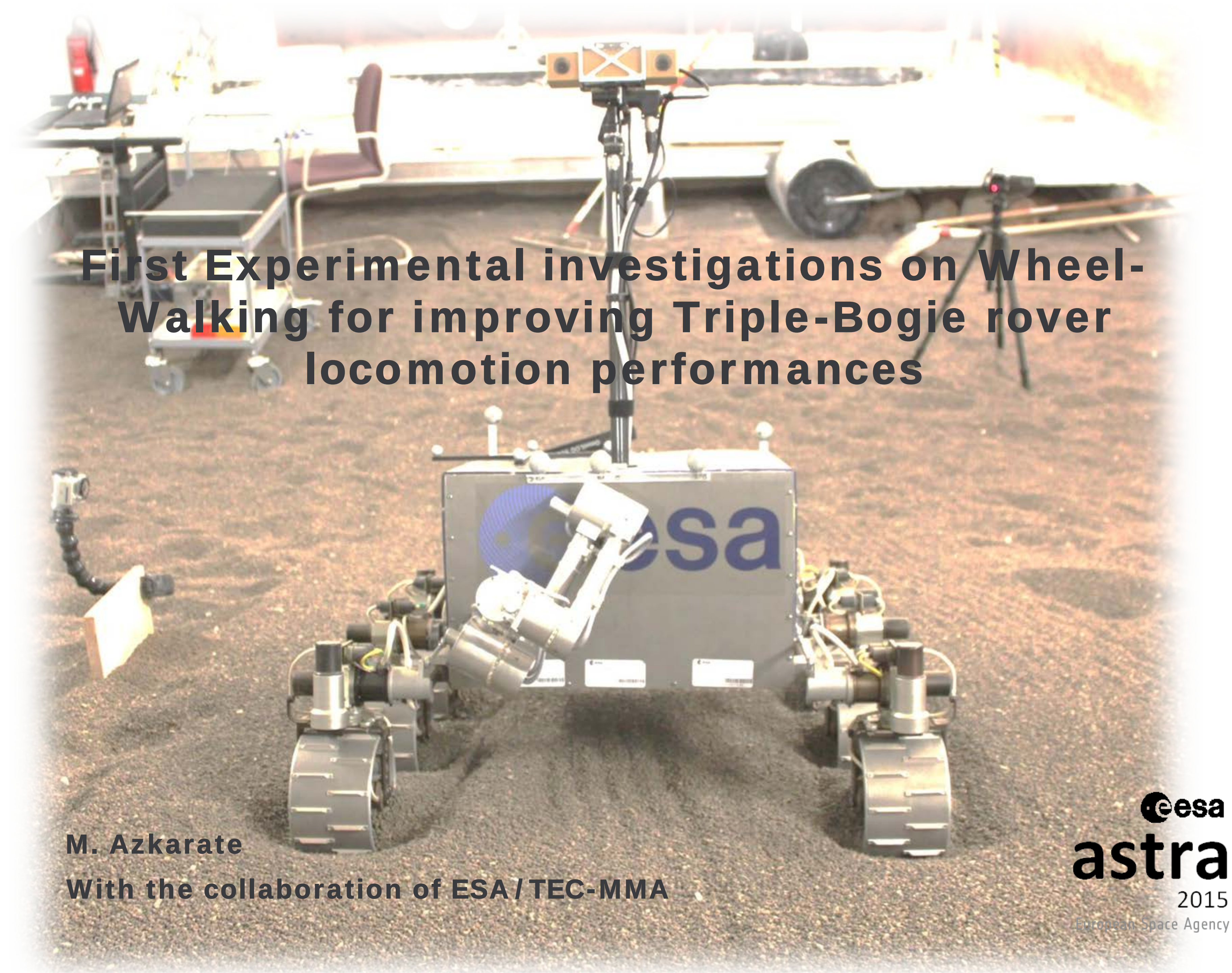

First Experimental investigations on Wheel-Walking for improving Triple-Bogie rover locomotion performances

