PLANETARY ROVERS WITH MECANUM WHEELS

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INTRODUCTION

Omni-directional wheels have been mainly applied to various types of vehicle operating over smooth, flat surfaces but no work appears to have been done in connection with the performance of such vehicles fitted with these wheels when traversing the extremely rough, and soft and hard surface terrains to be found on Mars, the Moon, or even on Earth. The object of the research study was, therefore, the design and testing of an omni-directional wheeled vehicle for "cross-country" use.

The research described here is based on the development of a proposal for a large-wheeled, manned, pressurized rover for use in exploring the Martian surface initially investigated by EADS Astrium, Bremen [1,2]. The original concept embodied ideas which would minimize the packaging volume needed to transport the vehicle to Mars and at the same time maximize the internal habitable and working volume. The result was a rover with very large diameter, individually driven and suspended wheels fitted with mesh-type tyres and actively-controlled, flexibly-spoked hubs (Fig. 1).

Subsequent development work, begun in 2005, reconsidered the design of the large wheels with a view to improving the rover's operational features and internal layout, wheel drive and suspension, and mode of steering. The resultant design, named *MarsCruiserOne* [3], as shown in Fig. 2, incorporated:

- hubless wheels which allowed ingress/egress for the astronaut crew for extra-vehicular activities and access to other surface modules and rovers,
- Mecanum wheels of a type and use patented by the Swedish engineer, Bengt Erland Ilon [4],
- an annular form of linear motor drive, and
- a single point rotary shock absorber/suspension system.

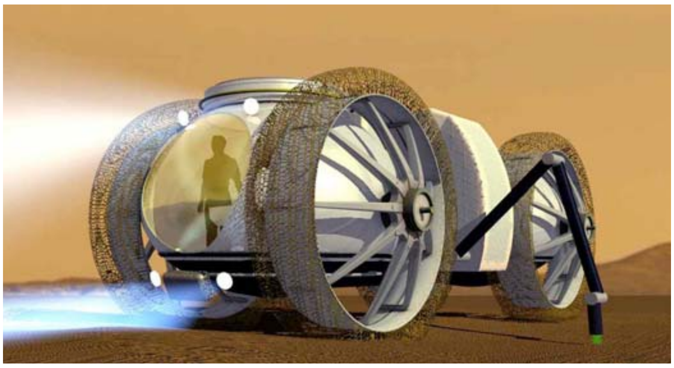

Fig. 1. EADS Astrium, Bremen, Mobile Pressurized Rover

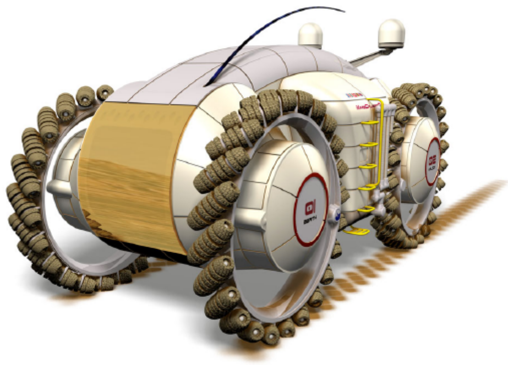

Fig. 2. *MarsCruiserOne*

(Both images courtesy of Architecture + Vision)

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DESIGN AND TESTING OF THE MECANUM WHEEL

The testing of the Mecanum wheel was conducted in two phases, namely:

1) Single wheel testing using the Single Wheel Testbed (SWT) at ESTEC (now relocated at the DLR Institute of Space Systems in Bremen) [5]. Tests were conducted with the soil simulant designated, MSS-D (see Appendix for soil properties). Additional tests were made with the SWT's soil bin covered by a sheet of Styrodur™ to simulate a "hard" Martian surface.
2) Small-scale rover testing (Fig. 3). For these tests the authors deliberately selected paved and loose pebbled surfaces, stepped surfaces and an unprepared building site near the University of Applied Sciences in Bremen, which provided a number of ridges, furrows, holes and slopes with inclinations of up to 10°. This site was covered with a random mixture of sand, loam and stones. The geometry of the Mecanum wheel for the test rover was identical to that of the test wheel but the rover's wheels were designed to be rim-driven to simulate the full-scale rover design (Fig. 4). The test rover has a mass of approximately 5.8 kg, the load on each wheel being about 15 N.

