RASSOR Excavator for ISRU Lunar Mining

Space Resources Roundtable

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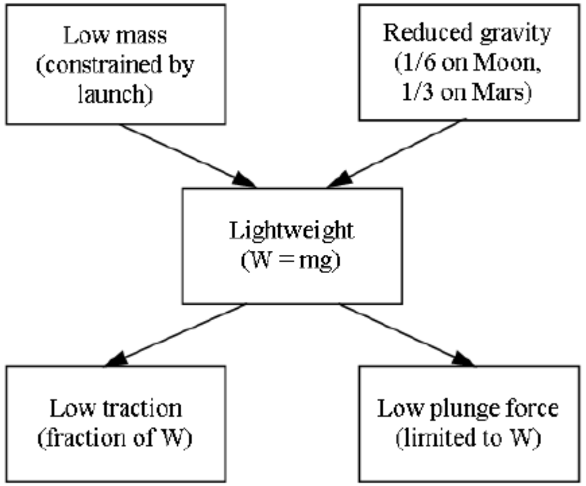
National Aeronautics and Space Administration

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.
- 50Kg target dry mass



Credit: Skonieczny, 2013

Challenge

Balovnev = Bekker

F_H = DP

(Horizontal Excavation Force) (Drawbar Pull)

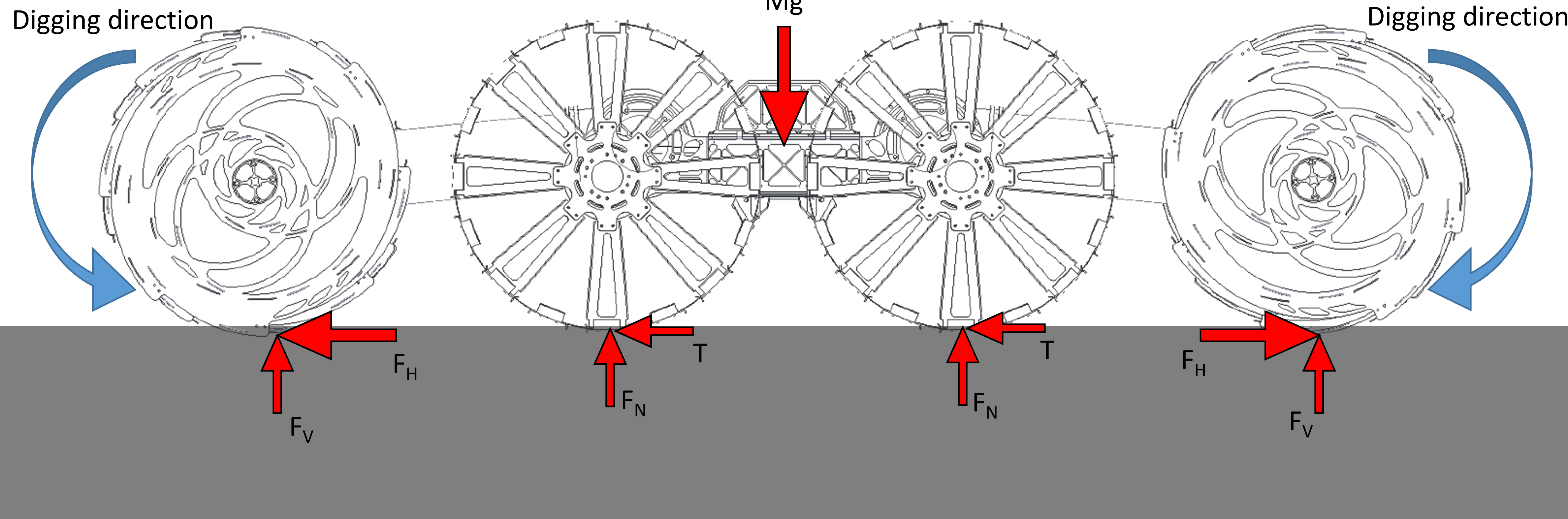
$$
\begin{aligned}
F_H = {} & wd(1+\cot\beta\tan\delta)A_1\left[\frac{dg\gamma}{2}+c\cot\phi+gq\right. \\
& \left.+B\times(d-l\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right] \\
& +we_b(1+\tan\delta\cot\alpha_\beta)A_2\left[\frac{e_b g\gamma}{2}+c\cot\phi+gq\right. \\
& \left.+d\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right]+2sdA_3\lef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

