Design of an Excavation Robot: Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0

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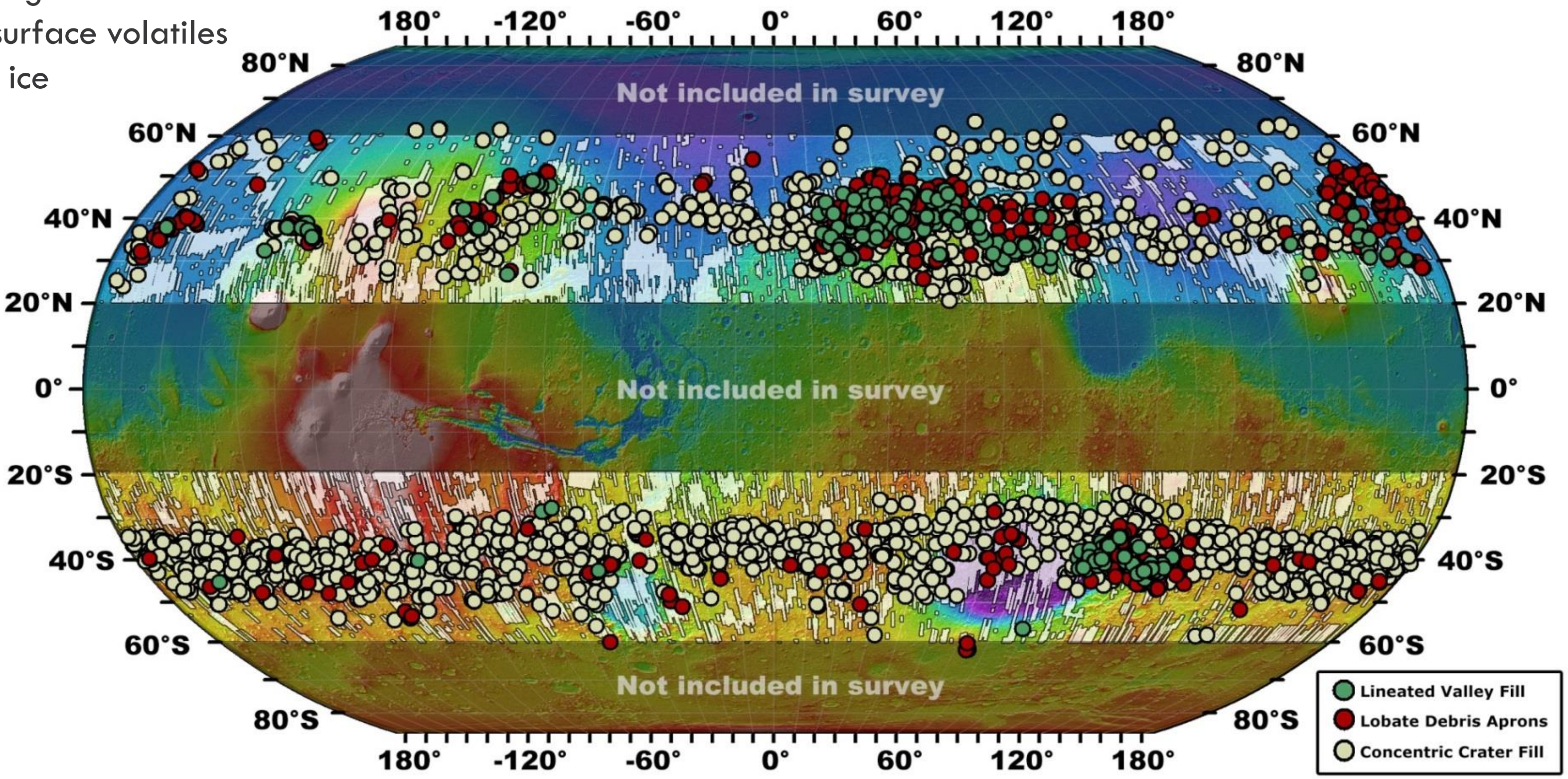
Space Resource Utilization