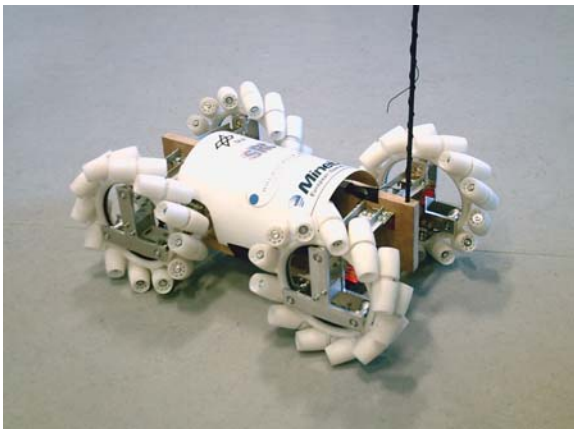

Fig. 3. A view of the radio-controlled, small-scale test rover.

Fig. 4. Mecanum wheel used on the small-scale test rover

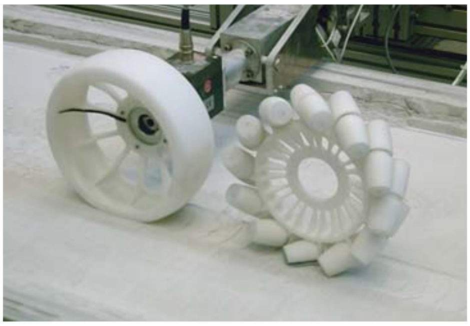

Fig. 5. Plain and Mecanum test wheels

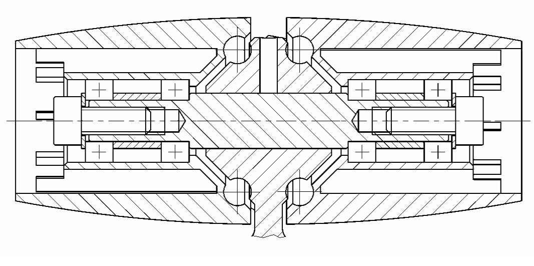

Fig. 6. Cross-section of Mecanum wheel roller

Two test wheels were manufactured, their diameters being determined by the limitations of the rapid-prototyping machine available at the University of Applied Sciences in Bremen (Fig. 5). The outside diameter of each wheel was 200 mm and the material used in their construction was acrylonitrile-butadiene-styrene. Both wheels were subjected to finite element model analyses to check that the loads imposed on them during testing would not exceed the material's structural properties.

The primary test wheel was of the Mecanum type with convex barrel rollers mounted on the periphery of the wheel with their axes indexed at 45° to the plane of the wheel. Each half of the roller was mounted on two sealed ball bearings together with additional seals to prevent the ingress of the fine soil simulant used in the test facility (Fig. 6). The diameter and length of the roller was determined by an analysis of wheel sinkage to be expected during testing. (A sinkage of 13 mm was calculated for a vertical load of 15 N.) The maximum diameter of the roller was 30 mm and its overall axial length was 73.2 mm. The wheel was fitted with 12 peripheral rollers.

The secondary, smooth-surfaced plain wheel was made with the same outer projected profile of the Mecanum wheel's rollers and was used for comparative tests.

Single-wheel Tests

Two test runs for each variation in test parameter were made using the SWT facility, i.e. variation of slip, speed and wheel orientation were varied. Four values of slip were used, namely, 0%, 30%, 50% and 70%. A driving speed of 10 mm/s was selected. Wheel orientation tests were conducted with the Mecanum test wheel at orientations of 0°, 45° and 90° relative to the driving direction of the wheel.

