Capabilities and Scalability of the Regolith Advanced Surface Systems Operations Robot (RASSOR)

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RASSOR – Low gravity excavator

Dry Mass: 66 kg   Payload Capacity: 90 kg

- Low mass excavator design was motivated by the end of the Constellation program
- Assumed near term missions would be robotic precursors with small, low payload landers.
- 50 kg target dry mass

Challenge

Balovnev = Bekker

F_H = DP

(Horizontal Excavation Force) (Drawbar Pull)

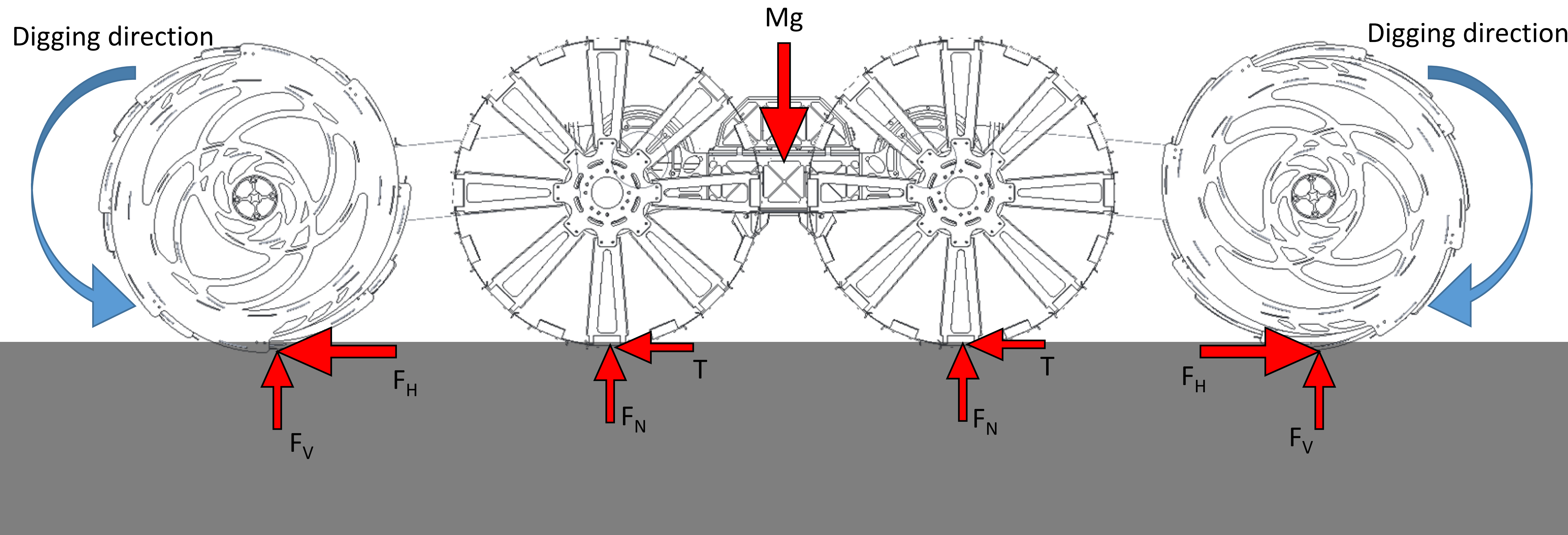
$$F_H = wd(1+\cot\beta\tan\delta)A_1\left[\frac{dg\gamma}{2}+c\cot\phi+gq + B\times(d-l\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right] + we_b(1+\tan\delta\cot\alpha_\beta)A_2\left[\frac{e_bg\gamma}{2}+c\cot\phi+gq + d\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right] + 2sdA_3\left[\frac{dg\gamma}{2}+c\cot\phi+gq + B\times(d-l_s\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right] + 4\tan\delta A_4 l_s d \times\left[\frac{dg\gamma}{2}+c\cot\phi+gq+B\times(d-l_s\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right]$$

$$R_i = b\left[\left(\frac{k_c}{b}+k_\phi\right)\frac{z_i^{n+1}}{n+1}\right]$$

$$H_i = rb\int_0^{\theta_0}(c+\{(k_c/b+k_\phi)[r(\cos\theta-\cos\theta_0)]^n\}\tan\phi) \times(1-\exp\{-r/K[\theta_0-\theta-(1-j)(\sin\theta_0-\sin\theta)]\})\cos\theta d\theta$$

