PARAMETRIC OPTIMIZATION OF RIGID WHEELS FOR PLANETARY SURFACE MOBILITY APPLICATIONS

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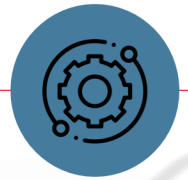

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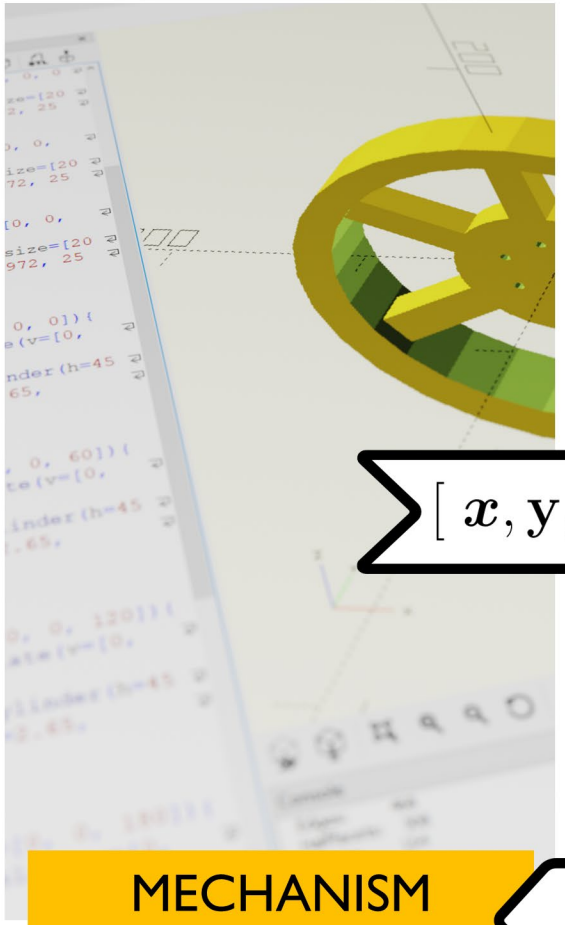
THE DESIGN-BUILD-TEST (DBT) APPROACH IS FLAWED

- Lengthy hardware development time, high cost.
- Limited testing capabilities due to environment differences.
- Unoptimized hardware wastes resources.

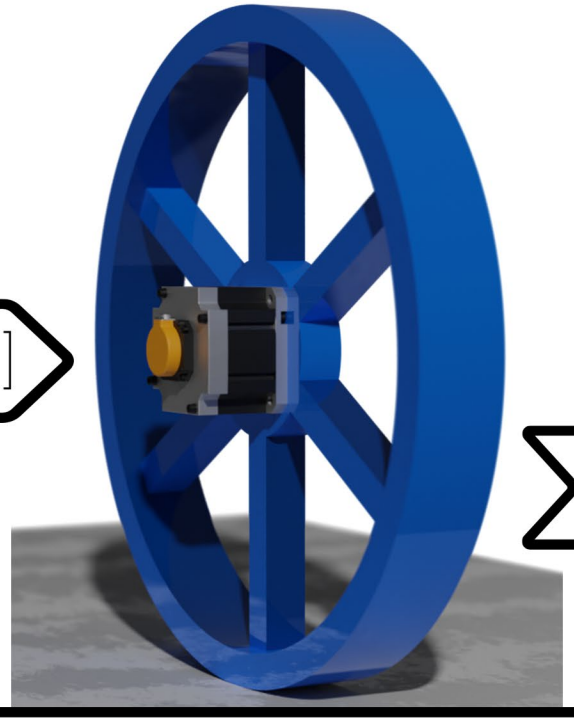
DESIGN CAN BE LARGELY AUTOMATED

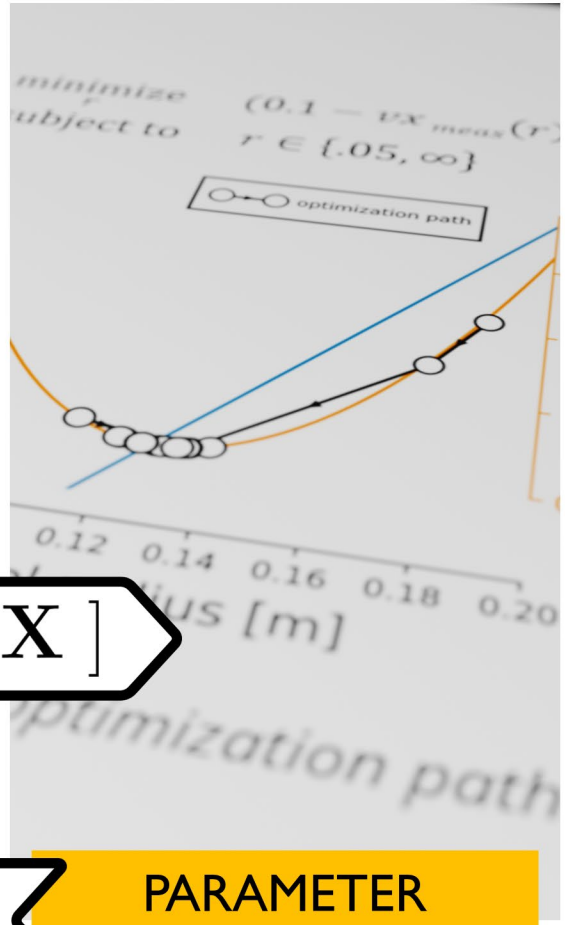
Optimization-based design with physical simulation can reduce the time, effort, and cost required to develop and deploy hardware that is *optimized for its operating environment*.

