FIRST EXPERIMENTAL INVESTIGATIONS ON WHEEL-WALKING FOR IMPROVING TRIPLE-BOGIE ROVER LOCOMOTION PERFORMANCES

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ABSTRACT

Deployment actuators of a triple-bogie rover locomotion platform can be used to perform Wheel-Walking (WW) manoeuvres. How WW could affect the traversing capabilities of rovers is a recurrent debate in the planetary robotics community. The Automation and Robotics Section of ESTEC has initiated a long term project to evaluate the performance of WW manoeuvres in different scenarios. This paper presents the first experimental results on this project, obtained during the test campaign run on November 2014 at the Planetary Robotics Lab (PRL) of ESTEC, and shows the performance analysis made when comparing WW with standard rolling. The PRL rover prototype ExoTeR was used to test three different scenarios: entrapment in loose soil, up-slope traverse and lander egressing. WW locomotion showed increased capabilities in all scenarios and proved its relevance and advantages for planetary exploration missions.

1. INTRODUCTION

Planetary rover missions to Mars such as NASA's MER or MSL have shown a clear decrease of the traversing capabilities while rolling across some particular surface areas of Mars. Loose soil and fine dust terrain is the scenario where rovers may experience the most significant loss of their tractive performance. The extreme of these cases was encountered in the Spirit rover which got permanently stuck on May 2009 while traversing the loose sandy area of Troy [Web].

Following the Lunokhod mission, Russian engineers developed numerous planetary exploration rover concepts where they demostrated major increase in gradeability and obstacle negotiation performances by implementing a "peristaltic" locomotion mode in some or a "wheel-walking" mode in others [EKKP98]. The triple-bogie rover concept was conceived in the early phase of the ExoMars mission [ea10] and has become the baseline for the rover's locomotion. Moreover this type of suspension has become widely accepted in the European space robotics community due to good locomotion performances and design simplicity. The location of the deployment actuators of the triple-bogie concept offers the WW mode for free and this is another great benefit of this suspension concept.

Based on the above and given that the triple-bogie concept will probably have a role in future European exploration missions, the Automation & Robotics Section has initiated a long term internal project to characterize the performances of this suspension concept. A significant part of this project focuses on the WW mode with the aim to fully understand and exploit its potential.

The target platform for the initial test results of this investigation on the WW mode is a triple-bogie laboratory prototype, namely ExoTeR.

This paper briefly presents the ExoTeR rover in section 2, the WW concept implementation in section 3 and focuses in section 4 on the first experimental results obtained for three different operational scenarios, comparing key performance metrics between the wheel walking and rolling locomotion modes. The three operational scenarios considered are: 1) entrapment in loose sand, 2) up-slope traverse and 3) rover egress. Section 5 gives the conclusions drawn from these experiments and in section 6 the future work and test plan is explained.

2. THE EXOMARS TESTING ROVER

The rover platform used for the experiments described hereafter is an ExoMars-like scaled down version laboratory prototype. The ExoMars Testing

Rover (ExoTeR) mimics the locomotion configuration of ExoMars (according to its design in 2007), a.k.a. triple-bogie passive suspension, with a parallelogram structure on top of each bogie. The locomotion subsystem comprises 6 wheels and 16 actuated joints, more precisely, 6 driving, 4 steering and 6 deployment (or walking) motors. Motion control electronics are a network of servo-drives, namely Elmo Whistles, connected in a CAN Bus together with the On-Board Computer (OBC). A driver module in the OBC acts as a CAN Master implementing the CANOpen protocol and sends joint commands timely synchronised to perform a certain locomotion manoeuvre. Each servo-drive takes care of the close-loop control of one active joint to reach the commanded (position and/or velocity) set point. Figure 1 illustrates the locomotion system of ExoTeR. Inside the uncovered body the motion control electronics can also be seen.

