A Notional TUG Concept Serves as a "Stalking Horse" to Facilitate Excavator Development

Planetary Surface Excavator

*sys*RAND Corporation™

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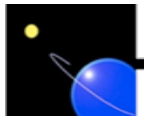


SPACE ENVIRONMENT TECHNOLOGIES
Infrastructure and Standards Division

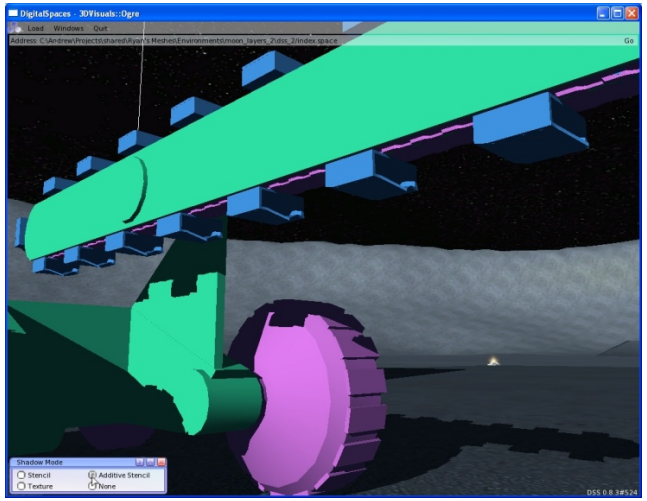
Why Develop a Notional TUG?

- ✧ Robotic Platforms have not been available from NASA to support our program
- ✧ Available NASA Platforms have unworkable restrictions
- ✧ The TUG is a foil which has allowed us to continue our development effort and adapt to fit to Chariot, HOBO, or Chassis A
- ✧ The TUG does not currently exist, *ergo*, it does not compete with NASA concepts
- ✧ *sys*RAND is developing a power source that can make the TUG the Lunar equivalent to the Jeep – the power source will position the TUG in a competitive and very real position

Why Develop a Virtual TUG?

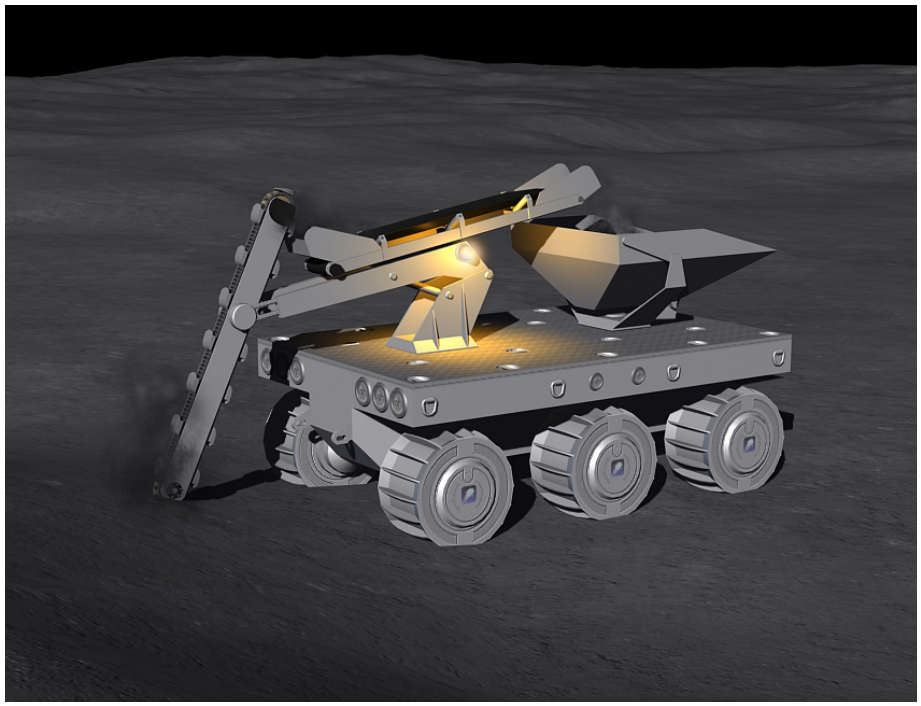
- ✧ Opportunity to work out modular, versatile tool concepts
- ✧ The TUG and excavator are scaled to support production rates up to and beyond 1 metric ton per hour
- ✧ The TUG supports industrial-scale development
- ✧ The TUG is the correct scale for working with crew, even transporting them in an emergency situation

TUG Design Space: Roles



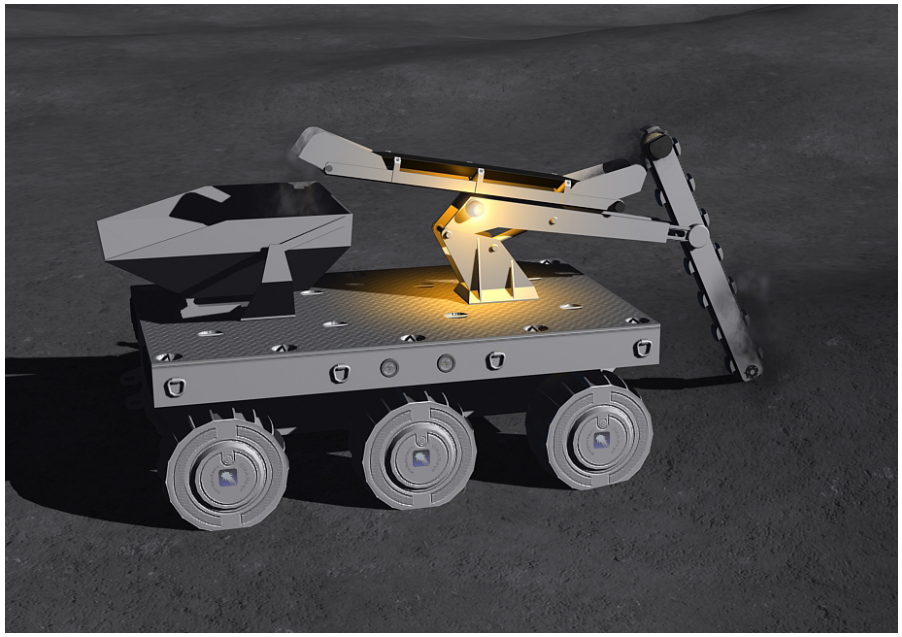
- Lunar Surface Civil Engineering and ISRU
- Support the Deployment of PS Excavator
- Provides dual-use for Robotics and Crew
- Mobile Powerplant
- Mobile Sensor Platform
- Mobile Bench

TUG Design Space: Operations



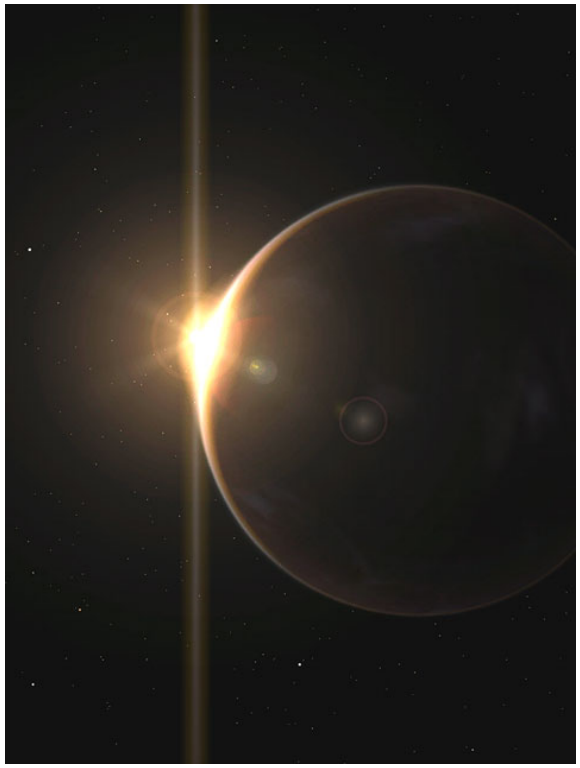
- Stand-alone, teleoperated, semi-autonomous and autonomous operating modes
- Shares a significant fraction of the platform and mechanical fixturing among other tools
- Multiple speed regimes from cross-country to a crawl in terms of *centimeters per second* to apply continuous pressure on the workface

TUG Design Space: Partitioning



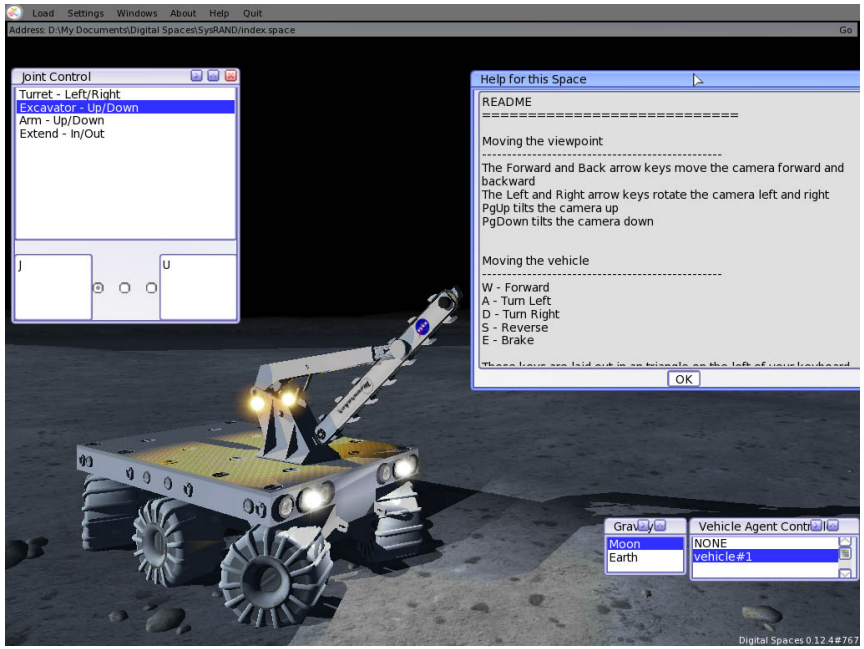
- Pushes as much of the design complexity as practical down into support layers, *ie*.: platform *vs*. turret or excavator
- Modularity encourages design evolution by minimizing the impact of any change to a single partition
- Recursive architecture provides many powerful features