M. Azkarate

With the collaboration of ESA / TEC-MMA

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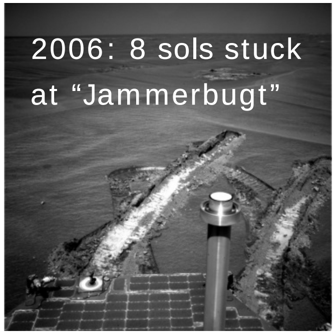
Some areas of Mars are difficult to traverse…

Opportunity

2005: 5 weeks immobilized in "Purgatory Ripple"



2006: 8 sols stuck at "Jammerbugt"

Spirit

2007: 10 sols stuck at "Tartarus"

2009: permanently lodged at "Troy"

Curiosity

Curiosity's left front wheel, sol 713

August 2014: Rerouting in "Hidden Valley" after finding slippery sand

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Russian planetary exploration rover early concepts

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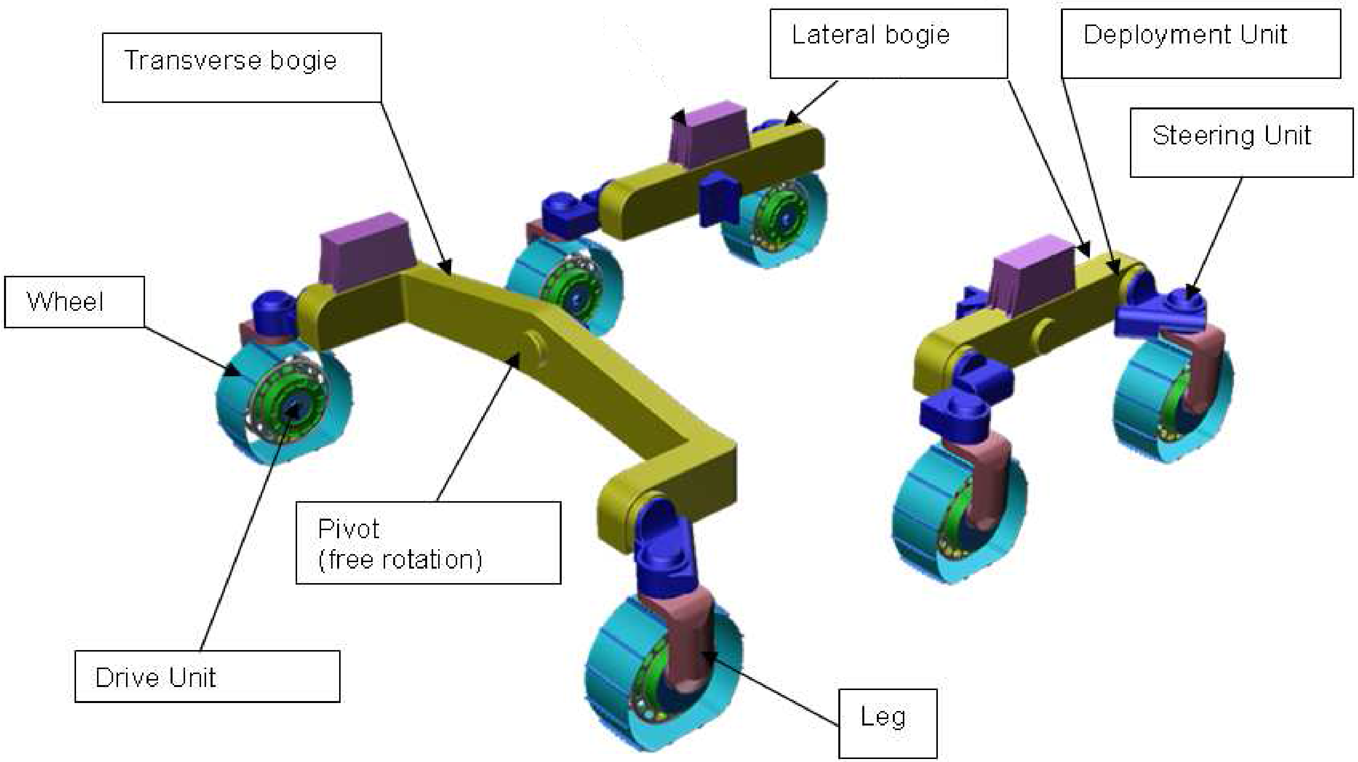
ExoTeR rover:
a Triple-Bogie platform

Triple-Bogie concept conceived in the early phase of the **ExoMars** mission.