$$DP = N_w(H_i - R_i)$$

Principle of operation



Shallow surface excavation

Excavate regolith/gravel mix and deliver to hopper

Dumping Collected Regolith

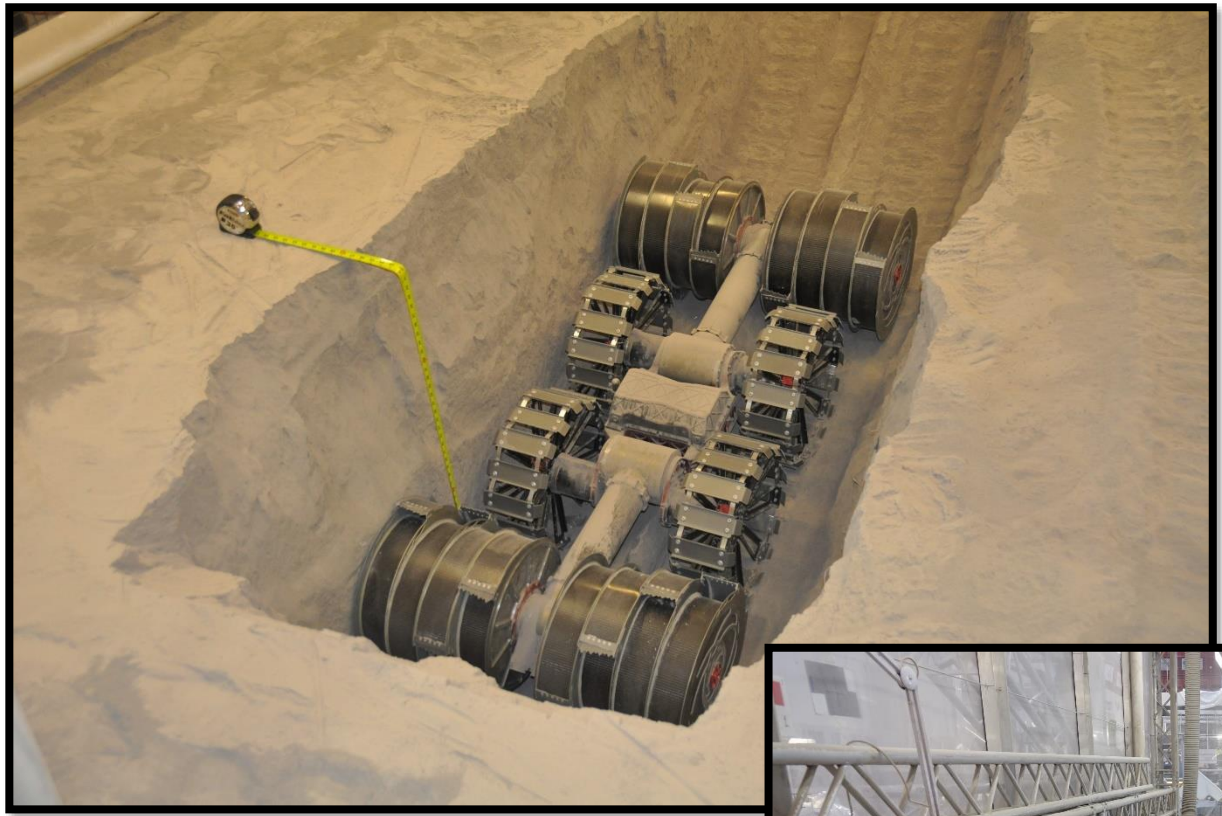
Nominal mode

Z-Position mode

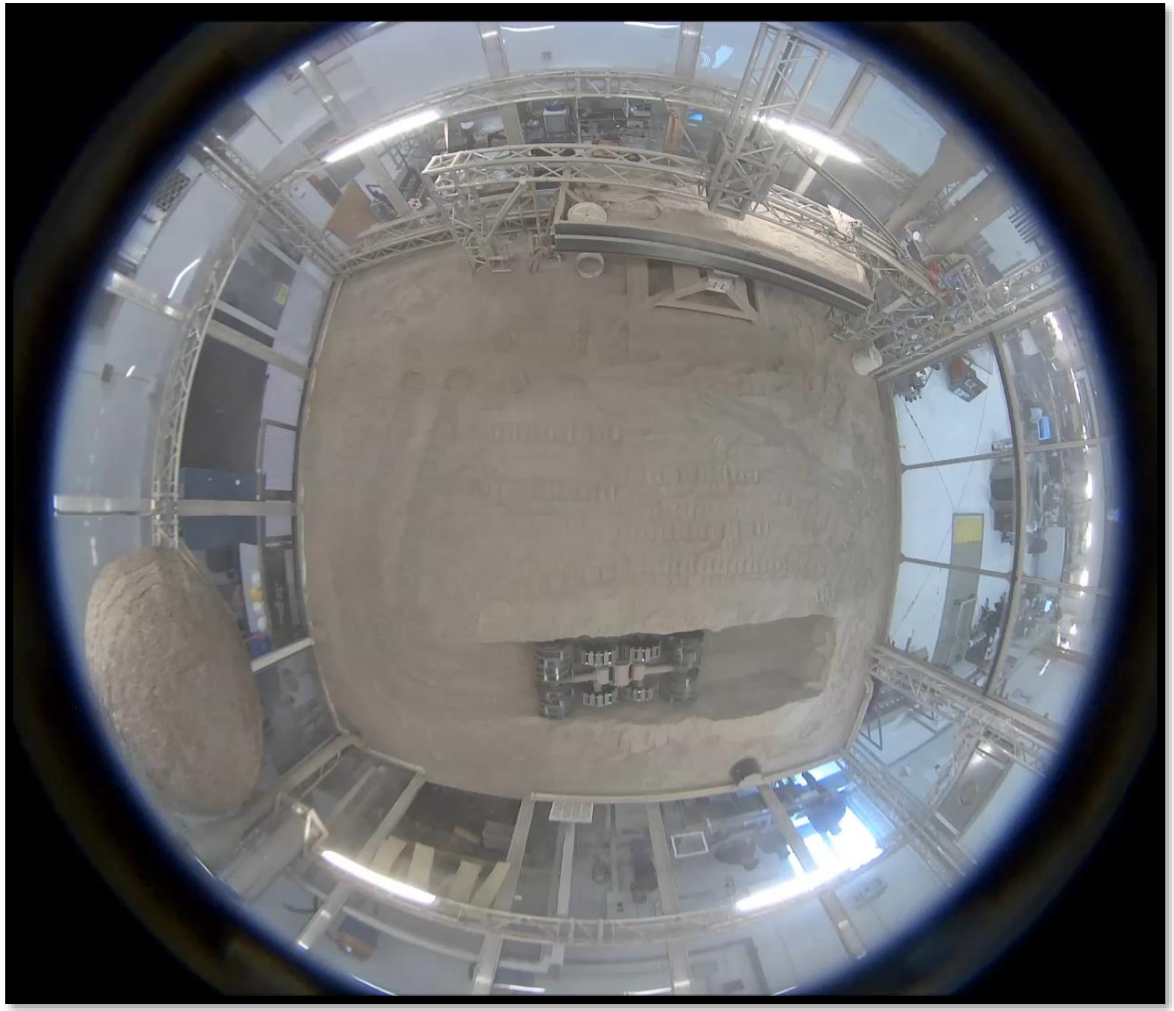
Lander egress/ingress & large obstacle traverse