SRA Platform Power



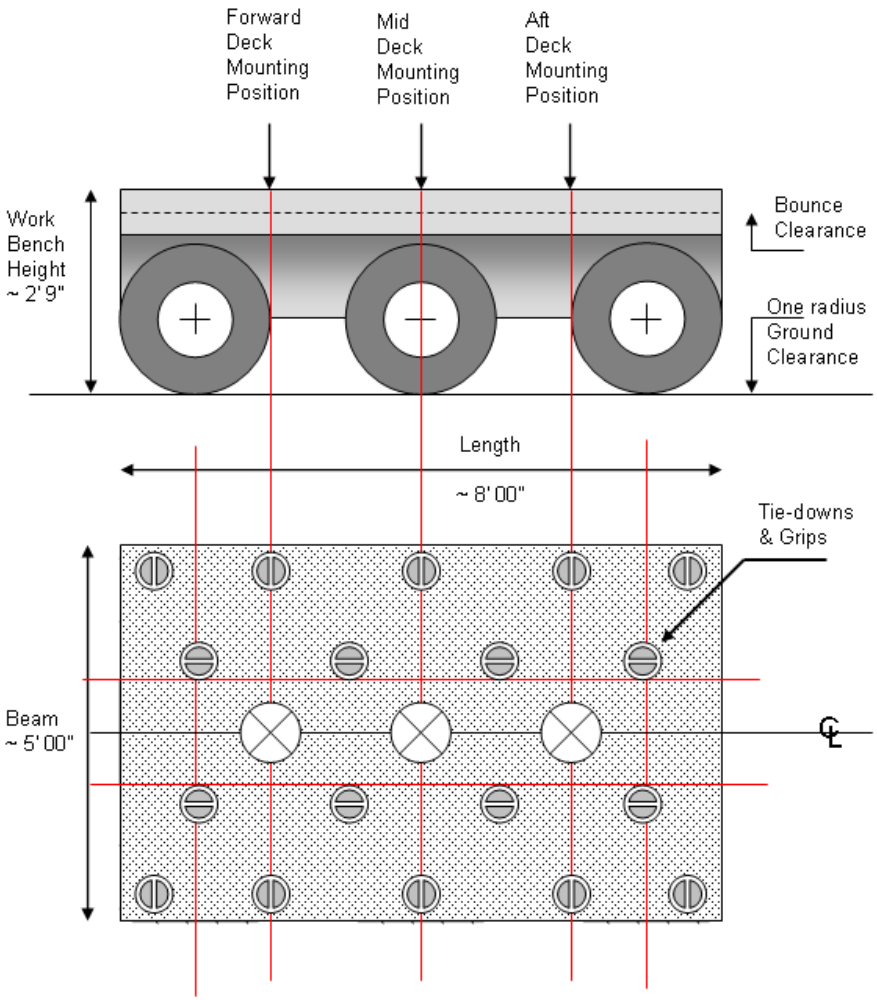
- Stirling Radioisotope Alternator
- Unconventional use of non-fissionable isotopes
- Dual Stirling plant delivers $3KW_e$
- Backside heat provides favorable thermal environment for platform internals, particularly avionics
- 24/7 Operation
- No bulky solar cell panels
- Excess power tops off batteries for surge operations
- Excess power supports a TUG role as a mobile APU

Platform Autonomy



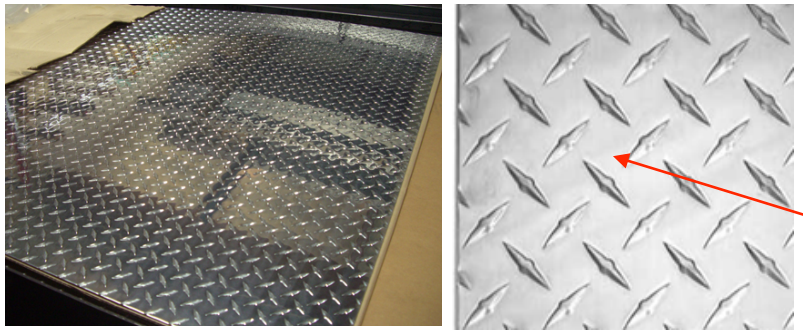
- ✧ Allows development of Site Operations Protocols
- ✧ Is a pre-requisite for "swarm" – collaborative operations
- ✧ Is strongly recursive and uses the Polar Coordinate Frame to advantage
- ✧ Supports a spectrum from teleoperations through unsupervised autonomy
- ✧ Development and Test includes pipes to *Digital Space* Visualization and Simulation platform

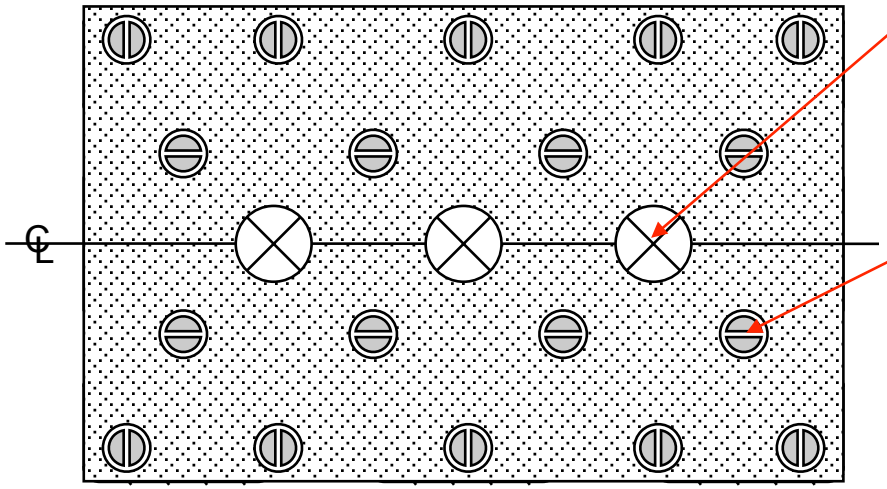
Points of Interest



- ✧ Deck
- ✧ Forward Deck Mount
- ✧ Mid Deck Mount
- ✧ Aft Deck Mount
- ✧ Robotic Arm Mount
- ✧ Turret Mount

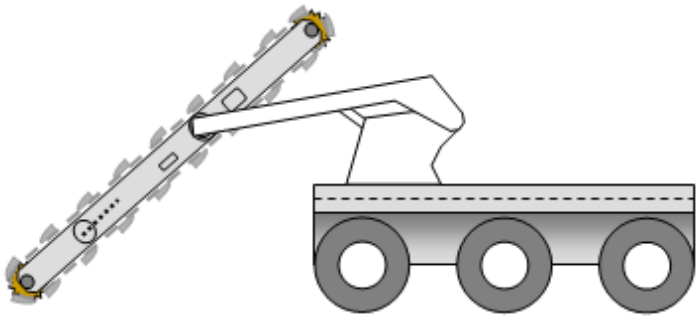
The Deck

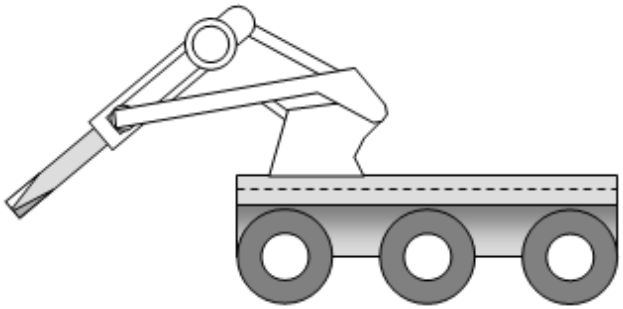




- The diamond-plate deck is intended to provide a workspace for modular tools and on-site personnel
- The surface of the deck provides traction for walking upon and temporary placement of objects
- Powered Modular Hardpoints are recessed into the deck
- Hardpoints are interchangeable mountings
- Handholds and Tie-downs are recessed into the deck
- Multiple platforms may be parked *end-to-end* or *side-by-side*
- The metal surface should negate dust charging
- Agnostic about Fore *vs*. Aft