- Why does NASA need ISRU?
  - Launch costs (~$4,000/kg)
  - Payload volume does not allow enough space and mass to send supplies, return propellants and equipment
- Why is excavation for ISRU difficult?
  - Reduced gravity
  - Various surface conditions
    - Soft regolith
    - Sub-surface volatiles
    - Hard ice

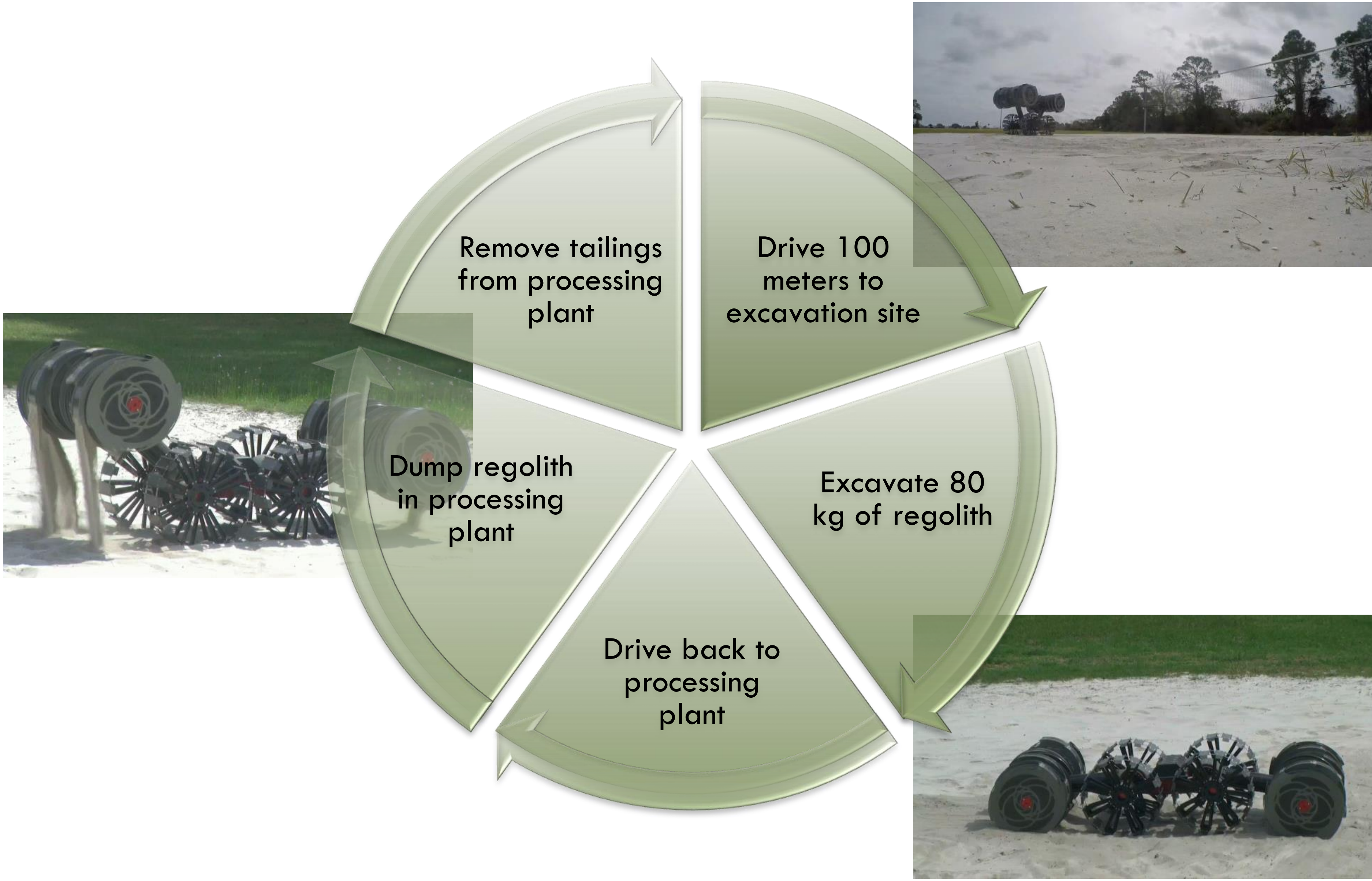


Solution for Mars ISRU Excavation

- RASSOR 2.0
  - Dual counter rotating bucket drums for canceling horizontal excavation forces
  - **66** kg mass
  - **80** kg payload capacity per excavation cycle
  - **0.25** m/s driving velocity
  - Obstacle detection, avoidance, and traversing
  - $\mathbf{0.377}\ \frac{kg}{\frac{kg}{hr}}\left(\frac{Vehicle\ mass}{\frac{delivered\ regolith}{hr}}\right)$ TA 7.1.2.5 Goal: < $\mathbf{2}\ \frac{kg}{\frac{kg}{hr}}\left(\frac{Vehicle\ mass}{\frac{delivered\ regolith}{hr}}\right)$
  - $\mathbf{0.610}\ \frac{W}{\frac{kg}{hr}}\left(\frac{Power}{\frac{delivered\ regolith}{hr}}\right)$ TA 7.1.2.5 Goal: < $\mathbf{7.0}\ \frac{W}{\frac{kg}{hr}}\left(\frac{Power}{\frac{delivered\ regolith}{hr}}\right)$

