beyond gravity

DynRPAT: A Novel Parametric Analytical Tool to Efficiently Simulate High-Speed or Low-Gravity Locomotion Conditions for Planetary Exploration Rovers

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Previous work

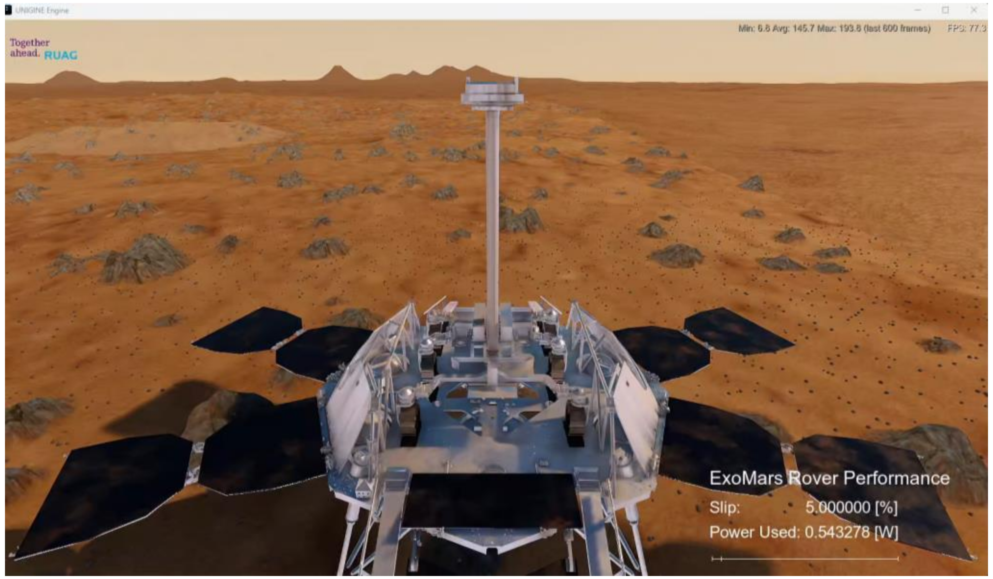
Quasi-static simulation - RPAT

DynRPAT extends the RPAT [Oett2012] Beyond Gravity's quasi-static rover simulation:

- What is kept:
  → Wheel-soil interaction [Oett2019] (slip from DP, load, sinkage)
  → DEM-based terrain modeling
  → Full mission post-processing

DynRPAT features a full dynamic rover model which supports:

- Rover acceleration / deceleration with changing wheel loads and slip-sinkage
- Wheel drop phase after a large obstacle (loss of soil contact)
- Long coasting phases, as in micro-g environments



Min: 6.8 Avg: 145.7 Max: 193.8 (last 600 frames) FPS: 77.3

ExoMars Rover Performance
Slip: 5.000000 [%]
Power Used: 0.543278 [W]

Quasi-static simulation with ExoMars rendered in Unigine.

Motivation

Why a simulation and why dynamic?

- Locomotion analysis drives the mission (e.g. landing site, mission targets)

- Modern rovers such as NASA/ESA SFR [Muirhead2020] travel up to 30x faster than ExoMars…

OR

- evolve in low gravity such as DLR MASCOT [Ho2017] or MINERVA-II

→ Dynamics needs to be included

The Sample Fetch Rover (SFR) in the field.

Motivation

State of the art for simulation

Multi body simulation (MBS):

- Highly accurate rover dynamics modelling
- Require comprehensive inputs

But

- Complexity prohibits quick parametric analysis

  → Low simulation speed

Quasi-static simulation:

- Trade-off between accuracy and simplicity / simulation speed
- Efficiently simulate and compare various rover designs

