Another Look at a Martian Rover - Vehicle Design and Performance D.N. Green 18 September 1992

Further consideration of the design problem has made it possible to propose more specific vehicle characteristics, especially with regard to the chassis and steering configuration. This proposal is the result of consideration of desirable rover characteristics, and of consultation with Professor Wong at Carleton. The resulting vehicle configuration is quite similar to a mars rover proposed by McTamaney et al. [4].

The rover is comprised of in-line front, centre and rear chassis (Fig 1). These chassis or cabs are connected to one another through revolute joints. The rear articulation will allow for roll. The front articulation will allow for both roll and pitch. The vehicle utilizes wagon steering, and hence there is no need to allow for yaw between the cabs. Each cab rides on one axel and pair of wheels. The centre axel is fixed to its cab, while the front and rear axels are able to pivot horizontally under their respective cabs.

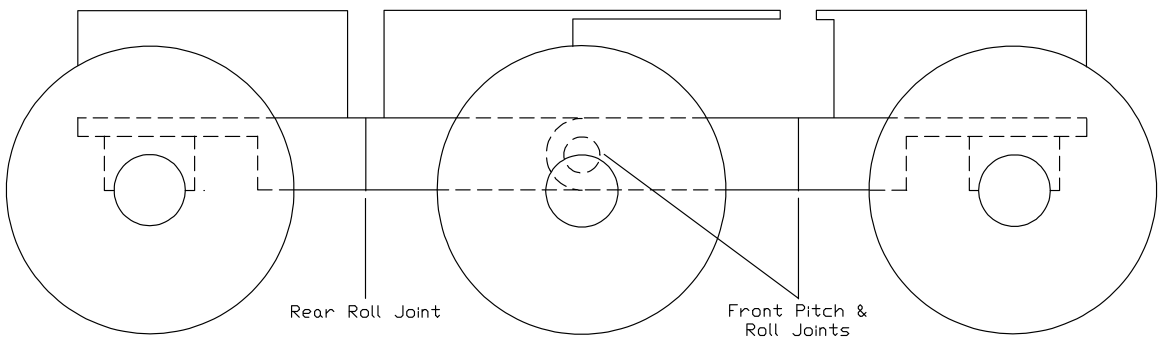

Figure 1: Six Wheel Articulated Rover (right-hand side view)

All six wheels are independently driven and no additional motors are required for steering. This configuration should result in low wheel slip in turning, and eliminates the need for a differential transmission. It may, however, be advisable to place some type of actuation on the steered axel joints to assist in difficult terrain or to facilitate steering in the event of a wheel motor failure. The pitch joint should have actuator drive or braking available to facilitate crevasse crossing. This requirement may also hold for the front and rear roll joints, depending on the mass distribution within each cab. Table 1 contains a summary of the joint and actuator requirements.

Table 1: Joint and Actuator Requirements of the Rover

Wheels:	6 motors
Front pitch joint:	1 drive or brake
Front & rear axel steering:	2 drives (optional)
Front and rear roll joints:	2 drives or brakes (optional)

The selection of the above design makes it possible to suggest a few changes to the previously proposed performance specifications [29]. The maximum gradability should be 60% on a hard packed surface and 35% on loose sand [4,27]. The nominal speed should remain at 10cm/s on level ground in loose sand, however a reduced speed of 6cm/s has been suggested as reasonable for the 35% grade [4]. To facilitate further study, a minimum speed of 5cm/s is chosen for each of the 35% loose sand and 60% hard packed soil grades. The current design also suggests a crevasse crossing ability of 1.5m, equivalent to the distance between wheel centres.

To study the ground/vehicle interaction forces and power, it will be assumed that the weight of the rover is equally distributed on the six wheels. This results in a weight of about 627N for each wheel, normal to the surface on Mars. It is also assumed that the worst case terrain would be that of loose sand, however it is noted that sliding on hard packed soil may also pose a problem. The sinkage, z_0, of a rigid wheel can be calculated using the empirical formula [21],

$$z_0 = \left[\frac{3\,W}{(3-n)\,(k_c + b\,k_\phi)\,\sqrt{D}}\right]^{\frac{2}{2n+1}}$$

where W, b and D are the weight, width and diameter of the wheel, respectively, n is the exponent of soil deformation, and k_c and k_Φ are the cohesive and frictional moduli of soil deformation, respectively. If the rover wheels are assumed to be 25cm wide, then using deformation parameters for dry sand [21],

$$z_0 = \left[\frac{3\,(627)}{(3-1.1)\,[950 + .25\,(1528000)]\,\sqrt{1}}\right]^{\frac{2}{2(1.1)+1}}$$

$$z_0 = .0241\,\mathrm{m}$$

which indicates that the rover wheels should sink about 2.4cm into dry sand. This is of course only an estimate of what might be expected in a similar environment to that in which the deformation parameters were determined.