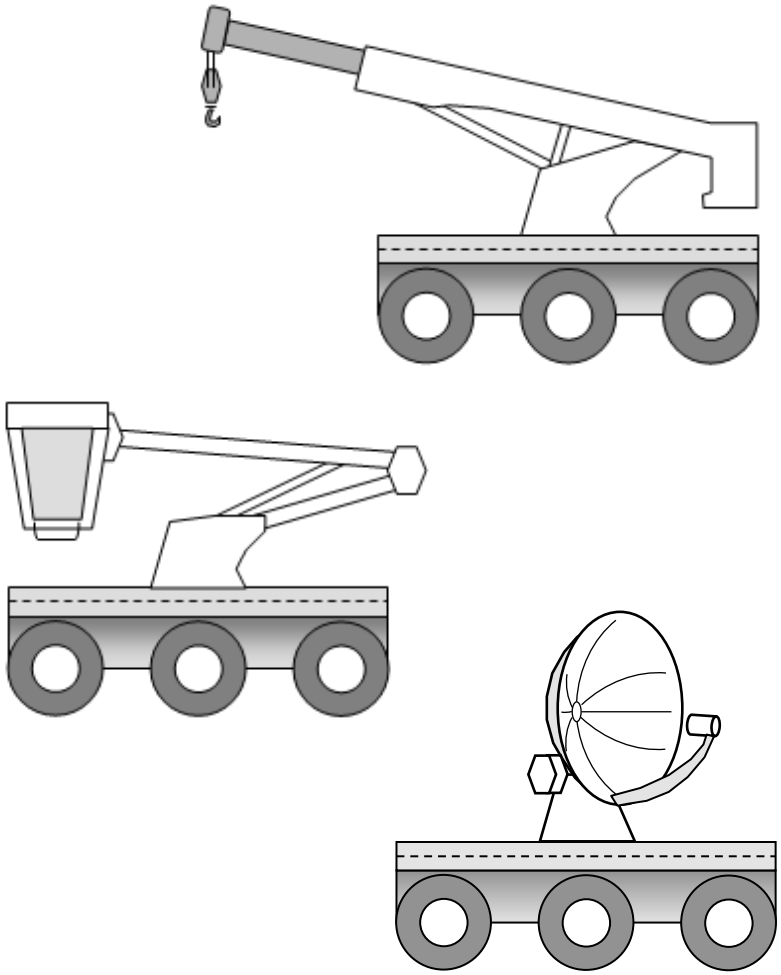
Forward Deck Mount





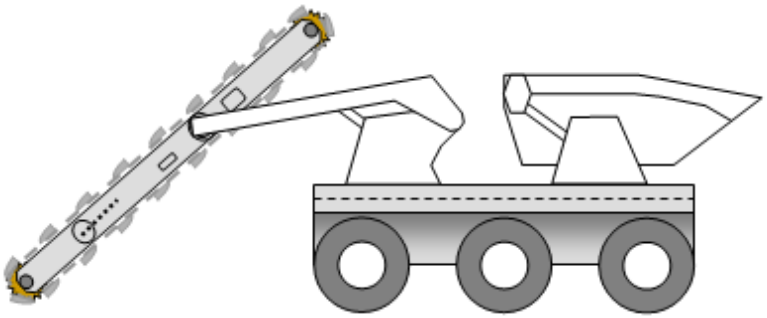
- The Forward Deck Mount is intended to support devices that have a forward reach, are to be pushed, or are a companion unit to an Aft-mounted unit
- Excavators and Star Hammers are typical of this installation

Mid Deck Mount



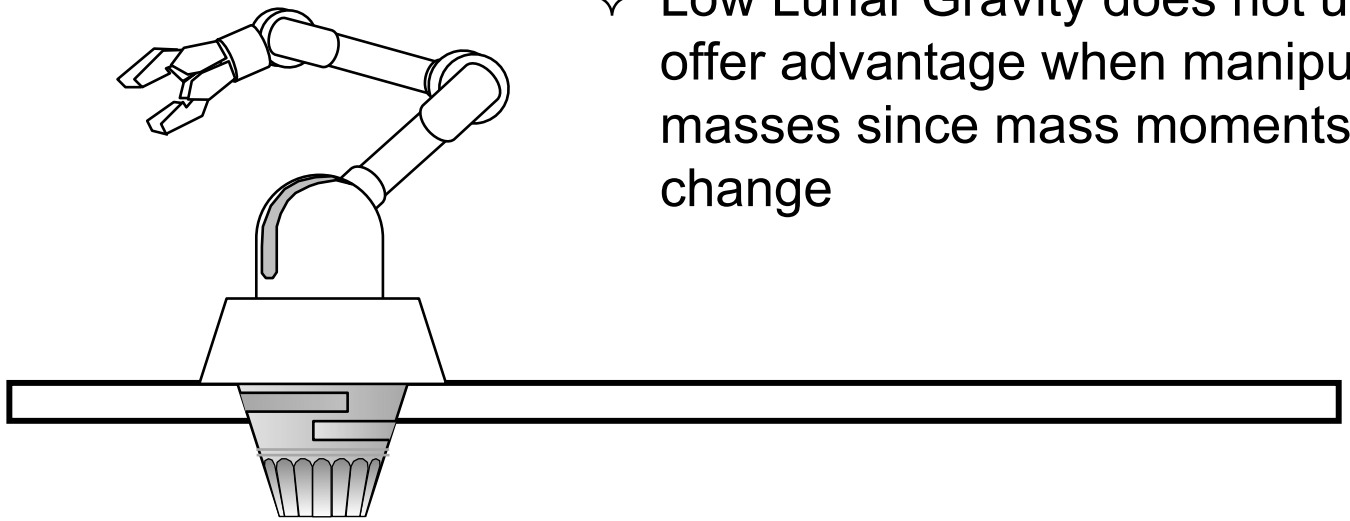
- The Mid Deck Mount is intended to maintain a *center-of-gravity* that agrees with the center of the vehicle working deck
- The Mid Deck Mount is interchangeable with the Fore and Aft Mounts
- Cranes and "Cherry-Pickers" are typical of this installation
- One or more rotating antennas may be installed for a temporary relay station or a mobile, high-power Terrestrial Link

Aft Deck Mount



- The Aft Deck Mount is intended to support devices that have a long forward reach, are to be towed, or are a companion unit to a Forward-mounted unit
- The Aft Deck Mount is interchangeable with the Fore and Mid Mounts
- Hoppers are typical of this installation

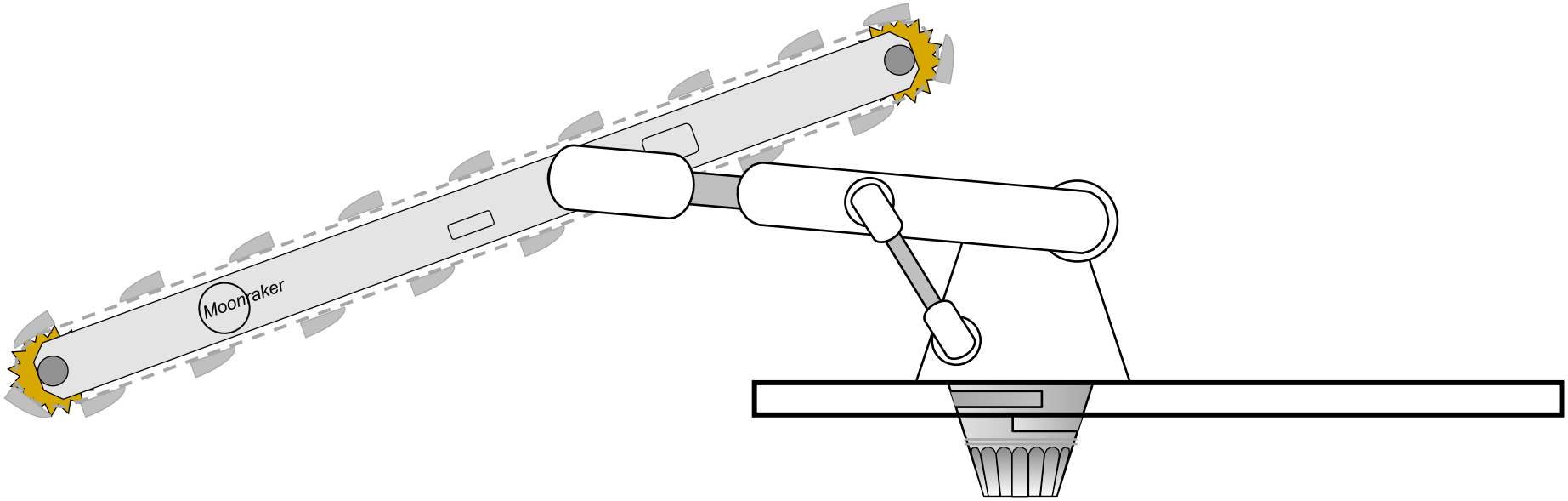
Robotic Arm Mount



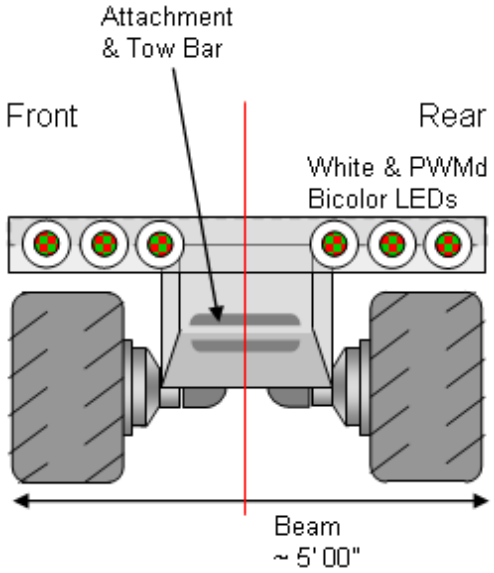
- Robotic Arms may be used when low-mass tools are deployed
- Low Lunar Gravity does not usually offer advantage when manipulating masses since mass moments do not change

