DEVELOPMENT AND VALIDATION OF A MODULAR PARAMETRIC ANALYTICAL TOOL FOR PLANETARY EXPLORATION ROVERS

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ABSTRACT

In the early development phase of planetary exploration rovers, simulation is an attractive alternative to rover testing in order to access locomotion performances and to provide relevant inputs for sizing the mechanical and electrical sub-systems. Based on previous publications by RUAG, this paper presents the architecture of the Rover Parametric Analytical Tool (RPAT), a modular simulation environment which provides 3-D simulation capabilities for rover motion sequences. An enhanced quasi-static local-force-equilibrium approach, automated database-interfaces, a Horn-method based Odometry-module and Digital Elevation Maps allow the significantly faster-than-real-time parametric analysis of nearly arbitrary wheeled locomotion subsystems (e.g. ExoMars, NEXT, NASA MER/MSL). In contrast to existing approaches, the paradigm is to primarily rely on wheel-level testing to guarantee precise wheel-soil interaction information. The comparison of RPAT simulation results with ExoMars LSS breadboard test campaign data validates the overall theoretical approach and emphasizes RPAT's potential to reduce rover development costs by decreasing the dependence on breadboards.

1 INTRODUCTION

The central problem in the locomotion subsystem design process is that it "remains a topic of ad-hoc speculation and is commonly pursued in a way that lacks rationalization" [1]. New designs often draw upon "knowledge of precedent robotic and conventional vehicles, intuition and experience" [1] and subsequently depend on building a costly breadboard and performing a comprehensive test campaign to verify the design [2]. Breadboards are also rarely able to take into account the frequent design changes implemented during the iterative LSS design process. This breadboard-based approach results in high rover development costs and can thus potentially endanger mission feasibility.

Model-based design constitutes a promising alternative to today's mostly testing-based rover development process [3,4]. Two main types of simulation types are commonly used. Multi body simulation (MBS) tools [3] allow a highly precise modeling of the rover dynamics and therefore mostly require comprehensive inputs. Their complexity tends to prohibit a quick parametric analysis (e.g. of the rover dimensions which are often represented by a detailed CAD model) and results in low simulation speeds. In contrast, quasi-static simulation tools [5,6] trade off some precision for simplicity and higher simulation speeds. Their ability to efficiently simulate and compare various rover configurations, e.g. for rover dimensioning or concept selection, make them good choices for the early rover design phases.

2 ROVER SIMULATION TOOL DESCRIPTION

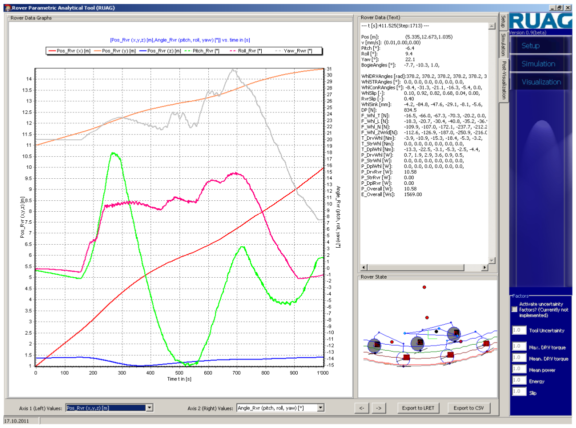
This paper presents the architecture and theory of a quasi-static simulation environment, the Rover Parametric Analytical Tool (RPAT). RPAT allows to either use high-fidelity experimental wheel performance data or wheel-soil-interaction models to accurately model wheel-soft-soil interaction. In contrast, similar simulation tools such as the quasi-static tool by Krebs et al. [5] did not support soft soils and flexible wheels at all, and the RCET quasi-static tools [2] are based on a wheel-soft-soil interaction model with limited accuracy especially at high slip [6], which decreases simulation accuracy e.g. for step-shape obstacle tests. RPAT is based on the application developed in [7], but improves upon it by adding full real time rover simulation on 3-D terrain through the methods described in this section.

2.1 Overview

The Rover Parametric Analytical Tool supports the preliminary design of rover locomotion subsystems by performing computationally-efficient 3-D simulations of a rover motion, thereby allowing a quick parametric analysis of various rover configurations. The simulation outputs