During the tests with 45° and 90° wheel orientation it became clear that a 15 N wheel load was too high and it was, therefore, reduced to 5 N (Figs. 7 and 8). At the higher load the rollers dug deep into the ground, piling up soil in front of them up to the height of the wheel axle! The rest of the soil was piled up at the side of the track where the wheel emerged from the ground. Also, the seals between the halves of the Mecanum wheel rollers were removed because they caused high frictional forces. All tests that had been done before these changes were introduced were repeated.

Fig. 7: Mecanum wheel subjected to a load of 15 N (90° wheel orientation).

Fig. 8. Comparison of tracks left by Mecanum wheel orientated 90° and under a load of 5 N (various values of slip)

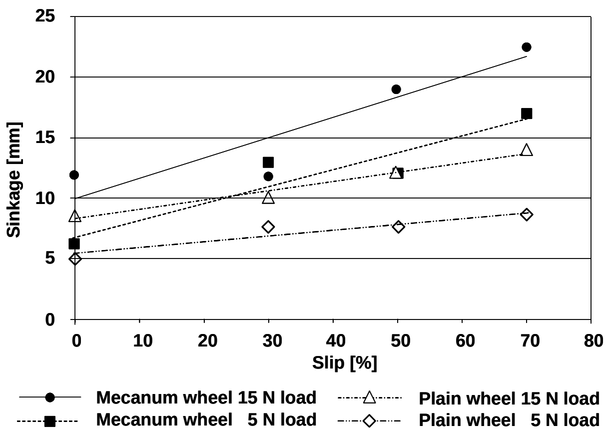

Fig. 9. Wheel sinkage in Martian simulant soil (0° orientation and speed 10 mm/s)

Measurements of wheel sinkage taken manually after a test run are shown in Fig. 9. These reveal an increasing linear tendency with increasing values of slip. Values for 0% slip show that the Mecanum wheel sinks about 40% more than the plain wheel but at 70% slip the sinkage is 50% higher. It is thought that if the rollers were to be regarded as grousers, then the difference should have been much higher. It is also noticeable that there is a relationship between wheel load and sinkage in the simulant soil, i.e. for a threefold increase in wheel load on both the plain and the Mecanum wheel the sinkage increases by about the same amount (2 mm). These effects are believed to be due to the simulant soil's properties. In the case of the Mecanum wheel, the displaced material is built up alongside the wheel's tracks, is trapped between adjacent rollers and is compressed, the "harder" compressed soil reducing sinkage. A similar effect was noted from tests with the plain wheel which left a track of small ridges of material created by bulldozing effects, the ridges being compressed as the wheel rolled over them. The ridges became more pronounced with increasing slip.

Figure 9 shows saturation in torque for 0° wheel orientation, the maximum torque being reached at approximately 30% slip. Driving with 90° wheel orientation torque increases significantly with slip. This situation corresponds with the massively increasing sinkage plus the size of the pile of soil in front of the wheel which does not exist at an orientation of 0°.

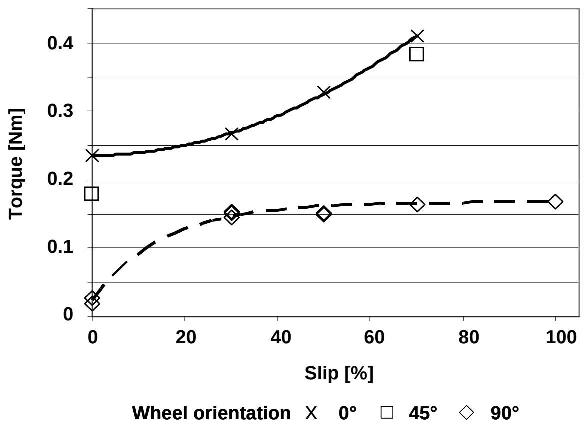

Fig. 9. Wheel torque at orientations of 0°, 45° and 90° with 5 N wheel load – “soft” soil

The torque in relation to the wheel orientation is shown in Fig. 10, the values rising with increasing angle of orientation. The two data points for 45° wheel orientation with 30% and 50% slip have been interpolated.