MECHANISM OPTIMIZATION TOOLCHAIN



SYSTEM SIMULATION





$[\ x, y, z\ ]$

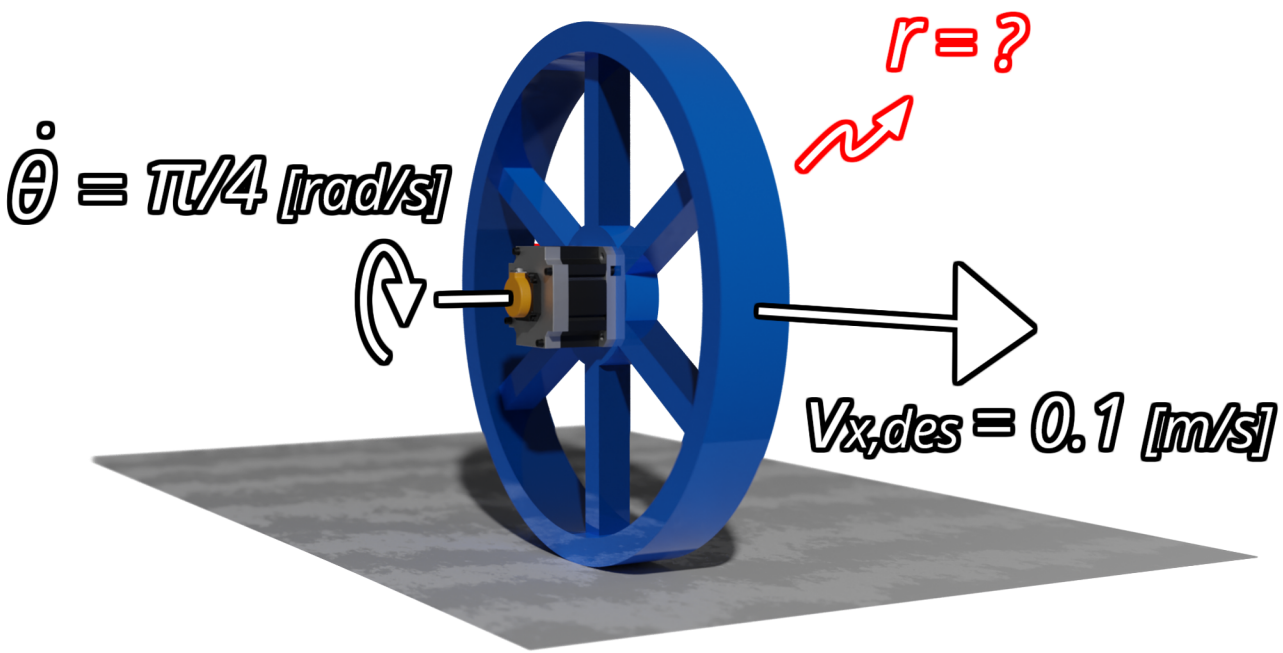
$[\ X\ ]$

MECHANISM GENERATION

$[\ d_1, d_2, ...d_n\ ]$

PARAMETER OPTIMIZATION

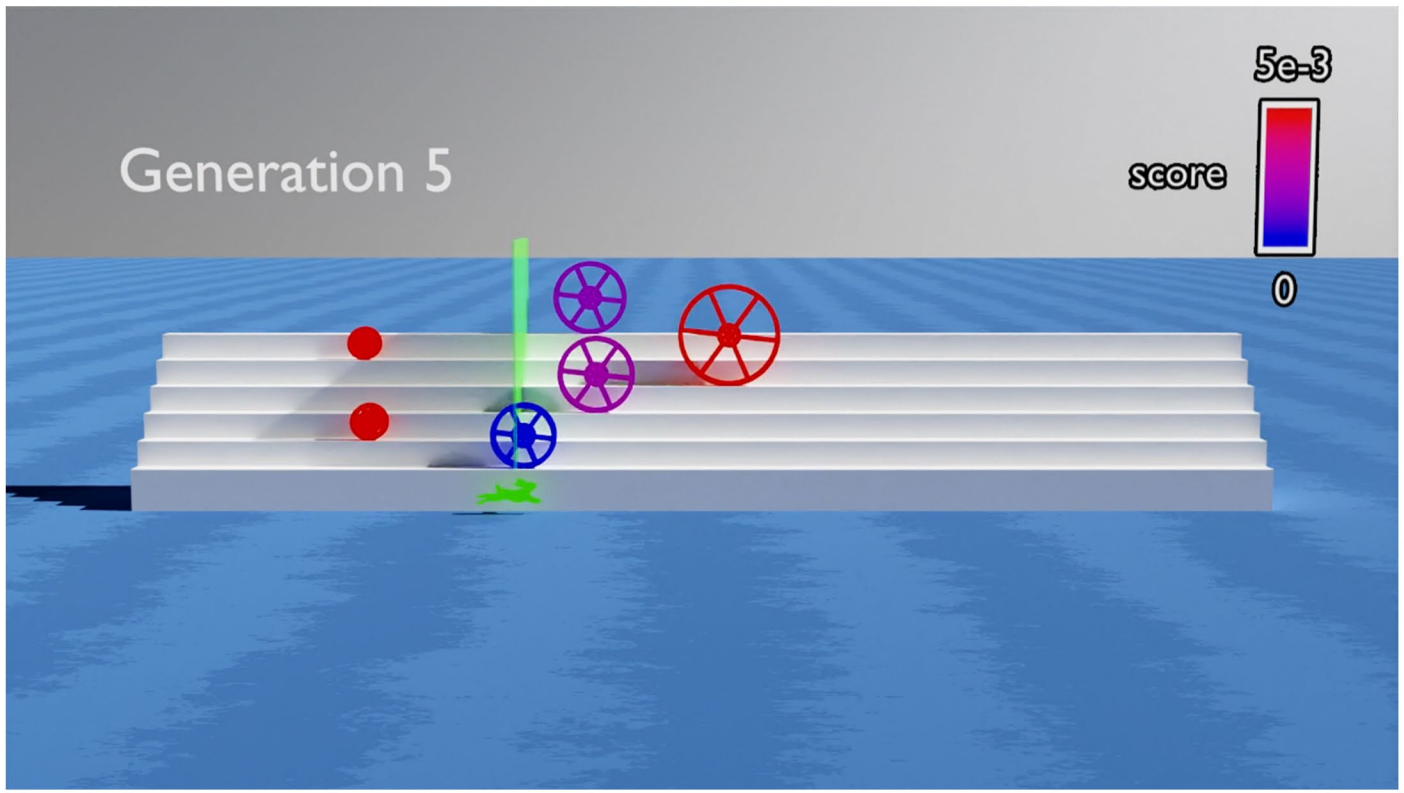
EXAMPLE: WHEEL RADIUS OPTIMIZATION



Wheel mechanism.

