded within the physical design of the rover. For example, tumbleweeds, having only an evolutionarily-developed set of behaviours, “rove” the surface of Earth, travelling large distances from their “starting point”, rolling over obstacles, accomplishing their “mission objectives” which include “wide dispersion” and release of seeds – all without any self-propulsion or computational capabilities.

**Feasibility of biomimetic tumbleweed rovers**

The unique constraints that planetary exploration places upon mobile robot design have resulted in a unique choice for biological inspiration, a mobile plant instead of an animal. The Russian Thistle, more commonly known as a tumbleweed, has a unique form of locomotion that is ideally suited to the design of planetary rovers as it requires no moving parts and no power and has a demonstrated capability to navigate varied terrain.

Recognizing that the tumbleweed rover will have to navigate varied Martian terrain under the motive force of Martian winds, an analysis of the tumbleweed rover’s ability to negotiate obstacles is necessary to ensure that a tumbleweed analogue is viable in the Martian environment. The mechanisms necessary for the tumbleweed success must be isolated and understood. Care must be taken not to attribute unwarranted importance to any particular characteristic as it may in actuality have little or no bearing on the problem at hand. For instance, the location of the centre of mass could be an artefact of the fact that the entire tumbleweed grows from a single taproot in the ground, or, it may help to impart a bouncing motion that aids in the negotiation of larger obstacles or it could help impart bouncing so that the seeds are more easily dispersed. Evolution tends to optimise for multiple objectives and in all likelihood, all of the above are true to some degree.
Quasi-static analysis

A simple, quasi-static model, shown in Figure 2 provides the initial analysis tool for establishing feasibility of the Martian tumbleweed rover concept. This model produces conservative estimates as momentum and other effects (i.e. bouncing) that improve the ability of the rover to negotiate obstacles are neglected. It also represents the initial condition for a static rover to begin moving after resting against an obstacle.

Assuming that the tumbleweed is a perfect, inelastic, homogeneous sphere that rolls without slip, that the tumbleweed contacts the obstacle at a single point and that the motive force due to drag acts through the centre of mass of the sphere, a force and mass balance analysis produces the following relationship [4,11]

\[
\xi_{\text{max}} = 1 - \frac{1}{\sqrt{Q^2 + 1}}
\]

where \( \xi \) and \( Q \) are dimensionless parameters relating the obstacle height, \( h \), to the tumbleweed's radius, \( r \), and the drag force propelling the tumbleweed, \( F_d \), to the gravity force acting on the tumbleweed, \( mg \), respectively

\[
\xi \equiv h / r
\]

\[
Q \equiv \frac{F_d}{mg}
\]

where \( F_d \) is defined:

\[
F_d = C_d A_{ref} \bar{q}
\]
where $C_d$ is the drag coefficient of the tumbleweed, $A_{ref}$ is the cross sectional area of the tumbleweed, and 
\[ q = \frac{1}{2} \rho V_{tw}^2 \]

is the dynamic pressure where $\rho$ is the atmospheric density of the Martian atmosphere and $V_{tw}$ is the velocity of the tumbleweed relative to the wind. Inspection of equation (3) shows that the drag force is a function of the tumbleweed radius, drag coefficient and wind speed. Two of these parameters, tumbleweed radius and drag coefficient are assumed to be tunable and form the parameter space used for the trade studies. Based upon results reported by Lorenz [12], a nominal free stream velocity, $V_{nom} = 7 \text{ m/s}$, is used for all simulation studies.