A sinkage of less than 1 mm was recorded during torque measurements made using a hard surface, the data in Fig. 11 indicating a similarity to that for 0° wheel orientation on soft soil (Fig. 10). The torque is a maximum at about 30% and for higher values of slip appears to remain constant. Although no torque was measured for 0° orientation and 0% slip it can be assumed that it will be about the same as for soft soil.

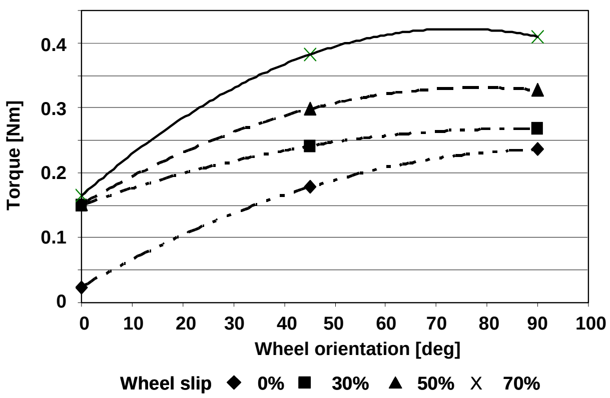

Fig. 10. Torque in relation to wheel orientation with 5 N wheel load – “soft” soil

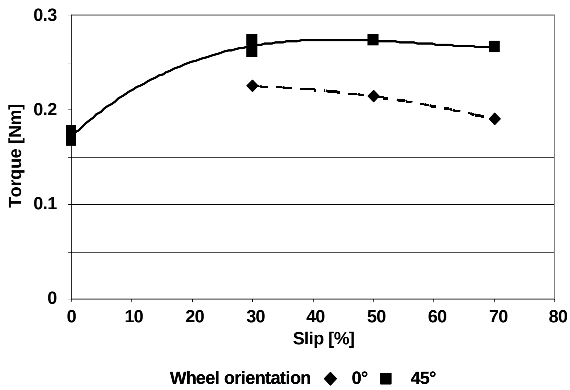

Fig. 11. Mecanum wheel torque at 0° and 45° with 5 N wheel load – “hard” surface

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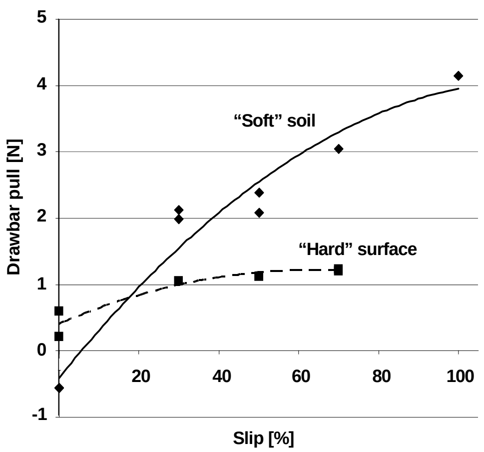

Fig. 12. Drawbar pull for 5 N wheel load and 0° wheel orientation

Drawbar pull is the force the wheel can apply to the ground minus the resistive forces. For 0° wheel orientation and 0% slip in Fig. 12 the drawbar pull should be 0 N or less for a hard surface because the wheel’s circumferential speed is the same as the speed of the wheel relative to the surface it drives on. The only force applied is rolling drag and, therefore, no drawbar pull should be generated. The measured value is between 0.2 N and 0.5 N which might be a sensor calibration problem. For the test on the soft soil a negative value was measured. Unlike the rigid surface the soft soil generates much higher drag. Because there is no slip, no soil thrust is generated and the drawbar pull becomes negative.

For higher values of slip the drawbar pull on the hard surface reaches a maximum of 1.2 N which is approximately constant between 30% and 70% slip. The reason for this might be that the smooth surface of the wheel’s rollers slide/skid on the hard surface at higher values of slip. The soft soil, however, generates much higher thrust with a maximum of about 4 N for 100% slip.