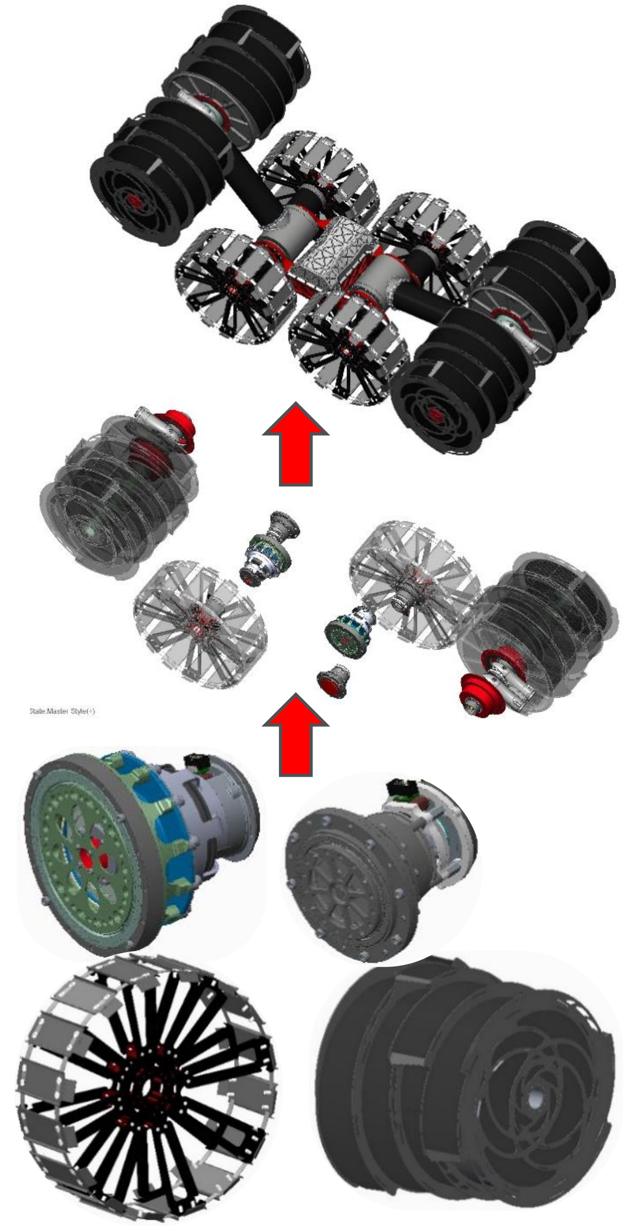


Concept of Operation



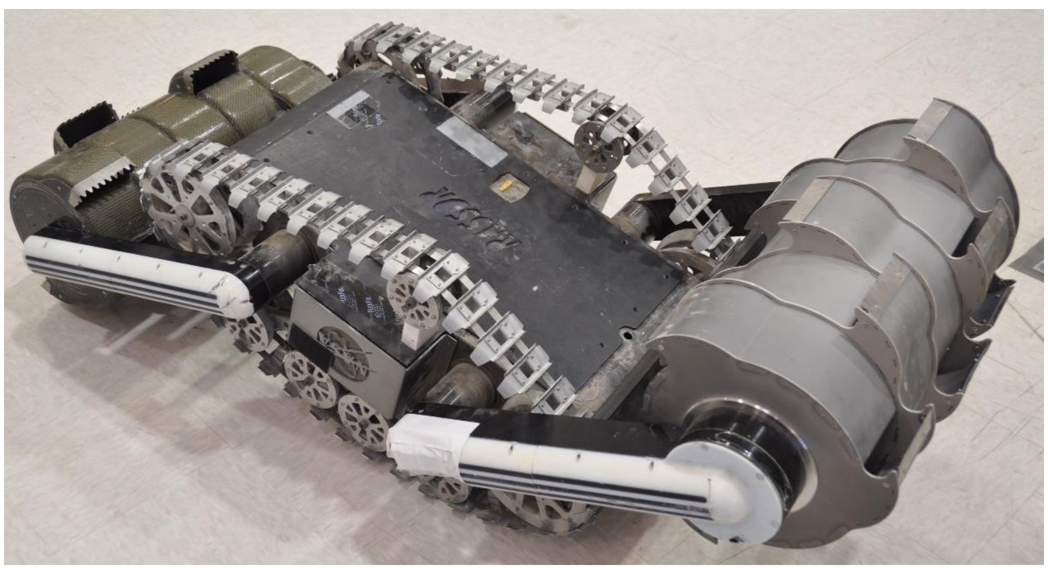
Bottom-Up Design Approach

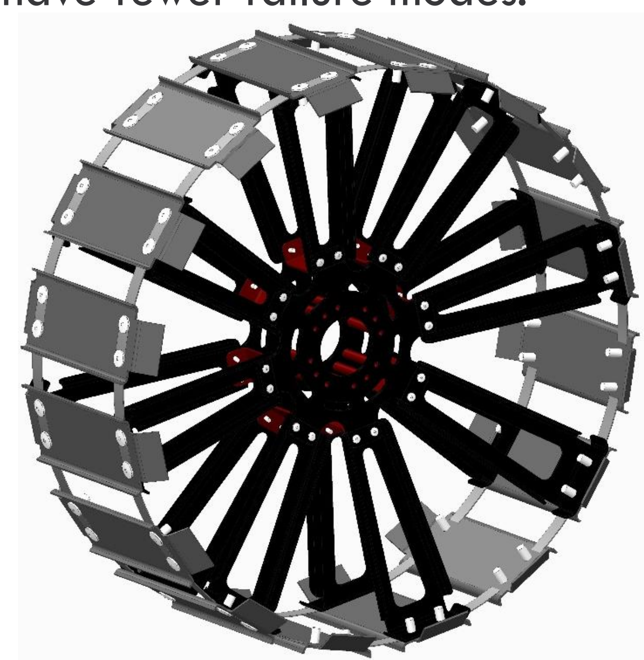
- RASSOR 1.0 was used to determine excavation loads utilizing the staggered bucket drum design
- Custom actuators were designed and optimized from loads recorded with RASSOR 1.0
  - Actuators were designed from frameless motors and component set harmonic gears.
  - Custom electro-magnet brake was designed for packaging and mass optimization.
- Fully developed subsystems were floated in the CAD model as needed according to the evolving system skeleton.
- *This approach drastically reduced the overall mass (~50% reduction) with the added benefit of seeing regular progress on actual hardware as the subsystems were developed.*



