LESSON LEARNED FROM EXOMARS LOCOMOTION SYSTEM TEST CAMPAIGN

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Abstract

A mobile surface element is required in the frame of the ESA ExoMars mission for exploring Mars in order to investigate the environment and to search for evidence of life [1]. The mobility aspect is important in terms of range and duration and was investigated by Oerlikon Space AG and its team during the phase B1 of the ExoMars project. An important outcome of this activity is the manufacture and testing of a full scale rover breadboard.

The breadboard mass was scaled down to 93.5kg in order to take into account the martian gravity. It is a 6 wheel drive, 6 wheel steered vehicle based on a three bogie suspension configuration. Despite the heavy payload and high location of the CoM, the vehicle is able to withstand a tilt of 40° in any direction without losing its stability. The passive suspension and flexible wheel design allows the traverse of obstacles with sizes of at least the wheel diameter (25 cm) on Mars representative soil.

The locomotion level test activity was conducted on the Rover Chassis Evaluation Tool (RCET) ESA test facility developed by Oerlikon and located in their premises. This test facility consists of a 20 square meter testbed featuring Mars representative soil (i.e. soft sand) [2]. A novel measurement system was developed in order to reconstruct the drawbar pull capability at different slippage values. Obstacles as well as slopes were accommodated during the test and the vehicle performance measured. These values represent the key traverse-related mission requirements. The success of individual traverses as well as the energy, speeds, and trajectory errors on the overall vehicle were recorded.

As a result of the testing program the team consolidates their understanding of the locomotion behavior and the effect of innovative development like flexible wheels, side grousers and the three bogies passive suspension system. The large amount of data coming from position sensors, force torque sensors and accelerometers are valuable for predicting the performance of the future flight model and to improve the accuracy of simulations tools.

The paper presents the results of the extensive testing activity carried out with the ExoMars locomotion subsystem breadboard, the lesson learned and preliminary correlation exercise of the simulation tools.

1. INTRODUCTION

In the frame of the ExoMars mission, a rover will provide regional mobility (several kilometers) searching for traces of past and present life over its planned 6-months of operation. It will do this by collecting and analyzing samples from within surface rocks, and from underground — down to a depth of 2 meters.

The elements that enable the rover to traverse the surface of Mars which handle the traction, obstacle traverse and slope climbing are called the ExoMars Locomotion Subsystem (LSS).

2. METHODOLOGY AND CHALLENGES

The testing of a planetary exploration rover is necessary in order to get the following key information:

a) Assess the locomotion performance so that the navigation system can select a safe path.
b) Characterize the locomotion S/S in particular in terms of energy consumption and driving torque in order to support the design of the flight model.
c) Check the correct implementation of all components in particular the control algorithm, the drive electronic, the actuators and sensors.

The main challenge is to reproduce on Earth the conditions that will be found on Mars during the mission.
The gravity can be adjusted by scaling the rover mass in order to have equivalent wheel load. However, it is not feasible to reduce the mass of all sub-elements in particular the actuators and the structure.
During field testing where human presence is necessary, the temperature and atmosphere cannot be Mars representative.
The Mars soil physical parameters (Bekker [4]) can significantly vary from one place to another and are relatively unknown making it difficult to produce of Mars representative sand.

For these reasons, the methodology applied during phase B1 in order to meet the tests aims was to combine field testing with simulation and analysis activities.
For overcoming the scaled mass issue at sub-system level, the rover body center of mass (CoM) was adjusted to be flight representative.
The temperature and atmosphere mainly affect the actuator performances. Therefore the forces and torques were recorded instead of the power in order to extrapolate the effective energy consumption during the mission.
Research was undertaken during the RCET project to ensure the correct preparing of Martian soil stimulant [2]. This work was used although additional investigations are still on-going.

3. BREADBOARD

A suspension concept based on the previous RCL-E heritage was proposed by Astrium UK. The so called “3 bogies” is based on three simple bogies located at each side of the rover and on the rear (i.e. a transverse bogie). The three point attachment is a kinematically defined system that passively keeps all six wheels in contact with the ground, even on an uneven terrain [3].