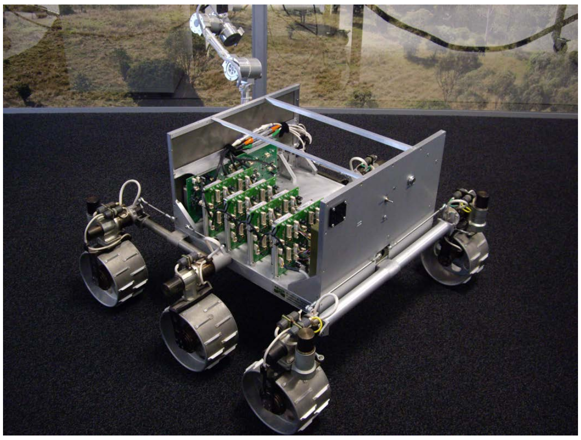

Figure 1. ExoTeR Rover, 2013

The general dimensions of the rover are summarised in table 1 below. The ground pressure calculation is based on the Effective Ground Pressure convention defined by JPL in [HML+13].

Locomotion platform type	$6 \times 4 \times 6$
Size ($L \times W \times H$)	$70 \times 70 \times 40$ cm^3
Wheel diameter	14 cm
Wheel width	9 cm
Total mass	24.08 kg
Ground pressure	6.25 kPa

Table 1. Rover characteristics and dimensions

The rover system has the possibility to run on battery or with an external power supply. It currently includes a 5 DoF anthropomorphic arm and a mast structure and PTU mechanism with mechanical interfaces to attach a stereo camera and a ToF camera as well. Other sensors include an Inertial Measurement Unit, and incremental encoders and absolute position sensors for the active and passive joints of the locomotion kinematic chain. For the acquisition of the ground truth data inside the lab the Vicon Tracking System is used. For outdoor testing the OBC has integrated a D-GPS receiver with *rtk* corrections. The control architecture of the rover, which comprises the functional layer for now, is implemented using the Rock[1] robotic software framework. The system is used to perform R&D activities in the fields of: system integration, locomotion performance, control architecture design and implementation, and sensor data fusion among others.

3. WHEEL WALKING IMPLEMENTATION

Global body commands of motion are commonly performed using a motion model. Kinematic motion models have real-time capabilities and are inexpensive in comparison with sophisticated wheel-dynamic simulation techniques. The WW evaluation presented in this paper uses a method which is able to *optimally*[2] combine the motion induced at each contact point by fusing, in a unified framework, desired body velocities to joint motion commands as a whole. The implementation of a complete motion model behaves more consistent and stable than previous WW techniques. The model makes use of the transformation approach [TM05] which is in turn based on [MN87] to accurately model 6-DoF kinematics. It derives from the work in [HCBK14] to invert the Jacobian formula from the odometry kinematics.

The key element of the approach is the formulation of one Jacobian matrix per kinematic chain (or “leg” of the rover) relating rover pose rates in Cartesian coordinates to joint rates of the locomotion system. The full velocity kinematics are obtained by combining the Jacobian matrices for all kinematic chains into one sparse matrix equation which is solved for the unknown joint rates using a least-squares approach. The acquired rates can then be commanded to the actuators. Different WW gaits (i.e. motion patterns [Jou10]) are achieved by dynamically setting constraints in the Jacobian (i.e. by defining set joint rates according to the current phase of the WW motion). At this point, a more thorough explanation of this approach is well outside of the scope of this paper.

4. EXPERIMENTAL RESULTS

Three different scenarios are considered to evaluate the traversability performance of the WW locomotion mechanisms, each of them referring to situations where the rover could potentially benefit from the WW actuation.

[1] http://rock-robotics.org

[2] Optimally here refers to the best estimated value from a least-squares perspective.

4.1. Entrapment In Loose Soil

4.1.1. Objective

This test aims at simulating a trapped situation from which the rover should free itself. Given that this is the first WW performance test executed with ExoTeR the test also serves to verify the operative readiness of the implemented WW algorithms in a load wise representative environment. No numerical metric is measured in these tests. Only for qualitative purposes the time that the rover takes to get unstuck is observed, if it gets unstuck at all.

4.1.2. Setup

The test facility is improvised in an outdoor volleyball court on a sunny day (see figure 2). The sandy part the rover is driving on has no overall slope. The soil is a normal beach volleyball silica sand with a mixed grain size of 0.063 - 2.0 mm. Due to previous rainfall some days before, the soil is slightly moist and develops cohesive properties as seen in figure 3.