CG shifting to climb steep slopes

Deep digging/trenching/(grading?)



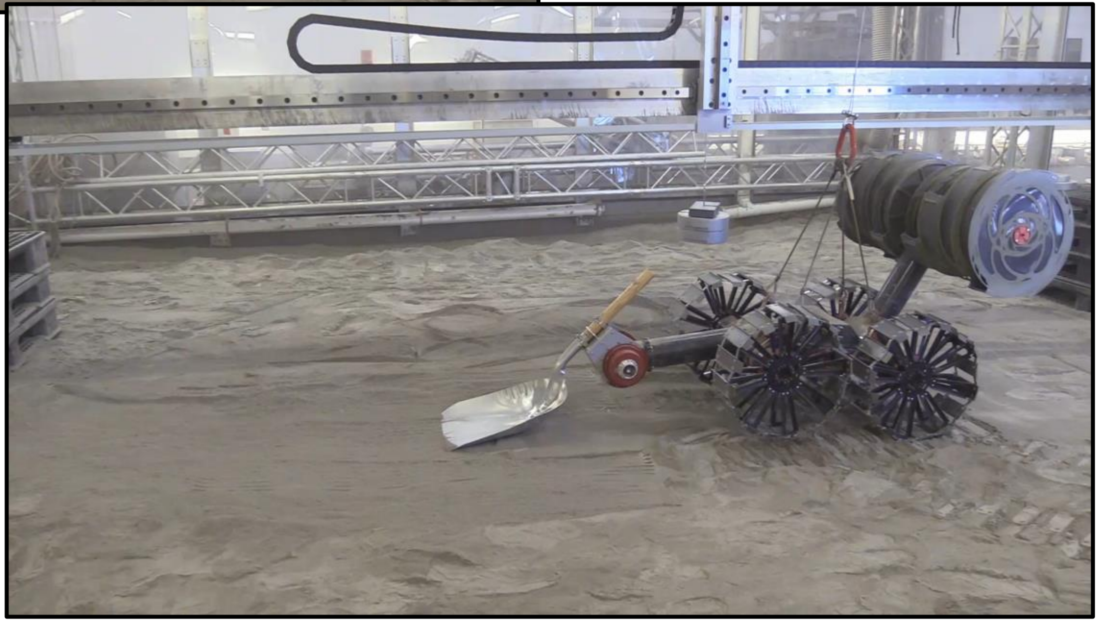
Deep digging/trenching



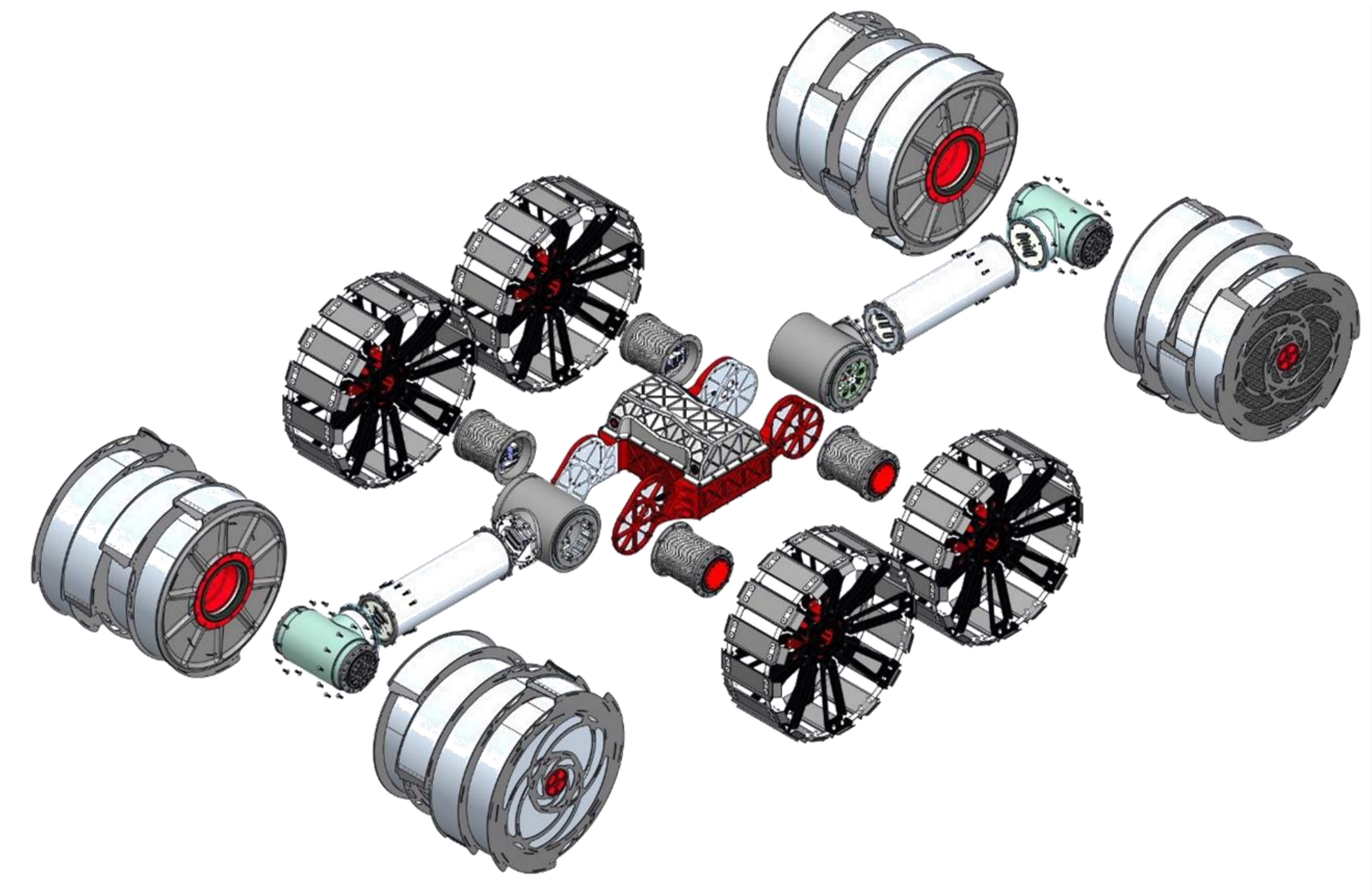
Self Righting

Driving on drums (wheel change)