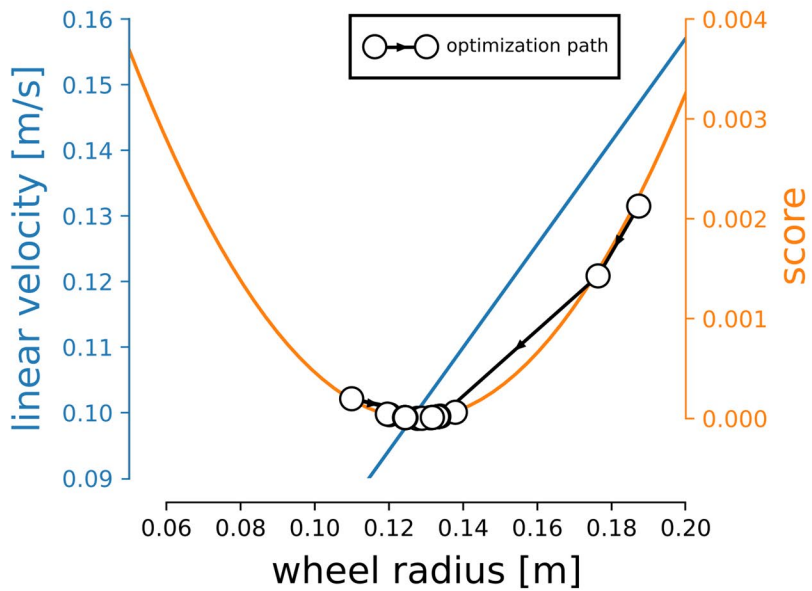
- **Analytically:**
  - $v = r\dot{\theta}$
  - $r = 127.3\ [mm]$

EXAMPLE: WHEEL RADIUS OPTIMIZATION (CONT'D)



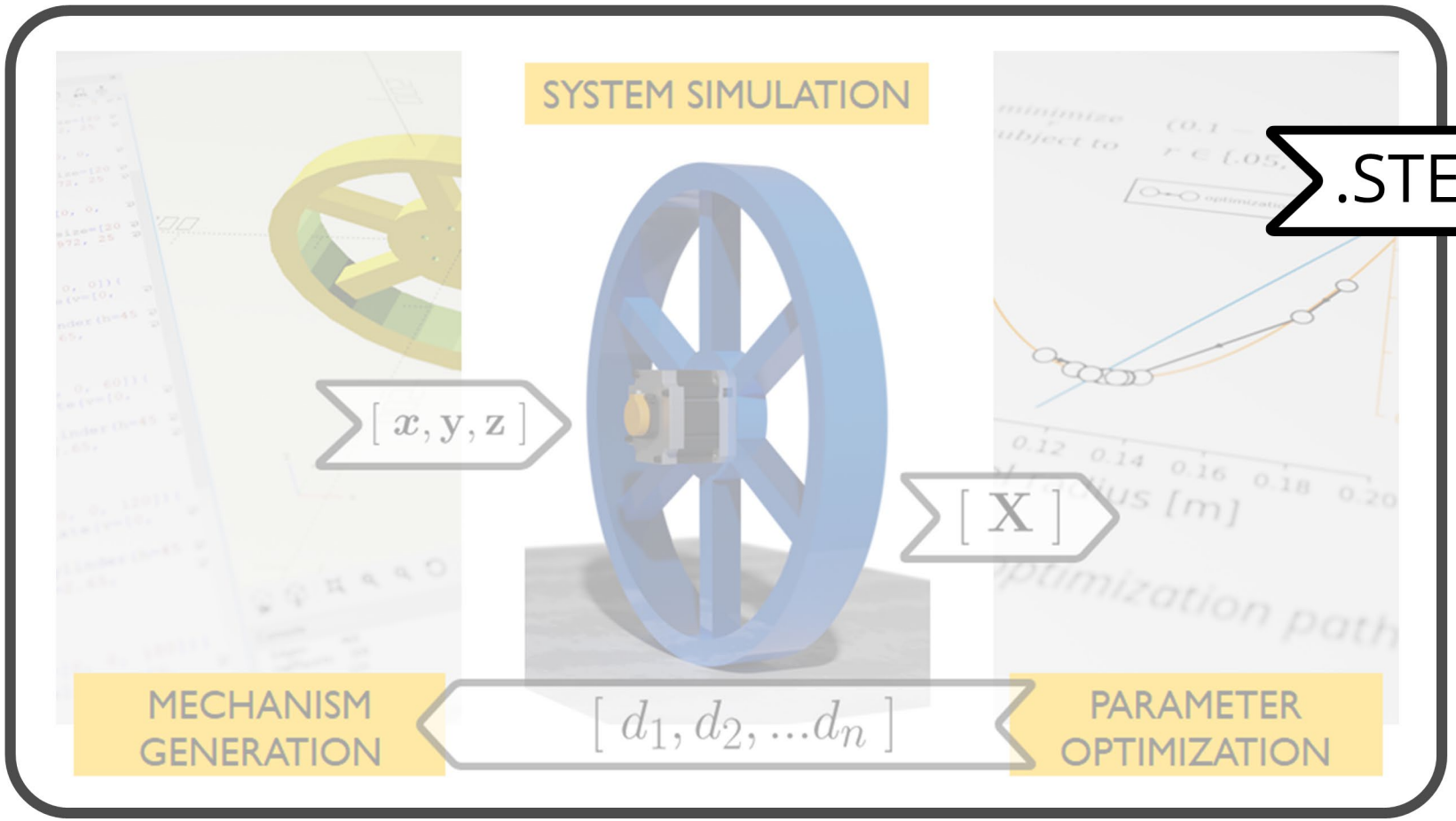
Wheel radius optimization in simulation environment via CMA-ES [1].

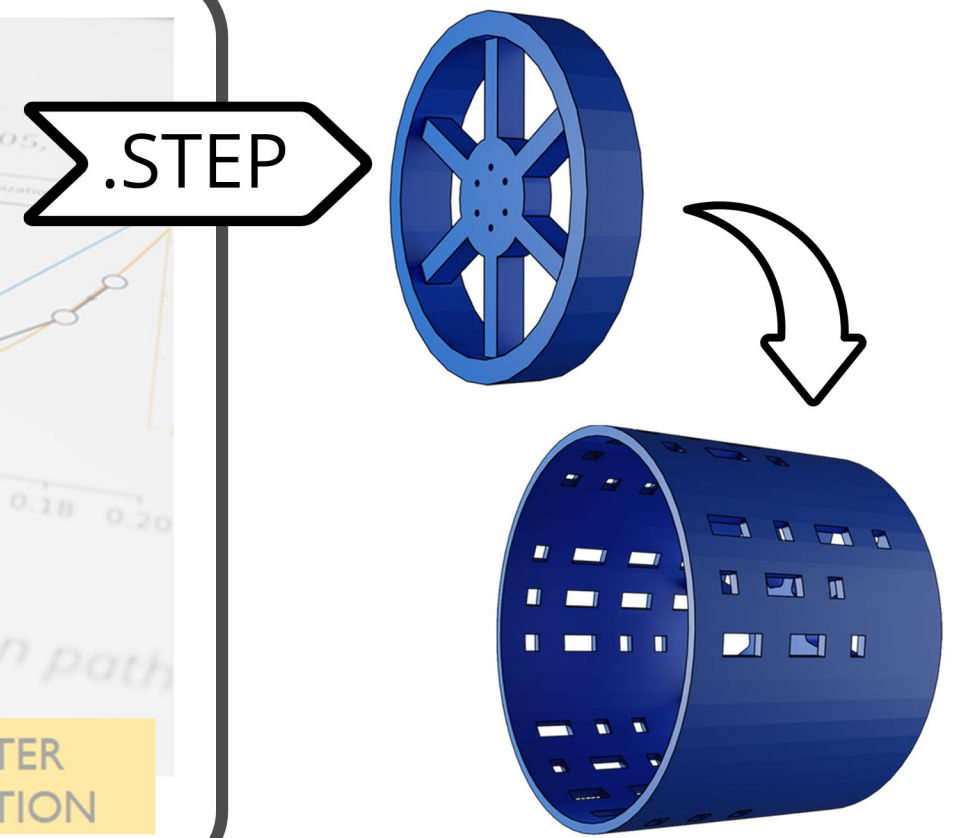
$$\underset{r}{\text{minimize}} \quad g(r) = (0.1 - vx_{meas}(r))^2$$
$$\text{subject to} \quad r \in \{.05, \infty\}$$