- Rover velocity v_{Rvr} and slip
- Rover Drawbar Pull
- Wheel forces F_i
- Wheel torques M_i
- Wheel sinkage
- Rover power and energy consumed

with respect to time. The results can then be used to dimension the key rover components such as drive motors or the locomotion-dependent part of the solar cell area.



```
--- t [s]:411.525(Step:1713) ---

Pos [m]:            (5.335,12.673,1.035)
v [mm/s]:  (0.01,0.00,0.00)
Pitch [°]:          -6.4
Roll [°]:           9.4
Yaw [°]:            22.1
BogieAngles [°]:    -7.7, -10.3, 1.0,

WhlDRVAngles [rad]:378.2, 378.2, 378.2, 378.2, 378.2, 3
WhlSTRAngles [°]:   0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
WhlConRAngles [°]: -8.4, -31.3, -21.1, -16.3, -5.4, 0.0,
WhlSlip [-]:        0.10, 0.92, 0.82, 0.68, 0.04, 0.00,
RvrSlip [-]:        0.40
WhlSink [mm]:       -4.2, -84.8, -47.6, -29.1, -8.1, -5.6,
DP [N]:             834.5
F_Whl_T [N]:        -16.5, -66.0, -67.3, -70.3, -20.2, 0.0,
F_Whl_L [N]:        -18.3, -20.7, -30.4, -40.8, -35.2, -36.
F_Whl_N [N]:        -109.9, -107.0, -172.1, -237.7, -212.2
F_Whl_ZWrld[N]:     -112.6, -126.9, -187.0, -250.9, -216.0
T_DrvWhl [Nm]:      -3.9, -10.9, -15.3, -18.4, -5.3, -3.2,
T_StrWhl [Nm]:      0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
T_DplWhl [Nm]:      -13.3, -22.5, -3.1, -5.3, -2.5, -4.4,
P_DrvWhl [W]:       0.7, 1.9, 2.9, 3.6, 0.9, 0.5,
P_StrWhl [W]:       0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
P_DplWhl [W]:       0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
P_DrvRvr [W]:       10.58
P_StrRvr [W]:       0.00
P_DplRvr [W]:       0.00
P_Overall [W]:      10.58
E_Overall [Ws]:     1569.00
```

☐ Activate uncertainty factors? (Currently not implemented)

1.0 Tool Uncertainty

1.0 Max. DRV torque

1.0 Mean. DRV torque

1.0 Mean power

1.0 Energy

1.0 Slip

Axis 1 (Left) Values: Pos_Rvr (x,y,z) [m]

Axis 2 (Right) Values: Angle_Rvr (pitch, roll, yaw) [°]

Figure 1: Analysis window of the RPAT GUI

The Windows GUI allows the precise setup of a simulation (rover type, terrain type, etc.) as well as an easy analysis of the simulation outputs (Figure 1). The rover motion sequence can also be illustrated using an OGRE-based 3-D visualization (Figure 2).

```
915.619080

Orientation [rad]
Yaw:3.320898
Pitch:0.193559
Roll:-0.068313

Torques [Nm]
-4.384807
-3.915063
-8.237388
-19.937130
-19.239195
-20.617456

FPS: 334.0
Average FPS:FPS: 334.0
Best FPS:    FPS: 334.0
Worst FPS:         48.9
Triangles:      360,180
Batches:            242
```

Figure 2: The OGRE based 3-D visualization showing a motion sequence of the ExoMars rover which was simulated with RPAT.

2.2 Design Characteristics and Features

To differentiate itself from existing simulation environments, RPAT is positioned to have more precision than usual preliminary design tools and higher flexibility and simulation speed than MBS tools. The main RPAT characteristics are therefore:

- **Full rover-level simulation from wheel-level data**
  Wheel-level data from either wheel testing or an existing wheel-soil interaction module (cp. Figure 3) is sufficient to perform full rover-level simulations with RPAT. Rover-level testing (e.g. with breadboards) is not necessary.
- **High accuracy through use of wheel test data**
  The possibility to use actual wheel-level test data (cp. section 3.2.2) such as DP, T, R and sinkage vs. slip curves allows RPAT to efficiently yet accurately represent soft-soil interaction and thus wheel-level motion.
- **Simulation speed and system engineering approach for parametric rover analysis**
  The quasi-static, local-force-equilibrium approach and the *Odometry-module* result in high simulation speeds of up to 150x real-time (on a standard Core 2 Duo PC) and good rover-level simulation accuracy suitable for LSS preliminary design and system engineering.

Additional features are:

- Support of arbitrary terrains (step-shape, slope, 3-D terrain, etc.) through .bmp Digital Elevation Maps
- Support of arbitrary rover geometries through the generic *Odometry-module* and databases. Currently implemented Rover-LSS are ExoMars, NEXT and NASA MER/MSL.
- User-friendly Windows GUI and analysis tools
- 3-D visualization via OGRE interface
- Modularity
- Compatibility with other RUAG software

2.3 Architecture and external interfaces

The architecture of the RUAG rover system engineering environment is shown in Figure 3. The wheel-level data management is performed by the Wheel Parametric Analytical Tool (WPAT). To generate wheel-performance (DP, T, R and sinkage vs. slip) curves, WPAT requires wheel-level tests as described in [8] or an existing wheel-soil interaction model e.g. as presented in [6]. With the WPAT-processed wheel-level test data, RPAT then performs the whole rover-level simulation. Terrain information is loaded from .bmp Digital Elevation Maps, while soil information is taken from similar .bmp soil maps. The rover component geometry and topology is dynamically loaded from an MS-ACCESS database, thus allowing the quick setup and parametric analysis of various locomotion subsystems.