Figure 1. ExoMars breadboard (vH&S, OSZ)

Specification

Mass	: 93.5 kg*
Track width	: 1200 ± 5 mm
Distance between wheels	: 700 ± 2 mm
Wheel	: ∅250 x 100 mm
Nominal wheel load	: 153 ± 5 N
Grouser height (12x)	: 4 mm

*The overall rover mass was scaled down in order to by representative to the Mars gravity. The equivalent mass will be a 246 kg heavy flight model.

4. STATIC STABILITY

The stability in all directions was determined on different slopes up to 40°. The wheel loads were recorded in order to determine the margin before a wheel loses contact with the ground.

Static stability testing requires a very high friction coefficient between wheels and ground to prevent the rover from sliding. Even though a very sticky material was selected to cover the tilt platform, the rover started to slide at angles just beyond 20° due to the metallic tire. Therefore the wheel was wrapped with a special material (see Fig. 3) which resulted in a sufficiently high friction coefficient. This could be done without the reduction of significance of the test results because static stability testing aims at finding the stability angle which is not influenced by the wheel-ground contact conditions.

The deformation of flexible wheels as shown on Fig. 5 is a function of the wheel load and therefore influences the static stability. The kinematics model computes a reduction of the stability due to the utilization of this flexible wheel to be in the 1° range.

Figure 3. Static stability test on a 40° slope

Figure 4. Rear wheel deflection

In order to determine the worst case orientation angle (yaw angle), the rover performed a turn on spot maneuver while the platform was set to a 15° inclination. The normal forces were monitored as shown on Fig. 5. The worst case angle is defined to be the angle where the wheel load value reaches the minimum value

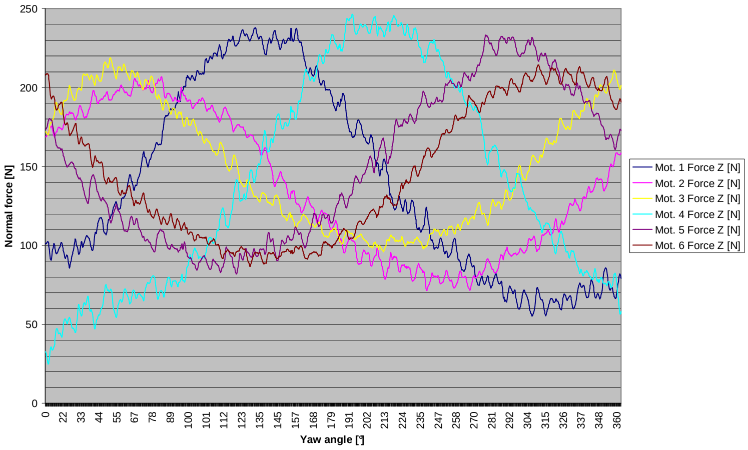

Figure 5. Plot of the yaw angle vs. the normal forces measured on the different driving hubs of the rover

Based on these measurements the static stability test was performed in the two worst case orientations (40° and 320°) on the required 40° slope. The rover is stable but a normal force of only 12N remained on a wheel showing that the breadboard is near to the point of instability.
Note: based on this margin, the kinematics model computes a static stability of slightly over 41°.

5. DRAWBAR PULL VS SLIP

Drawbar pull (DP) is the difference between soil thrust *H* and motion resistance *R* and is the additional force which is available until the maximum traction is reached. Drawbar Pull is a function of slip and provide valuable information about the trafficability.

Figure 7. Drawbar pull test set-up

The installation that allows reconstructing the drawbar pull versus slip characteristic on a Martian soil stimulant (MSS-D) is shown on Fig 7. This consists of a motorized tether that controls the rover speed from 0 up to the maximal operational speed of 40 m/h whilst and recording the pulling force.

By controlling the wheel angular velocity and the rover translational speed it is possible to assign a specific slippage value. The resulting pulling force represents the margin the rover has at this slippage value. This margin can be use for overcoming the resistance due to gravity or pushing against an obstacle in order to get sufficient traction to overcome it.

The results reported in the Fig. 8 show a small variation of the DP, in particular between 30% and 70% slip. However, the sinkage reported in Fig. 9 and the rover velocity are affected by the slippage. Having a DP between 250N and 320N means, for this rover and on this particular soil, a maximal slope gradeability of 15° to 18°. The other interesting information is that moving with a slippage beyond 30% does not provide significantly more traction and thus only reduces the rover motion efficiency.