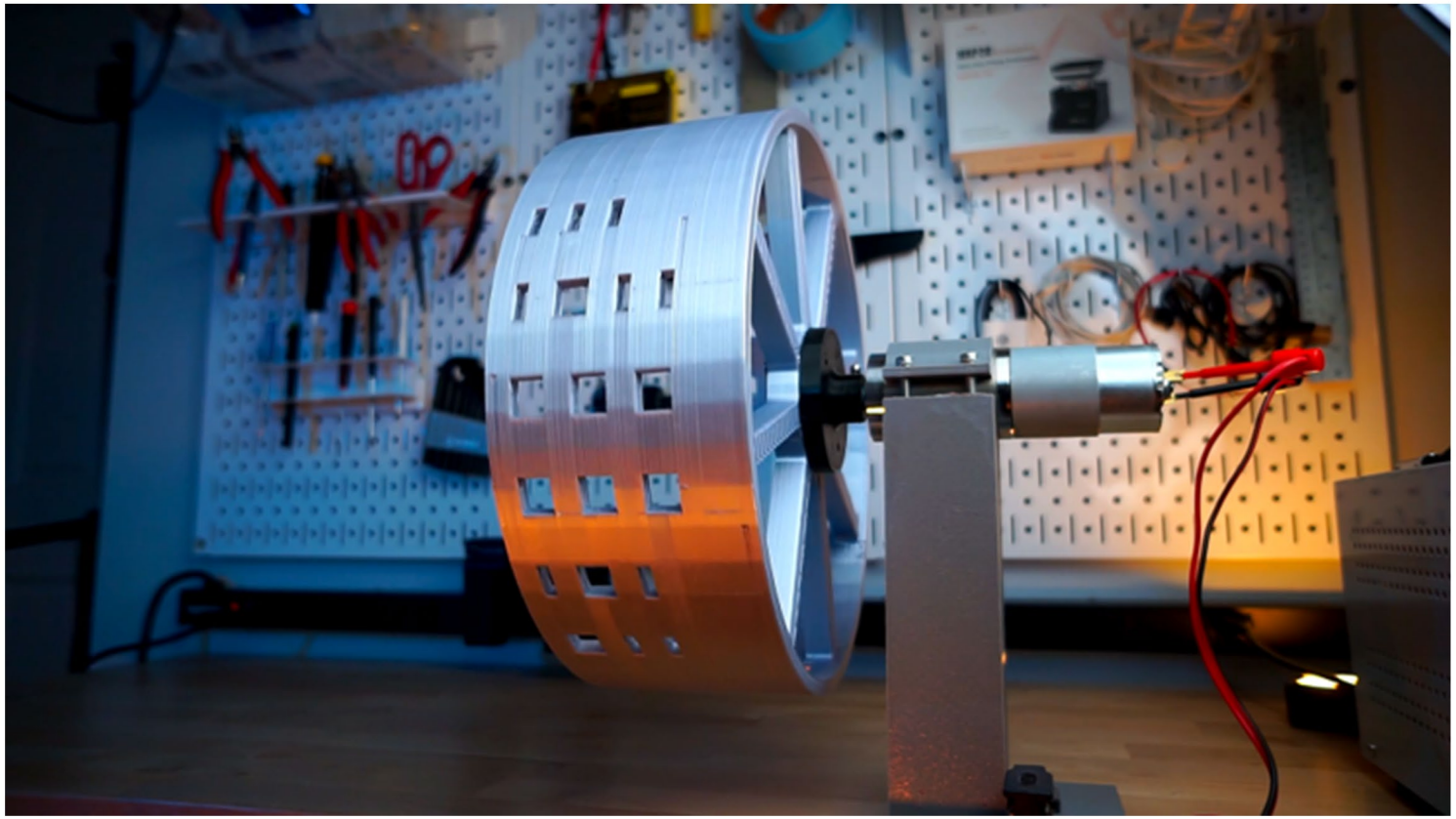
Cost space and optimization path.