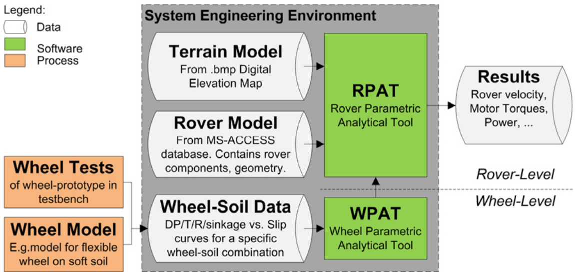


Figure 3: RUAG rover system engineering environment

3 DETAILED SIMULATION THEORY

3.1 Simulation Architecture

The Rover Parametric Analytical Tool is an object-oriented C++ application which is separated into four modules (Table 1).

Module	Main function
Rover	Rover modeling and simulation. Sub-modules: *Geometry, Positioning, Static, Wheel, Control, Actuator, 3-D Odometry*
Terrain	Provision of terrain data (height, soil). Sub-modules: *Terrain-DEM, Wheel-DEM*
Wheel	Provision of wheel performance data (e.g. DP vs. slip) from WPAT
Actuator	Modeling of the rover actuators

Table 1: RPAT modules and sub modules

RPAT coordinates the cooperation of the modules, with the *Rover-module* performing the majority of the simulation work (Figure 4). At the beginning of each iteration, the *Terrain-module* (section 3.2.4) supplies the *Rover-module* with the wheel heights based on the current x,y- position of the rover. The *Positioning-sub-module* then recalculates the new rover altitude and orientation on the map. Based on the rover- and wheel-orientations, the *Static-sub-module* calculates the loads and subsequently the necessary traction- or Drawbar-Pull forces per wheel (section 3.2.1). As described in [8], the *Wheel-module* subsequently retrieves the slip at each wheel from the respective DP such that the *Odometry-module* can update the x,y-position and orientation of the rover by combining the wheel-level slips (section 3.2.3). The *Wheel-module* also determines the necessary motor torques, thereby enabling the *Actuator-module* to determine the Rover-LSS power consumption. The updated position and orientation of the rover is finally used as an initial value in the next iteration.

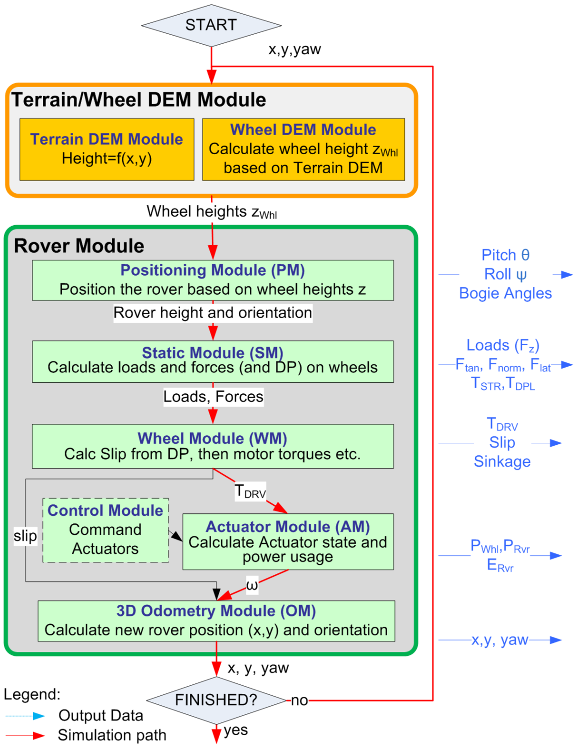


Figure 4: RPAT simulation architecture

3.2 Detailed Module Description

Of the RPAT modules in Table 1, the *Geometry-sub-module* and the *Positioning-sub-module* are based on previous RUAG tools and are explained in more detail in [7]. Further information on the *Control-* and *Actuator-modules* can be found in [9].

The main innovation in RPAT comes from the combination of the quasi-static local-force-equilibrium approach with the novel wheel motion calculation in the *Wheel-module*, the fusion of wheel-level motion to rover-level motion in the *Odometry-module* and the wheel-terrain placement in the *Terrain-module*. A detailed description of the theory behind these modules is given below.