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

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

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

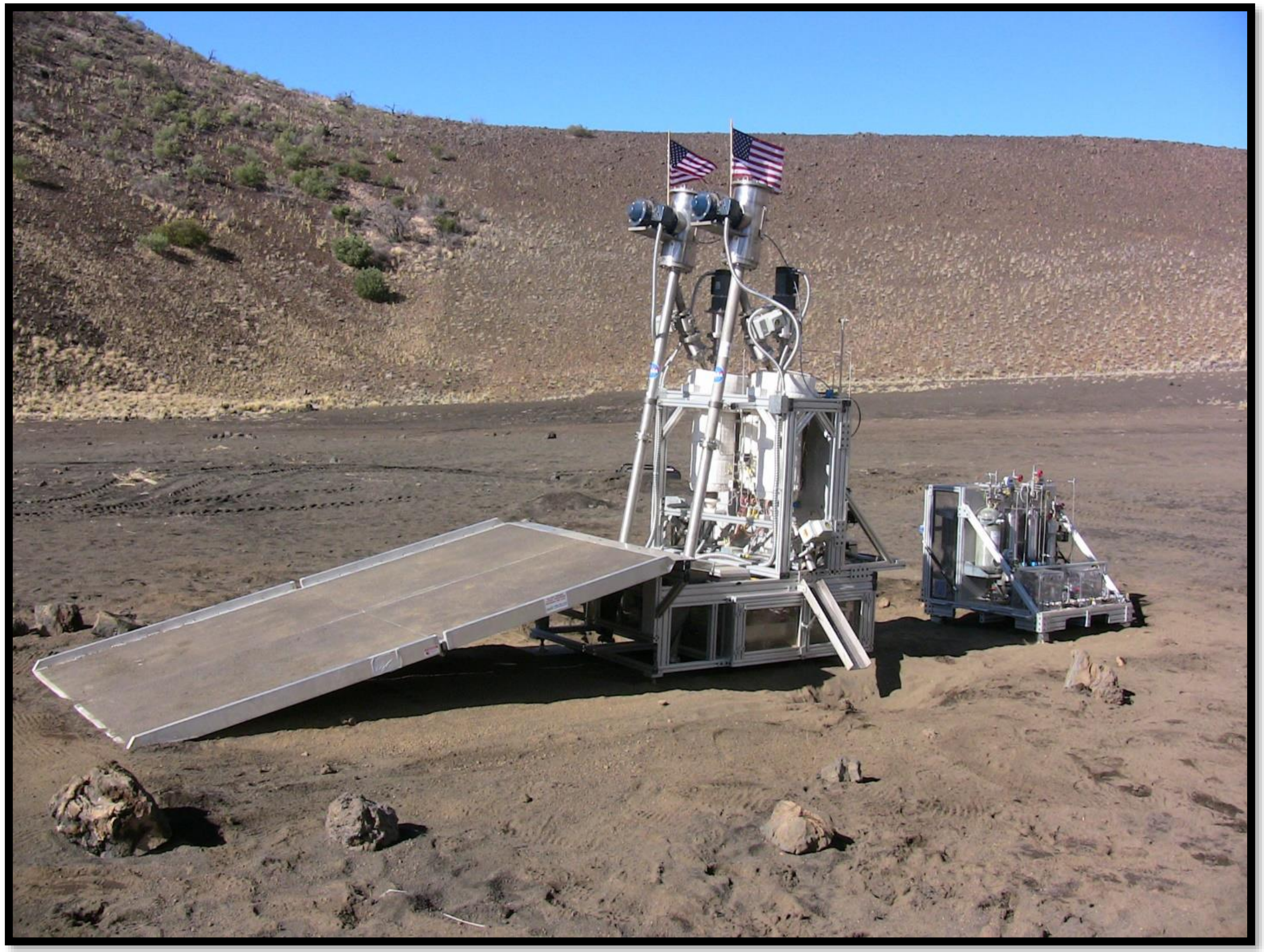
Principle of operation



Shallow surface excavation

Excavate regolith/gravel mix and deliver to hopper

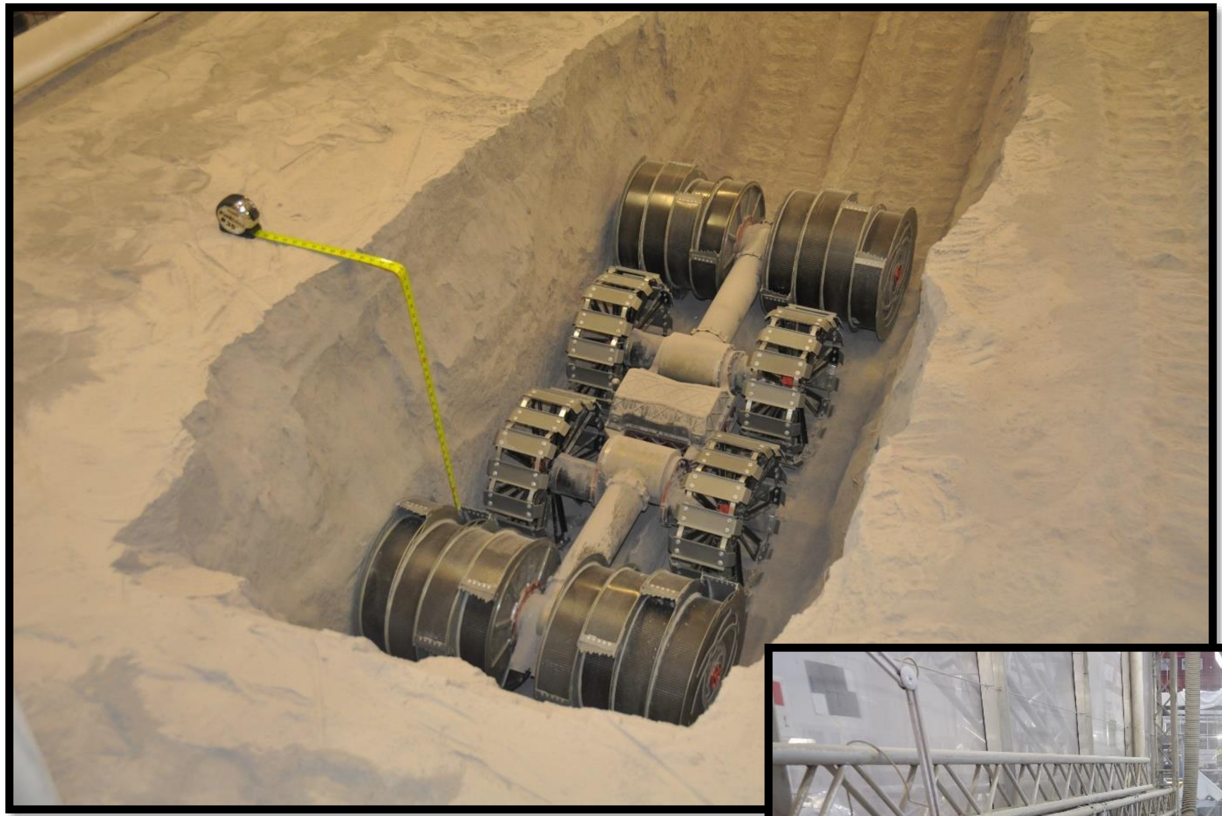
Option to reach tall hopper without a ramp