It should be noted that only at 100% slip we have measured a significant increase in the DP of up to 700N.

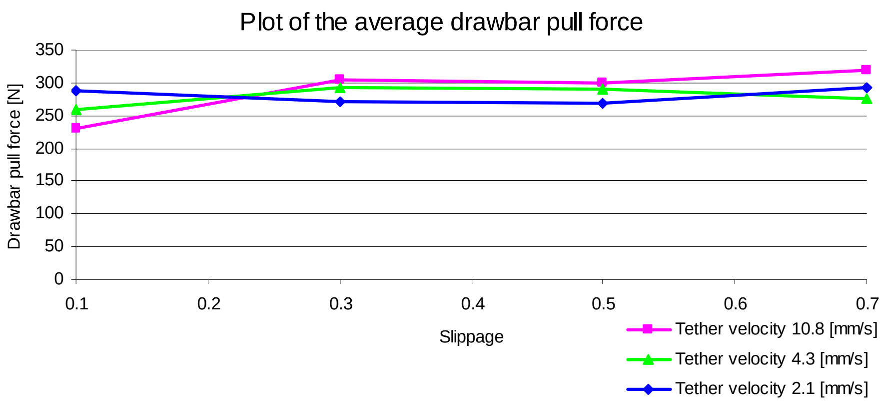

Figure 8. Rover drawbar pull force versus slip

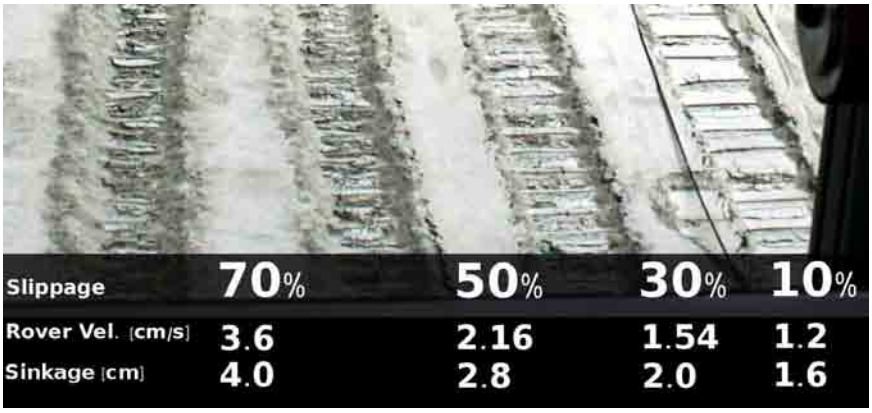

Figure 9. Sinkage as a function of the slip

The ExoMars rover as well as most of the planetary rovers is controlled in speed and therefore the slippage is a result of the wheel-ground interaction and cannot be controlled. However, by measuring the slippage it is possible to make an estimation of how safe the current path is with the available margin.
Concerning obstacle climbing, the rover can push against an obstacle with a force of approximately 300N. Assuming a friction coefficient of 0.5, this implies a wheel can move up 150 N. This is close to the nominal wheel load and means that the rover can overcome simple obstacles. However climbing with two wheels simultaneously (like over a step shaped obstacle) seems not possible.
Such behavior was confirmed by the simulation but did not correspond to the reality. The fact is that the grousers interact with the texture of the terrain and wheel slippage is avoided when moving over the obstacle. When taking into account this effect, the rover can move over a step shaped obstacle.

6. UNEVEN TERRAIN

From drawbar pull test it is possible to extrapolate the slope gradeability and some obstacle climbing performances. However this is an indirect measurement that needs to be confirmed by motion on uneven terrain. The methodology is not to create a Mars representative terrain based on a probabilistic approach. Instead, as mentioned in section §2, the aim is to characterize the rover over well defined terrains and obstacles.

6.1. Slope gradeability

A test was performed on a 15° slope with and without multi-pass (wheel moving in the same rut) and the slip measured. The test was successful even when directly placing the rover on the slope.
It should be noted that when moving on lose soil, the multi-pass effect reduces the slippage and helps the rover to climb slopes.
This test shown in Fig. 10 highlights the challenge of preparing the soil homogenously and measuring accurately the translational speed. This is due to significant variation of the wheel slippage (between 30% and 60%) that directly affects the rover velocity.