3.2.1 *Static-module*: Force Calculation via a „quasi-static, local-force-equilibrium“ Approach

In common simulation tools (e.g. of the MBS-type) the rover motion is determined using the Newton-Euler-Equation, which for the 1-D can be written as

$$\sum F_{Rvr} = m_{Rvr} \cdot \frac{\partial v_{Rvr}}{\partial t} \tag{1}$$

. Due to the dynamic term, this approach may however cause significant numerical instabilities. Given that typical planetary exploration rover velocities are

$v_{Rvr} \lesssim 10cm/s$, the equation can be safely simplified to

$$\sum F_{Rvr} = 0 \qquad (2)$$

using a quasi-static approach. However, as illustrated by the exemplary two-wheeled rover on a slope depicted in Figure 5, equation (2) has an infinite number of solutions for $n_{Whl} > 1$. The problem is thus under-determined and additional assumptions need to be taken to find a unique solution. RPAT assumes that each wheel exerts exactly the Drawbar-Pull to counteract the resistive force (e.g. due to a slope) acting on it, thereby enabling the calculation of the wheel slip and velocity as described in section 3.2.2. For common test cases this "local-force-equilibrium" approach can be validated experimentally, while for special cases (e.g. step-shape obstacles) additional calculations are implemented in RPAT [7,9]. All together, the quasi-static local-force-equilibrium approach thus yields the force-equation

$$\sum F_{Whl} = 0 \qquad (3)$$

. In accordance with the system engineering focus of RPAT this equation allows a simple, numerically stable, computationally efficient yet sufficiently accurate determination of the wheel forces.

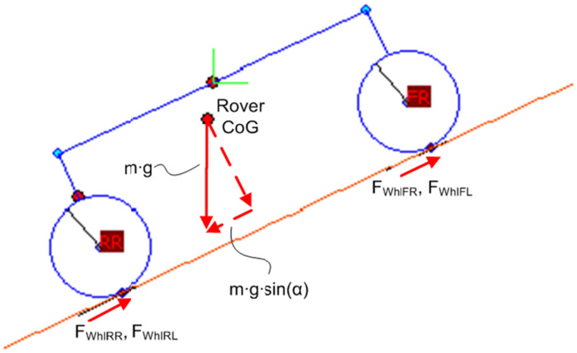


Figure 5: Illustration of the under-determined force equilibrium for rovers with more than one wheel

3.2.2 *Wheel-Module*: Calculation of wheel motion

In contrast to the quasi-static tools developed in [2] and [5], RPAT features the efficient yet accurate modeling of flexible wheels on soft soils (with potentially hard obstacles) through its *Wheel-module*. From the Drawbar-Pull calculated by the *Static-module*, the *Wheel-module* determines the wheel slip (and thus the wheel velocity $v_{Whl,i}$), torque, resistive force and sinkage. This wheel performance data is accessed via RUAG's *Wheel-Performance-module*, an external dynamic link library (DLL) optimized to give highly efficient access to actual wheel test data via parameterized curves. The wheel performance data is retrieved for the current wheel load and multipass case (cp. Figure 6). Detailed information on wheel test data generation and processing in the *Wheel-Performance-module* can be found in [8].

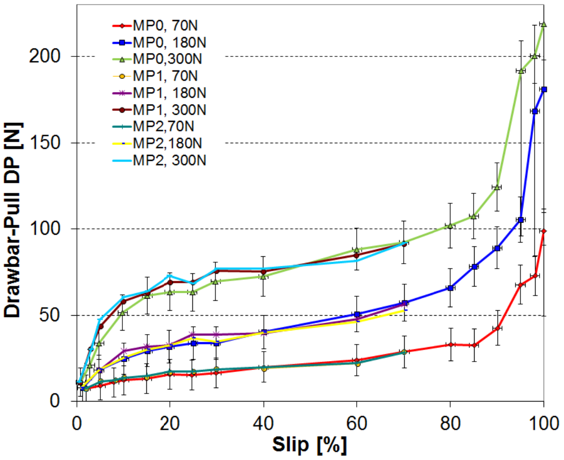


Figure 6: Experimental Drawbar-Pull vs. slip data at different loads and multipass cases for the ExoMars BB2 wheel on Martian soil ES-3

3.2.3 *Odometry-module*: Calculation of the rover motion via a generic Horn-based method

The purpose of the *Odometry-module* is to fuse the wheel velocity vectors $v_{Whl,i}$ to determine the overall rover motion (v_{Rvr}, Δyaw) and thus the new position and orientation (Figure 7). For that purpose RPAT employs the Horn-method [10], a quaternion-based approach which calculates the optimum transformation between two point clouds based on a Least-Squares-Optimization via

$$[\boldsymbol{R},\vec{T}] = \min\left(\sum_i \left\|\left(\vec{T}+\boldsymbol{R}\cdot\vec{s_i}\right)-\left(\vec{s_i}+\overrightarrow{v_{Whl,i}}\right)\right\|\right) \qquad (4)$$