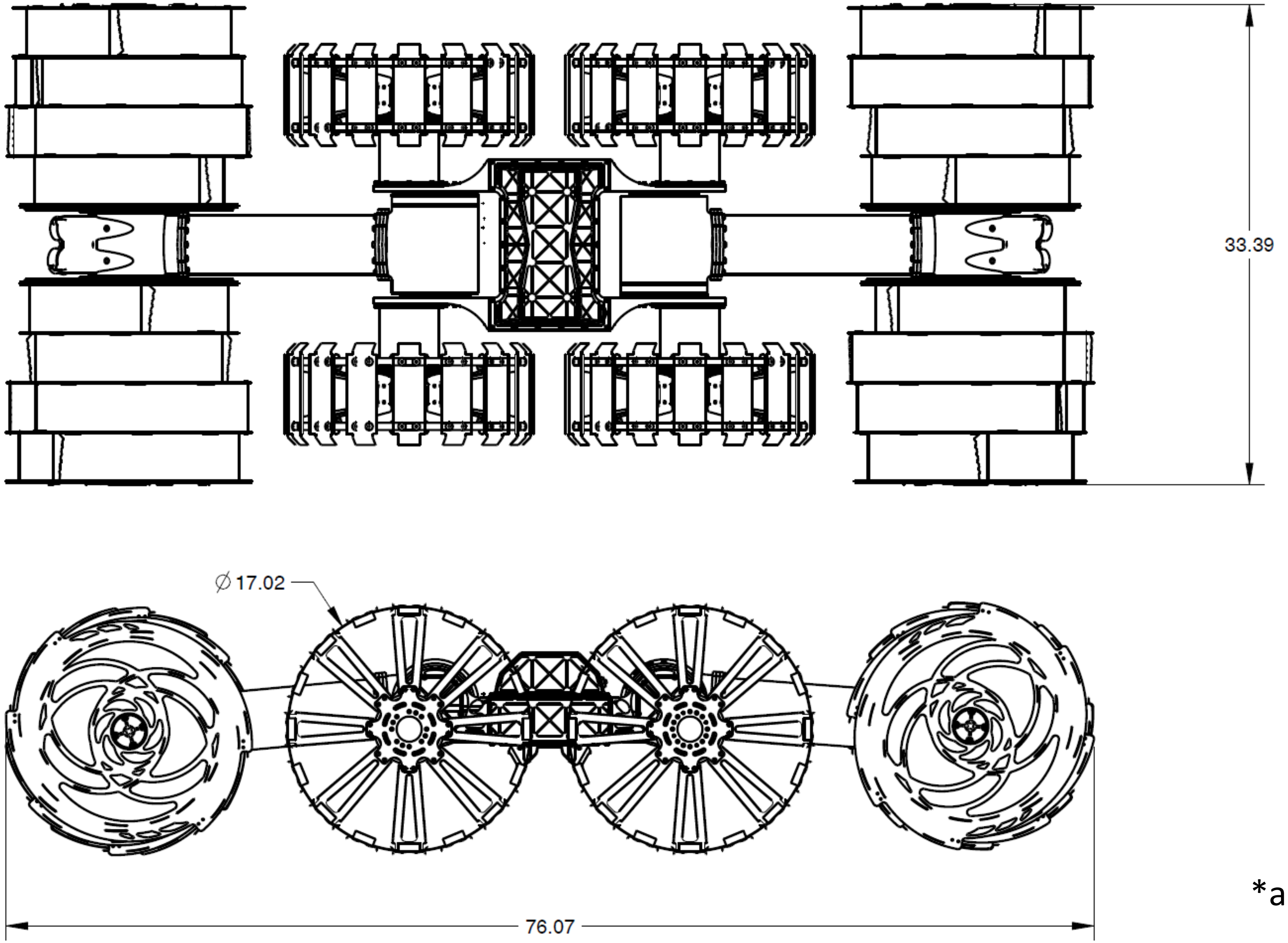
Gravity Offloading Tests



Modular design

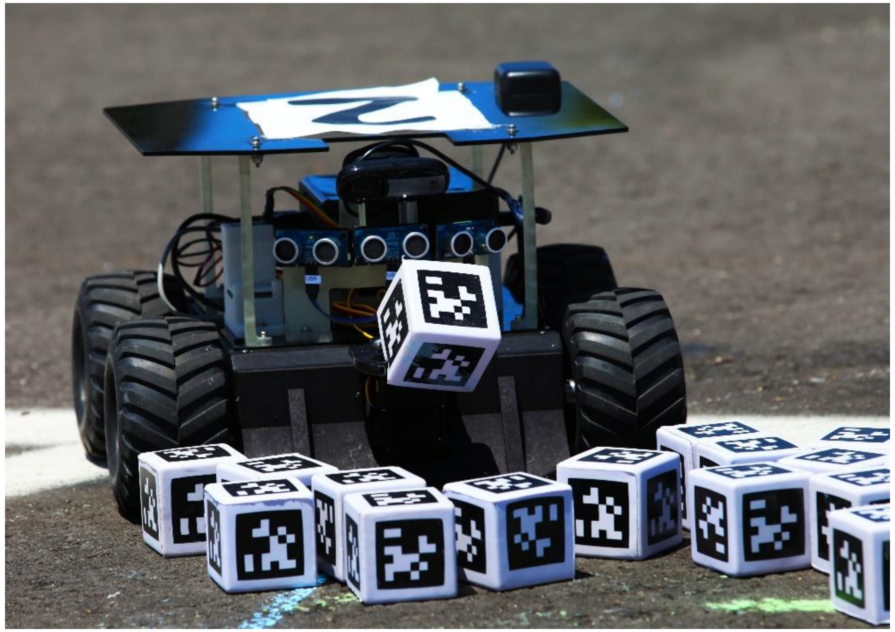


Current overall dimensions

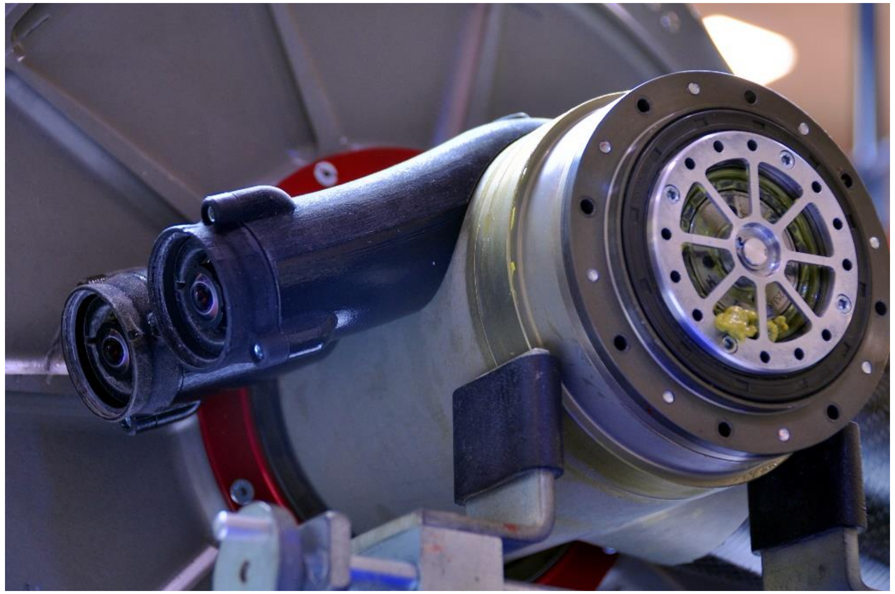


*all units are inches

Navigation/Autonomy Strategy



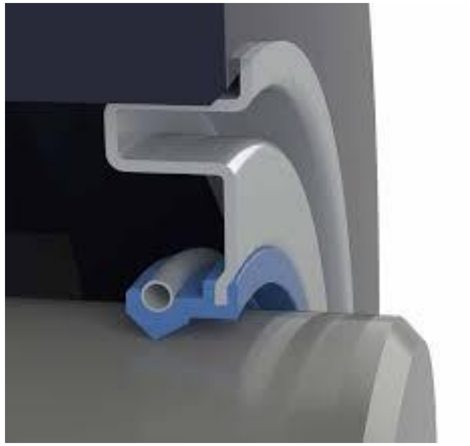
- Currently uses april tags for point-to-point navigation in the KSC regolith testbed
- On-board sensors: Stereo camera pairs on each arm, central IMU

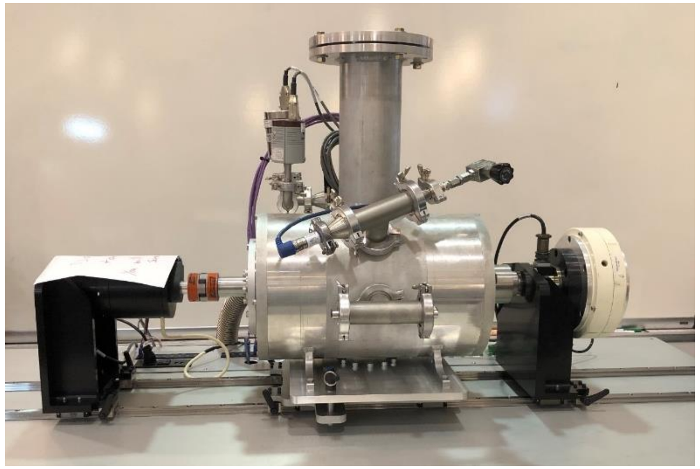


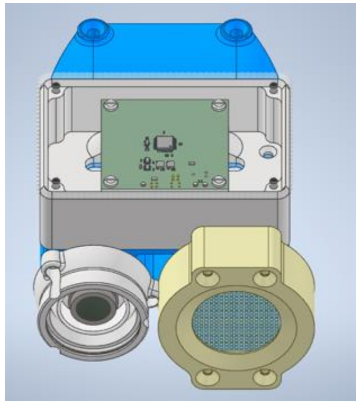
- Lunar con-ops
  - Use combination of navigation aides/beacons and terrain relative navigation
  - Supervised autonomous operation
  - Initial traverse to excavation site slow then repeat trips at a faster pace following initial path
  - Communications to lander and relayed to ground

Dust Mitigation

- Current version uses elastomeric spring energized seals.
  - Very successful but not appropriate for lunar environment
- Leading agency work on rotary joint dust seals for sustained lunar operations
  - Evaluating the state-of-the-art sealing technique used on Mars rovers for long-term lunar ops.
  - Operational lifetime testing in dirty thermal vacuum dynamometer
- Electrostatic dust shield
  - Repels and removes dust using pulsed electrical current
  - Currently building a prototype for stereo camera lenses
- Thermal control system
  - Dust will adhere to radiator surfaces reducing their effectiveness
  - Considering alternatives such as phase change materials to temporarily store heat with reset at lander during battery recharge.