  → Good for early rover design

But

- Cannot support dynamic locomotion

Motivation

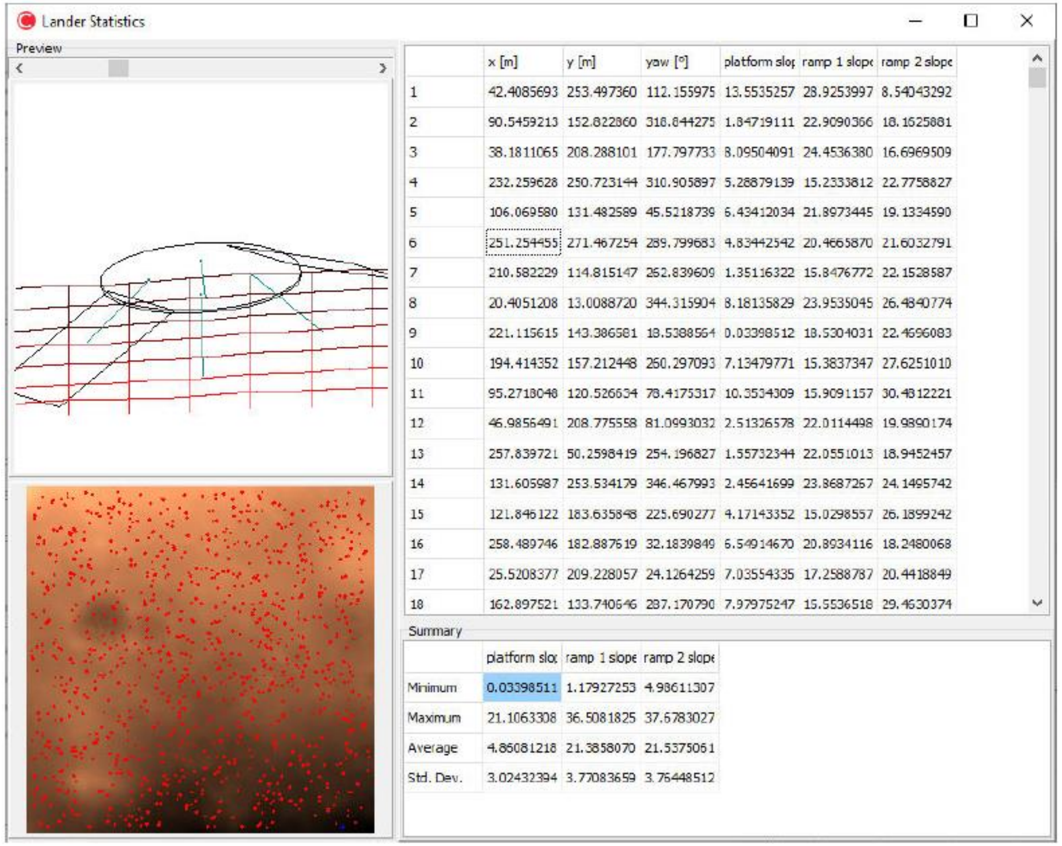
What we propose

DynRPAT simulation that is computationally efficient and features:

- Highly-dynamic rover motion
- Full 6-DOF rover kinematics
- Newton Euler Equations of Motion
- Accurate wheel-soil interaction

Furthermore, it supports:

- High-quality planetary terrain import
- Statistical mission analysis



	x [m]	y [m]	yaw [°]	platform slo	ramp 1 slop	ramp 2 slop
1	42.4085693	253.497360	112.155975	13.5535257	28.9253997	8.54043292
2	90.5459213	152.822860	318.844275	1.84719111	22.9090366	18.1625881
3	38.1811065	208.288101	177.797733	8.09504091	24.4536380	16.6969509
4	232.259628	250.723144	310.905897	5.28879139	15.2333812	22.7758827
5	106.069580	131.482589	45.5218739	6.43412034	21.8973445	19.1334590
6	251.254455	271.467254	289.799683	4.83442542	20.4665870	21.6032791
7	210.582229	114.815147	262.839609	1.35116322	15.8476772	22.1528587
8	20.4051208	13.0088720	344.315904	8.18135829	23.9535045	26.4840774
9	221.115615	143.386581	18.5388564	0.03398512	18.5304031	22.4696083
10	194.414352	157.212448	260.297093	7.13479771	15.3837347	27.6251010
11	95.2718048	120.526634	78.4175317	10.3534309	15.9091157	30.4812221
12	46.9856491	208.775558	81.0993032	2.51326578	22.0114498	19.9890174
13	257.839721	50.2598419	254.196827	1.55732344	22.0551013	18.9452457
14	131.605987	253.534179	346.467993	2.45641699	23.8687267	24.1495742
15	121.846122	183.635848	225.690277	4.17143352	15.0298557	26.1899242
16	258.489746	182.887619	32.1839849	6.54914670	20.8934116	18.2480068
17	25.5208377	209.228057	24.1264259	7.03554335	17.2588787	20.4418849
18	162.897521	133.740646	287.170790	7.97975247	15.5536518	29.4630374

Summary

	platform slo	ramp 1 slope	ramp 2 slope
Minimum	0.03398511	1.17927253	4.98611307
Maximum	21.1063308	36.5081825	37.6783027
Average	4.85081218	21.3858070	21.5375061
Std. Dev.	3.02432394	3.77083659	3.76448512

Statistical mission analysis tool.