Subsystems

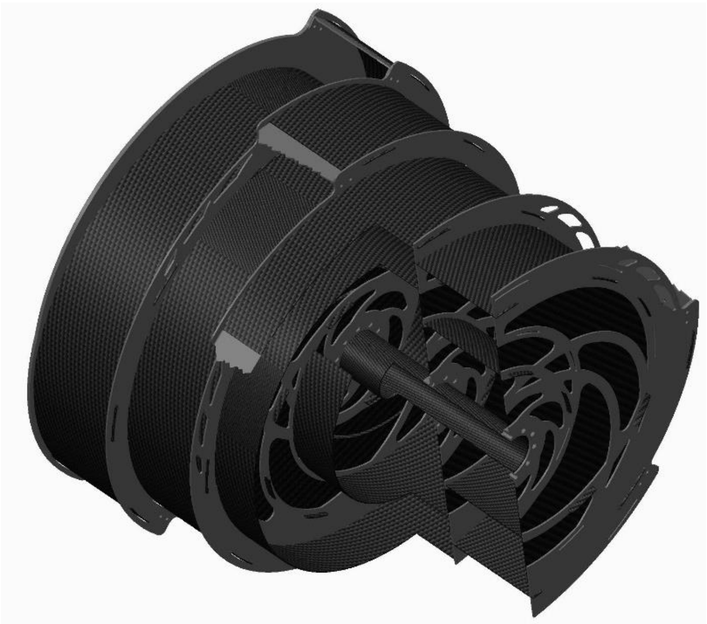
- Wheels:
  - Wheels vs. Track testing
    - Many terrestrial mining excavators use tracks for mobility, as well as, RASSOR 1.5
    - Drawbar pull, tilt table and free driving were tests performed with RASSOR 1.5 tracks, 4-17 inch diameter wheels, 4-13 inch wheels, and 6-13 inch wheels
    - Conclusion: 17 inch wheel configuration performed comparably to the tracks. Inherently wheels are more robust than tracks and have fewer failure modes. Therefore 17 inch wheels were selected.



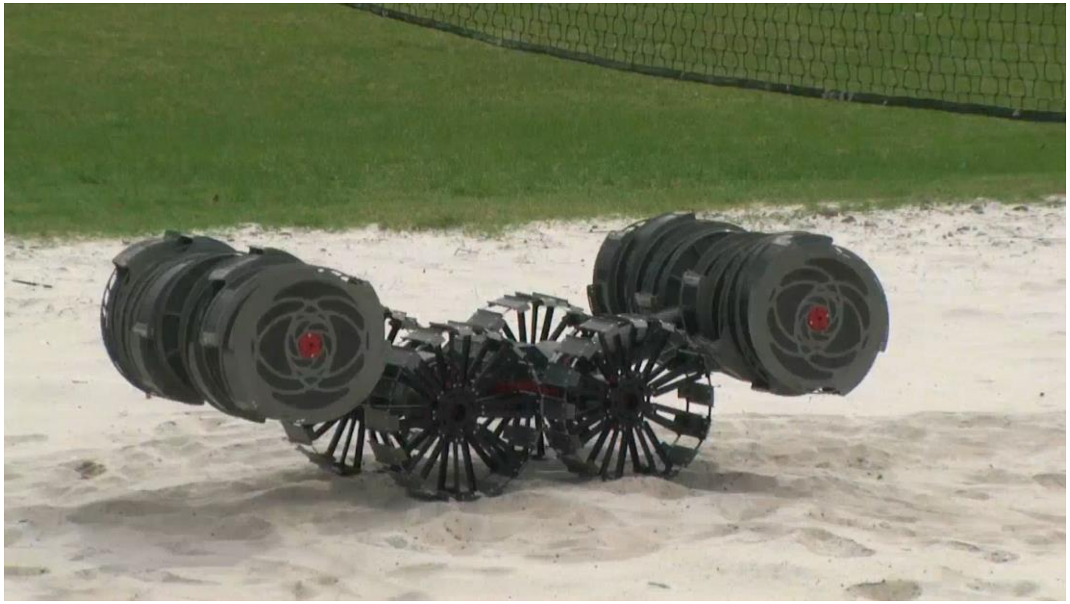


Subsystems

- Bucket Drums:
  - Designed to hold a total of 80kg of regolith
  - Scoops are clocked from one another to reduce the excavation forces and to keep the drums anchored to the surface while digging
  - The rake angle of the scoops was designed where the scoops would act as self-anchoring once engaged into the regolith.