Turret Mount

- A Turret Mount takes advantage of leverage to operate at a substantially lower power budget
- Shoulder-mounted pivots provide the leverage
- Offers 8DOF in manuevering the excavator and other heavy tools



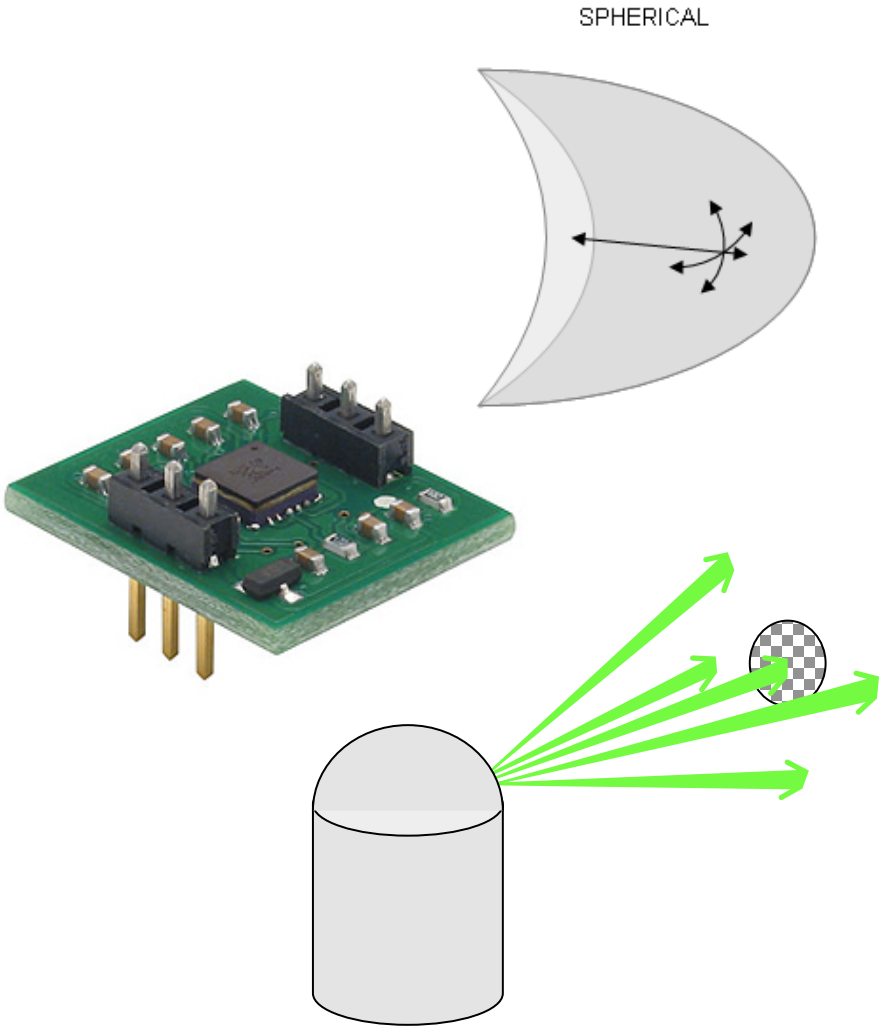
Fore & Aft



Includes other functions:

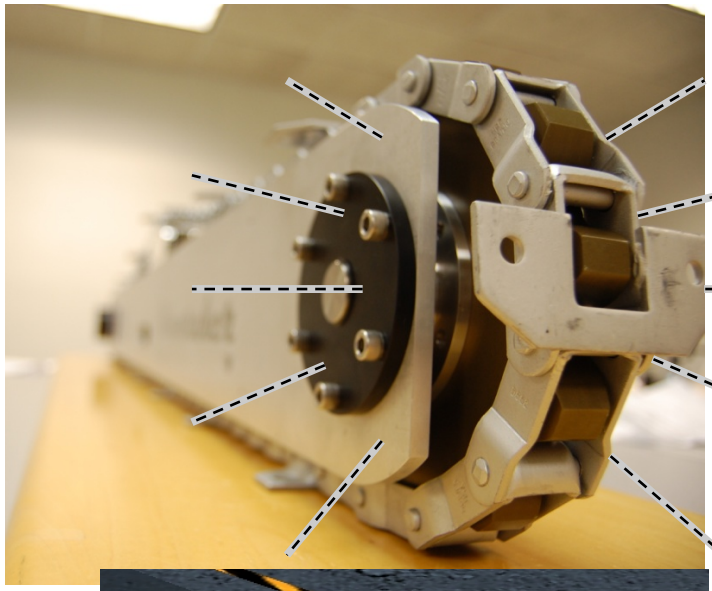
- ✧ Winch
- ✧ Lighting
- ✧ Tow Points
- ✧ Power Take-Offs

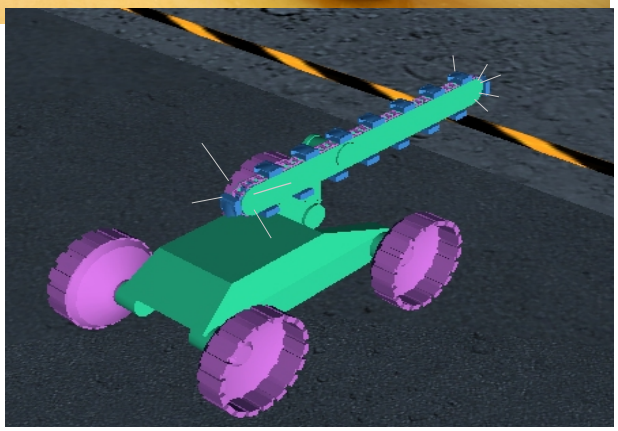
Positional Sensing



- The spherical (polar) reference system substantially reduces the positional computation load
- Solid state Angular Rate Sensors can replace bulky and brittle index wheels and gyroscopes
- Cross-coupling sensor data can be used to cancel motor and chain noise
- LASER Diodes are used to calibrate position at any of several radials by "peaking" the modulated signal to a CMOS photo sensor on the excavator