Figure 2. Setup on outdoor beach volleyball court

The sand gets equally prepared with a raking procedure into approximately 10 cm depth before each run. The rover is commanded wireless and is powered from an external power line. No ground truth system is used in this experiment. The used procedure is divided in two characteristic parts. The first part is to get the rover stuck in a repeatable way. Therefore the rear bogie is tied to the bench with a detachable rope. With the rope on tension, the rover starts driving away from the bench. Once the drawbar pull and the tension have the same value, the rover does not produce any forward motion anymore and keeps digging itself into the ground as shown in Figure 3. This stops once the rear wheels are sunk by half their diameter into the soil. After that, the rope gets untied and part two starts. The system restarts in normal driving (ND) or WW mode and the data starts being recorded.

Figure 3. ExoTeR bogged down by half a wheel diameter

4.1.3. Results

As already mentioned both locomotion modes, i.e ND versus WW, are compared. The used WW gait is syde-by-syde or left-right [Jou10]. Both modes are commanded at a 2 cm/s body velocity.

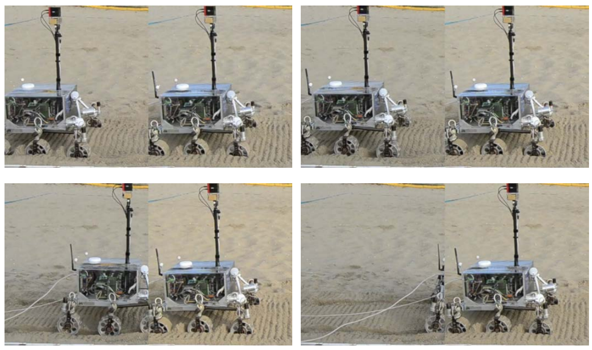

Figure 4. top-left:t=0s, top-right:t=15s, bottom-left:t=30s, bottom-right:t=45s; each picture has WW on the left half and ND on its right half

The photo array in figure 4 shows the progress of the two modes while trying to set the rover free. The result is a tremendous benefit of WW. After 45 seconds, normal driving reaches 3 cm and thereby averages a 97% slip ratio. The WW run is completely freed after 20 seconds. Assuming that under normal circumstances the rover gets trapped while ND, it would be even more unlikely that it would be able to free itself without WW.

4.2. Gradeability

4.2.1. Objective

Areas with high inclination are particularly interesting to test rover capabilities for planetary exploration. The objective of the experiments is to test the WW capability on slopes with the aim of evaluating if the maximum gradeability of the system can be increased by means of WW. As metric for these tests the slip-ratio is accurately measured using the motion tracking system (Vicon) of the Planetary Robotics Lab (PRL). The slip-ratio is computed as shown in formula 1. This unit is used in the results section for comparison.

$$slip = 1 - \frac{real\,position\,tracked\,by\,cameras}{position\,estimated\,by\,wheel\,odometry} \quad (1)$$

The motors consumption, although measured, it is not used as a metric for these tests and therefore not shown in the results section. Therefore, this tests do not aim to measure the efficiency of the locomotion modes in terms of power consumption but rather to check if WW mode could be used in some extreme cases enabling the traverse where the ND would not be able to perform[3].

4.2.2. Setup

The rover has to drive from the bottom to the top of the slope in two modes and repeat this successfully at least three times per mode (for statistical reasons). First the rover performs the traverse three times in ND mode followed by three tests in WW mode. The tests are done on 0°, 10°, 15° & 20° slope angles.

The different slope angles are realized with a soil filled one axis automotive trailer (see photo 5). Its pivot is the single axis which allows an inclination from approximately -10° up to +25°. Due to the limited bearing capacity of the trailer, only a 2 m × 1.1 m × 0.25 m (length × width × depth) is filled with soil. Cardboard boxes fill the leftover volume. In this setup, the filling depth is more than twice the wheel diameter and the distance to any walls during a test run is high enough to assume the boundary effects to be negligible.

In table 2 the characteristics of the soil used for the gradeability tests are given.