MECHANISM DESIGN TOOLCHAIN

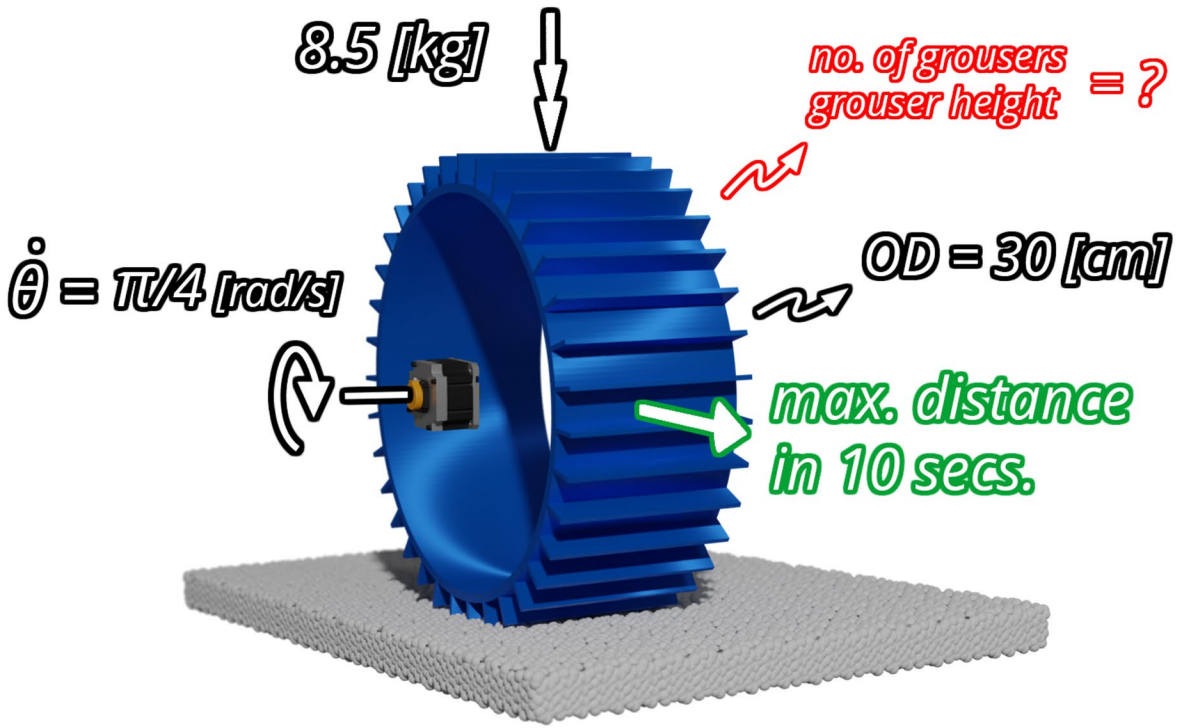




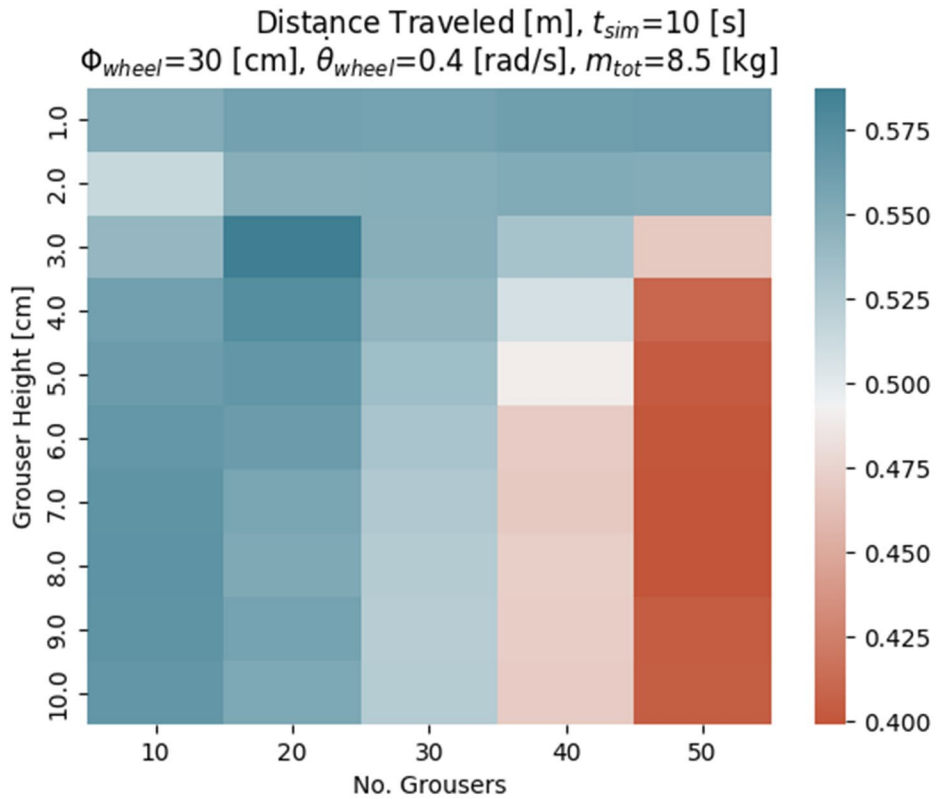
OPTIMIZED MECHANISMS ARE PARAMETRIC AND REMAIN FULLY EDITABLE



MULTI-DIMENSIONAL OPTIMIZATION

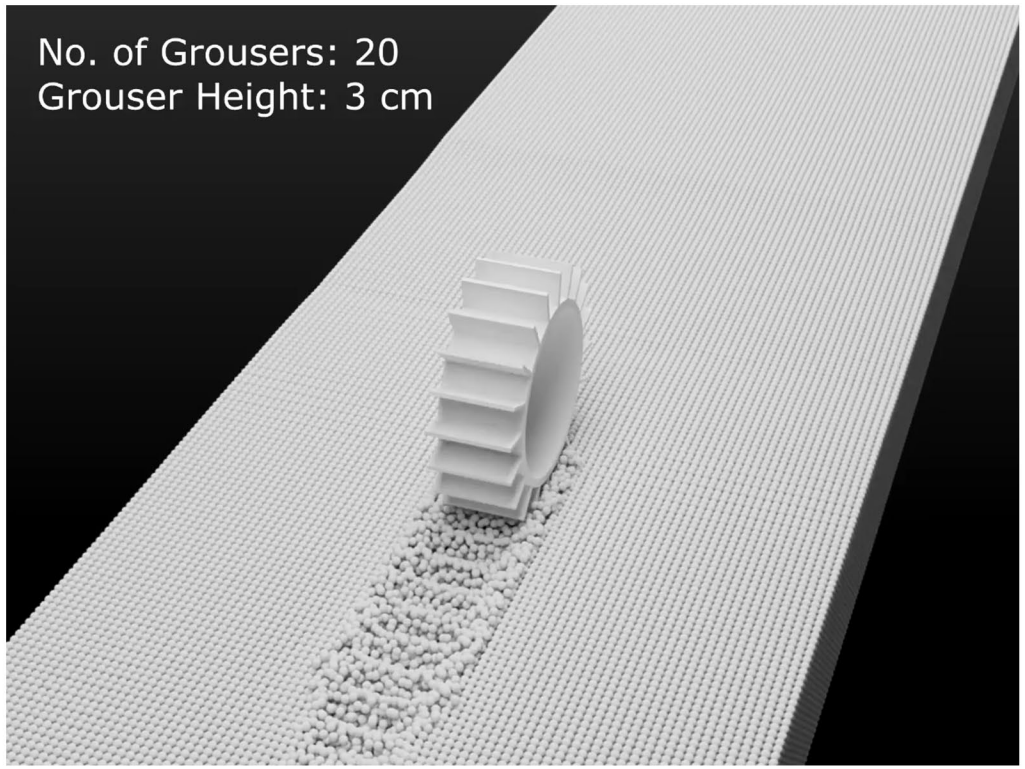


2D wheel optimization problem in granular media.