Whiskers for Proximity Sensing

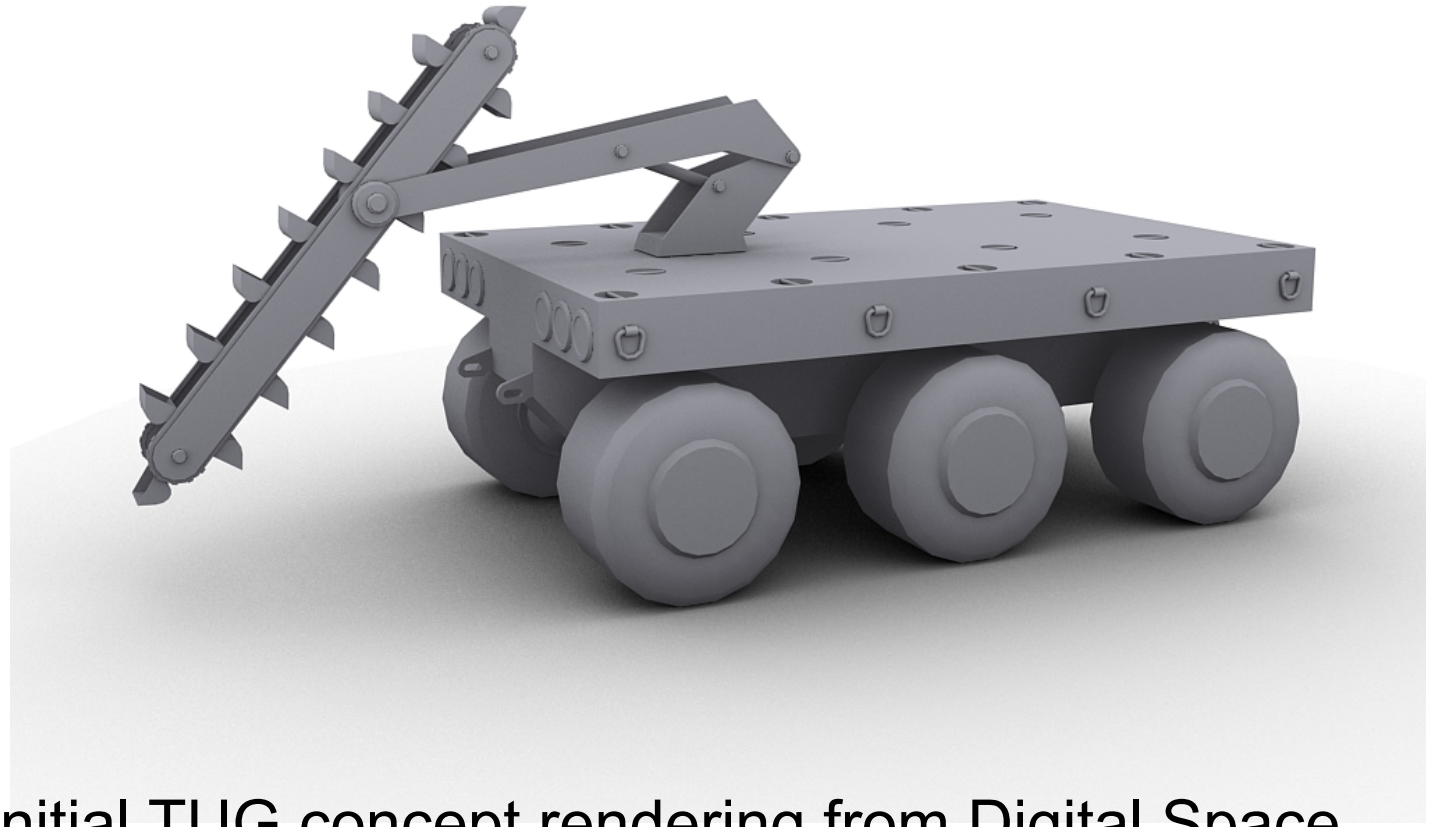




Proximity Detecting Whiskers Provide Downhole Visibility through Dust Clouds

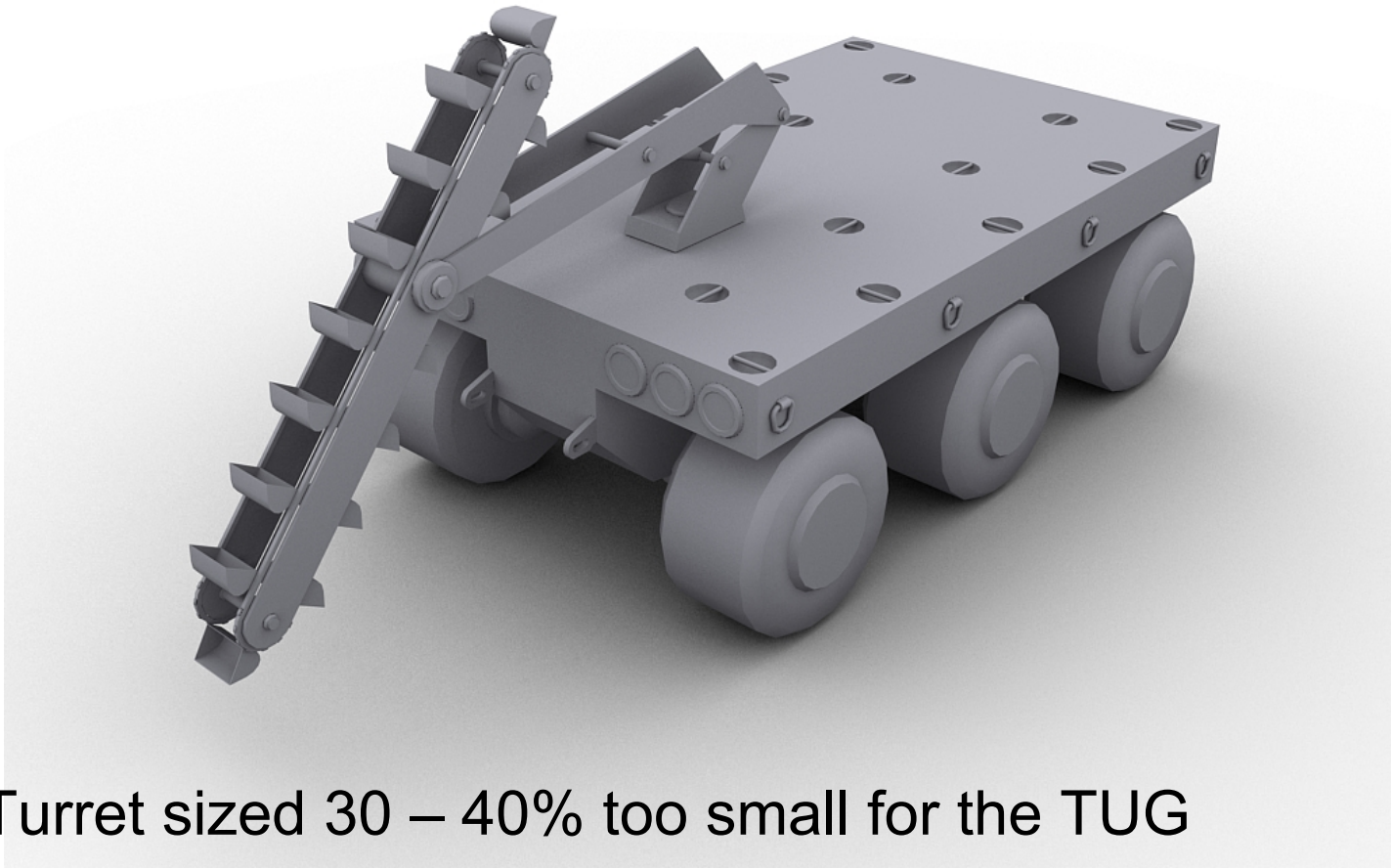
- Whiskers are proximity detectors fabricated of flexible metal
- A set of 'Rabbit Ears' mounted on the upper rear of the excavator blade establishes the reference field strength in ambient space Individual whiskers measure the field gradient
- Whiskers are multi-mode and multiplexed, which allows other testing to include 'shorts' between adjacent whiskers, whiskers and the blade, *etc*.
- The *field contour processing* provides guidance
  - re-inserting the blade into a trench
  - maintaining position wrt the workface
  - during operation to avoid collisions with rocks
  - avoiding disruption of the walls of a trench

TUG (Version 1-View 1)



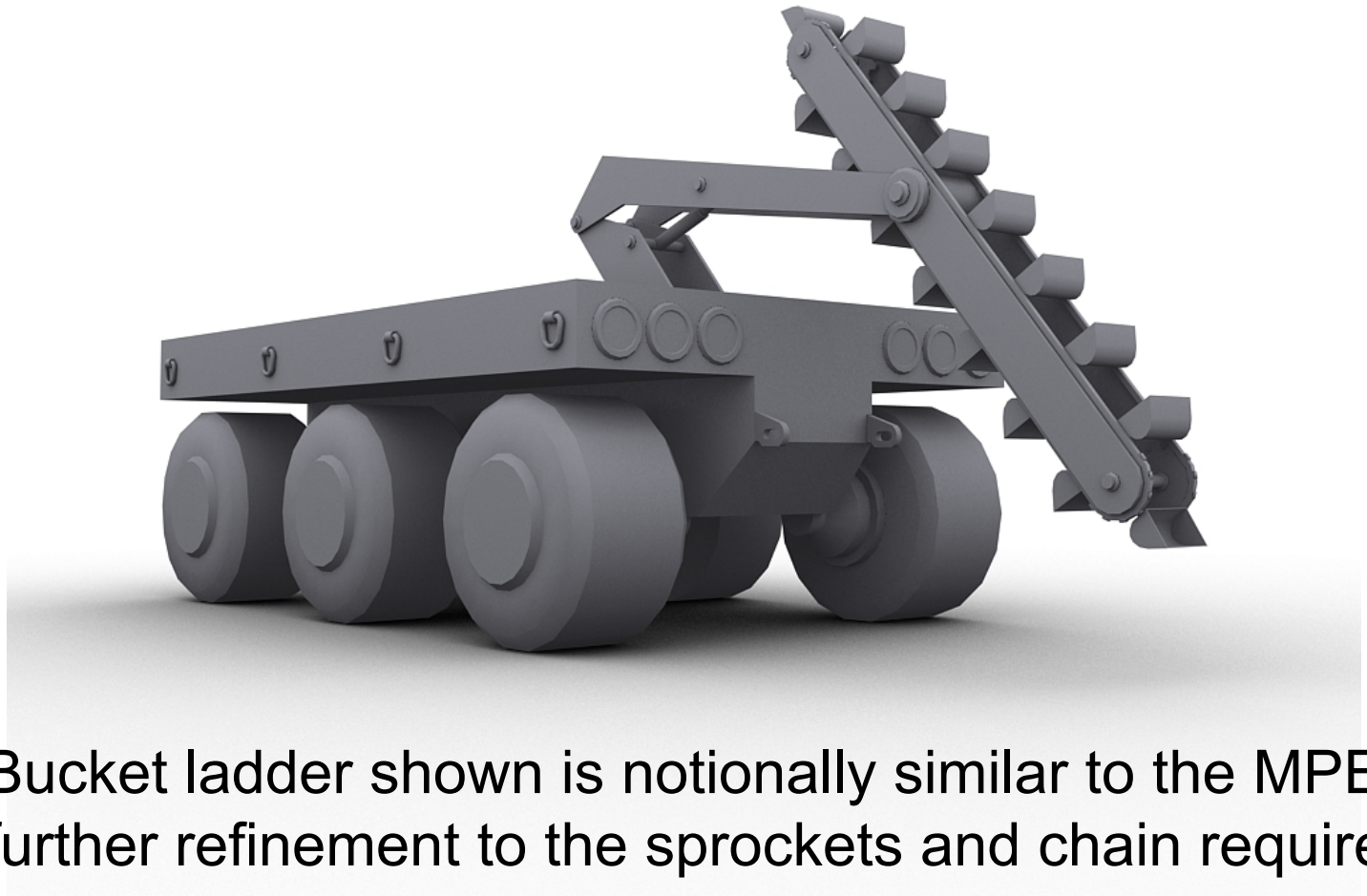
Initial TUG concept rendering from Digital Space based upon preliminary *sys*RAND documentation.