Soil Simulant	ES3 with gravel
Constitution	80% ES3-OMR from Sibelco 20% gravel from KIBAG
KIBAG gravel grain size	16% 0-4 mm, 18% 4-8 mm, 15% 8-11 mm, 21% 11-16 mm and 30% 16-22 mm

Table 2. Soil characteristics

The ES3 itself simulates a coarse sandy to gravelly material occurring in scree, polymodal surficial lags and local coarser aeolian accumulations. The coarse scree and aeolian accumulations can occur in terrain with rocky escarpments [MKvW14].

[3] A traverse stint with slip-ratio higher than 90% is considered not-performing.

Prior to the hereafter analysed tests, preliminary runs are executed on a 17.5° slope to roughly define the most performing WW gait (see figure 6). The side-by-side gait performs best in terms of slip and heading stability and is therefore chosen.

Figure 5. Gradeability tests setup in ESTEC's Planetary Robotics Lab

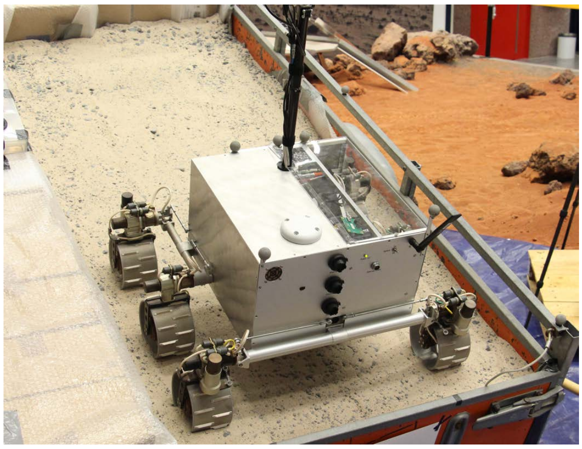

Figure 6. ExoTeR rover on 17.5° slope in the trailer

4.2.3. Results

The following subsections show for each of the tested slope angle degrees the resulting slip ratios obtained for ND and WW. All off them show three valid WW tests and three ND tests. These sets are always shown in the same color. The blue lines represent the slip of the three ND tests on a scale from 0 to 1. The red ones do the same for the WW tests. The distance the ND accomplished with respect to time are represented in green. Cyan shows the distance over time for the WW ones. The slip value is calculated continuously throughout the tests within a local time window of 0.1 seconds.

0° Slope Tests

In the 0° run (Figure 7) the different driving modes have barely any performance difference even though all WW lines show a slightly better performance in the slip plots. But this difference is negligible for such low slip values. Both plot groups show a small peek in the first 10 seconds in which the rover develops a little sinkage and goes into steady state.

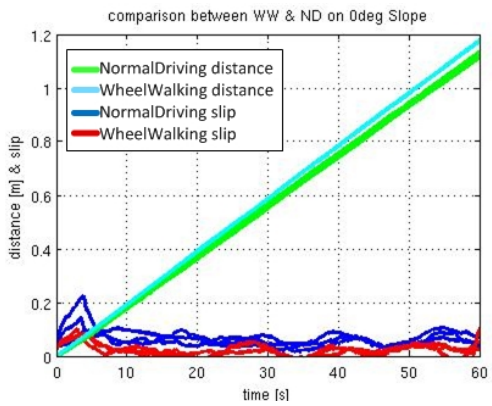

Figure 7. Comparison between wheel walking and normal driving on flat terrain

10° Slope Tests

The performance difference in the 10° slope already shows the benefit of WW compared to ND. The slip value of the former is about 50% less than in the later case. Still, the slip for both is considered low.

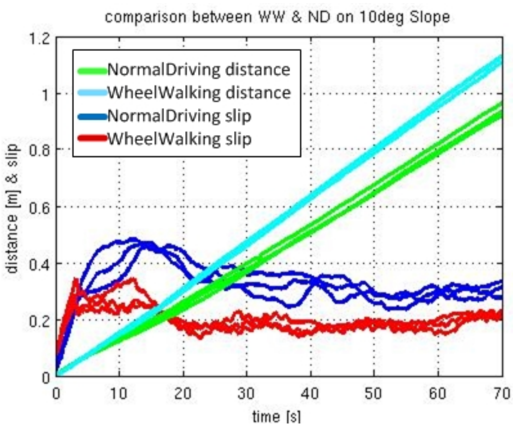

Figure 8. Comparison between wheel walking and normal driving on a 10° Slope

15° Slope Tests

At 15° slope however (see figure 9), the difference gets way more visible in terms of traversed distance.