Based on the DP versus slip characteristic it was expected that the slippage variation on a slope will be significant. In general, this test confirms the estimation coming form the DP test. The main difference is due to the wheel load repartition on a slope. The additional load on the rear wheel combined with speed control results in unequal torque distribution between the different wheels as shown on Fig. 11.

Figure 10. Motion on a 15 slope

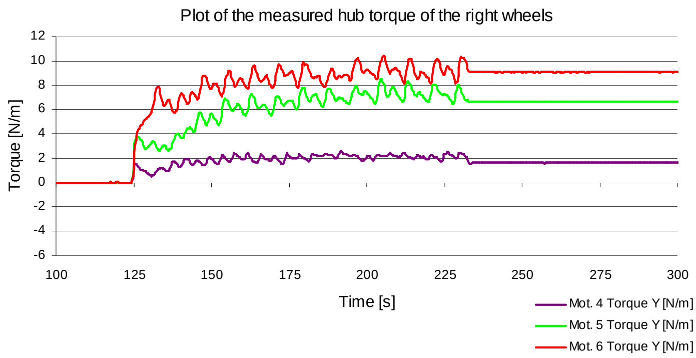

Figure 11. Wheel torques on a 15 slope (right side)

6.2. Obstacles

The motion over a 250mm obstacle was successfully performed in both directions (i.e. forward and backward). The obstacle height corresponds to the wheel diameter, but the sinkage and wheel flexibility lower the rover so that the obstacle is in reality above the upper part of the wheel as shown in Fig. 12.

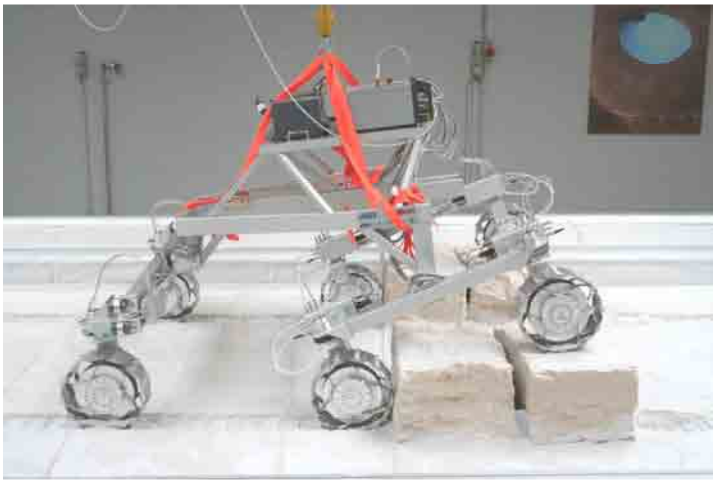

Figure 12. 250mm step shape obstacle

Due to the speed control mode, the wheel rotation velocity is constant during the overall motion independent of the terrain as shown on Fig. 13. Because the distance between the wheels is the same, the wheels would normally descend down the obstacle after the same time interval. This is not the case as shown in Fig. 13 and illustrates that the rover vehicle speed is not constant due to a variation of the slippage value. Video analysis confirms this assumption and in particular the front and back wheel have more difficulties to overcome the obstacle than the middle wheel. However, it never appeared that the wheels were ever blocked.

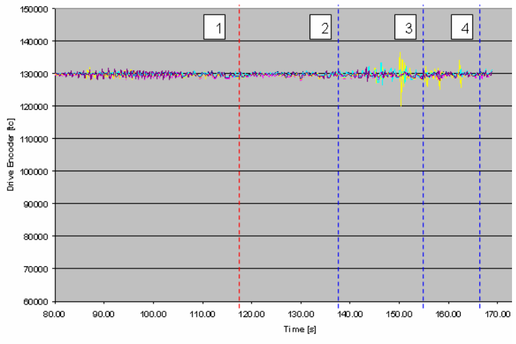

Figure 13. Encoder raw data versus time

The events indicated in the graph are as followings:

1. First wheel starting to climb the obstacle
2. First wheel moving down the obstacle
3. Middle wheel moving down the obstacle
4. Rear wheel moving down the obstacle

7. PATH FOLLOWING

The control algorithm provides the actuators with commands to follow a predefined path. For testing the accuracy of this algorithm, a certain number of via points were defined as shown on Fig.14.