- **Simple** & **Performing** -> Baseline design with wide acceptation in Europe



Deployment actuators of the concept offer the possibility of performing **wheel-walking maneuvers**.

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ExoTeR rover: a Triple-Bogie platform (cont.)

Lab rover prototype **ExoTeR** based on the triple-bogie design.

Keeps the **kinematic properties** of ExoMars design (as of 2007).

Locomotion platform type	6 x 4 x 6
Size (L x W x H)	70 x 70 x 40 cm^3
Wheel diameter	14 cm
Wheel width	9 cm
Mass	24.08 kg
Ground pressure*	6.25 kPa

Table – Rover general characteristics and dimensions

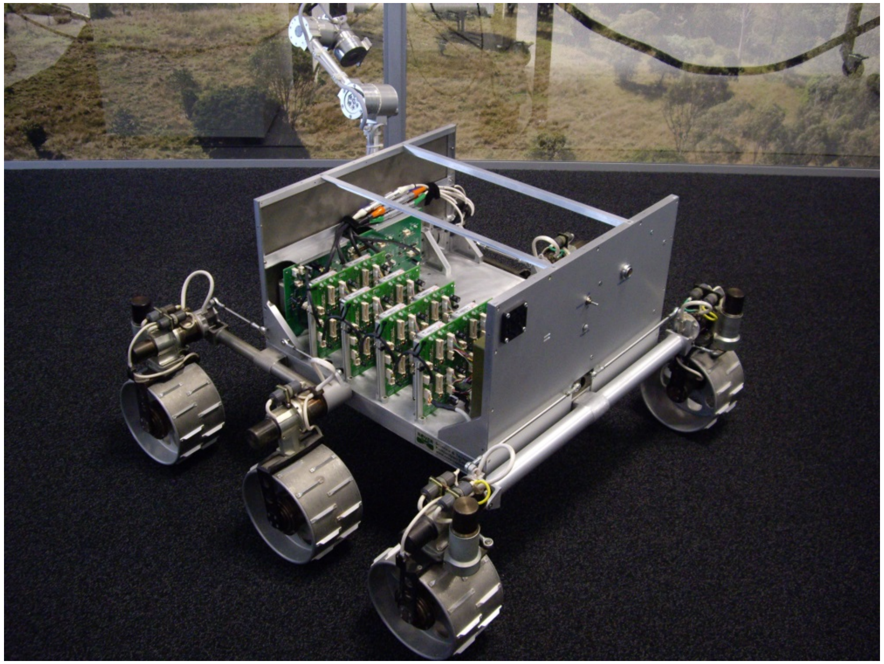

Figure - ExoTeR Rover, 2013

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* Ground pressure calculation based on Effective Ground Pressure (EGP) defined in "M Heverly et al. Traverse performance characterization for the mars science laboratory rover. *Journal of Field Robotics*, 30. 2013"

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Wheel Walking
Concept and Implementation

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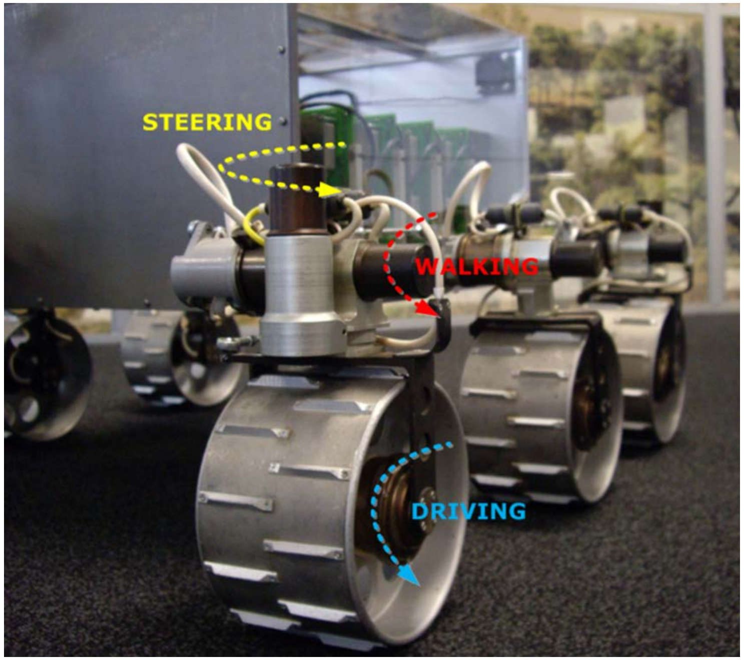
Key concepts:

- Wheel-walking: **synchronised** actuation of **driving** and **deployment** motors.
- Implementation based on a complete **kinematic motion model** relating desired body velocities to joint motion commands.
- Define **transformations** for kinematic chains (“legs”) from body centre to each contact point.
- **Jacobian** matrix maps Cartesian to joint and contact points rates.
- Joints commanded considering desired body rates and current state of all joints.
- Different combinations of actuation (by sets of constraints to the Jacobian) lead to different WW **gaits**.



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Gait name	# of active wheels	# of phases	Active wheel sequence	Sequence illustration (green = active wheels)
Single wheel	1	6	(1) → (2) → (3) → (4) → (5) → (6)	
Axle by axle	2	3	(1,2) → (3,4) → (5,6)	
Side by side	3	2	(1,3,5) → (2,4,6)	
Tripod	3	2	(1,4,5) → (2,3,6)	

Table – Implemented wheel-walking gaits (motion patterns) explained

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Test Campaign

OBJECTIVE

Test the traversability performance that can be achieved when using wheel-walking locomotion mode compared to normal driving actuation.

SCENARIOS

- Entrapment In Loose Sand
- Gradeability
- Lander Egress

OUTPUT

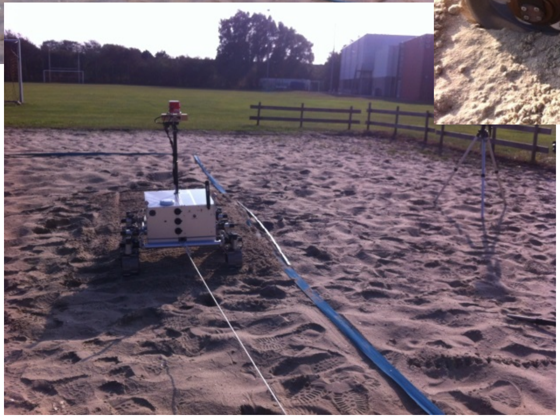
Provide test results data in qualitative and quantitative form to help assess the usability case of wheel-walking for planetary exploration missions.

Entrapment in loose soil

<u>OBJECTIVE</u>

Simulate **trapped situation** from which the rover should try to free itself. **No numerical metric** is measured in these tests.