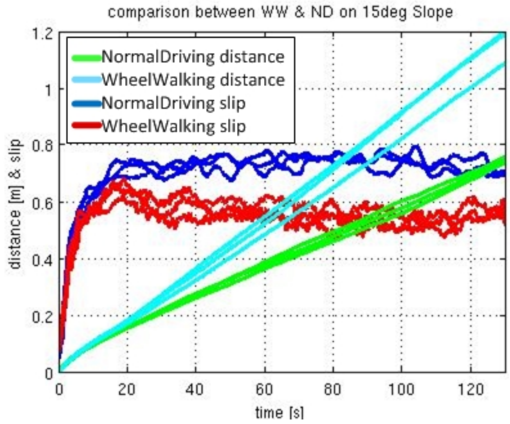

Figure 9. Comparison between wheel walking and normal driving on a 15° Slope

20° Slope Tests

Figure 10 referring to the 20° slope tests shows the biggest performance difference. The travelled distance is roughly double in case of WW, what means that it has half the average slip.

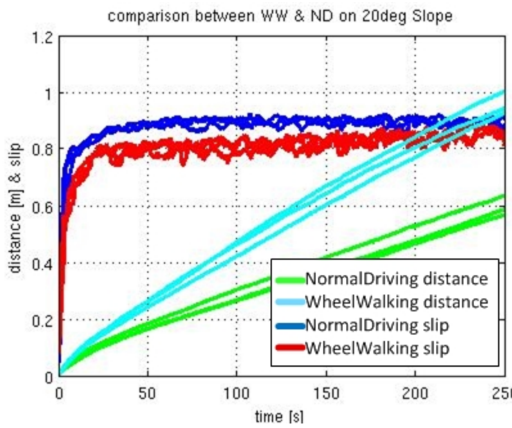

Figure 10. Comparison between wheel walking and normal driving on a 20° Slope

Gradeability Tests Results Overview

Table 3 summarises the results obtained in terms of average slip-ratio at each slope angle for ND and WW.

Incl.	**Avg slip ND**	**Avg slip WW**
0°	5.0%	1.0%
10°	33.6%	20.7%
15°	68.8%	55.4%
20°	89.4%	82.2%

Table 3. Gradeability tests summary table

Note that due to the formula used to calculate the slip-ratio (equation 1) a “small” difference in slip-ratio can be traduced in a big difference in the real traversed distance. In the case of the 20° slope tests, where the average slip for the three runs for WW is 82.2% compared to 89.4% in the ND (averaged in steady state from t=75 s - t=250 s), the real traversed distance is almost the double in the case of WW. Basically, while WW actually moved the 17.8% of the wheel odometry ND only moved 10.6%. It is important to note that at 20° slope ND is in the limit of its capabilities, as a slip-ratio higher than 90% is considered non-performing. Therefore, we could conclude that WW can add to the rover system an increased gradeability, pushing the limit of traversable slope inclination to a higher level. Due to the limits of the testbed facility no further tests can be run at higher slope angles at this point.

On the other hand, the small periodic ripples in the WW runs are generated by the walking motion. While having slip ratios above approximately 10%, the rover starts waving around a point in between the two rear axes (which is not the rover origin for the Vicon system). Therefore the tracking shows ripples with a frequency of about 0.7 Hz.

Additional Tests

A series of tests at 20° slope angle are run changing the *step length*[4] at each run, from 2.5 cm to 12.5 cm incrementing the step length by 2.5 cm at each test. The results of these series of tests are inconclusive so far, as no specific relation can be identified between the step length and the slip ratio.

With the objective of trying to reduce further the slip-ratio, the WW algorithm is modified to include an offset constant rolling speed in all driving motors. This is supposed to increase the traction of "anchoring" wheels during the WW motion. However, this hybrid implementation does not seem to have a positive impact in the slip-ratio.