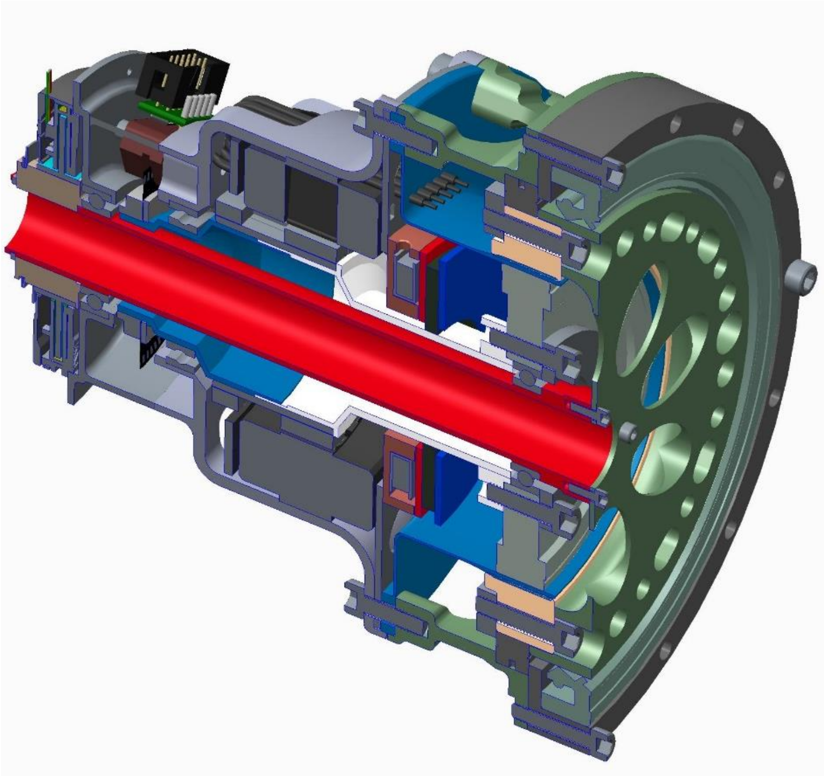
Section View of Bucket Drum



Subsystems

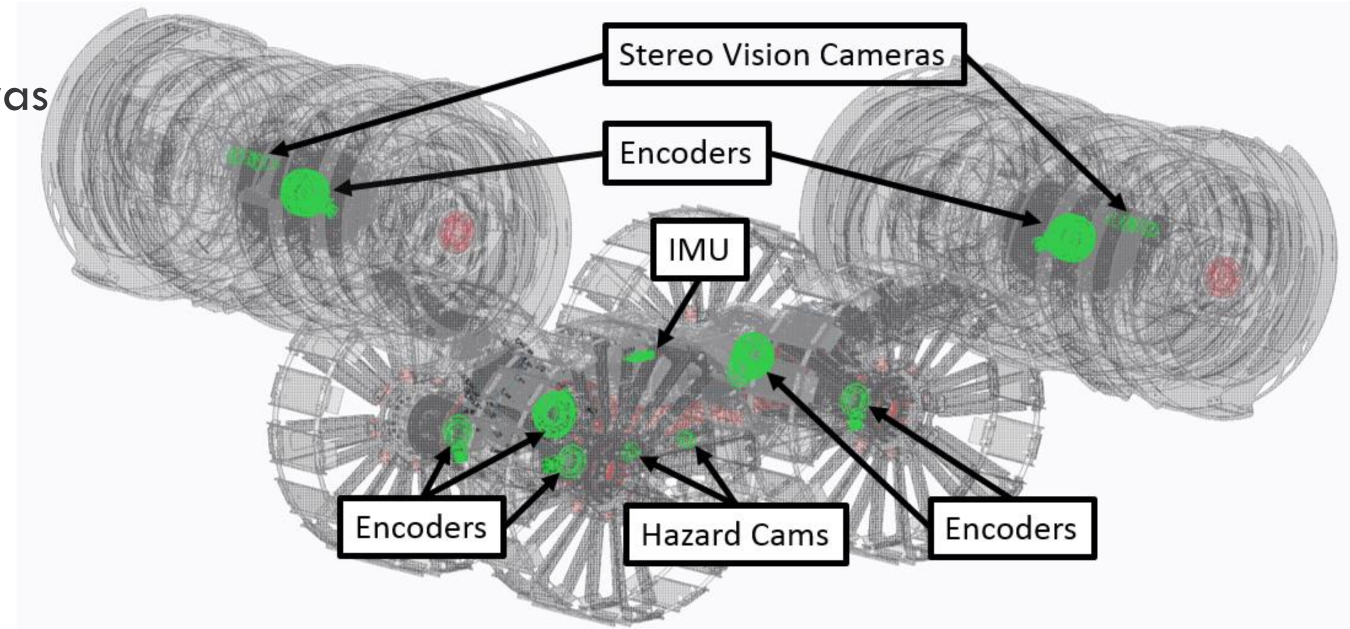
- Actuators:

	Shoulder Actuator	Bucket Drum Actuator	Drive Actuator
Gear Ratio	161	161	161
Max Torque	644N*m (~5700in*lbf)	191N*m (~1690in*lbf)	191N*m (~1690in*lbf)
Continuous Torque	236N*m (~2093in*lbf)	93N*m (~821in*lbf)	93N*m (~821in*lbf)
Max Speed	~16 RPM	~25 RPM	~25 RPM
Rated Speed	~10 RPM	~18 RPM	~18 RPM
Velocity Feedback Resolution	10,000 counts/rev	10,000 counts/rev	10,000 counts/rev
Position Feedback Resolution	19 bit (524288 counts/rev)	19 bit (524288 counts/rev)	N/A
Safety Brake	yes	no	no
Mass	3.58 kg (7.89 lbs)	1.3 kg (2.87 lbs)	1.17 kg (2.58 lbs)



Sensor Feedback