Lander egress/ingress & large obstacle traverse

CG shifting to climb steep slopes

Deep digging/trenching



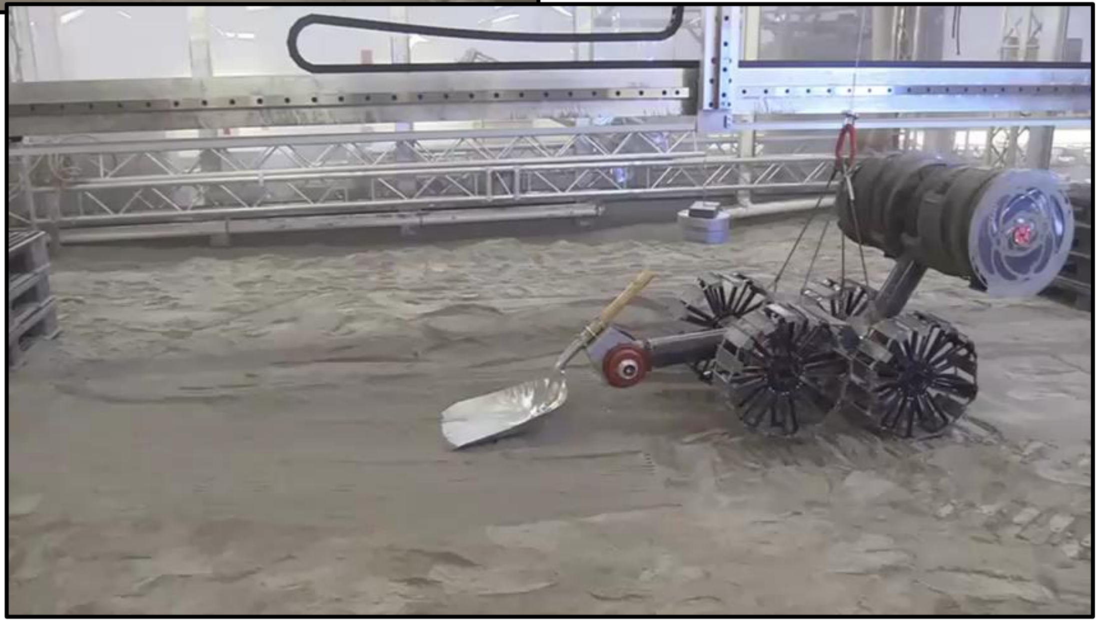
Deep digging/trenching

Self Righting

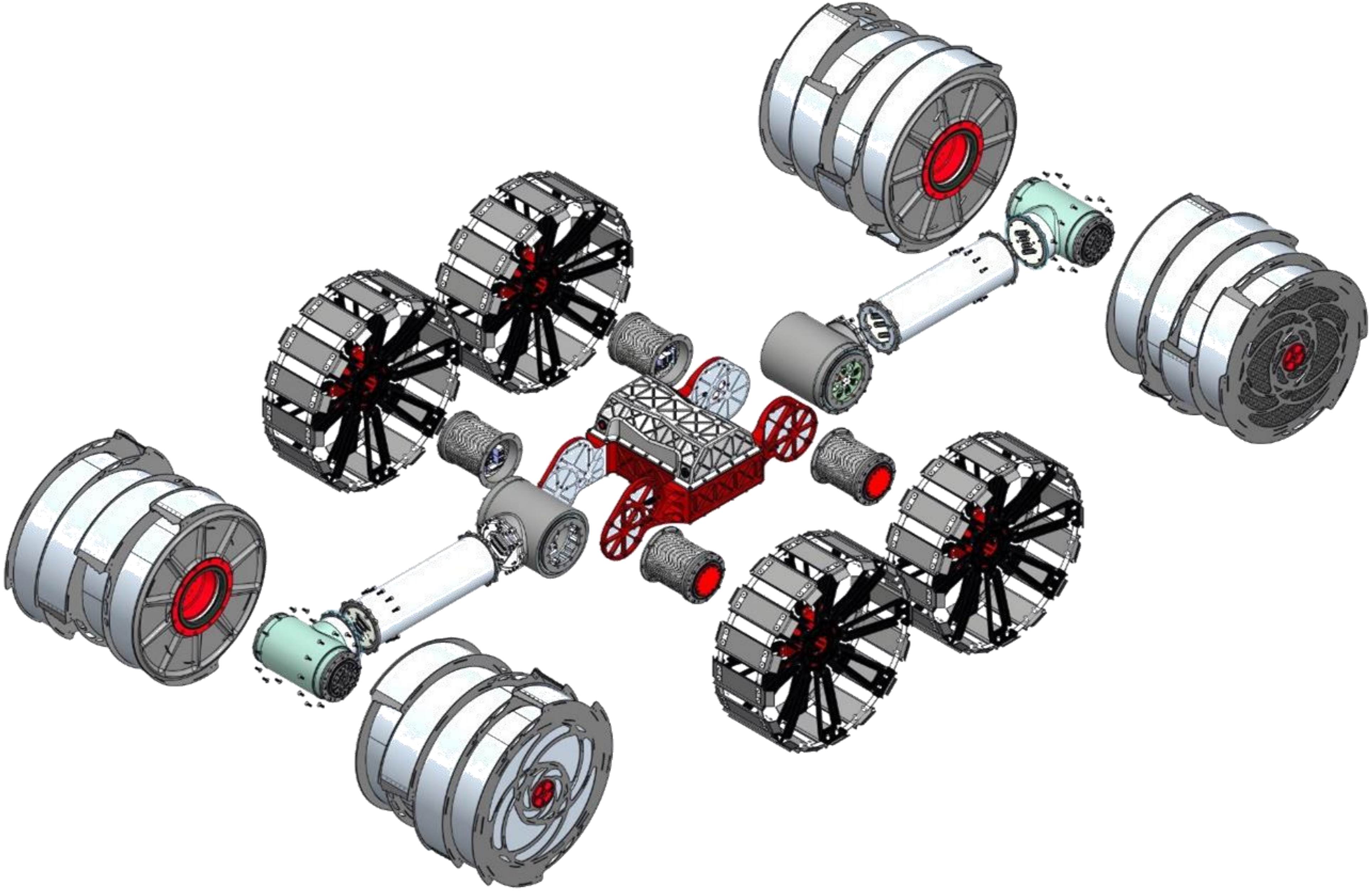
Driving on drums (wheel change)