Interpretation of the single wheel lateral motion test data revealed that with 50% slip the wheel turns 0.4 revolutions which corresponds to a driven distance of 100 mm. With 70% slip the wheel rotates about 0.45 revolutions and the corresponding distance driven is 130 mm. These values are low but when scaled are considered sufficient for a full-scale rover to perform lateral docking manoeuvres.

Rover Tests

On completion of the tests with the Mecanum and plain wheels, a small-scale rover was built with Mecanum wheels of the same diameter as the test wheel. The intention was to compare the test facility results conducted on smooth surfaces with trials on extremely rough terrain. The rover was required to perform longitudinal, lateral and turning manoeuvres on all of the rough surfaces.

The major difference between the test wheel and the wheels fitted to the rover was in the design of the wheel itself. Rather than axially-driven it was to be rim-driven in a manner emulating the full-scale rover, *MarsCruiserOne*. For this purpose the wheel was driven by a geared electric motor fitted with a sprocket which meshed with a chain embedded in a channel on the inside of the wheel's rim (see Fig. 4). This type of driving mechanism was chosen to represent that which might be used on a large-scale rover and to investigate the effect on driving performance of dust or dirt on the mechanism. Each wheel was independently suspended, the wheels' motion being damped with adjustable spring-oleo shock absorbers.

This first tests on paved surfaces proved very successful. The rover was able to move in any direction without deviating from its course. Driving with two wheels on stone and the other two wheels on a steel grating also did not have any influence on course stability. There was also no difficulty driving diagonally at 45° relative to the rover axis on this surface. This is considered a very hard test because only two wheels are driven while the other two are blocked although their rollers are still free to rotate.

Fig. 13. Climbing an obstacle

Testing the ability of the rover to climb over obstacles revealed that the rover could climb a step equivalent to 40% of its wheel diameter with its left front wheel. The rear left wheel was not able to climb over the obstacle because the rear right wheel did not have enough grip and slipped away (Fig. 13). When the rover drives over obstacles that are larger than one roller the best way to pass them is to approach the obstacle at under 45°. The edge of the roller rests on the obstacle and then lifts the whole wheel on top of the obstacle.

Tests on relatively soft but very rough soil were also successful. Driving forwards and backwards could be accomplished without difficulty (Fig. 14). The lateral direction was also successful but problems were experienced with the electric driving motors—their torque was not high enough to cope with the terrain at full speed. However, the rover was able to move laterally but slowly. Turning the rover around its vertical axis was also achieved on this surface. Because of its suspension system, all wheels have sufficient ground contact and allow the

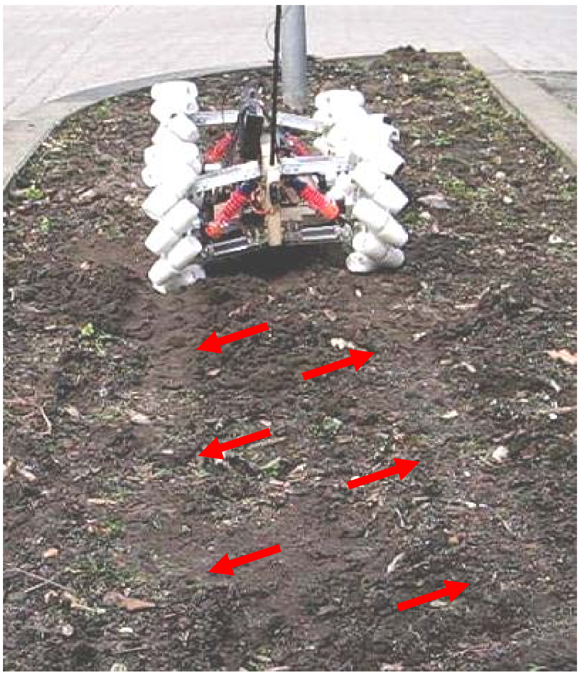

Fig. 14. Rover driving over very rough terrain. Arrows mark the vehicle's tracks

rover to drive in a straight line. Figure 14 also shows the large deflections of the suspension—the rover chassis stayed perpendicular to the ground.