Dynamic Modelling Approach

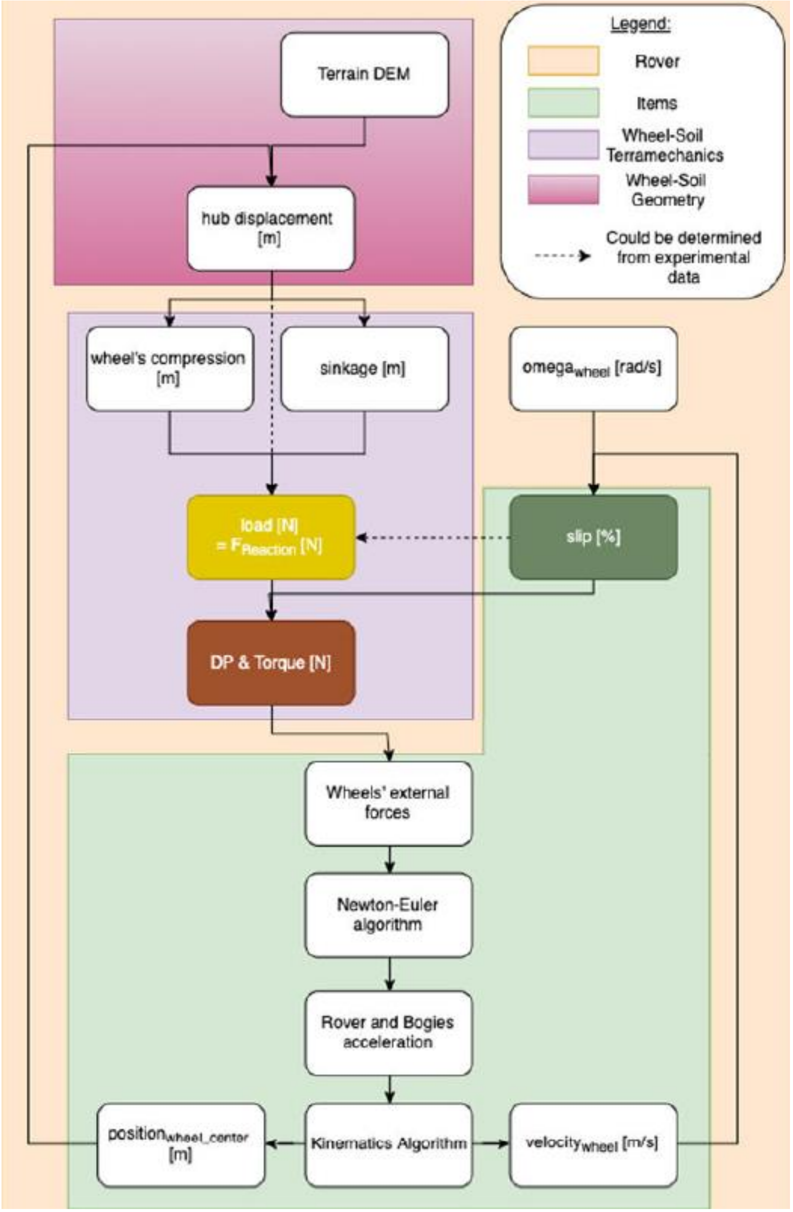
Simulation loop design & assumptions

Based on 3 principal models:

- Wheel-soil interaction model
  → Compute external forces and moments on each wheel
- Equation of motion of the different bodies
  → Compute acceleration of system
- Kinematic model from acceleration
  → Compute the state vector of each sub-system

Assumptions:

- No air friction and no friction at joints (bogies)
- Infinite stiffness of kinematic chain (except wheel and soil)
- Ideal motor step response



Dynamic Modelling Approach

Improved dynamic wheel-soil interaction

Serial double spring + damper system described as:

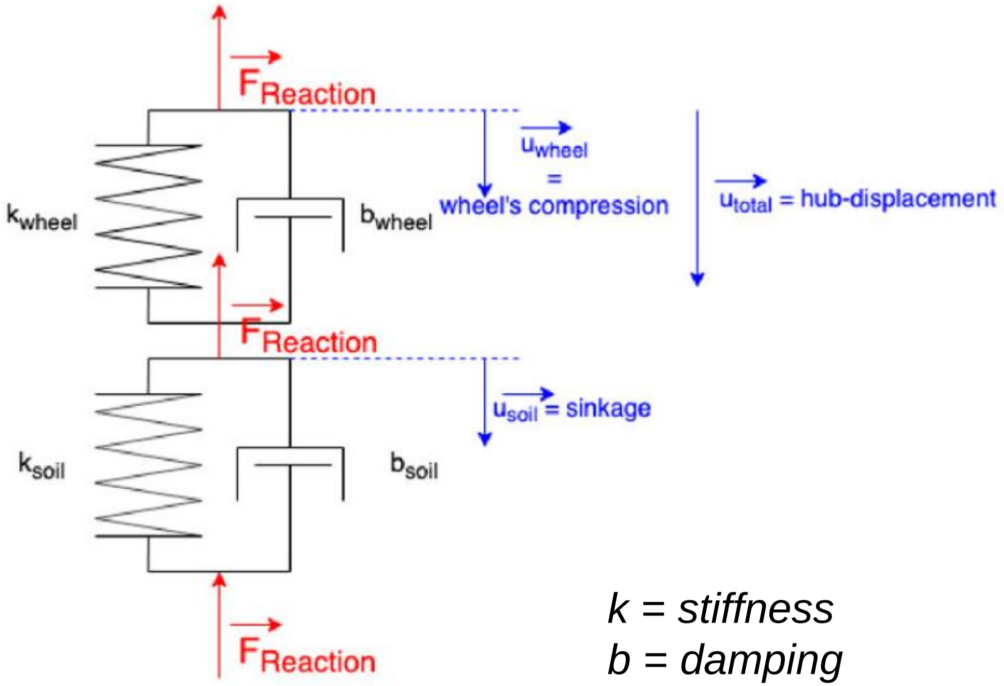
$$\begin{cases} F_{Reaction} & = F_{R,wheel} = F_{R,soil} \\ u_{tot} & = u_{wheel} + u_{soil} \\ F_{R,wheel} & = k_{wheel} u_{wheel} + \beta_{wheel} \dot{u}_{wheel} \\ F_{R,soil} & = k_{soil} u_{soil} + \beta_{soil} \dot{u}_{soil} \end{cases}$$