TUG (Version 1-View 2)



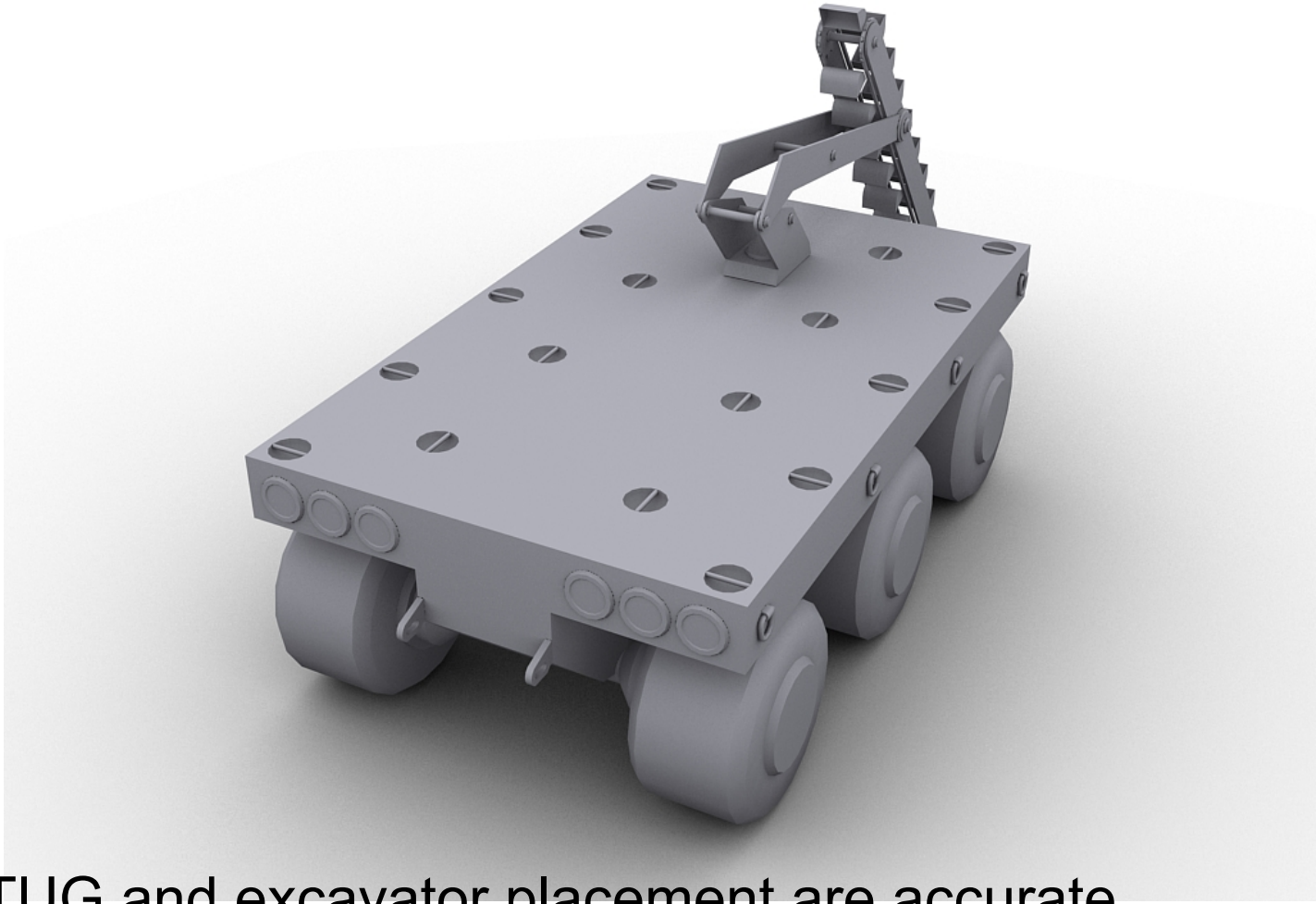
Turret sized 30 – 40% too small for the TUG and bucket ladder scale.

TUG (Version 1-View 3)



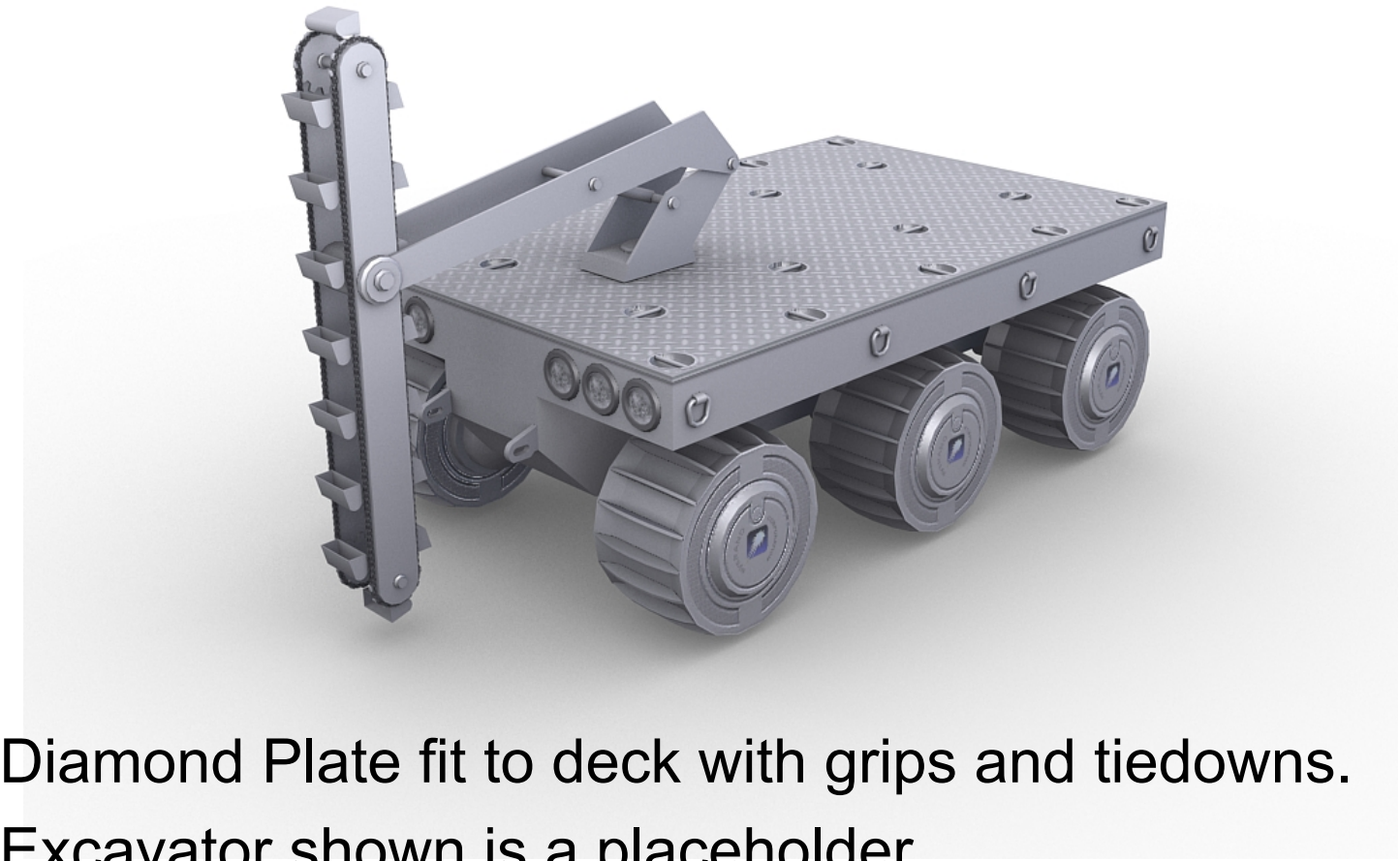
Bucket ladder shown is notionally similar to the MPED; further refinement to the sprockets and chain required.

TUG (Version 1-View 4)



TUG and excavator placement are accurate.