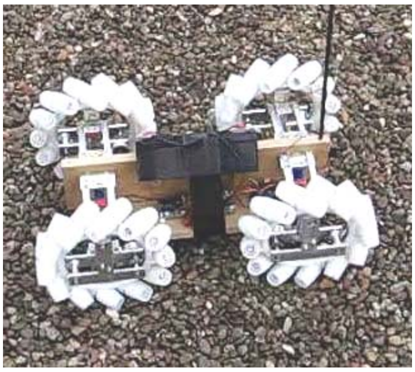

Fig. 15. Rover driving over pebbles

The tests on a loose pebble surface were successful apart from driving in the lateral direction which proved impossible (Fig. 15). Even turning the rover round its vertical axis was successful and the rover remained manoeuvrable in this situation. The reason why the rover cannot drive laterally on this type of surface is that there are only a few points of contact between the plain rollers and the plain pebbles and, therefore, only a small force can be transmitted. Another factor is that the ground is very loose, the small stones having little contact with one another and are easily moved. These factors do not allow compression of the surface which could enlarge the grip. Driving forwards on pebbles did not prove to be a problem because the rollers do not have to revolve. In this situation they worked like grousers.

Fig. 16. Rover driving over extremely rough terrain

Rover tests on sandy and extremely rough terrain were performed on an unprepared building site. The first test with the rover was made to check its tracking capability on a very rough terrain. (Fig. 16). The soil was dry sand with a small amount of pebble. The track the rover had to pass was interrupted by “dune-like” structures running at about 45° to the course of the rover. The suspension was used to its maximum degree of freedom. The rover was able to travel along this track without problems. After driving several metres the rover deviated about 5° from its course.

The rover was tested on the same terrain to check if it was able to turn about its vertical axis. This test was passed successfully. It also proved possible to turn the rover using only the front two or the rear two wheels.

Figure 17 shows the rover driving through a “crater” with a diameter of about 400 mm and a depth of 80 mm. In this case the rover always stayed in a stable position and had no tendency to tip. Although the rover wheels are loaded differently, the course of the rover stayed nearly constant with a small diversion from its track of about 5° to the left at the end of the manoeuvre. During the manoeuvre the wheels had a very low slip ratio even when climbing out of the crater. The degree of freedom of the suspension was fully used.

Fig. 17. Driving through a “crater”. The rover traversed the crater in 12 seconds.

Figure 18 shows the rover crossing from a flat terrain over a “dune” which had a height equivalent to 50% of the wheel diameter. The dune had a very soft consistency leading to a high sinkage of about 15 mm. The rover approached the dune, which had a slope of about 30°, at an angle. This gave an indication of how much influence the different wheel loads on each wheel had in this situation. The rover showed no deviation from the original course. During another test with a dune of about the same height but a higher angle of ascent, the rover body got stuck at the peak of the dune. The reason for this was the lack of ground clearance between the rover and the surface. Although the rover could not continue its course forward it was able to free itself by driving backwards.

Fig. 18. Traversing a “dune”

Fig. 19. Driving in lateral direction on a rough surface

Driving the rover in a lateral direction proved difficult. Figure 19 shows the rover at the end of its movement. It was able to drive a distance equivalent to its own width. The wheel tracks indicated a high slip ratio of about 50% - 70%. As with the tests on the SWT, the soil piled up in front of the two left wheels making further movement in the desired direction impossible. The movement becomes impossible from the point where the rollers that are in ground contact have a pile of soil of about 60% of their own diameter in front of them. At that point the rollers could not rotate freely and no lateral force was transmitted to the ground.