→ u_{wheel} and u_{soil} updated at each timestep given u_{hub}

$$\dot{u}_{wheel} = \frac{-(k_{wheel} + k_{soil}) u_{wheel} + k_{soil} u_{tot} + \beta_{soil} \dot{u}_{tot}}{\beta_{wheel} + \beta_{soil}}$$

→ solve a differential equation ensuring stability in case of high stiffnesses (lower integration error)

$$u^n_{\text{wheel}} = \frac{-(\beta_{\text{wheel}} + \beta_{\text{soil}}) \sum_{i=1}^{n-1} c_i u^i_{\text{wheel}} + \Delta t \; k_{\text{soil}} u^n_{\text{tot}} + \beta_{\text{soil}} \sum_{i=1}^{n} c_i u^i_{\text{tot}}}{(k_{\text{wheel}} + k_{\text{soil}}) \Delta t + (\beta_{\text{wheel}} + \beta_{\text{soil}}) c_n}$$



k = stiffness
b = damping
F = force
u = displacement

Dynamic Modelling Approach

Newton-Euler equations / solver and rover kinematics

Newton-Euler equations:

- Model accurately influence of external forces / torques
- Solved recursively for each part of the system
- Use rover geometry database (relative position, mass, parent parts)

Motion

$$\sum_{i=0}^{nbParts}(J_{P_i}^T m_i J_{P_i} + J_{R_i}^T I_i J_{R_i})\overrightarrow{\ddot{q}} + \sum_{i=0}^{nbParts}(J_{P_i}^T m_i \dot{J}_{P_i})\overrightarrow{\dot{q}}$$

$$= \sum_{i=0}^{nbParts}(J_{R_i}^T \overrightarrow{M}_{EXT_i}) + \sum_{i=0}^{nbParts}(J_{P_i}^T \overrightarrow{F}_{EXT_i}) + \sum_{i=0}^{nbParts}(J_{P_i}^T \overrightarrow{F}_{G_i})$$

External forces

Solver:

- Forward integration
  → Allow real-time simulation with error *O(Δt)*
- Beeman's method [Beeman1976]
  → Allow smaller error *O(Δt³)*

$$\overrightarrow{\dot{q}}_{t+1} = \overrightarrow{\dot{q}}_t + \Delta t\,\overrightarrow{\ddot{q}}_t$$

$$\overrightarrow{q}_{t+1} = \overrightarrow{q}_t + \Delta t\,\overrightarrow{\dot{q}}_t$$

$$\overrightarrow{\dot{q}}_t = \overrightarrow{\dot{q}}_{t-1} + \boxed{\frac{5}{12}}\Delta t\,\overrightarrow{\ddot{q}}_t + \boxed{\frac{2}{3}}\Delta t\,\overrightarrow{\ddot{q}}_{t-1} - \boxed{\frac{1}{12}}\Delta t\,\overrightarrow{\ddot{q}}_{t-2}$$

$$\overrightarrow{q}_{t+1} = \overrightarrow{q}_t + \Delta t\,\overrightarrow{\dot{q}}_t + \boxed{\frac{2}{3}}\Delta t^2\,\overrightarrow{\ddot{q}}_t - \boxed{\frac{1}{6}}\Delta t^2\,\overrightarrow{\ddot{q}}_{t-1}$$

$$\overrightarrow{\dot{q}}_{t+1}^{(\text{predicted})} = \overrightarrow{\dot{q}}_t + \boxed{\frac{3}{2}}\Delta t\,\overrightarrow{\ddot{q}}_t - \boxed{\frac{1}{2}}\Delta t\,\overrightarrow{\ddot{q}}_{t-1}$$

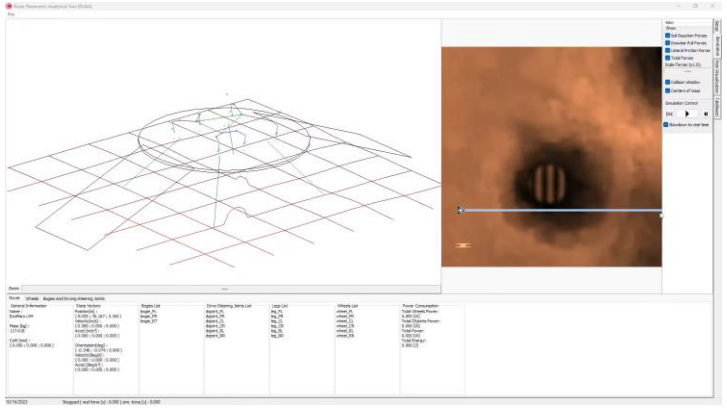
Other optimisation:

- Custom Single Instruction Multiple Data (SIMD)
- Adaptive time step based on speed and hub displacement

Preliminary Results

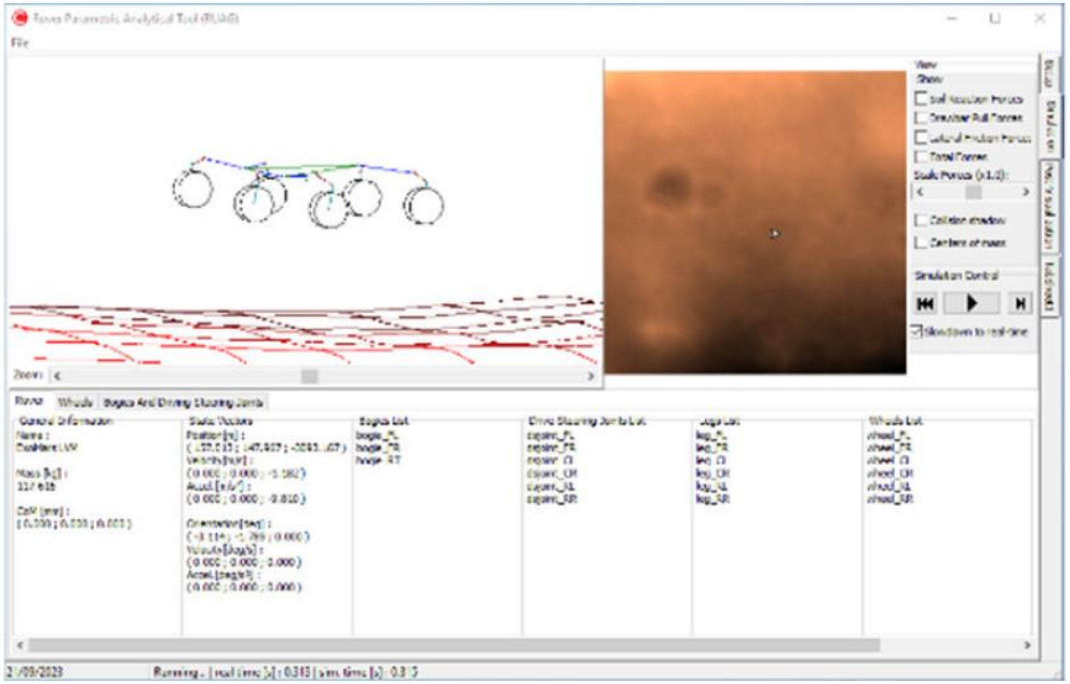
Demo

Egress from landing platform:



Dynamic Egress (“Crane”) testing:

- “skycrane” deployments, e.g. NASA MSL rovers
  - → Accelerations, bogie motion and, orientation during free fall
  - → Reaction forces and dynamics upon impact into soft or hard soil.



“skycrane” deployment in DynRPAT

Preliminary Results

Computational speed

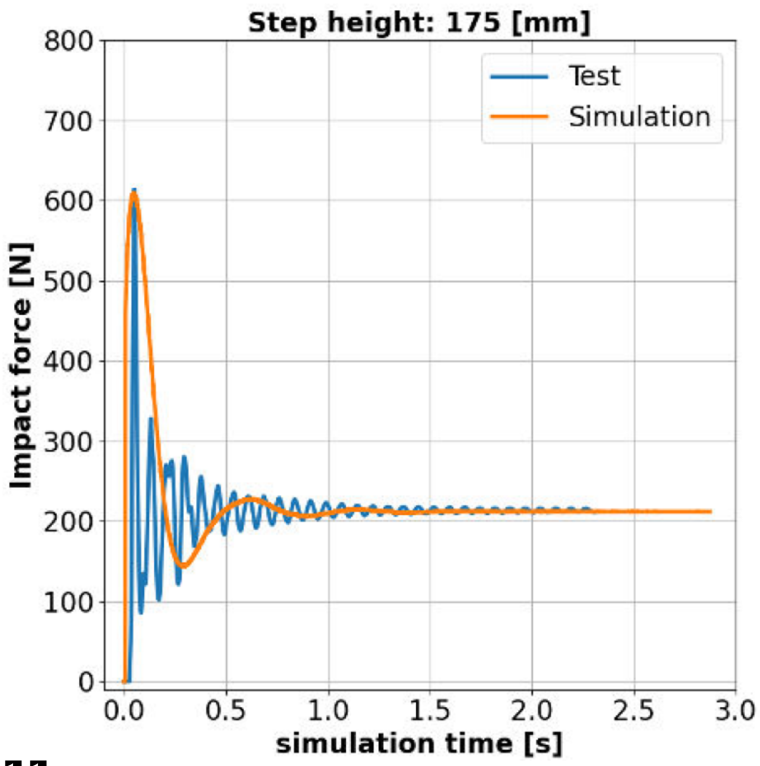
- The quasi-static original RPAT (quasi-static) was **~150x real-time speed** during simulations
- DynRPAT with simple Newton Euler forward integration is **5x slower** than real-time
- DynRPAT with the computational speedups (Beeman's method, wheel-soil accurate finite-difference approximation, and SIMD support) is **~8x faster than real-time** on typical CPU.