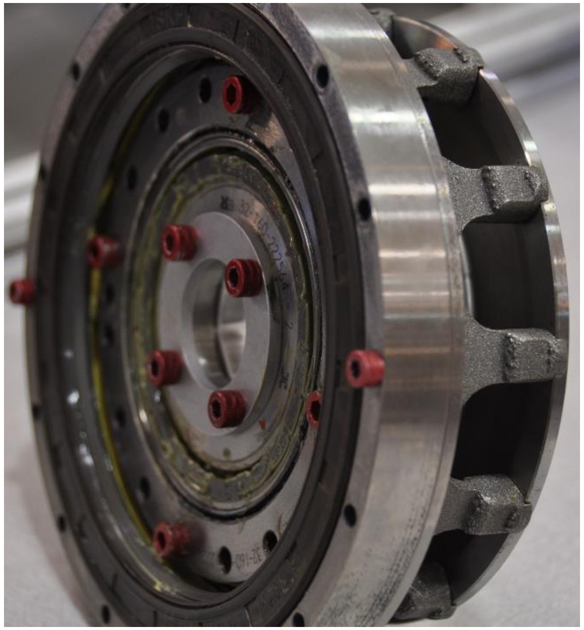
- RASSOR 2.0 has 10 actuators equipped with incremental encoders and hall effect sensors for velocity and commutation feedback.
- The 4 Bucket drum and 2 shoulder actuators are also equipped with absolute encoders for position feedback.
- The actuators are controlled by Elmo Motion Control G-Sol WHI20/100. The feedback sensors are directly read by the Elmo motor controllers and are used to close Proportional-Integral (PI) loops for position and velocity. The bucket drum and arm motor controllers use the absolute encoders and incremental encoders to perform a dual loop position over velocity closed loop control.
- Xsens IMU
- Stereo Vision Cameras