Different tests were performed on a 10° slope. The first was a simple forward driving test in the direction of the slope. The rover accomplished this test without problems. The wheels had a slightly increased slip ratio and were partly spinning because localized areas of the soil were very loose. The rover climbed the slope without significant diversion from its course.

Turning around the vertical axis of the rover at the 10° slope was possible, although the centre of rotation moved downhill during the turn. This is a problem for the radio-controlled steering since it was not possible to fine tune all four wheels simultaneously.

CONCLUSION

The research study showed that the use of Mecanum wheels fitted to rovers for the exploration of planetary surfaces is feasible. Scaling of the wheels to meet the requirements of much larger rovers, e.g. *MarsCruiserOne*, which has a wheel diameter of 3.8 m, and even of rovers with wheels of diameters in the range of 1 - 2 m should be the subject of further investigation.

The SWT test results indicate that the Mecanum wheel is capable of driving on soft ground. The tests at 0° wheel orientation showed that the wheel can deliver thrust in any situation even if the rollers are completely buried. This enables a rover to do all necessary manoeuvres: the rover is capable of driving forwards and backwards and it can turn around its vertical axis to change direction.

During lateral driving of the Mecanum test wheel the build up of soil through bulldozing prevents driving over distances of more than 100 mm. Because of this situation it was not possible to fully determine lateral driving performance. It is concluded for the wheel loads used in the SWT tests that the diameter of the peripheral rollers is too small. Although the rollers were revolving it would appear that they did not compress enough soil. This is the primary reason for the large mounds of soil built up in front of the rollers. Although calculations reveal that larger roller diameters will have no positive effect, they will reduce the effect of pushing soil around. A larger diameter will enable the rollers to compress the soil instead of piling it up. The sinkage will also be reduced because the rollers do not have to push in the vertical direction.

The use of “soft” soils for developing sizing parameters for Mecanum wheels should be re-examined as the surface of Mars in particular, appears to have much larger areas of much firmer surfaces.

In general, the results from tests with the rover were as follows:

- The testbed results showing a high sinkage due to the bulldozing effect when driving in a lateral direction was also observed on rough sandy terrain. The wheel load in this case, however, was 15 N and the sinkage was lower.
- The rover was able to drive forwards and back-wards in a straight line with little or no diversion from its route, even on paved or very rough surfaces.
- The rover is able to turn about his vertical axis on hard, rough and sandy surfaces and even on pebble.
- The front or rear wheels can be used for steering.
- The rover is able to climb up hard, soft and very rough slopes with an inclination of up to 10°.
- The rover can traverse along slopes with an inclination of 20-30°.
- Turning on a slope of 5° around its vertical axis is possible for the rover.
- Lateral movement on hard or relatively firm surfaces is not a problem.
- It was always possible to "free" the rover if the surface proved too rough by driving forwards or backwards or using front or rear wheels for steering.
- Diagonal movement is possible with two of four wheels on hard and relatively firm surfaces.
- The rover is capable of climbing over large obstacles using, if necessary, a diagonal approach. The step height is equivalent to the radius of the rover wheel.
- The rover is able to traverse large "craters" up to a width equivalent to the diameter of the wheel.
- Change of direction is achieved continuously with hand control. (Available videos of Mecanum-wheeled rovers moving on flat surfaces show distinct pauses in motion before they change direction.)
- The rover has no tendency to tip due to its low centre of gravity. Theoretically, it will not tip up to an angle of 45°.
- Trimmed controls allow the rover to follow a straight path without manual correction.

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APPENDIX

Soil type	ρ [kg/m^3]	n [-]	k_ϕ [kN/m^{n+2}]	k_c [kN/m^{n+1}]	c [kPa]	ϕ [deg]
Type G (MSS-D)	1330	1.8	$1.92 \cdot 10^5$	$-6.675 \cdot 10^2$	0.013	13.4

k_Φ Frictional modulus; k_C Cohesive modulus; c Cohesion; n Exponent of sinkage; ρ Bulk density; Φ Internal friction angle

Table 1: Soil parameters of the DLR Mars soil simulant "MSS-D"