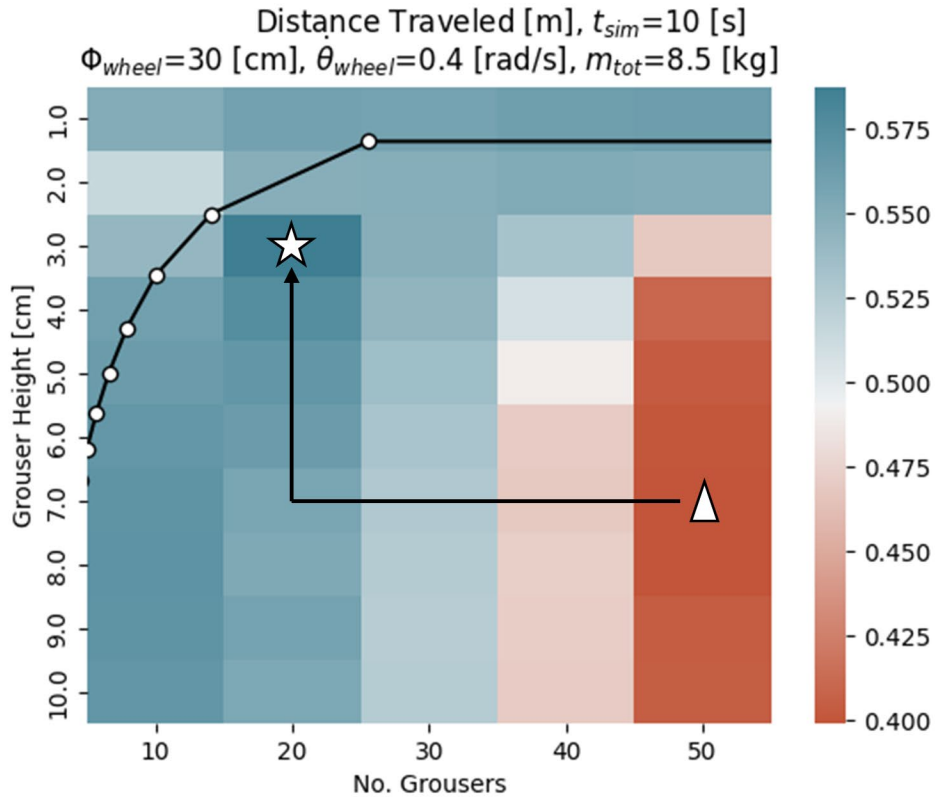


Design space parameter sweep. Simulated in Chrono [2].

MULTI-DIMENSIONAL OPTIMIZATION

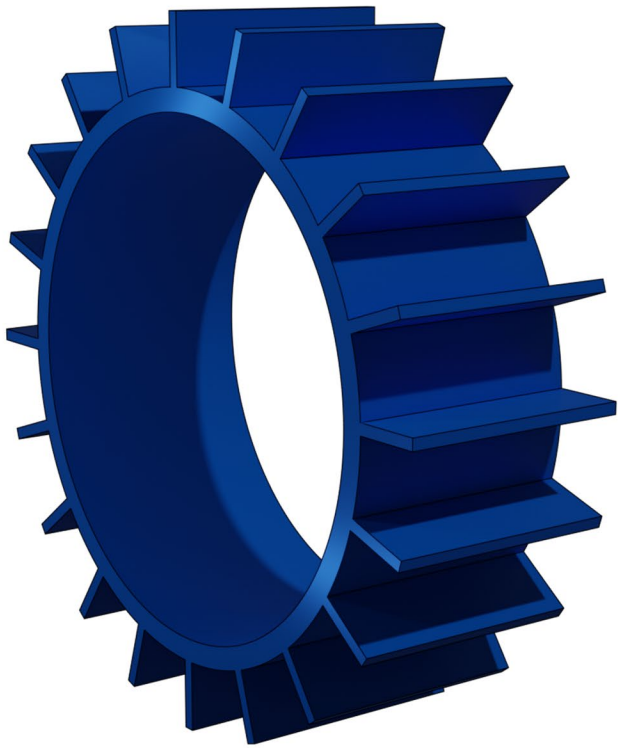


Wheel simulations.

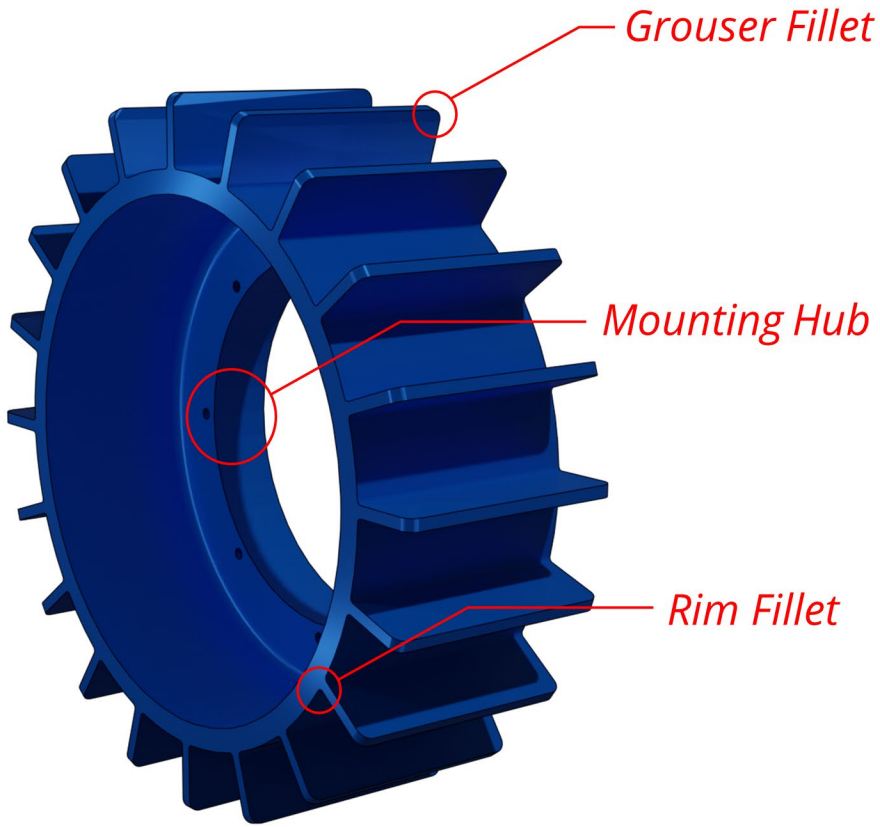


Parameter optimization using discrete hill climbing.
(△→☆: Optimization path. ○: Optimum design at 20% slip suggested by [3].)