. The point cloud $\vec{s_i}$ herein includes the wheel positions before the movement, while $\left(\vec{s_i}+\overrightarrow{v_{Whl,i}}\right)$ represents the wheel positions after movement. The implemented method allows to directly determine v_{Rvr} and Δyaw and thus the new rover position and orientation from the rotation matrix $\boldsymbol{R}$ and the translation vector $\vec{T}$. In comparison to other tested methods, the implemented Horn-Algorithm has significant advantages: It is completely rover-generic, supports arbitrary drive- and steering maneuvers and provides good computational stability and efficiency due to its closed form. In contrast to most other rover simulation tools, RPAT also allows the mathematically correct simulation of the step-shape obstacle test case (which is crucial for a correct rover motor torque dimensioning, see section 4.2) via its *Odometry-module* [9].

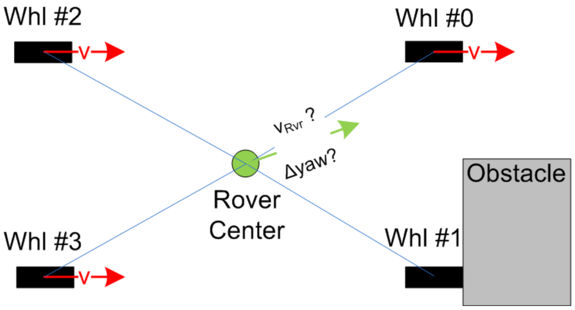


Figure 7: Calculation of the rover motion from wheel velocities in the Odometry-module

3.2.4 *Terrain-module:*

The purpose of the *Terrain-module*, or more correctly the *Terrain-and-Wheel-DEM-Module*, is to determine the height z_{Whl}, contact angle θ_{CA} and the soil-ID of each rover wheel at its current position. The terrain height is represented by a x,y- Digital Elevation Map (DEM) which can be loaded from an easy-to-create RGB or greyscale bitmap-file. In comparison to the 1-D approach presented in [5], RPAT therefore allows to simulate rover motion on complex real-world terrains such as actual Martian terrain. A similar 2-D Soil-Map assigns the soil-ID (e.g. representing Martian sand, Lunar soil or rocks), while a 2-D multipass-map always contains the current multipass value (0,1,2) of a certain x,y terrain position.

In contrast to a Rover placement approach which iteratively places the whole rover on the terrain, RPAT follows a Single Wheel Placement approach, meaning that only after $z_{Whl,i}$ has been determined separately for each wheel the new rover angles are calculated. Z_{Whl} is determined by simply scanning the whole wheel-space (represented by a wheel-DEM, Figure 8) for the maximum accumulated height of the Terrain-DEM, the slope and the Wheel-DEM, i.e.

$$z(x,y) = z_{TerrainDEM} + z_{slope} + z_{WhlDEM} \qquad (5)$$

$$z_{Whl,i} = \max(\mathrm{z}(\mathrm{x}_i + \Delta\mathrm{x}, \mathrm{y}_i + \Delta\mathrm{y})) \qquad (6)$$

.

The advantage of the described single-wheel-placement approach is that it is more rover-generic because the only rover-specific part is to determine the new rover angles from the wheel heights $z_{Whl,i}$ e.g. via the equations given in [7]. The approach is platform independent and proved to be 10x faster than a rover-level-placement approach used in other RUAG rover simulation tools. However, a disadvantage is the handling of terrain-DEM discontinuities such as step-shape obstacles, which can be compensated for example via a Kalman-filter as described in [9].

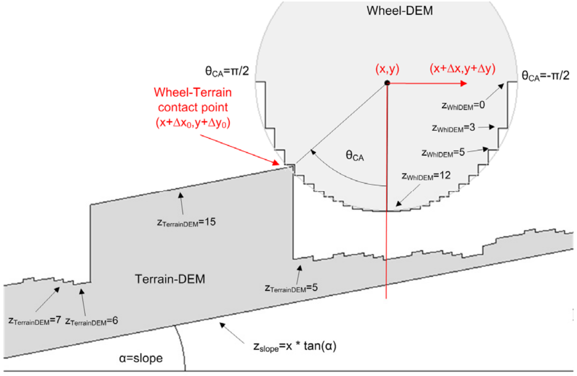


Figure 8: Visualization of the wheel height calculation process. Shown are the Terrain-DEM, Wheel-DEM and the height due to the slope of the terrain.