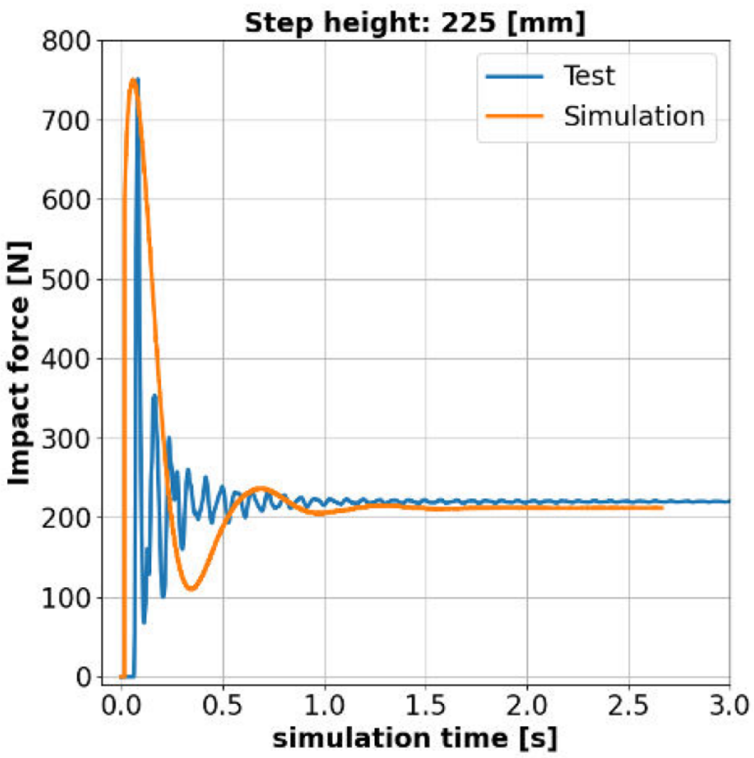
Preliminary Results

Wheel drop testing

Comparison with ExoMars LVM rover:

- Wheel drop from different heights and impact on a hard plate equipped with force sensor





→ Maximum force and steady state load correlate between simulation and test

→ Frequency response was not correlated → DynRPAT is not designed for structural modal analysis.

Usability Features

Importing realistic features

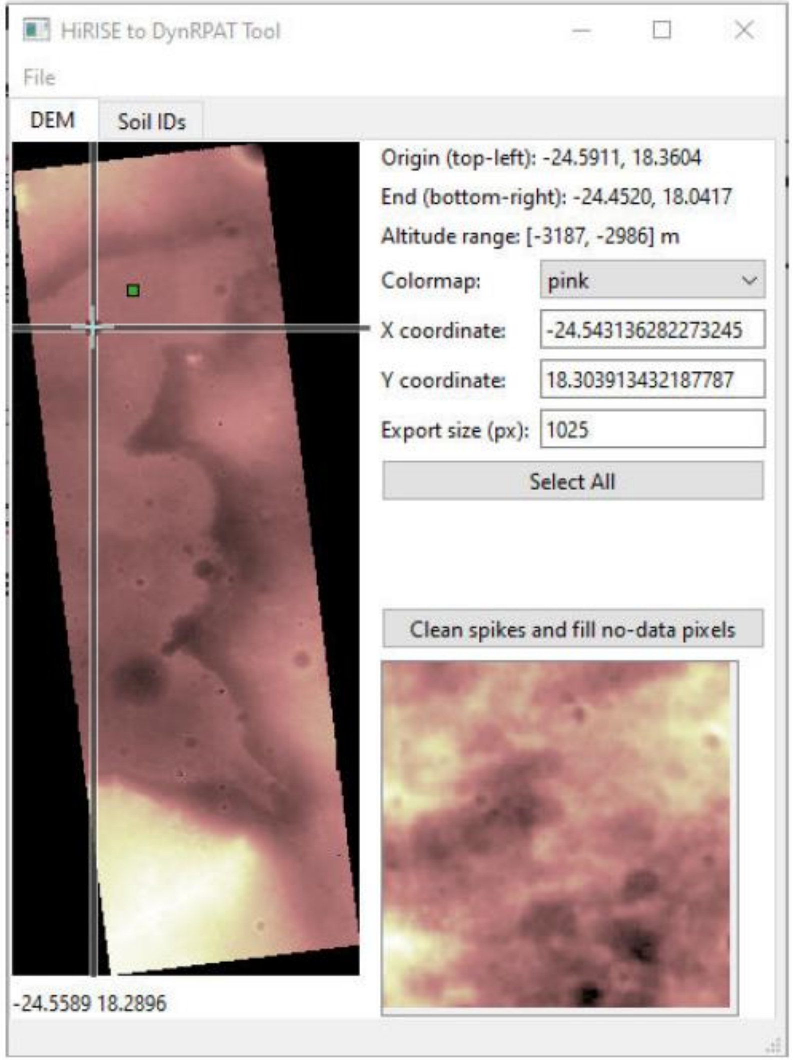
GeoTIFF terrain import module:

- Feature high-resolution realistic terrains
- Support digital elevation models (DEMs)
- Include an editor to specify the heterogeneous soil types
  → a soil map: ES1/2/3/4

But

High-resolution terrain topography reconstruction with HiRISE can have noisy terrain with missing values

→ Especially true around extremes or blocking terrain such as craters



Origin (top-left): -24.5911, 18.3604
End (bottom-right): -24.4520, 18.0417
Altitude range: [-3187, -2986] m
Colormap: pink
X coordinate: -24.543136282273245
Y coordinate: 18.303913432187787
Export size (px): 1025
-24.5589 18.2896

Terrain selected in Oxia Planum for import into DynRPAT

Usability Features

Importing realistic features

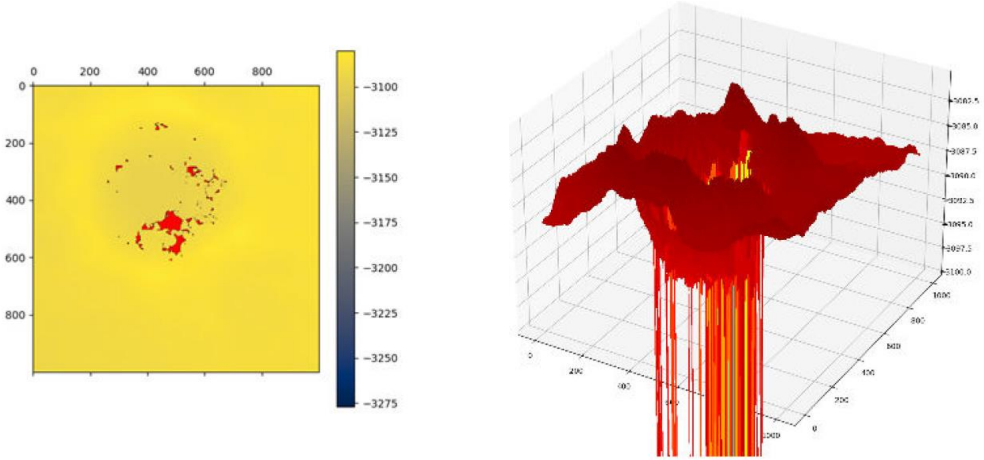
Cleaning:

- The algorithm is divided into three steps:

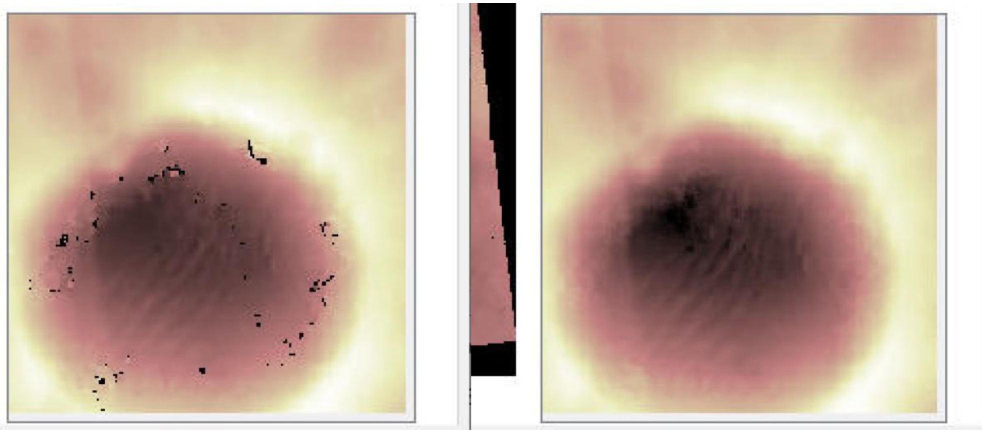
1) Outlier detection
   → Apply a Gaussian kernel (70x70) on terrain image
   → Compute difference between convolved and original image and ∆>0.7m = outlier

2) Interpolation by kriging [Margaret1990]
   → Train a Gaussian process regression (GPR) model on terrain to interpolate outliers and missing values

3) Correction of discontinuities from GPR
   → Convolve an averaging kernel (7x7) on boundaries (link heights)



Terrain with missing values.



Terrain cleaning algorithm applied on noisy terrain with missing values.