<u>SETUP</u>



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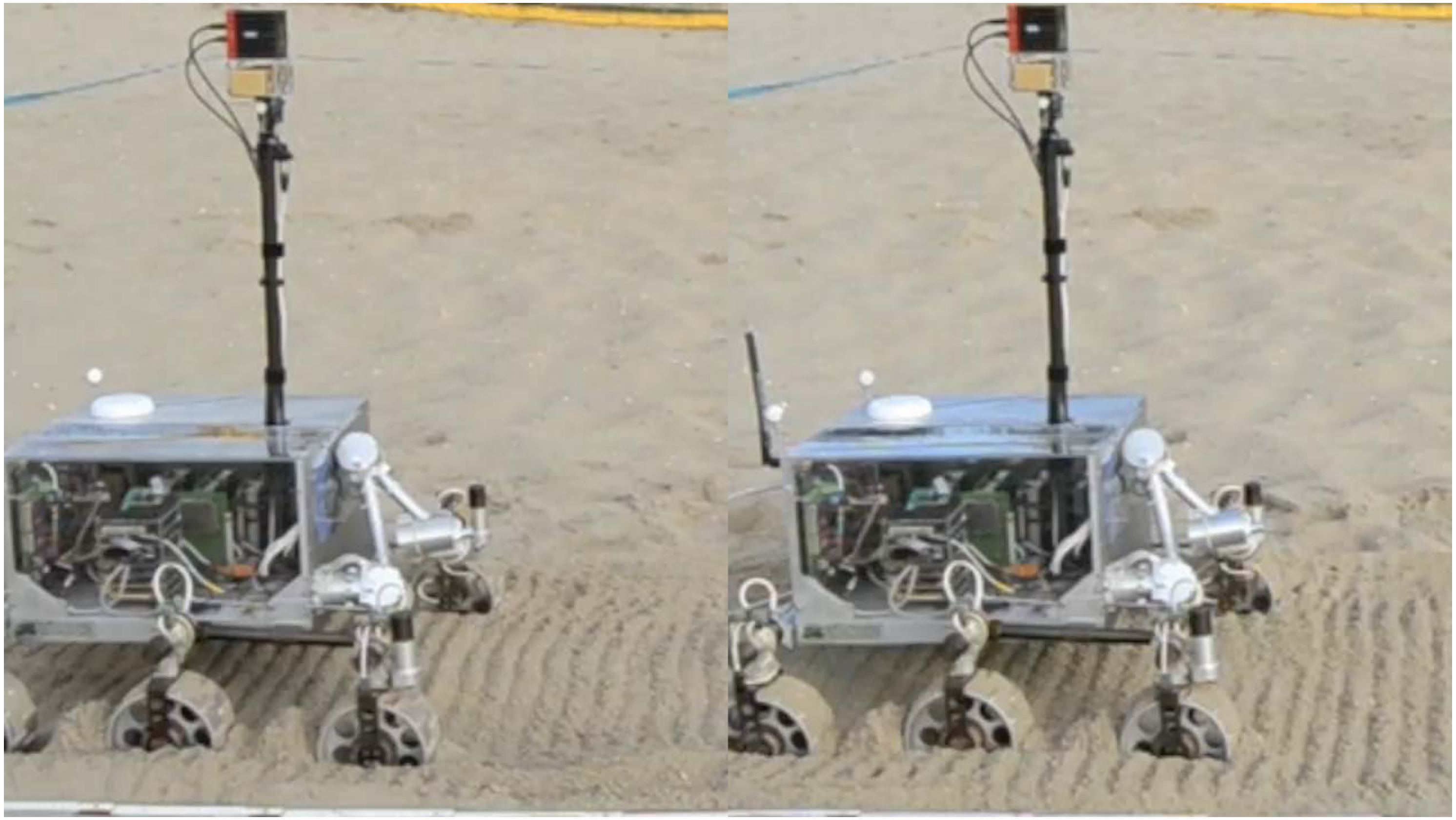
Entrapment in loose soil (cont.)

<u>RESULTS</u>

The rover benefits from WW to quickly unstuck. Standard rolling keeps digging.



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Gradeability

Objective

Test the WW **performance on slopes**, rover system gradeability increased?

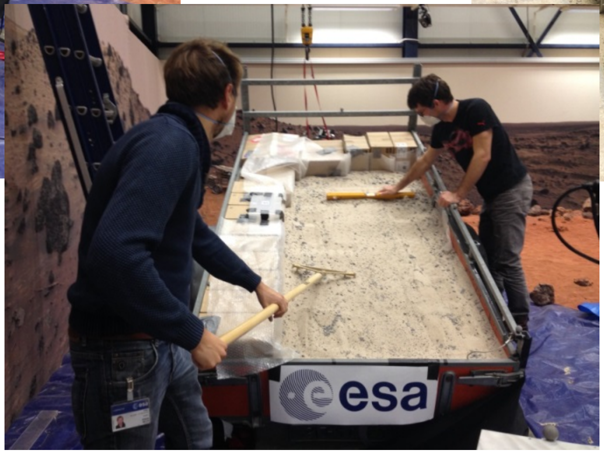
Metric is the **slip-ratio**. Accurately measured by Vicon motion tracking:

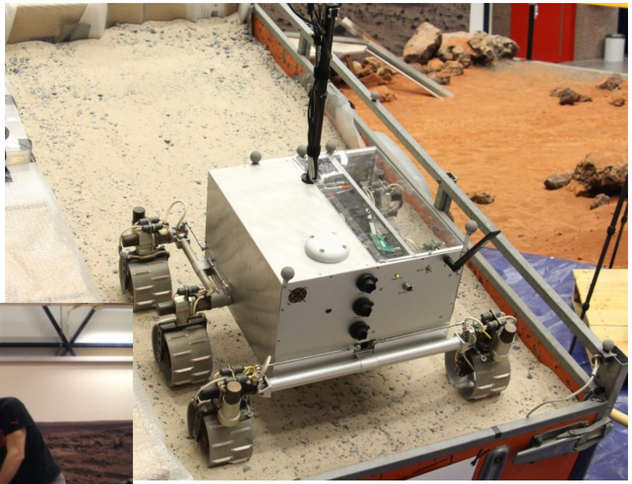
$$slip = 1 - \frac{real\ position\ tracked\ by\ cameras}{position\ estimated\ by\ wheel\ odometry}$$

Setup

Adjustable-slope soil-filled facility. Tested on **0°**, **10°**, **15°** & **20°** slopes.

Repeatable **raking** procedure





Soil type: ES3 with gravel
WW **gait**: syde by syde

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Gradeability (cont.)

RESULTS

Wheel-walking (WW) improves gradeability compared to normal driving (ND)

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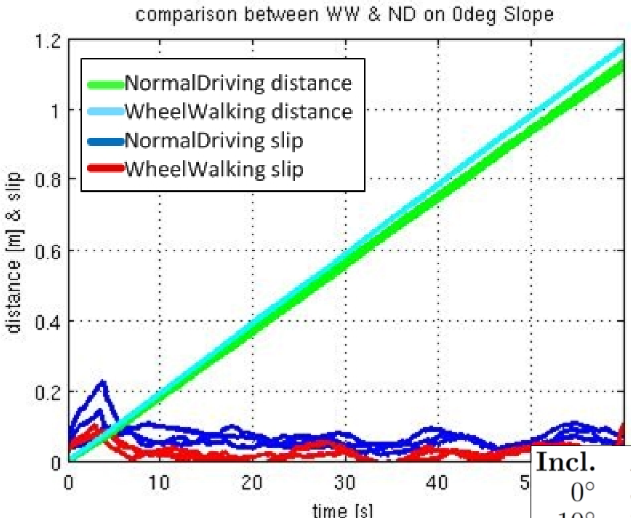
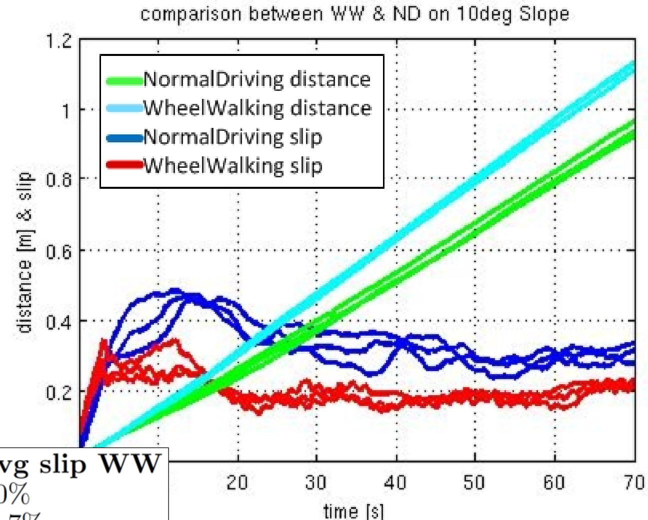
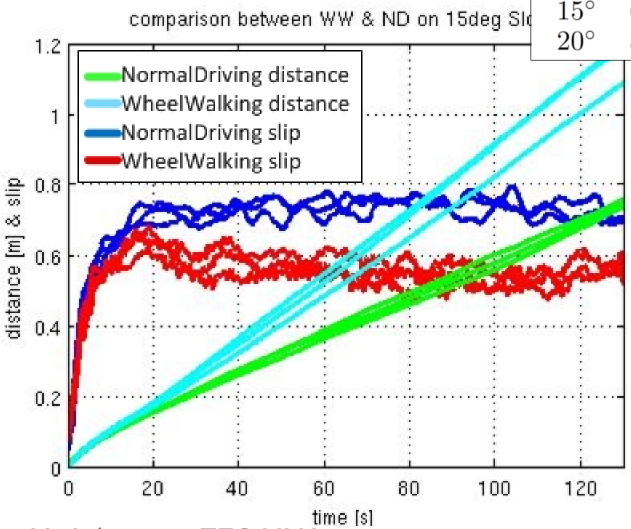
Gradeability (cont.)