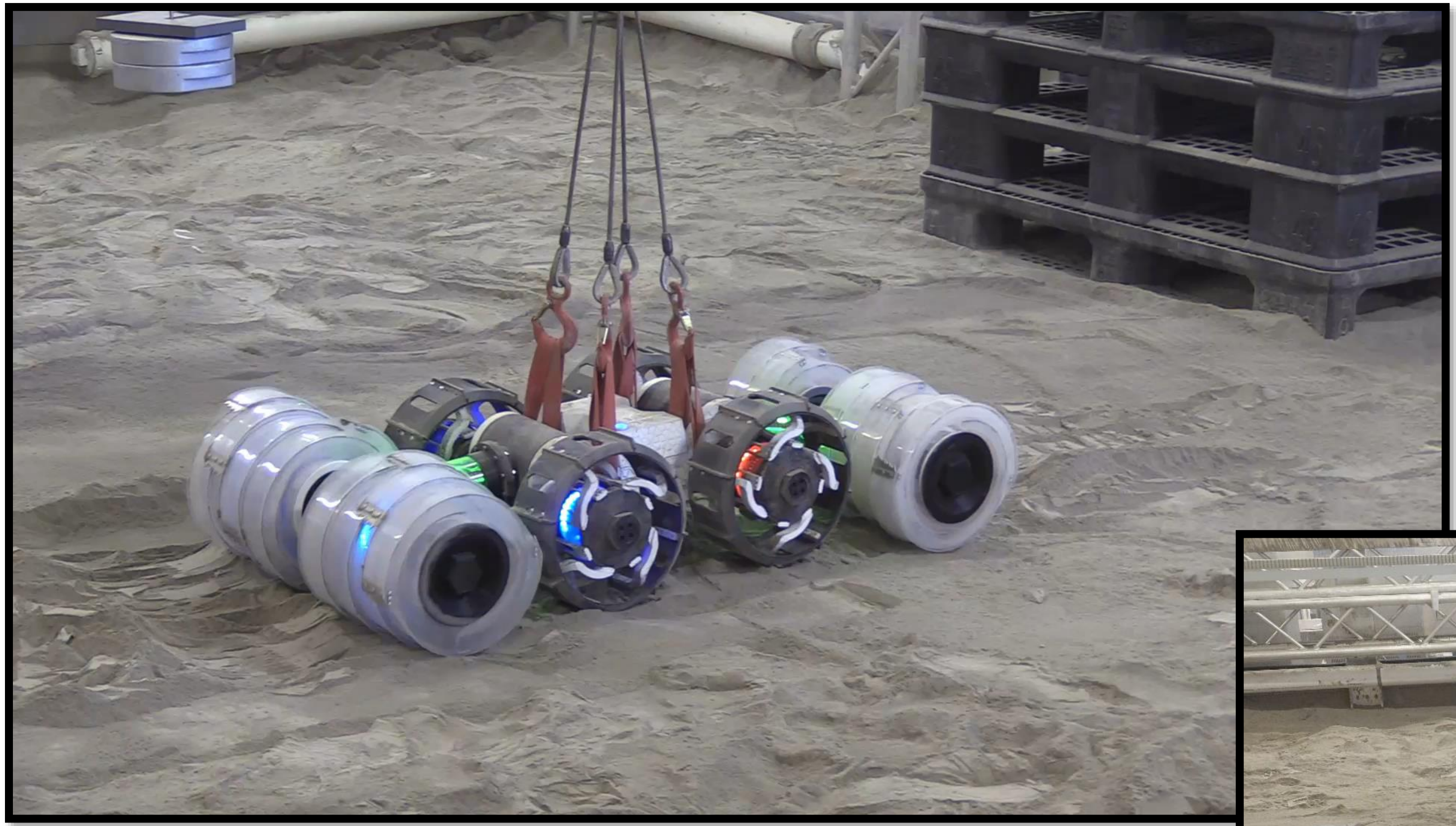
Can we scale the design?

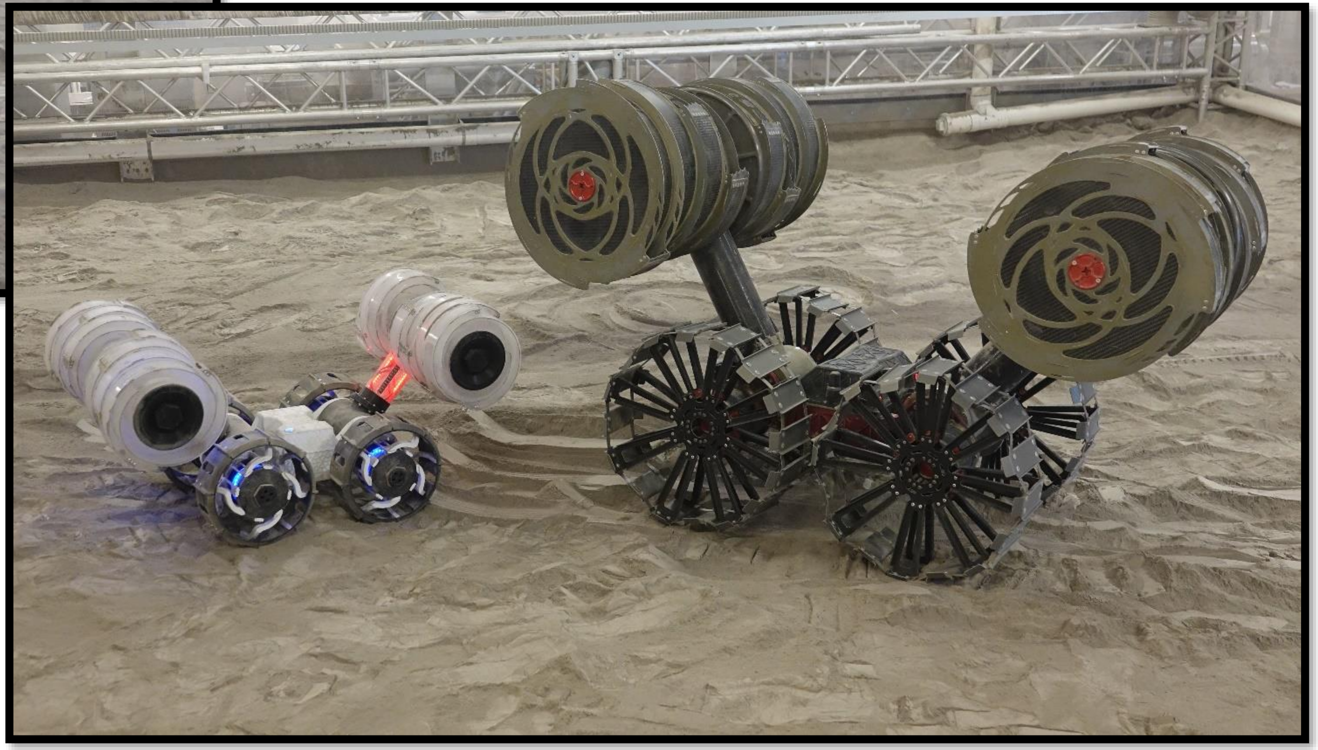
- Reducing the scale of RASSOR may allow for demonstration of the excavator on future CLPS missions.
- Reduction in scale of conventional excavators will exacerbate their lack of reaction forces and may no longer weigh enough in 1/6g to be able to overcome the excavation resistance.
- RASSOR however does not rely on its weight to provide the reaction force and therefore can scale up or down with little effect.