Usability Features

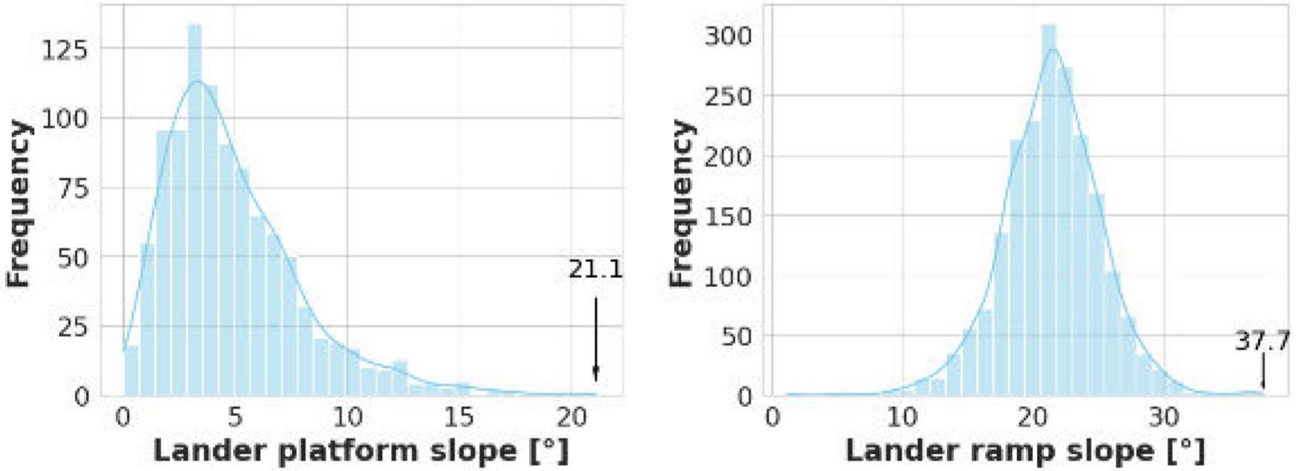
Mission analysis and visualization

Parametrically tradeoff different missions against each other:

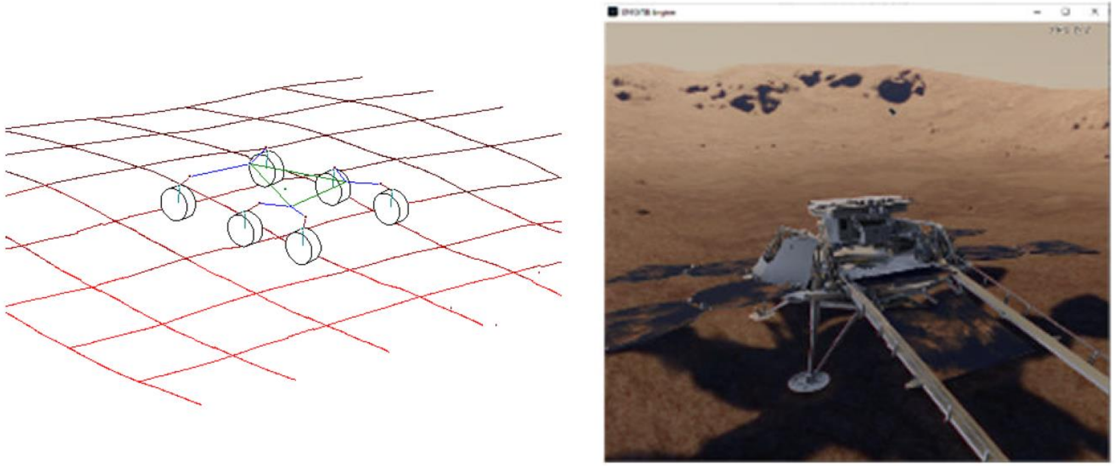
- Estimate instability of lander Egress by retrieving statistics of slope angles
  - → Place lander randomly in realistic terrain
  - → Calculate lander body and ramp angles
  - → Assess percentage of lander placement which results in successful Egress

Realistically visualize in real-time simulated rover traverses:

- → Use Unigine 3D engine
- → Rover/lander states transferred via TCP/IP



Retrieved lander and ramp angles after 1’000 placements. Maximum values are indicated.



DynRPAT live simulation of ExoMars (left) and DynRPAT visualization of ExoMars using Unigine 3D (right)
4

Conclusion

DynRPAT is simulation tool for planetary exploration rover locomotion.

- Initial comparison with ESA ExoMars LVM rover test data show a **good agreement** with gradeability tests, wheel drop tests, and Egress tests from lander platforms

- DynRPAT features a combination of **computational efficiency and medium-accuracy** dynamic modeling

- DynRPAT is well suited to **support iterative use-cases**, such as preliminary design or operations support for future high-speed planetary exploration rovers

Future Work

- **Full correlation with ExoMars test data**
  → With more step shape obstacles drop tests

- **Correlation with test data from faster rovers, such as ESA/NASA's SFR**
  → Tests were performed at Beyond Gravity's Zurich

- **Improvement of wheel-soil contact point modeling**
  → Unstable behavior of contact point quickly switching between hard soil (e.g. step shape obstacle) and soft soil → affecting drawbar pull

- **Given computational speed, mission statistics can be retrieved for Egress and traversability to support locomotion optimization and selection of mission landing site**
  → Random rover placements and related motion paths on realistic HiRISE/MRO terrains
  → Traversability by measuring the percentage of cases where the rover successfully reaches its target