4 CORRELATION AND VALIDATION

4.1 Correlation with EXM-BB2 test data

To validate the RUAG system engineering environment, the RPAT results are compared to the experimental test results obtained with the ExoMars LSS breadboard 2 (BB2). The test cases are taken from the ExoMars phase B1 and B2 test campaigns [11,12,13] as well as own tests performed at the RUAG Space test facilities.

The summarized results in Table 2 show a very good accuracy for the rover position, velocity, orientation, average motor torques and rover power consumption, with deviations mostly ranging between 3-15%. For the maximum motor torques, deviations range up to 34% in the relevant test cases. Detailed explanations for this behavior are given below and in [9].

4.1.1 Drawbar Pull Tests

The drawbar pull test results (Figure 9) correlate well and thereby confirm the accuracy of the wheel-level data. The average DP error is 7% and is primarily caused by the regions with high test data uncertainty, i.e. the very low and very high slip regions. Average wheel torque errors are 16% and are partly caused by the torque sensor installation in the experiment [9].

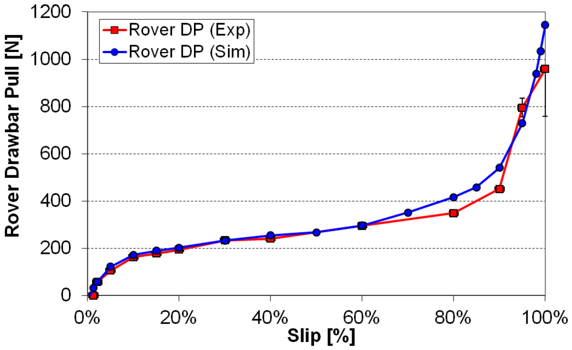


Figure 9: Drawbar pull for the ExoMars BB2 on ES-3. For the simulation, wheel data from [8] was used.

4.1.2 Slope Climbing Tests

In the slope climbing test, the rover slip deviations are 2-11% depending on the slope angle (Figure 10). The average wheel driving torques (Figure 11) show a relative error of less than 5%. Only the 26° case shows major deviations for the rear wheels with a maximum error of 11% or 3Nm due to irregularities in the wheel test data at high slip. The results confirm the overall approach to wheel load computation and torque calculation from test data.

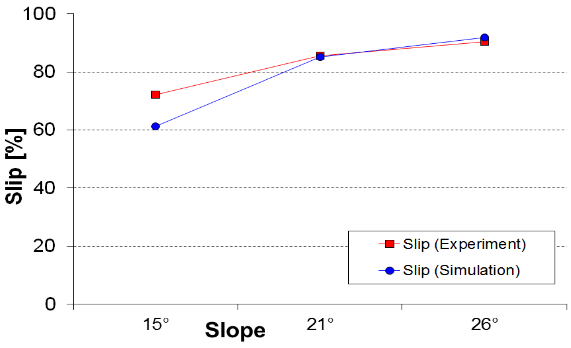


Figure 10: Rover slip during slope climbing

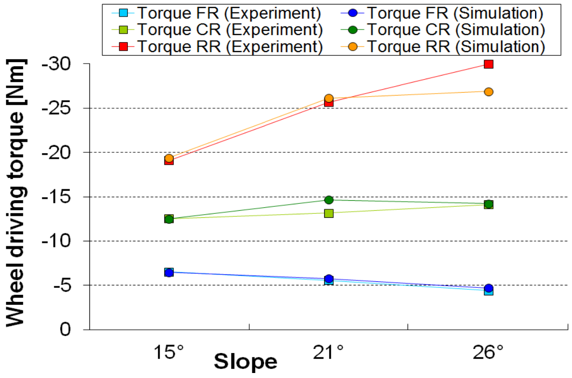


Figure 11: Average wheel torques for the right side wheels (F=Front, C=Center, R=Rear) during slope climbing

4.1.3 Step-Shape Obstacle Test

In the simulation-wise demanding step-shape obstacle test, the rover position and rover angles are well represented versus time (Figure 12). It is important to note that the rover simulation exhibits the same high slip rates during obstacle climbing that are also observable in the experiment.

However, while the driving torques (Figure 13) exhibit a good qualitative agreement, the maximum experimental T_{Drv}-values deviate up to 25% from the simulated values. The detailed deviation analysis revealed multiple error sources, e.g. the neglect of internal forces or the time-dependant Drawbar-Pull vs. slip curves [8, 9] in the simulation. Methods to avoid the error sources and to therefore increase the simulation accuracy are presented in [9].