> Another important observation is that reducing an excavator's scale magnifies the effects of cohesion. Because the 'gravity' term in F_{ex} includes a product of 3 lengths (wd^2) while the 'cohesion' term just 2 (wd), reductions in scale lower the 'gravity' contribution more than they lower the 'cohesion' contribution. A related analysis with similar conclusions was put forward by Zacny et al [81].
>
> **Credit: Skonieczny, 2013**

Smaller scaled excavators see proportionally higher excavation forces.

Reduced Scale Proof Of Concept

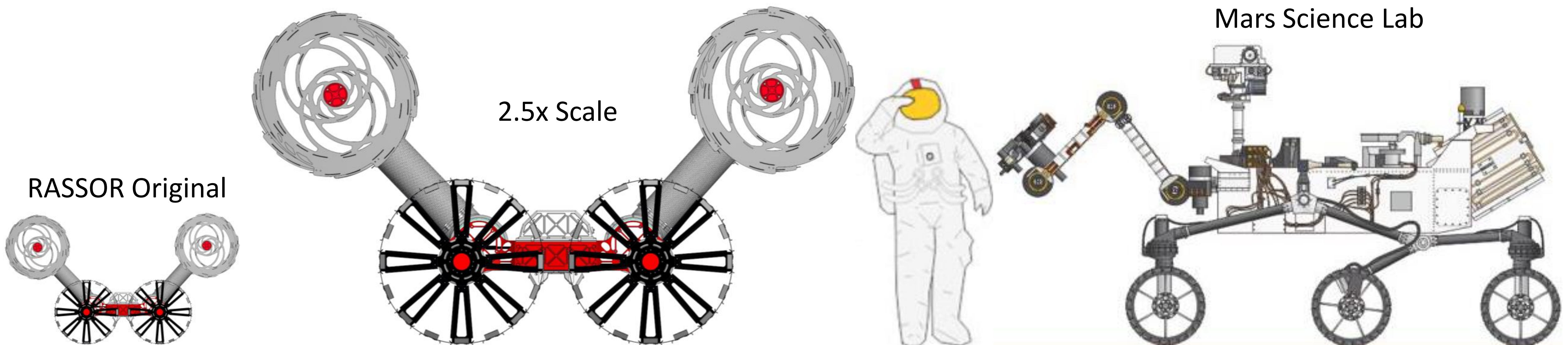




Increasing RASSOR scale

- To meet the demand of 4 metric tons of excavated material per hour for LUNOX production RASSOR must be scaled up.
- A linear geometric scaling factor of 2.5x was assumed
  - Provides a point design to serve as a baseline
  - With additional inputs future work could focus on the optimal scale with consideration to power, mass, volume, and operational time.

Graphics Credit:
HistoricSpacecraft.com



Increasing RASSOR scale

- The current RASSOR bucket drum geometry has a fill ratio (volume of captured regolith/volume of bucket) drum of about 50%.
- Keeping this ratio and RASSOR physical proportions constant with a scaling factor of 2.5 yields the following metrics:

Metric	Value
Dry Mass	1333 kg (assumed PR 1:1)
Regolith Payload Mass	1333 kg
Cycle Time (100m case)	20 minutes
Power/Cycle	206 Whr
Battery Size	3.5 kWhr
Cycles/Battery Charge	13
Operational time/Battery Charge	4.3 hrs
Battery Charging Time @ 2kW	1.8 hrs

Summary

- Counter acting bucket drum excavators such as RASSOR are the state-of-the-art for reduced gravity excavation
  - Most efficient excavator for surface regolith collection

    Delivers the most regolith for the lowest mass, volume, and energy.
  - Largest payload/dry mass ratio
  - Modular configuration
  - Insensitive to mission architecture changes (landing site, mass allocation, production rates)
  - Built in redundancy and contingency options without adding requirements.
  - Undergone extensive testing: ~250hrs and ~50 tons of excavation
- Scaling to a delivery rate of 4t/hour is possible
  - Linear 2.5x scale of existing RASSOR dimensions
  - MSL/Mars 2020 class volume and mass
- Future Work:
  - Integration of dust tolerant thermal management system
  - Design and specification of flight ready actuators and avionics
  - Integration of dust tolerant charging port
  - Life-time testing of actuators and excavation components in a relevant environment
  - Development of autonomous excavation software
  - Dust tolerant autonomous sensors

Questions