Gravity Offloading Tests

Dual drum: 16.1 kg/Wh
Single drum: 11.1 kg/Wh
Frontend loader: 3.8 kg/Wh

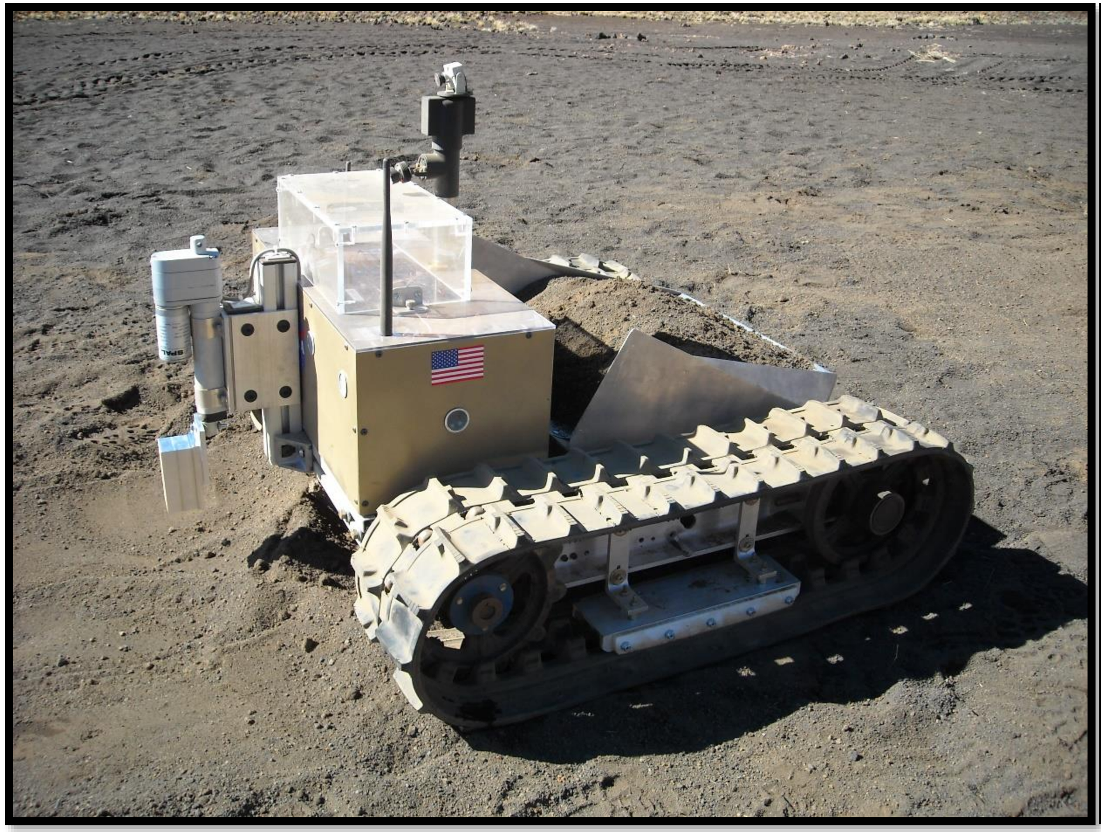


Modular design



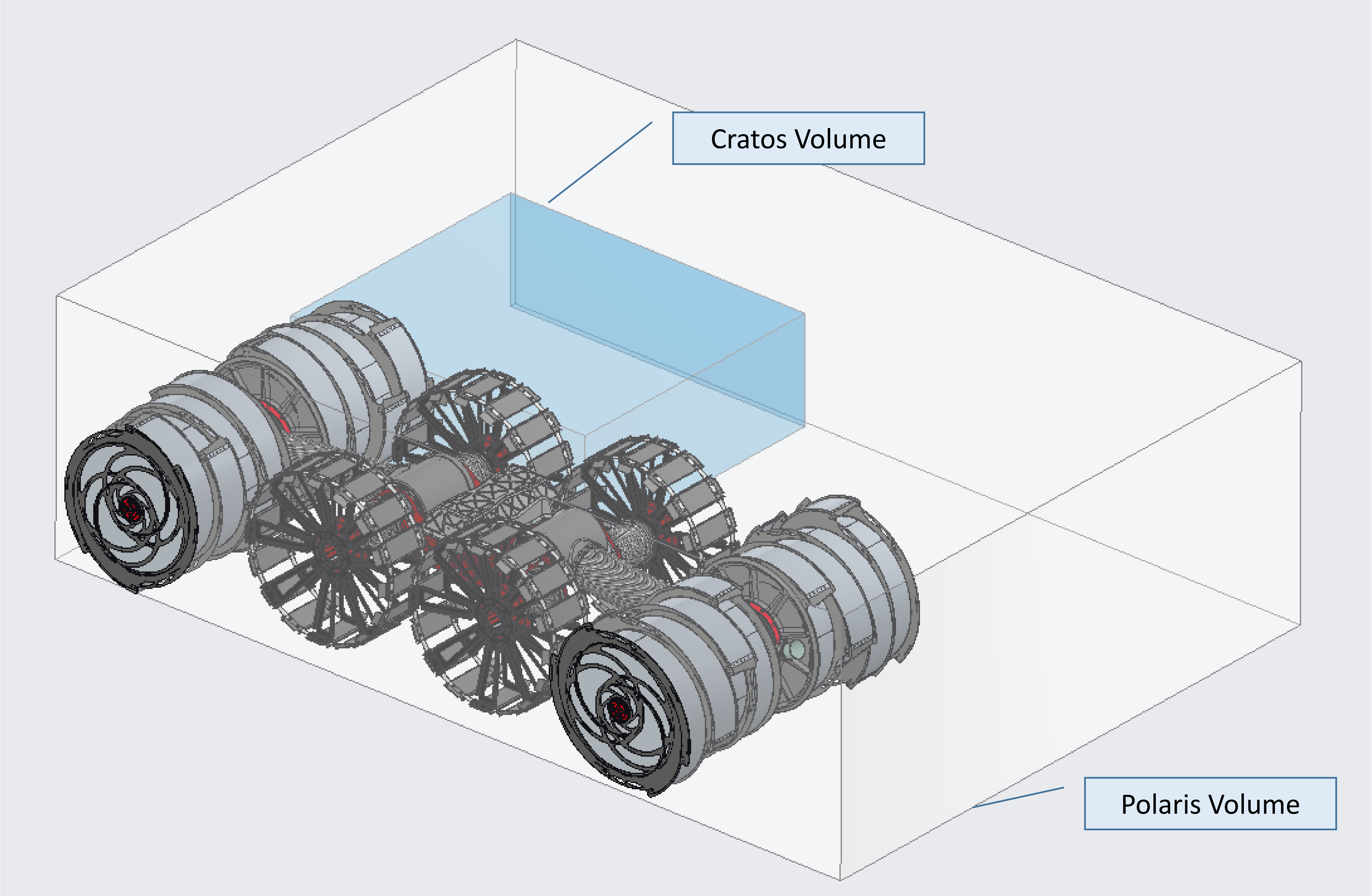
Other excavators designed for the Moon

GRC CRATOS excavator



Astrobotics Polaris excavator

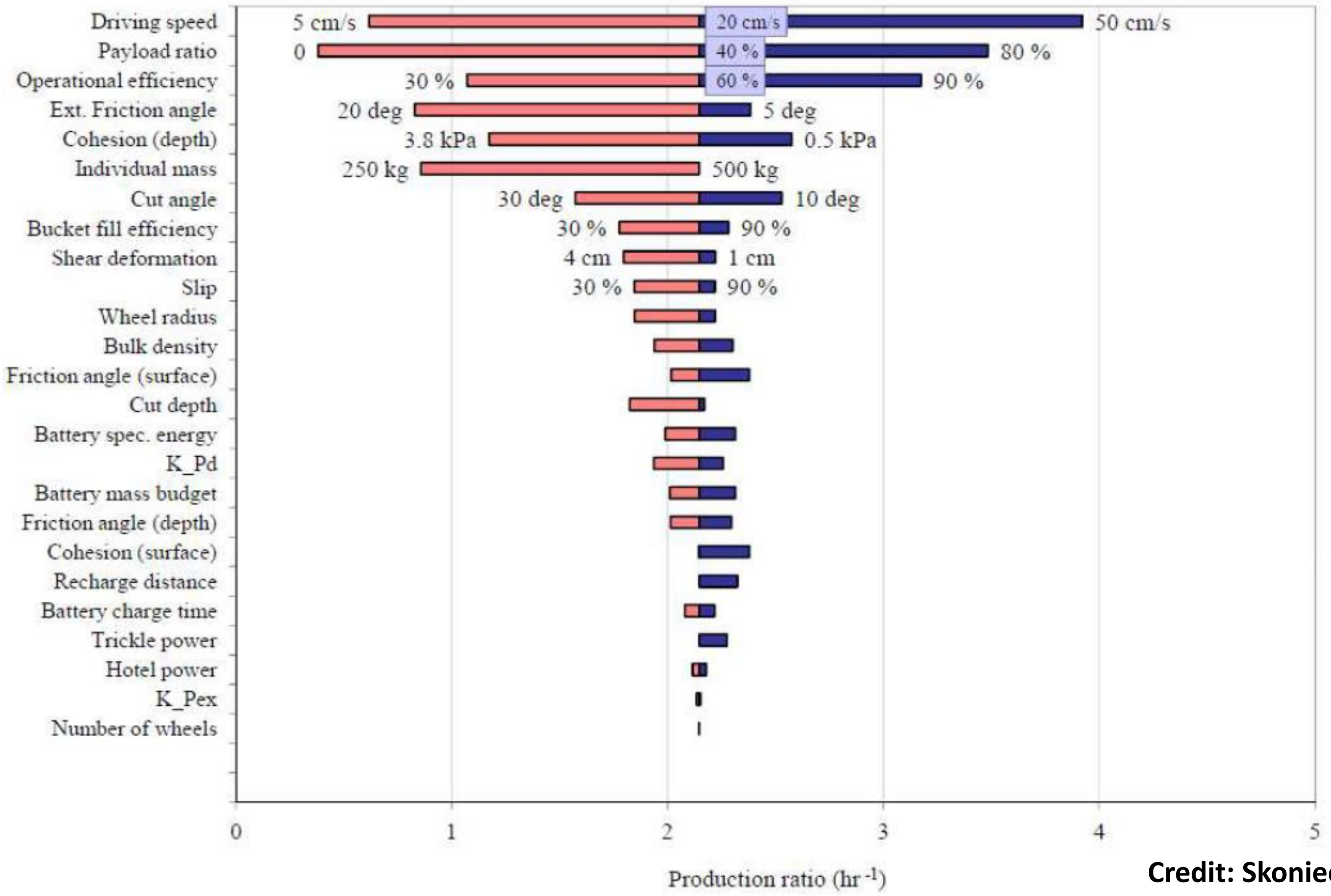
Design Constraints/Parameters	RASSOR	Cratos	Polaris
Propulsion System	Electrically motorized wheels	Electrically motorized tracks	Electrically motorized wheels
Excavation/Storage System	Counter-rotating Bucket Drums	Shallow Rake Angle Bucket	Transverse Bucket Wheel
Dumping System	Reversing Bucket Drum direction	Lift bucket past angle of repose	Lift bucket past angle of repose