Figure 14. path following on leveled surface

An open loop test was performed without a navigation system. The breadboard relies exclusively on 2D wheel odometry and wheel steering angle. Because the aim was to validate the LSS control which is only a part of the overall navigation system and works only in 2D, the test was conducted on a perfect leveled surface without any obstacles.

The test was completed successfully. The rover was able to follow the waypoint list and reached the end of the path. To our surprise, the rover moved further than each waypoint and the final cumulated error is as follows:

$$\Delta_x = 5cm \ \Delta_y = 2.5cm$$

This error is over a 2 meter long trajectory. The error is explained by the fact that the algorithm is implemented such that the rover travels the distance needed to reach the next waypoint, but stops only when the corresponding computed odometry distance is reached. This means the accumulated error makes the rover move further than the ground truth. It also means that the slippage (not taken into account by the algorithm) which should counter this effect, is negligible on a leveled surface. In uneven terrain the situation will be different and interaction with the navigation system will be essential in order to correct any deviation from the correct path.

8. LESSON LEARNED

A number of lessons were learnt during the tests campaign of the LSS breadboard. The most relevant are mentioned here.
A dedicated testing facility that allows for the preparation of terrains in a reproducible way is necessary for the production of valid and useful data. The characterization of the soil is a critical task in order to produce inputs for the simulation team.
Reproducing all Mars environmental conditions on Earth is too challenging. Therefore specific sensors must be accommodated on the rover that undergoes field-testing to correctly characterize the system. In particular force / torque sensors are used to produce the necessary information for the design team. This data in particular allow the actuators' performance on Mars to be estimated by analysis and simulation.

Test data are necessary for updating and validating simulation tools. The data and test conditions needed for this validation may differ from a standard locomotion test. Interaction between test engineer and the simulation team, therefore, are critical for an efficient and productive rover testing activity. In particular for such validation testing it is more important to have accurate data and a well defined test case than having Mars representative conditions.
Flexible wheel is a technology which has not been used in previous robotic missions. The LSS team are developing flexible metallic wheel in order to improve the locomotion performance and reduce the shock level transmitted to shock-sensitive items. In certain hard motion conditions, the stress within the flexible element overcomes the value computed by the analysis team and lead to a permanent material deformation. Understanding this effect was possible trough extensive picture and video analysis and will permit updating the FEM and structural analysis for developing a suitable wheel for the ExoMars mission.
When descending an obstacle, a hole is created by the first wheel so that the effective drop is much higher for the following wheels. This important reduction of the ground clearance leads to contact between the suspension and the lander platform during a step down of 250 mm. It is therefore necessary to increase the ground clearance or modify the lander egress maneuver.
The holding torque of the drive unit based on a brushless motor and a harmonic drive is below 5 Nm and thus insufficient for maintain the rover in position in un-powered state. An iteration of the drive concept is therefore necessary to ensure that motor power is not required when the rover is not in motion and thus minimize the power consumption during the mission.

9. CONCLUSION

The ExoMars breadboard demonstrated excellent locomotion capability on a Mars representative soil and over critical obstacles. The simple suspension concept is very efficient in uneven terrain and it is clear that the flexible wheel and grousers have a positive effect on motion capability. The test campaign demonstrates that the rover is stable in all directions on a 40° slope and the obstacle capability is over the specified 25 cm. The torque required to move on the terrain is below 17 Nm even during motion over obstacles and the peak torque never exceeded 30 Nm.
The test facility developed within the ESA RCET [2] activity was upgraded and extensively used. The improvement significantly reduces the manpower and the time required to perform the test. However, post-processing is a time consuming task and the correlation exercise with simulation tool is still on going. Therefore the development of a tool capable of performing this task (more) automatically will be necessary for future test campaigns.

In conclusion, the combination of analysis, testing and the additional sensors mounted on the breadboard generate valuable data that support the engineering phase of the flight model. The lesson learned and experience gained during the testing phase show the importance of breadboard testing during the early phases of the project. Based on this experience, significant improvement can now be expected in the rover chassis in particular for the actuators and wheel design.

10. ACKNOWLEDGEMENTS

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