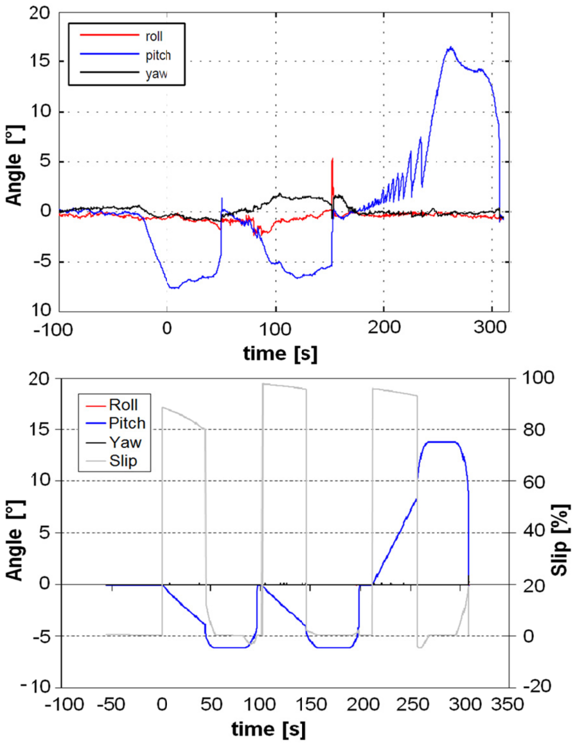


Figure 12: Rover orientation versus time for experiment (top, from [11]) and simulation (bottom)

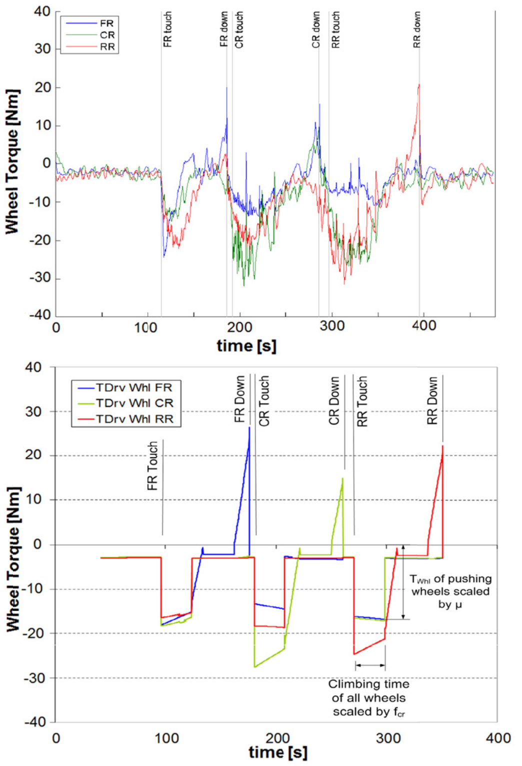


Figure 13: Wheel torque esults from the experiment (top, from [13]) and simulation (bottom) for the step-shape obstacle test with the ExoMars BB2 LSS

4.2 Validation

To guarantee the correctness and reliability of the RPAT-based rover locomotion subsystem design process it is necessary to exactly quantify the deviations described in section 4.1. Table 2 therefore lists the relative error $e_{Rel} = (y_{sim} - y_{exp})/y_{sim}$ of the simulation in comparison to the ExoMars BB2 experiment for every parameter which is important for the rover dimensioning, i.e.

- T_{Max} and T_{Avrg} for the actuator dimensioning
- P_{Avrg} for the solar cell dimensioning
- E_{spec} for the battery capacity dimensioning
- $slip$ for an estimate of feasible rover velocities.

For each and every dimensioning parameter it has to be assured that the maximum experimental value over all test cases is covered through the simulation-based rover dimensioning. The highest experimental maximum motor torque T_{Max} for example occurs in the 2-side obstacle test, where the simulation exhibits a deviation of 25% with respect to the experimental value of -36.73Nm. Exactly this relative deviation in the dominating test case is considered as the uncertainty factor of the simulation result for the respective T_{Max} parameter. It is therefore added on top of the highest simulation value (as a so called "Dimensioning Uncertainty Factor") such that all other experimental results are also automatically covered by the resulting simulation output.

To sum up, a complete rover dimensioning during a preliminary design phase only requires the user to do two things: First, he needs to simulate all test-cases required by the mission profile (e.g. those in Table 2), and second, the dimensioning uncertainty factors have to be added to the maximum simulation values of the respective dimensioning parameters. Assuming an additional 15% margin (a common practice for software in the early stage of development) this approach allows a simple yet reliable dimensioning of a rover locomotion subsystem.