Navigation Sensors	Stereo Cameras, IMU, Encoders	Mono Camera	Mono Cameras
Nominal Bus Voltage (V)	51	24	48
Battery Capacity (Whr)	1410	1410	1410
Max driving slope (deg)	35+	10	15
Nominal driving obstacle height (cm)	15		30
Max contingency obstacle height (cm)	75		30
Max height of dump hopper (cm)	75		50
Max pebble size collected (cm)	4		10
Traverse Speed (Max) (cm/s)	44	5	40
Number of trips per charge (100m case)	27	14	12
Recharge time (hrs)	2	2	2
Element Lifetime (goal) (yrs)	5	5	5
Dry Mass/Delivery Rate (kg/kg/hr) (100m)	0.191	5.691	0.413
Power/Delivery Rate (W/kg/hr) (100m)	0.577	4.245	1.006
Dry Mass (kg)	67	77	184
Payload Capacity (kg)	90	23	115 (60)
Payload Ratio	1.34	0.30	0.63
Volume (m^3) (LxWxH)	0.71 (1.93 x 0.85 x 0.43)	0.21 (0.79 x 0.90 x 0.30)	2.77 (2.4 x 1.65 x 0.7)
Self Righting / Self Recovery	Yes (any orientation)	No	No
Number of actuators	10 (8)	3	8
Regolith delivered per charge (100m case) (kg)	2430	322	1380
Time to deliver 1000 metric tons of regolith (hrs)	3672	80135	3698
Time to deliver 1000 metric tons of regolith (24 hr days)	153	3339	154
1000t 5 year mission operational time (hrs)	18362	400674	18488
% daylight required	41.92%	914.78%	42.21%
Total distance traveled for 5yrs (km)	5556.6	21739.2	4348.8
Total time spent excavating (hrs)	2315	1812	1087