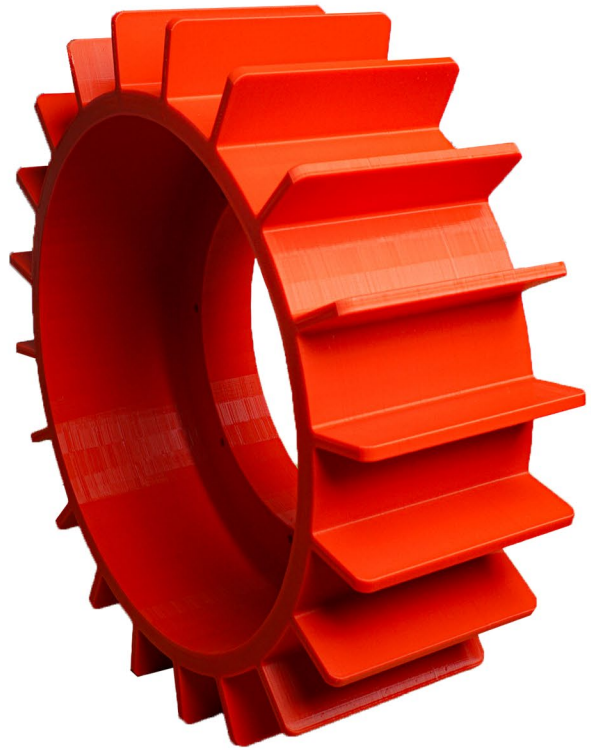
WHEEL MANUFACTURE



Optimized wheel.

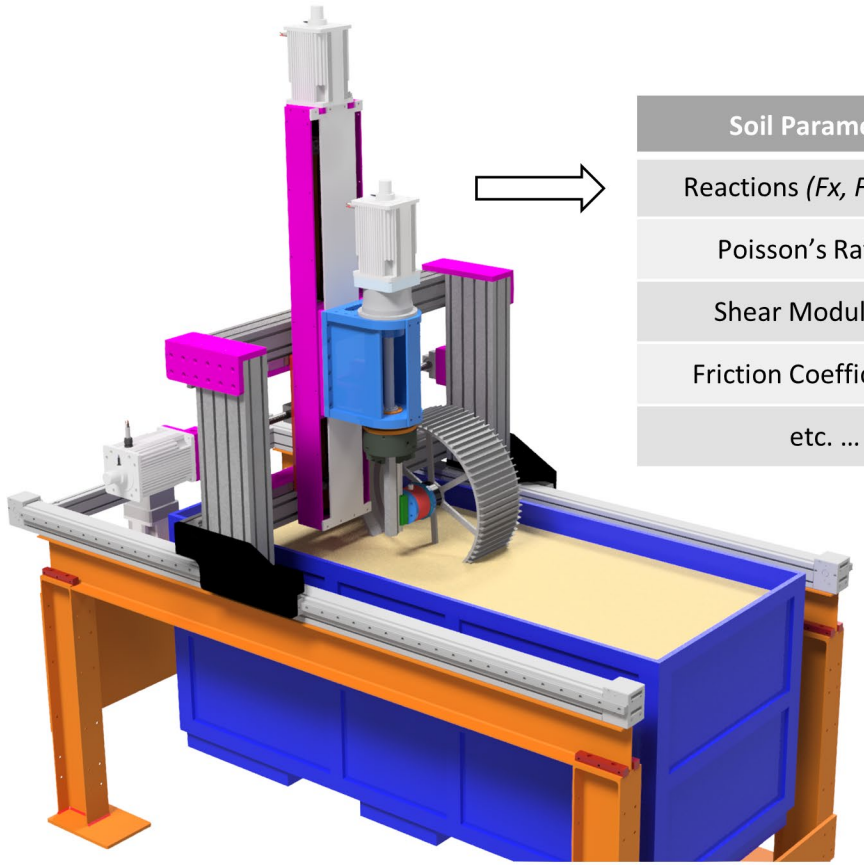


User-modified wheel CAD model.



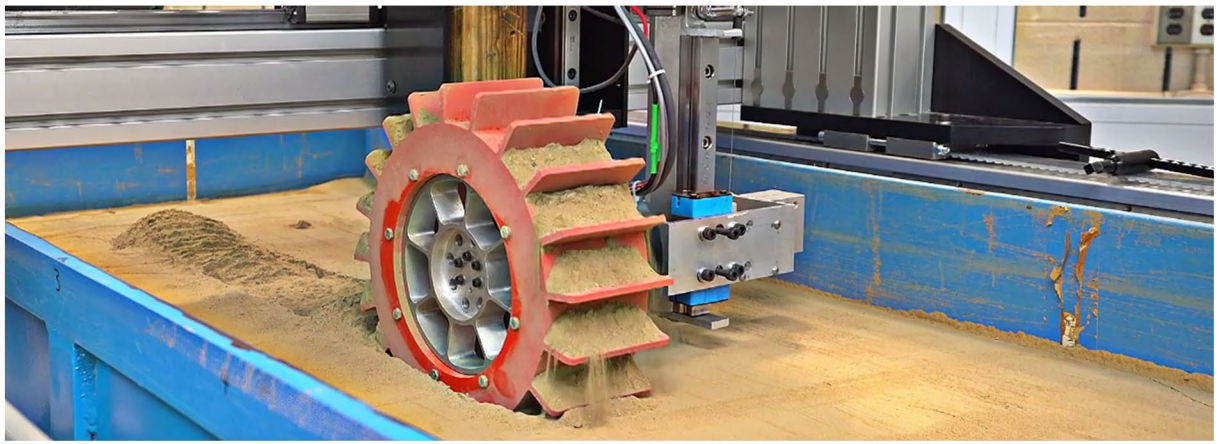
Additively manufactured wheel.

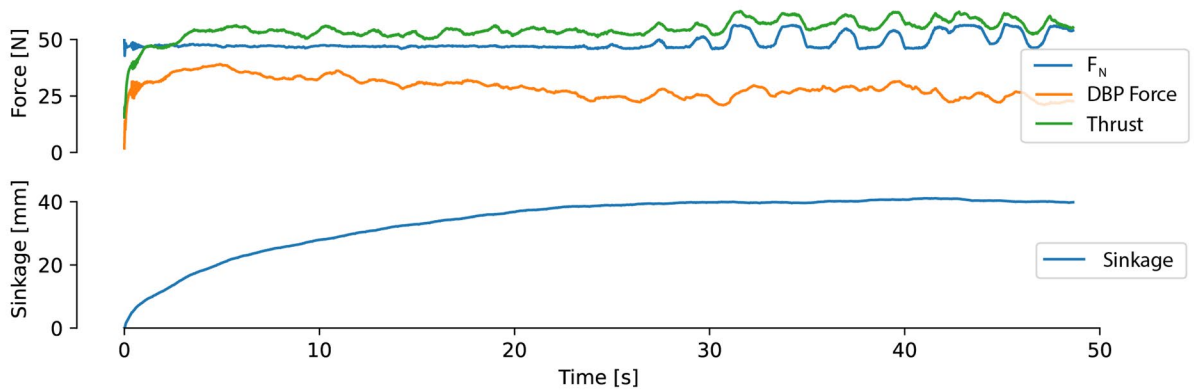
PRELIMINARY WHEEL TESTING



Soil Parameters
Reactions *(Fx, Fy, … Mz)*
Poisson's Ratio *(v)*
Shear Modulus *(G)*
Friction Coefficient *(μ)*
etc. …