5 FUTURE WORK

To further increase the RPAT simulation accuracy, the major simulation error sources and methods for their avoidance are identified in [9]. These are:

- **Implement the drawbar-pull time dependence** to better model step-shape obstacle test cases.
- **Implement internal force modeling** to improve the accuracy of slope and step-shape obstacle test cases
- **Implement later wheel sliding** to allow precise simulation of 1-side obstacles

In addition, the comparison of RPAT results with a second rover breadboard (e.g. the ESA HDPC breadboard) would help to verify the accuracy of the uncertainty factors listed in Table 2.

6 SUMMARY

This paper presents the development of the Rover Parametric Analytical Tool, a simulation environment with the purpose to decrease the dependency on rover breadboards by enabling quick model-based analysis and preliminary design of rover locomotion subsystems. RPAT supports arbitrary rover geometries and terrains through a generic Horn-method based Odometry-module and provides significantly faster-than-real-time simulation speeds due to a quasi-static local-force-equilibrium approach. RPAT only requires the user to perform wheel-level performance tests in order to provide a full rover-level LSS simulation. In contrast to the quasi-static tools developed in [2,5], the possibility to rely on actual wheel test data approach allows a more accurate representation of flexible wheels on loose soils.

The validation with ExoMars LSS BB2 test data exhibits maximum errors of 4-15% for the power and energy consumed and up to 34% for the maximum motor torques. However, the rover LSS is dimensioned exclusively by the most demanding test case. Taking this into account, the relative errors decrease to 2-5% for the power and energy and 25% for the maximum motor torque. Adding these relative errors (plus a 15% general margin due to the early development stage of the software) as uncertainty factors to the respective simulation result is thus sufficient to guarantee a reliable rover dimensioning.

		T_{max} (at Whl)	T_{avrg} (at Whl)	P_{avrg}	E_{spec}	slip
Leveled soil Test	(Max) value	6.38 Nm (CR)	2.87 Nm (CR)	1.44 W	131.10 Ws/m	0.005
	Rel. Error	110.07 % (CR)	4.44 % (CR)	7.44 %	7.44 %	15.551 %
Slope Test	(Max) value	-34.93 Nm (RR)	-25.64 Nm (RR)	7.89 W	4942.00 Ws/m	0.856
(21°, all whls)	Rel. Error	33.67 % (RR)	1.85 % (RR)	4.03 %	1.99 %	0.570 %
Slope Test	(Max) value	-24.99 Nm (RR)	-19.09 Nm (RR)	6.77 W	1973.10 Ws/m	0.722
(15°, all whls)	Rel. Error	28.87 % (RR)	1.53 % (RR)	0.44 %	24.32 %	0.570 %
2-Side Obstacle Test	(Max) value	-36.73 Nm (CR)	-13.92 Nm (CR)	5.71 W	1800.88 Ws/m	0.41
(Values for DLR-test)	Rel. Error	24.52 % (CR)	30.28 % (CR)	14.08 %	12.56 %	10.33 %
1-Side Obstacle Test	(Max) value	-32.03 Nm (CR)	-9.05 Nm (CR)	- W	- Ws/m	-
(Values for DLR, μ=0.51)	Rel. Error	16.11 % (CR)	15.41 % (CR)	- %	-	- %
DIMENSIONING UNCERTAINTY FACTORS		**25 %**	**2 %**	**(5) %**	**(2) %**	**2 %**

Table 2: RPAT dimensioning uncertainty factors resulting from the relative simulation errors w.r.t. the experimental values in the respective dominating test case. Maximum motor torques over all wheels are given.

7 CONCLUSION

The RPAT approach of using a quasi-static local-force-equilibrium method and fusing wheel-level test data to estimate the motion on rover level has been successfully validated. While the use of actual wheel-level data allows for high accuracy, the local force equilibrium approach avoids the complexities of a full rover-level force calculation and therefore allows a very time-efficient simulation. For the often “intuition and experience”-based [1] rover preliminary design phase - and also in comparison to similar simulation tools - the accuracy of RPAT is very satisfactory. However, a local-force-equilibrium approach is only a simple approximation of reality with the inherent limitation that internal forces are neglected. A high-accuracy simulation tool used in the later phases of a rover project may thus be better served with implementing a multi-body-simulation approach for force calculation and combining it with other RPAT technologies such as the reliance on precise wheel-level test data for motion determination. For a preliminary design and system engineering tool however, the RPAT quasi-static local-force-equilibrium approach is a very beneficial and unique compromise between flexibility, speed and accuracy.

All in all, the Rover Parametric Analytical Tool allows an efficient analysis and comparison of a wide range of rover configurations and is therefore a powerful tool for LSS concept selection and LSS component dimensioning. It has the potential to significantly decrease the dependence on rover breadboards, reduce the need for extensive test campaigns and consequently eventually reduce the cost and time necessary for the preliminary design of future planetary rovers.

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