Cratos Volume
Polaris Volume

Production Ratio - Sensitivity

- The factors that effect production the most are the factors RASSOR is the best at:
  - Speed
  - Payload Ratio

- And the least sensitive to:
  - Unknown regolith properties (especially at the poles)



Credit: Skonieczny, 2013

Figure 3.6: Sensitivity analysis using Balovnev excavation model shows productivity governed by driving speed, payload ratio, and operational efficiency

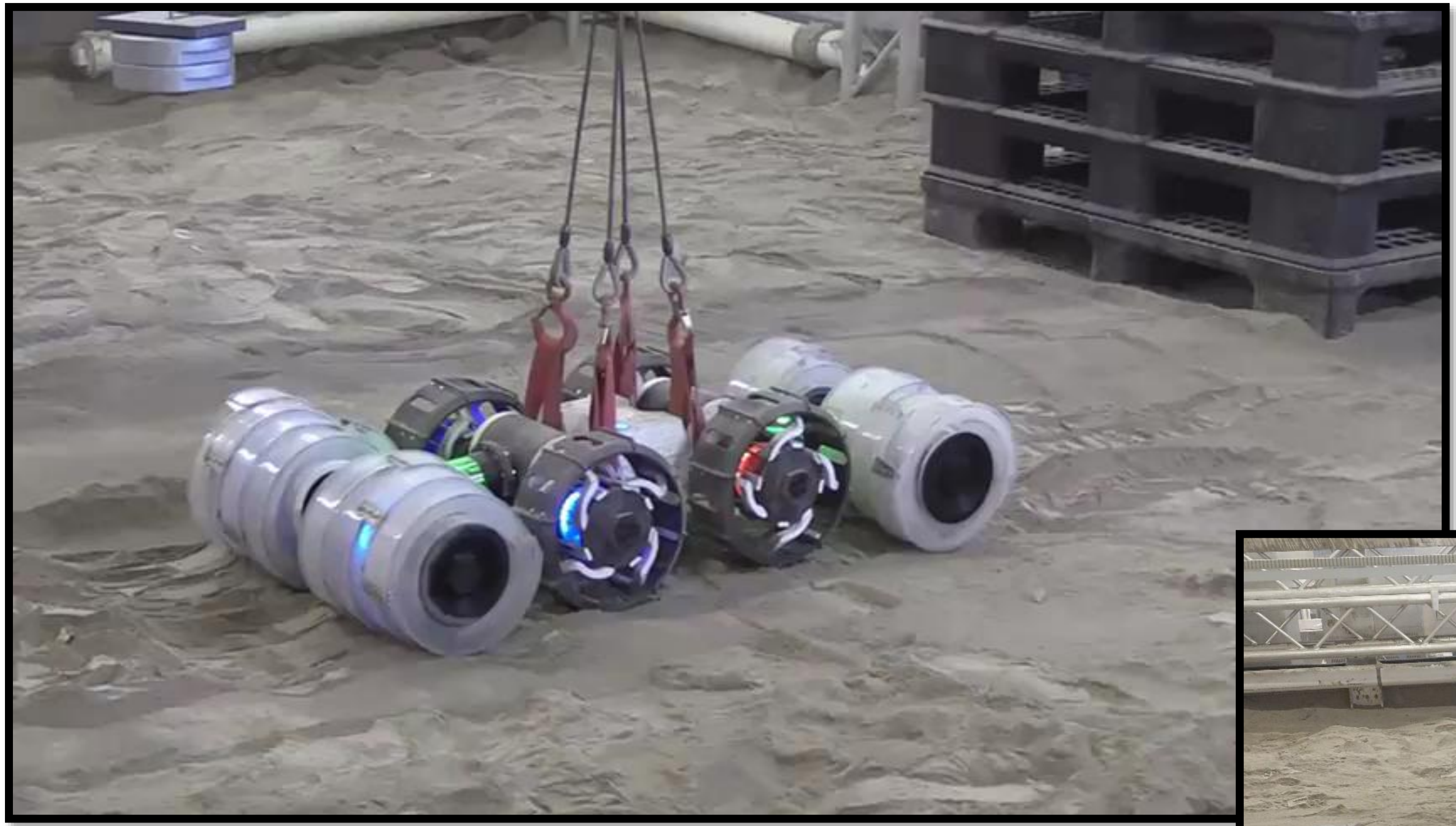
Can we scale the designs?