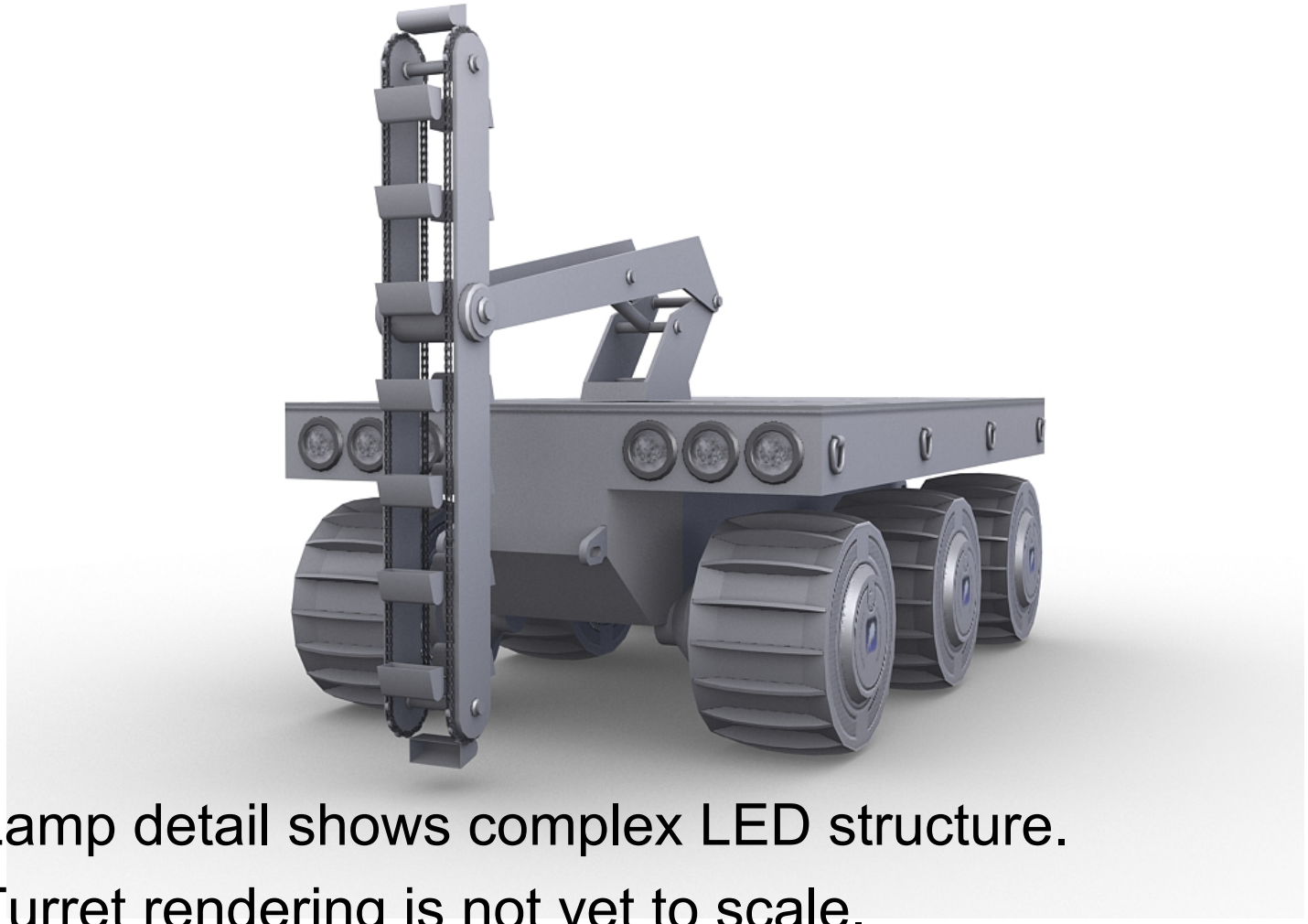
TUG (Version 2-View 1)



Diamond Plate fit to deck with grips and tiedowns.

Excavator shown is a placeholder.

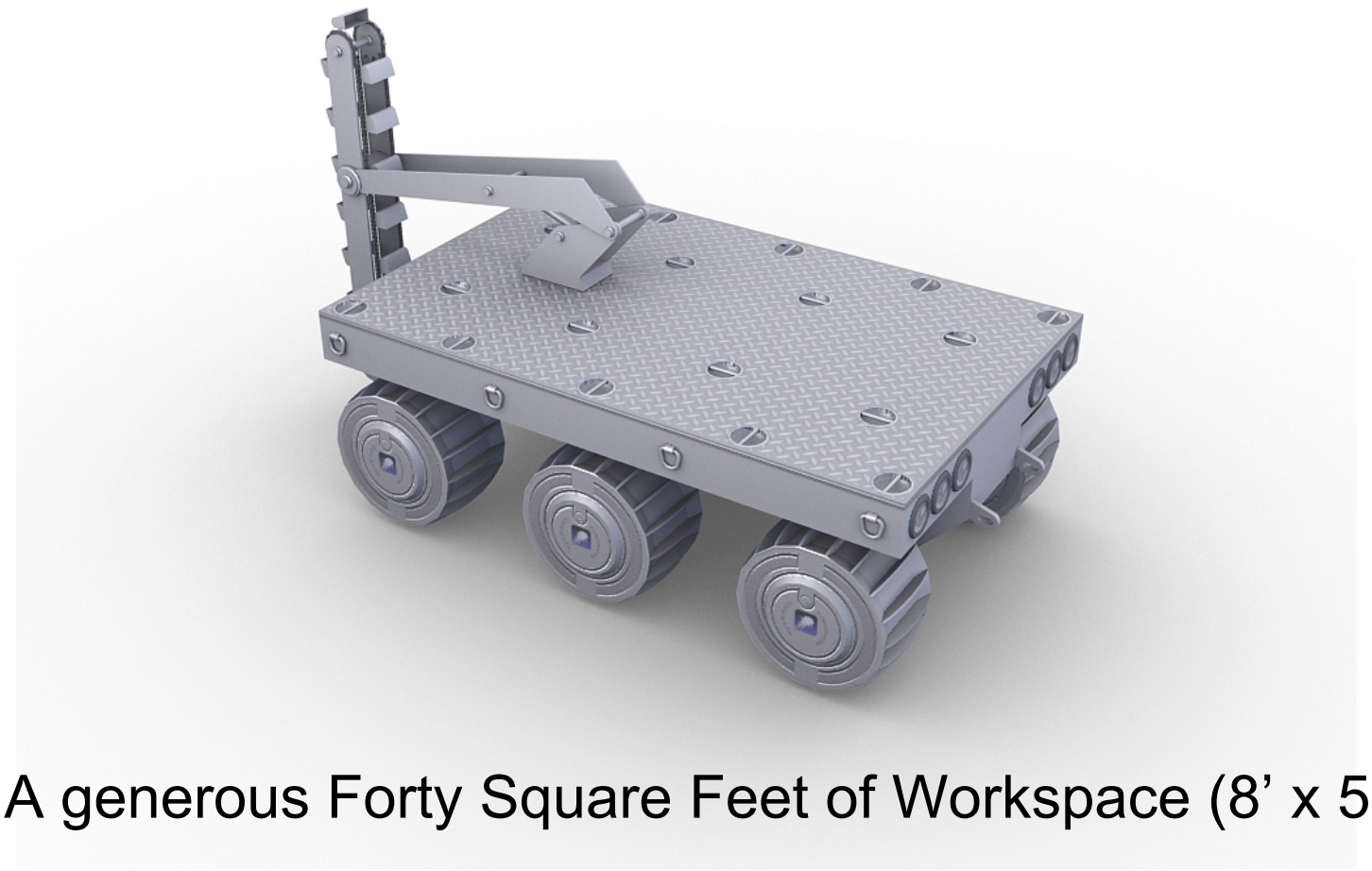
TUG (Version 2-View 2)



Lamp detail shows complex LED structure.

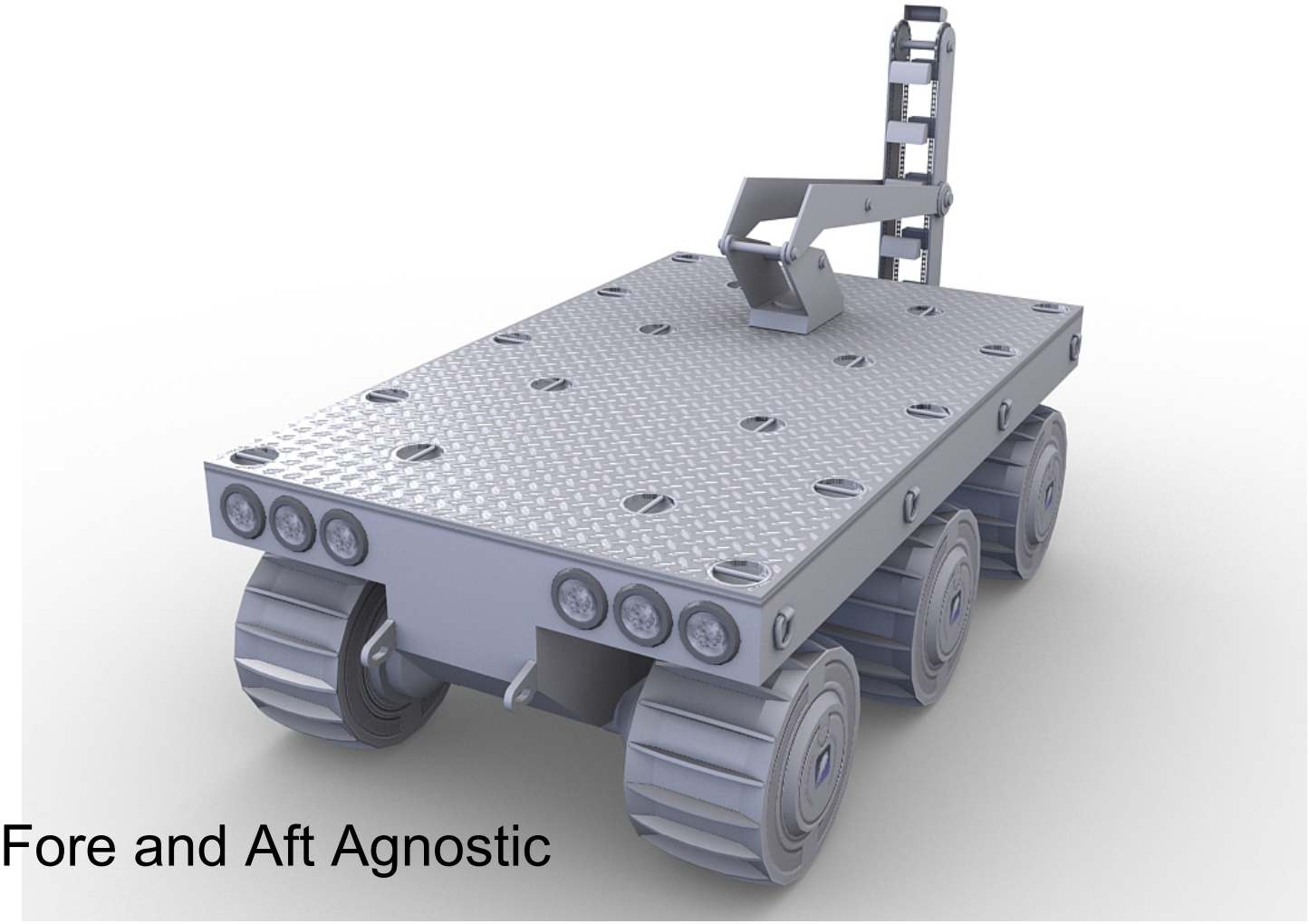
Turret rendering is not yet to scale.