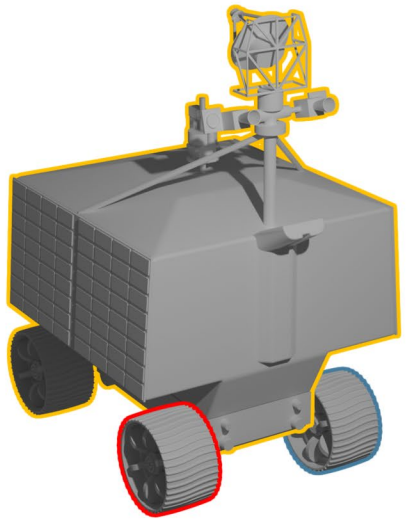
GRC soil characterization rig.

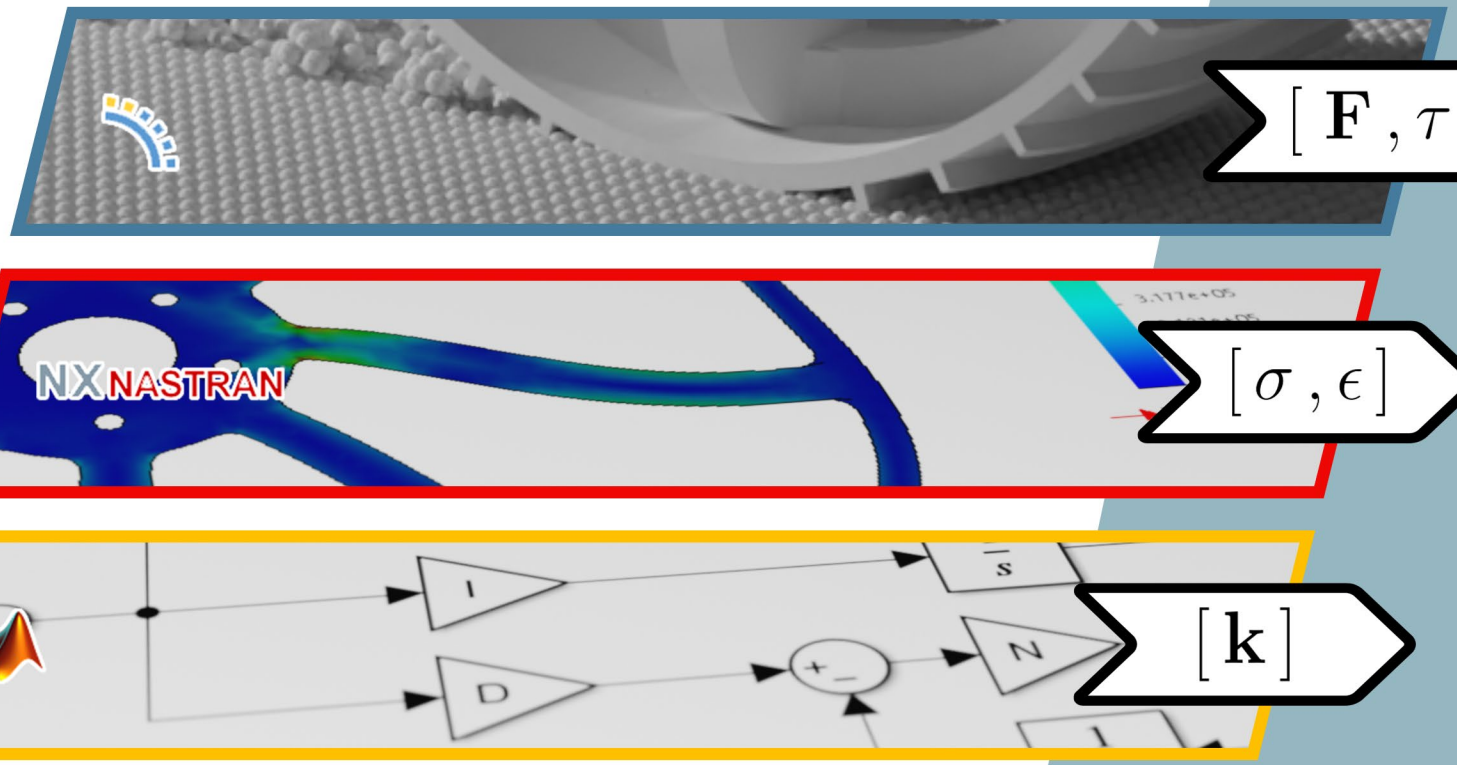




Drawbar pull (DBP) testing with optimized wheel in GRC-3b [4].
(Slip controlled to be 54% (v_{ref}=1.67 [cm/s], v=0.77 [cm/s]).)

MULTI-OBJECTIVE FORMULATION ENABLES MODULARITY AND CO-OPTIMIZATION



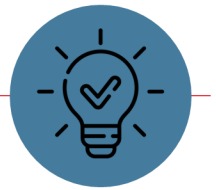


$[\mathbf{F}, \tau]$

$[\sigma, \epsilon]$

$[\mathbf{k}]$

$g(\mathbf{x})$



SUMMARY

- We have developed a modular mechanism optimization tool.
- Outputs parametric CAD that can be further post-processed.
- Can leverage high-fidelity simulation tools for virtual design.
- Simulation calibration and validation is in progress.
- Toolchain development is ongoing (comparison to [3]).

THANK YOU! QUESTIONS?

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Sources:
[1] N. Hansen and A. Ostermeier. Completely derandomized self-adaptation in evolution strategies. *Evolutionary Computation* 9(2).
[2] A. Tasora *et al*. Chrono: An open source multi-physics dynamics engine. *High Performance Computing in Science and Engineering – Lecture Notes in Computer Science,* Springer, 2016.
[3] K. Skonieczny *et al*. A grouser spacing equation for determining appropriate geometry of planetary rover wheels. *IEEE/RSJ IROS*, 2012.
[4] C. He *et al*. Geotechnical properties of GRC-3 lunar simulant. *Journal of Aerospace Engineering* 26(3), 2013.