The relationship between the maximum navigable rock size, given by equation (3) is depicted in Figure 3 for a range of tumbleweed radii and drag coefficients from 0.5 (the baseline case of a smooth sphere) to 1.75 (a drag coefficient of 2.0 corresponds to the drag on a 2-dimensional plate). Based upon results reported by Lorenz [14], a nominal free stream velocity, $V_{nom} = 7 \text{ m/s}$ is used to compute the dynamic pressure and a constant mass of 5 kg is assumed. As can be seen, increases in radius produce the most effect on maximum navigable rock size for radius values over 3 meters. Increases in drag coefficient greatly increase the maximum navigable rock size. These results clearly show that a smooth, spherical

| **Martian Environment Parameters** |
|-----------------|-----------------|
| $\rho_{mars}$   | $1.55 \times 10^{-2} \text{ kg/m}^3$ |
| $V_{mars}$      | $1.3 \times 10^{-3} \text{ m}^2/\text{s}$ |
| $g_{mars}$      | $3.69 \text{ m/s}^2$ |

Table 1: Atmospheric and gravitational parameters of Mars [13]
tumbleweed is not the best design and that a significant benefit can be achieved by designing the tumbleweed to maximize drag.

**Dynamic analysis**

The quasi-static analysis indicates that the rover should have a minimum radius of about 3 meters so that it can initiate movement starting from rest and overcome small obstacles. In order to determine the effect of momentum another parameter study was performed using a dynamic model. As in the quasi-static analysis, the rover was assumed to be a sphere and the parameters that were varied included its radius and the drag coefficient. The goal was to determine how momentum could improve the rover’s obstacle climbing behaviour.

Working Model® was used to predict the motion of the rover as it accelerated from rest for 100 meters on a horizontal plane, motivated by Martian wind, and then contacted a rectangular obstacle. Martian environment parameters used in the analysis are tabulated in Table 1 and for consistency with the quasi-static analysis the wind speed was assumed to be constant at 7 m/s. The contacts between bodies were modelled using coefficients of restitution and a Coulomb friction model was used.

The spherical rover was assumed to have a mass, m, of 5 kg independent of its radius, R, but its inertia was determined by the equation 0.4mR². The static and kinetic coefficients of friction were assumed to be 0.5 and 0.4, respectively, and the coefficient of restitution was assumed to be 0.5. Figure 4 shows that the speed of the sphere after travelling 100m and just prior to contact with the obstacle depends on the radius and, as the radius grows larger, the rover’s speed approaches the speed of the wind. These results are for a drag coefficient of 0.5. The plot indicates that the rover should have as large a radius as possible to increase its momentum, but that this benefit diminishes after about 4 meters.

![Figure 4: Maximum speed of rover vs. radius for drag coefficient of 0.5](image-url)
The dynamic simulation was run repeatedly with a drag coefficient of 0.5 and with different obstacle heights to determine the maximum height that the rover could overcome given a particular radius. The results are plotted in Figure 5. Corresponding results for the quasi-static simulation are repeated in this figure for comparison. The largest difference by percentage is for small radii. Dynamic effects enable a rover with a 2m radius to overcome an obstacle that is 0.9m tall, whereas the rover using quasi-static effects can only climb obstacles roughly 10% that size.

Both quasi-static and dynamic effects motivate the rover to overcome obstacles. It is useful to analyse the separate effects of these two impetuses. The maximum obstacle height the sphere can overcome using motion alone can be determined by using conservation of energy. If the sphere is assumed to be rolling without slip and its kinetic energy just before impact with the obstacle is equated with the gravitational potential energy, mgH, the height H can be solved for and expressed as H = 0.7 V^2/g, where V is the velocity of the sphere. The velocity of the sphere for each radius plotted in Figure 4 was inserted into this equation and the resulting H was plotted versus radius in Figure 5. Of course, energy is not conserved during the impact of the sphere with the obstacle and this plot indicates the maximum effect of dynamics. However, this plot does explain why a moving rover can climb over obstacles much taller than a static rover of the same radius. Based on a percentage of obstacle height, the effect of momentum dominates for rovers with smaller radii.

The dynamic simulation was also run repeatedly with a drag coefficient of 1 and with different obstacle heights to determine the maximum height that the rover could overcome given a particular radius. The results are plotted in Figure 6 and

Figure 5: Maximum navigable obstacle vs. radius of rover for a drag coefficient of 0.5. (a) Theoretical limit using conservation of energy. (b) Dynamic simulation. (c) Quasi-static simulation.