Other experimental tests include running the system backwards and/or fixing the walking motors to the position equal to the angular value of the slope. This is supposed to reduce the load in the back wheels of the rover by shifting the CoM forward and therefore distribute the weight equally over the three axes and hence increase in theory the traversability performance. Figure 11 shows the slip ratios obtained for the case of running backwards with the walking actuators angled in position compared to normal forward driving. Backward driving here means that the two bogies are in the back and make an equal load on all four wheels of these bogies due to ExoTeR's parallelogram structure. None of these measures shows a clear benefit in the slip-ratio.

[4] The step length is here defined as the amount of distance covered by each wheel in a walking sequence.

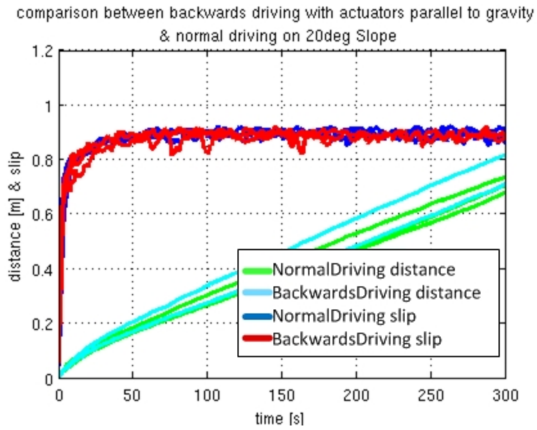

Figure 11. Comparison between normal driving and reverse driving with gravity aligned legs on a 20° Slope

4.3. Lander Egress

4.3.1. Objective

It is evident that having the "walking" degree of freedom in the control-space of the rover offers more than just performing WW gaits. It allows for configuring the rover posture and shifting the CoM to assist different operations. The objective of this test is to experiment on how the "walking" DoF can assist egress operations from a lander, which is one of the most risky phases of a mission. To simulate these egress conditions, the Planetary Robotics Lab has built an adjustable lander mockup that is loosely based on the preliminary design of the ExoMars lander, appropriately scaled-down to fit the size of the ExoTeR rover.

4.3.2. Setup

The rover egress platform as shown in figures 13 & 14 has two egress directions with different ramp lengths and is adjustable in its height. Thereby the egress angle can be set. It is also adjustable to the track width of the rover. The ramps are covered with a rubber mat to provide sufficient traction. The following tests have a step of 8 cm in height at the end of both ramps to simulate a worst case landing in a rocky environment. Due to the lack of any designed flexibility in ExoTeR, the floor is prepared with foam covered by carpet to absorb part of the impact energy and simulate the behaviour of flexible wheels. It is worth mentioning that the static stability of ExoTeR has been tested in advance and was found to be greater than 40°.

At the beginning of the test procedure, the rover is steady on the egress platform and is commanded to drive down with a constant body velocity of 1 cm/s.

A emergency safety rope is attached to its back and is hand-held without tension.

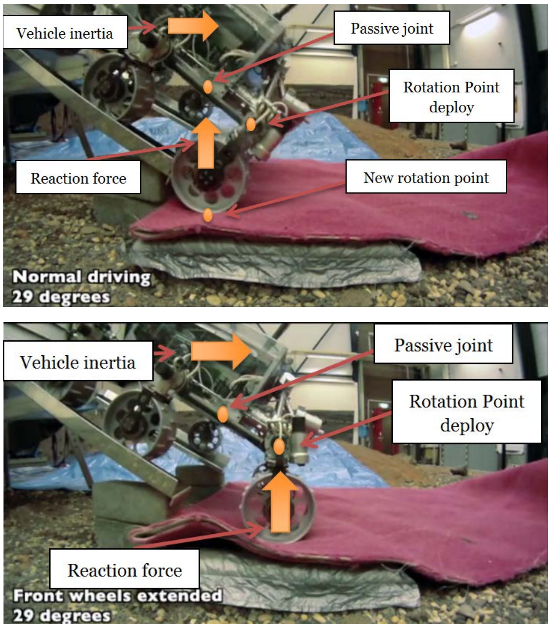

Figure 12. Comparison between egressing in normal configuration (top) and 34° forward shifted front wheels (bottom) on a 29° egress ramp with a step at the end