The climbing or otherwise useful force available for a given vehicle/terrain interaction can be characterized by the drawbar pull. Drawbar pull is defined as the difference between the wheel thrust and the motion resistance. Wheel thrust is given by the formula [21],

$$F_{thrust} = A\,c + W\tan\phi$$

where A is the wheel contact area, and c and Φ are the cohesion coefficient and angle of internal shearing resistance of the soil, respectively. For a sinkage of 2.4cm, the wheel/ground contact area is about 778cm^2. Once again using soil parameters for dry sand [21],

$$F_{thrust} = .0778\,(1040) + 627\tan 28°$$

$$F_{thrust} = 414\,\mathrm{N}$$

which is the total thrust available at each wheel. The motion resistance in this case is equal to the compaction resistance of the soil, given by the formula [21],

$$R_c = \frac{(3\,W)^{\frac{2n+2}{2n+1}}}{(3-n)^{\frac{2n+2}{2n+1}}\,(n+1)\,(k_c + b\,k_\phi)^{\frac{1}{2n+1}}\,D^{\frac{n+1}{2n+1}}}$$

which, by substitution of the known parameters from above, results in compaction resistance, $R_c \approx 73$N. The difference between the thrust and compaction resistance of each wheel is about 341N. Therefore the total drawbar pull of the rover is about 2046N.

The above analysis yields similar information for dry sand on a 35% grade, where W = 589N, z_0 = 2.3cm, A = 761cm^2, F_{thrust} = 392N and R_c = 67N, for a difference between wheel thrust and compaction resistance of 325N, and a total rover drawbar pull of 1950N. In this case the downhill force on the rover, due to gravitational acceleration, is about 1286N. Performance on a 60% grade of hard packed soil or rock may vary considerably, depending on the surface conditions, however the drawbar pull must exceed about 1880N to overcome gravitational acceleration.

The above analysis is intended only to yield 'ballpark' data. The analysis has assumed certain vehicle characteristics (or lack of - wheel grousers), it does not account for the actual Martian surface conditions and is itself based only on specific experimental data. Table 2 summarizes the torque and power requirements, based on the above analysis, to facilitate further consideration of the drive system.

Table 2: Wheel Torque and Power Requirements

Terrain Condition	Wheel Torque (N·m)	Wheel Speed (rad/s)	Wheel Power (Watts)	6-Wheel Power (Watts)
0% grade, sand, 10cm/s	36.5	0.2	7.3	43.8
35% grade, sand, 5cm/s	140.7	0.1	14.1	84.4
60% grade, hard, 5cm/s	156.7	0.1	15.7	94

The 60% gradability requirement, in Table 2, indicates that a minimum torque of about 160N·m should be available at each wheel, and that each drive motor should be capable of delivering at least 16W. The likelihood of considerable wheel slip in normal operation suggests that a stepper motor or backlash-free type of motor (ex. harmonic) may be of little value. Considering the requirement of a low power/torque ratio, one should be able to apply suitable wheel torque using a low power dc motor and high gear-reduction transmission. Wright [23] offers a handy set of tools to scale electric motors to the wheel diameter of the rover. Using these tools, with the current rover specifications, the required 16W motor might have a diameter of about 7cm. A motor power of about 60W, the projected average available to each wheel [29], should require a motor of perhaps 10cm in diameter. Alternatively, one could choose a direct drive type motor, capable of producing torque in the range required, with minimal or no gear reduction. Such a motor could be more easily integrated directly into the wheel, reducing space, transmission loss and increasing reliability. It should be noted that without significant gear reduction, a braking system may be required to conserve power when the rover is still. Finally, it may be possible to adapt any of the above motors to meet the drive requirements, as long reliability, compactness and maximum available power constraints are observed.

General Rover Specifications

Length:	4 m
Width:	2 m
Mass	1000 kg
Wheel (6) diameter:	1 m
Step height crossing:	1 m
Crevasse crossing:	1.5 m
Climbing grade	
- hard packed:	60% (~31°)
- loose sand:	35% (~19°)
Nominal speed (sand)	
- flat ground:	10 cm/s
- 35% grade:	5 cm/s
Acceleration:	10 cm/s^2
Single wheel torque:	160 N·m
Vehicle drawbar pull:	2000 N
Total rover power:	250 - 500 W

References

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[21] J.Y. Wong, *Theory of Ground Vehicles*, John Wiley & Sons, 1978.

[23] D.D. Wright, "Power and Propulsion Systems for Mobile Robotic Applications", *Mobile Robots*, Proc. SPIE, vol. 727, pp. 10-16, 1987.

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[29] D.N. Green, *A Quick Look at a Mars Rover Design and the Drive System Requirements*, August 1992.