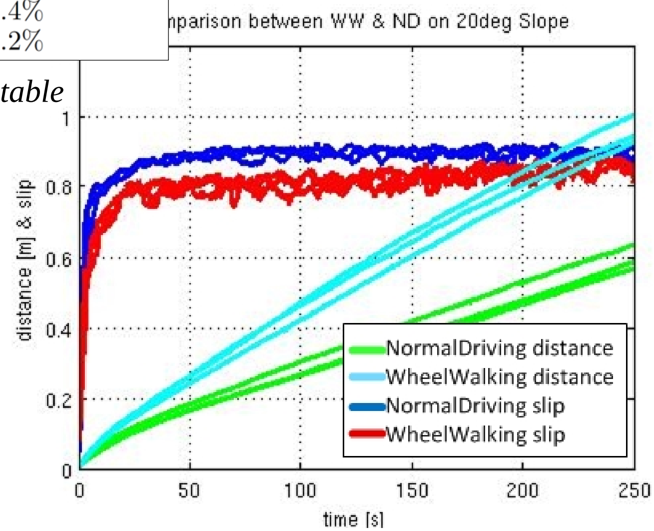




Incl.	Avg slip ND	Avg slip WW
0°	5.0%	1.0%
10°	33.6%	20.7%
15°	68.8%	55.4%
20°	89.4%	82.2%

Results summary table





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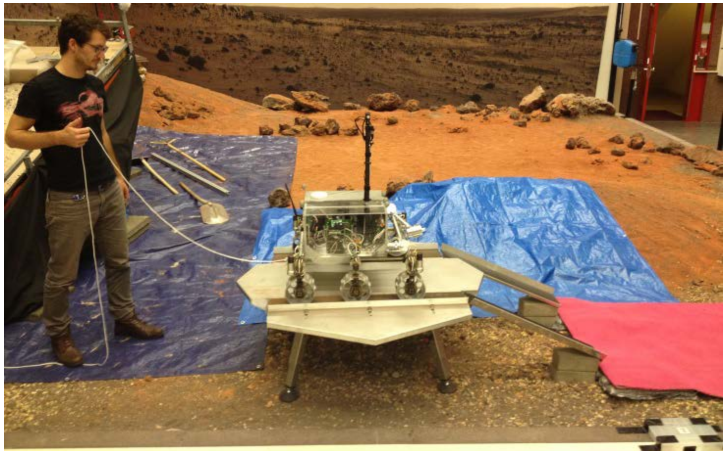
Lander Egress

<u>OBJECTIVE</u>

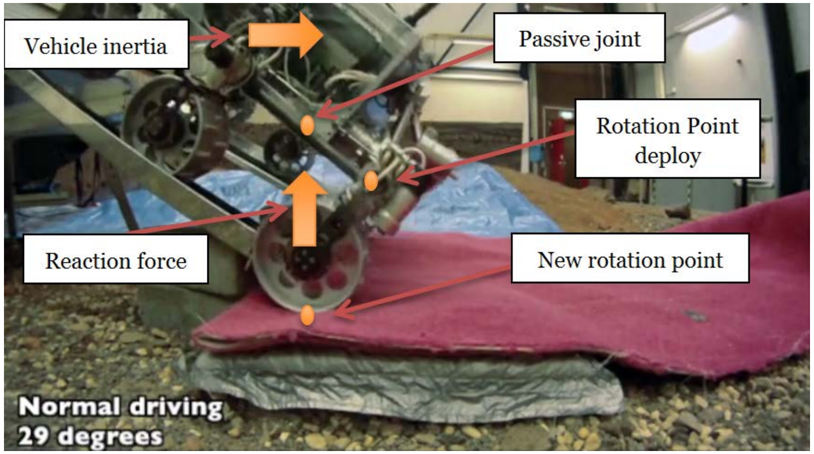
Experiment on how the "walking" DoF can **assist lander egress** operations.