The dynamic simulation was also run repeatedly with a drag coefficient of 1 and with different obstacle heights to determine the maximum height that the rover could overcome given a particular radius. The results are plotted in Figure 6 and
are qualitatively similar to the quasi-static results for varying drag. The benefits of the larger drag force are more apparent with larger radii.

Other dynamic simulation experiments were run to determine the effect of a variation in coefficient of restitution. In these experiments the drag coefficient was 0.5 and the other parameters were unchanged. When a rover with a 3 or 5 meter radius had a coefficient of restitution of 0.1 it navigated obstacles that were 0.3 meters higher than when the coefficient was set to 0.5. When the coefficient of restitution was set to 1, the results were similar to those with the coefficient set to 0.5.

**Navigation of Martian rock fields**

In order to determine appropriate tumbleweed radii, not only must the maximum navigable rock size be determined, but a relationship between the maximum rock size and the composition of Martian rock fields must also be determined. Once a realistic relationship has been constructed, the likelihood that a particular tumbleweed design can traverse a Martian rock field under the motive power of the wind can be estimated via Monte Carlo simulation. Based upon an exponential fit of the Size-frequency distribution of rocks in the vicinity of the Viking 1 lander proposed by Golombek and Rapp [15], a probability distribution function that describes the probability of encountering a rock of a particular size, $D$, in a 1 square meter area can be constructed

$$F(D) = \int_0^D f(\xi)d\xi = 1 - e^{-sD}$$

Where $s$ is a parameter determined via a Least Square Estimation using Viking image data. For rocks observed in the image near and far field but neglecting those

![Figure 6: Maximum navigable obstacle size vs. rover radius for drag coefficient of 0.5 and 1.](image-url)
in the vicinity of a crater rim, $s = 3.38$. This fit has been shown to slightly over predict the area covered by large rocks and hence provides a conservative model of a Martian rock field in the absence of geologic disturbances.

The results of a Monte Carlo analysis [4,11] examining the mean distance that a particular design configuration (drag coefficient and radius) will travel under the motive force of the wind before encountering an un navigable rock (up to a maximum distance of 10 km) is shown in Figure 7. These results are based on the quasi-static analysis. The results demonstrate that an increased drag coefficient will significantly improve the ability of the tumbleweed to negotiate a Martian rock field. As the drag is increased, a point of diminishing returns is reached. In the range of coefficients that could be reasonably affected ($C_d \in [1.25,1.75]$), however, a significant increase in performance can still be obtained. Assuming that the median value of this range, $C_d = 1.5$ (approximately the drag of a low porosity parachute), is achievable, the tumbleweed rover concept is feasible with a radius of approximately 4 m. Considering the results of the dynamic simulation as compared to the quasi static simulation (Figure 5), if the rover strikes the obstacles while moving, it should be able to move similar distances with a drag coefficient as small as 0.5. Furthermore, it can be expected to range over much larger distances with the help of momentum and a high drag coefficient.

![Mean Distance Made Good vs Radius](image)

**Figure 7**: Monte Carlo simulation of tumbleweed in a Martian rock field using quasi-static analysis

**Conclusions**

The quasi-static and dynamic simulation results in this paper indicate that a simple, passive wind driven rover can navigate much of the Martian terrain. Clearly a spherical Mars rover with a larger radius or shaped such that it has a larger drag coefficient will be able to travel over larger obstacles and therefore travel longer distances. However, both of these parameters have practical limits. The results in this paper indicate that a spherical rover with a 3 meter radius and drag coefficient of 0.5 can start from rest despite being adjacent to a downwind obstacle about 0.1m
high. Furthermore, once it is moving, its momentum can carry it over obstacles taller than 1.5m. Momentum plays a greater role for rovers with smaller radii. Results also indicate that a lower coefficient of restitution can improve its obstacle climbing performance.

References