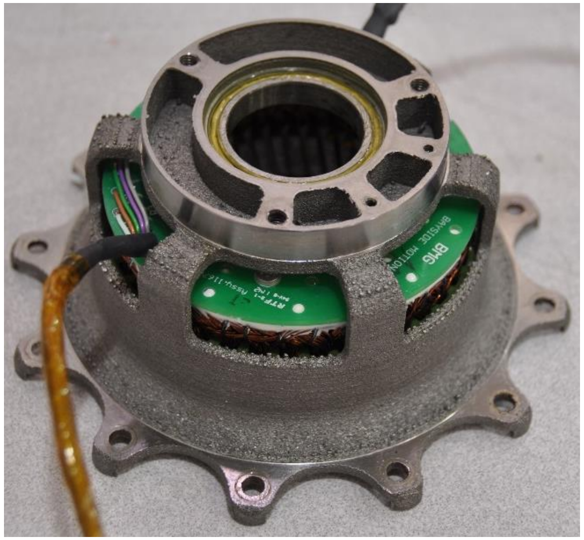


Automation and Software

- RASSOR 2.0 utilizes Robot Operating System (ROS)
  - Xsens IMU, stereo cameras, and actuator feedback use sensor fusion techniques to close the loop for autonomy
  - During excavation the auto dig routine balances the excavation load on each drum by sensing torque on the drums and adjusting the height of the arm.
  - Currently in work:
    - Obstacle avoidance and path following
    - Track following
    - Automated self-righting
    - Automated Dumping
    - Autonomous trenching

Lessons Learned





- 3D Printing of actuator housings
  - Titanium 3D printing was utilized for fabricating the housing for the shoulder actuator.
    - Post machining the bearing surfaces and tight tolerance features was difficult.
- Wire Terminations
  - The use of Molex Pico connectors were selected for all wire to wire and wire to board connections.
    - The wire to board connection worked perfect if the proper wire gauge was available
    - The wire to wire connectors proved to be very difficult. The pins were easily bent, the positive lock on the pins and sockets wore out, most manufactures wire gauge that was used at these connections were not of proper gauge.
- Braided shielding was used on all wires
  - The shielding was susceptible to fraying and creating shorts across the connectors.

Evolvable Mars Campaign Architecture

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Case Study:

Case	Mass of Ore Required (tons)	# RASSOR-class loads (@80 kg/load)	Distance from Ore to Plant, typical	# RASSOR – class Excavators used (@ 60% On-Duty)	Duration Required (sols, <480 available)
Regolith A	~2,050t	>25,000	~100 m	**3** excavators	382 sols
Regolith B	~1,270t	>15,800	~100 m	**2** excavators	350 sols
Smectite	~580t	>7,000	~100 m	1 excavator	318 sols
Gypsum	~185t	>2,000	**~100 m**	1 excavator	88 sols
Gypsum	(same)	(same)	**~1,200 m**	1 excavator	480 sols
Gypsum	(same)	(same)	**~3,000 m**	**2** excavators	453 sols

For every kilogram of landed mass
(hardware mass + including terrestrial propellants):

- A LOx/LCH_4 ISRU system can produce 20 kg of propellant
- A LOx-only ISRU system can produce 4 kg of propellant

So harnessing the Mars regolith water for ISRU offers a 5x improvement over Mars ISRU atmosphere processing alone.

- Technology trades within the ISRU system will continue to improve these numbers

Future Work

- Obtain funding to complete TRL 5 and 6 testing.
  - Relative environment testing
  - Thermal considerations
  - Automation Software

Questions

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