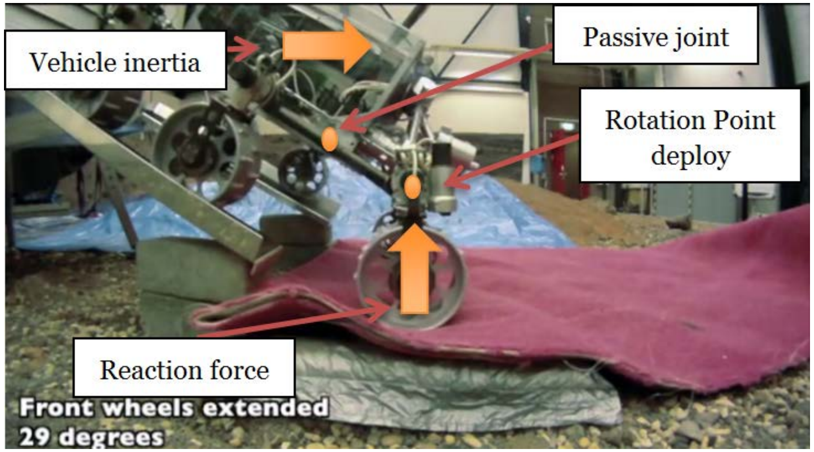
The metric is to check the **dynamic stability** at different egress inclinations.

<u>SETUP</u>



Safety rope hand-held without tension.
Step height at the end of the ramps of 8 cm.
Cushions at the ground to reduce impact and simulate the flexible wheel behaviour.
Proven **static stability** of the rover > 40º.





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Lander Egress (cont.)

<u>RESULTS</u>

The “walking” DoF improves dynamic stability in egress operations.

Egress Tests 29 degrees

Angle of the egress slope: 29 degrees
Angle front walking motors: 34 degrees

Step height: 8cm

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Conclusions

- The wheel-walking locomotion mode **outperformed** standard rolling **in all the tested scenarios**.
- The results shown here demonstrate WW **improves traction in loose soil** and **dynamic stability limit** during egress maneuvers and quantify the **gradeability increase** obtained with respect to ND.
- 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.

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Future Work

- Following the results of these first experiments, Authors have decided to continue this research path and have planned further tests to get more experimental data and **increase the confidence in 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 Oberpfaenhofen.

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Questions?

THANK YOU!

ACKNOWLEDGEMENTS

To all co-authors and TEC-MMA

Note: Come **see the walking rover** at the open lab tour this evening during the conference cocktail!

BackUp Slides

1. ES3 + gravel soil characteristics
2. Gait selection
3. Extra tests: step length variation
4. Extra tests: additional offset speed
5. Extra tests: backwards driving and CoM shifting.

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ES3 + gravel soil characteristics

- Short soil name:

ES3-OMR with gravel

- Full description of this soil:

OMR DRY (from Sibelco Ltd, United Kingdom) 80% by mass, with uniformly admixed Hart-splitt gravel, 16% 0-4 mm, 18% 4-8 mm, 15 % 8-11 mm, 21% 11-16 mm, 30 % 16-22 mm (from KIBAG Zentrallabor, Switzerland).

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Gait selection

- The final wheel walking gait was selected by <u>criteria of best performance</u> during <u>the dry run day of tests</u>. The best performing gait has been used during the whole test campaign.
- After the planned test campaign, modifications over this gait were tested attempting to find the configuration parameter that could influence the performance of the overall test. Those are explained in “<u>extra tests</u>”

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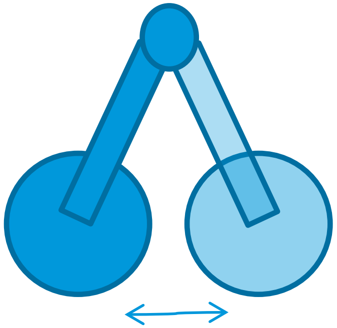
Step length variation

- The step length is the distance the wheel travels from the start at the back until fully extended at the front during one walking maneuver.

- The following step lengths where used during the tests.

Length	speed
1cm	0.328
2.5cm	0.294
5cm	0.383
7.5cm	0.344
10cm	0.44
12 cm	0.35



Conclusion:

NO conclusion can be drawn. No clear trend or relation.