Figure 12 describes the concept behind this test. The forward shifting of the front axis should increase the stability of the whole system due to a bigger horizontal distance between the contact point on the ground and the CoM. That way the angle at which it tips over is increased. Second, due to the passive bogie, the maximum angle of egress is limited to the angle in which the contact point on the ground falls behind the pivot point of the bogie using their horizontal coordinate. After this point, the two center wheels would lift off and destabilize the system even further. In addition, the deployment actuator has to withstand very high holding torques, both during driving and at the final impact on the ground. Figure 12 (bottom) has its front axle shifted by 34°. The 34 herein is the optimized angle for the 29° ramp plus the 8 cm drop.

4.3.3. Results

The tests show how the dynamic stability of the rover is increased when using the walking mechanisms to angle the front wheel forward and verify the stated thesis. In standard egress manoeuvring, the rover already loses stability (close to capsize/fall) at the ramp of 26° (see figure 14 (top)) and literally capsizing at the 29° test (see figure 13 (top)). Contrary to this, using the walking mechanisms shows the rover going down keeping constant stability in the 34° ramp (see figure 14 (bottom)), which is the maximum possible ramp for the current setup.

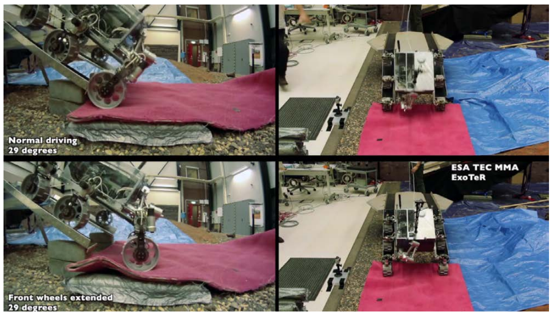

Figure 13. Comparison between egressing in normal configuration (top) and 34° forward shifted front wheels (bottom) on a 29° egress

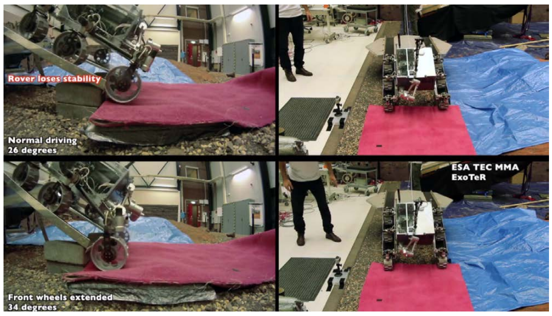

Figure 14. Comparison between egressing in normal configuration (top) on a 26° ramp versus a 39° forward shifted front wheels (bottom) on a 34° egress ramp

Another side observation is that the wheel actually drops much less than the full 8 cm of the step height. The traction of the rear four wheels is big enough to let the front wheel pair roll down smoothly until roughly half of the wheel diameter, reducing therefore the "free falling" distance.

5. CONCLUSIONS

The wheel-walking locomotion mode outperformed standard rolling in all the tested scenarios demonstrating better traction in loose soil, increased gradeability performance and improved dynamic stability limit during egress sequences. The experiments run and the results shown in this paper demonstrate the advantages of using wheel-walking manoeuvres in low-tractive terrains and egress scenarios and quantify the improvement that can be achieved in gradeability. Future rover exploration missions, specially in the case of systems with high EGP, could potentially benefit from the increased locomotion capabilities of wheel-walking to mitigate the risk of getting stuck in loose soil, to enable safe egress operations or to simply allow a faster or more efficient navigation by reducing the ground track to straight distance ratio.

6. FUTURE WORK

Following the results of these first experiments, the Authors of this paper have decided to continue this research path and have planned further tests to get more experimental data and increase the confidence on the performance of wheel-walking. Future tests will focus on gradeability analysis to better assess the performance of different wheel-walking gaits in several types of soil. The next testing campaign is planned for March 2015 in the Robotics and Mechatronics Centre (RMC) of DLR Oberpfaffenhofen.

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