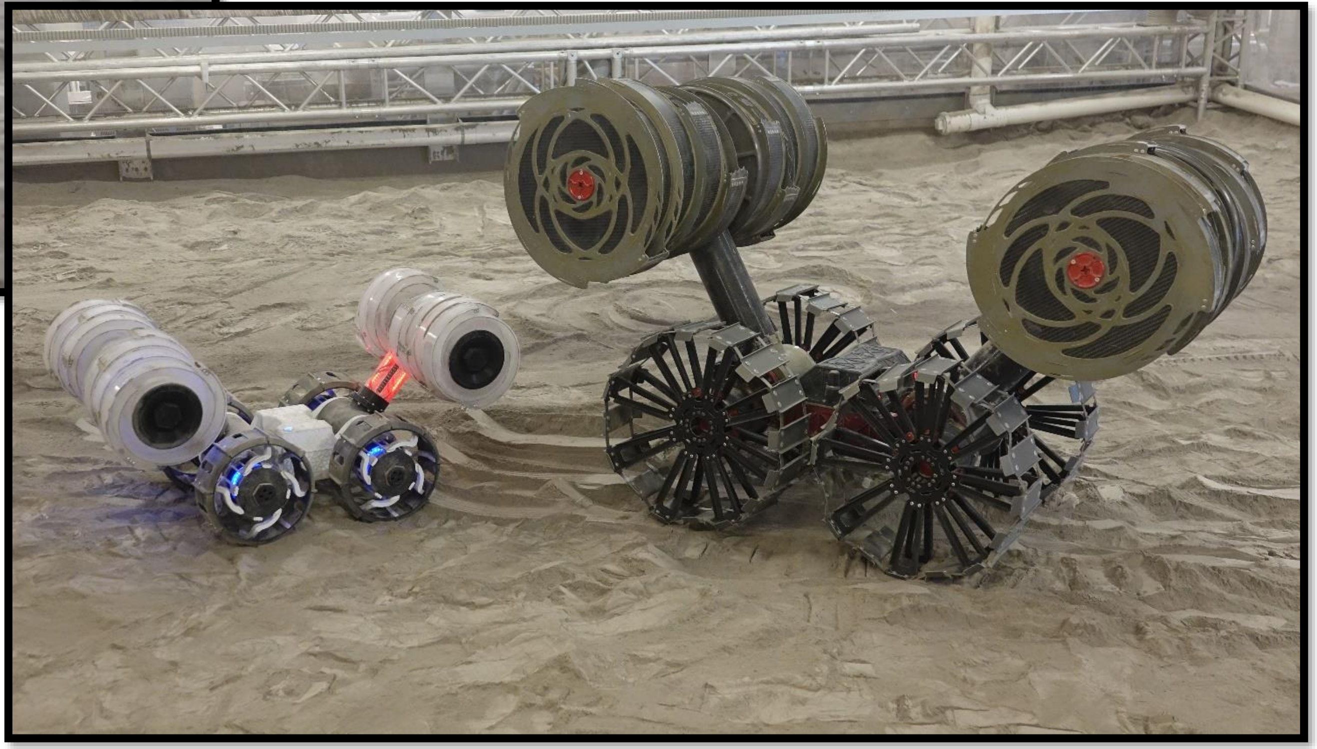
- RASSOR and Polaris already have similar production ratios. Any scaling of Polaris to match the mass/volume of RASSOR will similarly reduce its production ratio.
  - **At current scales RASSOR does the same job as Polaris for 1/3 the mass and volume and ½ the energy.**
- At some reduced scale, both the Cratos and Polaris design will 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.

Scaled Proof Of Concept





Summary

- We believe a counter acting bucket drum excavator similar to RASSOR is the best design because:
  - It is the most efficient excavator for surface regolith collection

    It delivers the most regolith for the lowest mass, volume, and energy.
  - It has the largest payload/dry mass ratio
  - It is already in a configuration to be modular
  - It is the least sensitive to mission architecture changes (landing site, mass allocation, production rates)
  - It has built in redundancy and contingency options without adding requirements.
  - It has undergone extensive testing: ~250hrs and ~50 tons of excavation
- Future Work (Pending Funding):
  - 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?

Appendix: Design concerns

- How to get a stuck rock out of the entrance of the scoop
  - Use other bucket drum, passive hook at lander, or repair station
- Will larger rocks get stuck inside the drum?
  - Video of large flat rock in and out in the Appendix
- How do you collect spent regolith from processing system?
  - Re-excavate it from the surface (estimated 3.4% cycle energy penalty)
  - Develop a port/interface to dump into the bucket drum scoops
  - Add a dump bed and additional actuator for estimated 8.5kg
- RASSOR has too many actuators
  - Actuators can be reduced by assuming a higher risk posture.
- Others?

Appendix - Large rock test