TUG (Version 2-View 3)



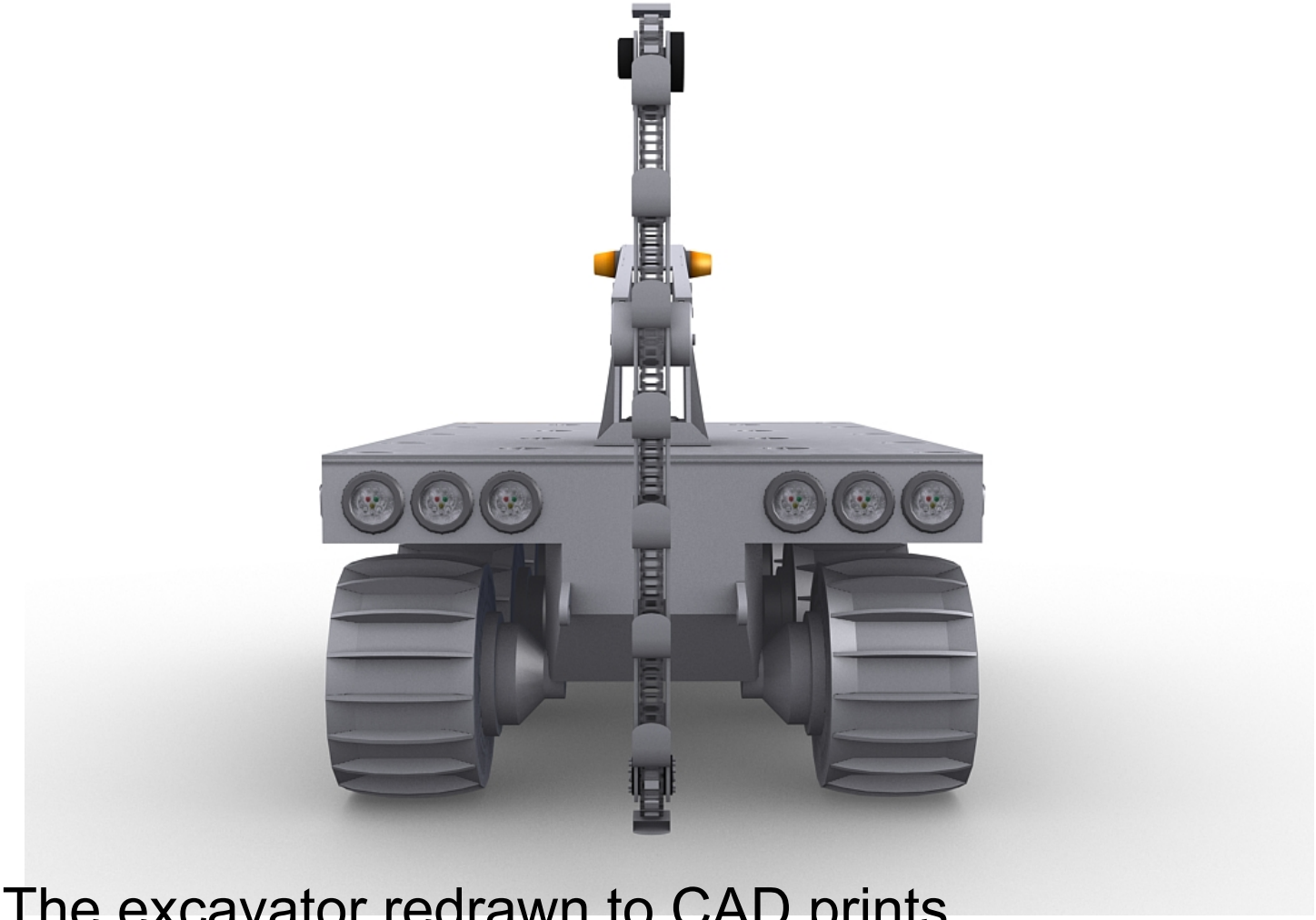
A generous Forty Square Feet of Workspace (8’ x 5’).

TUG (Version 2-View 4)



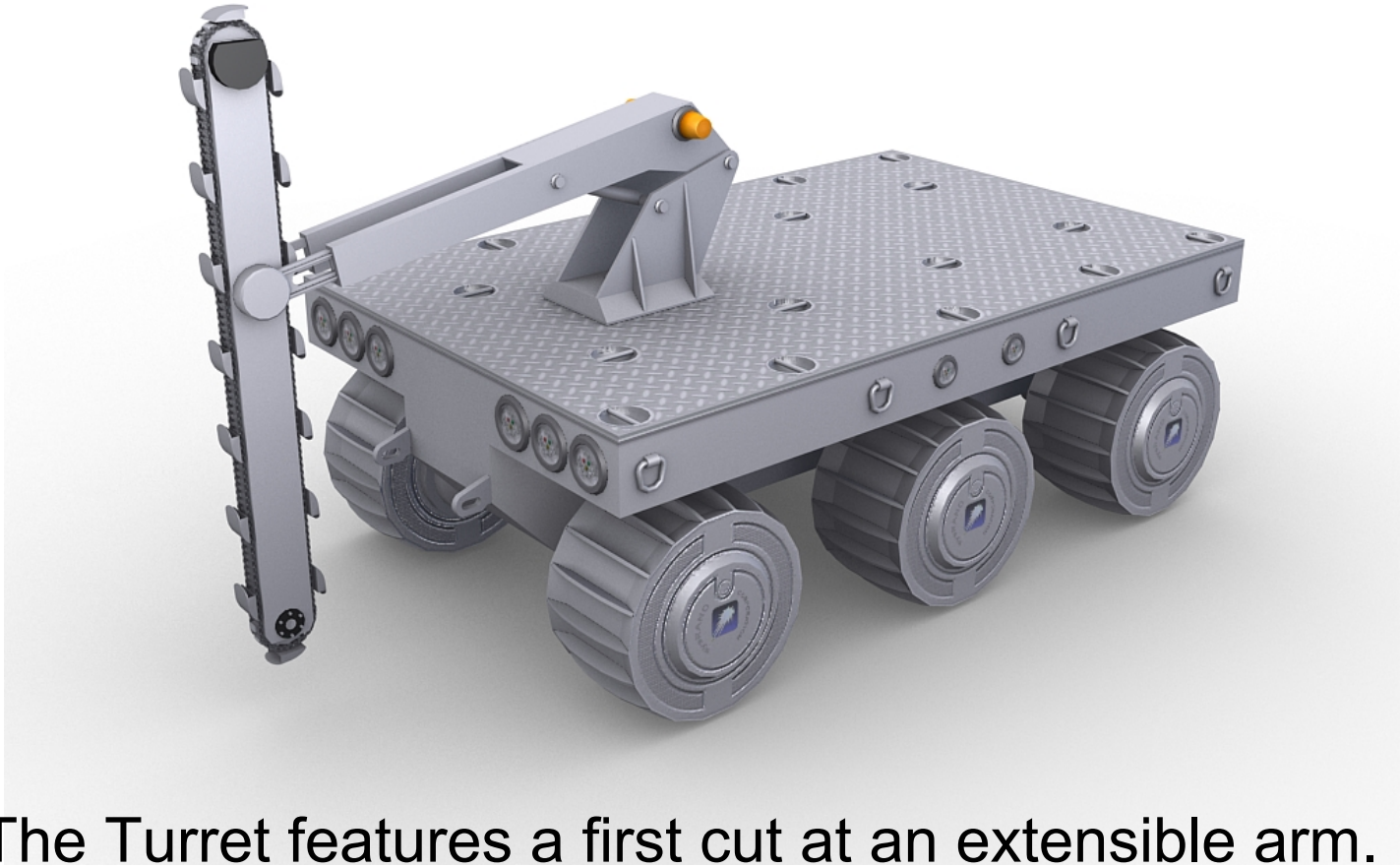
Fore and Aft Agnostic

TUG (Version 3-View 1)



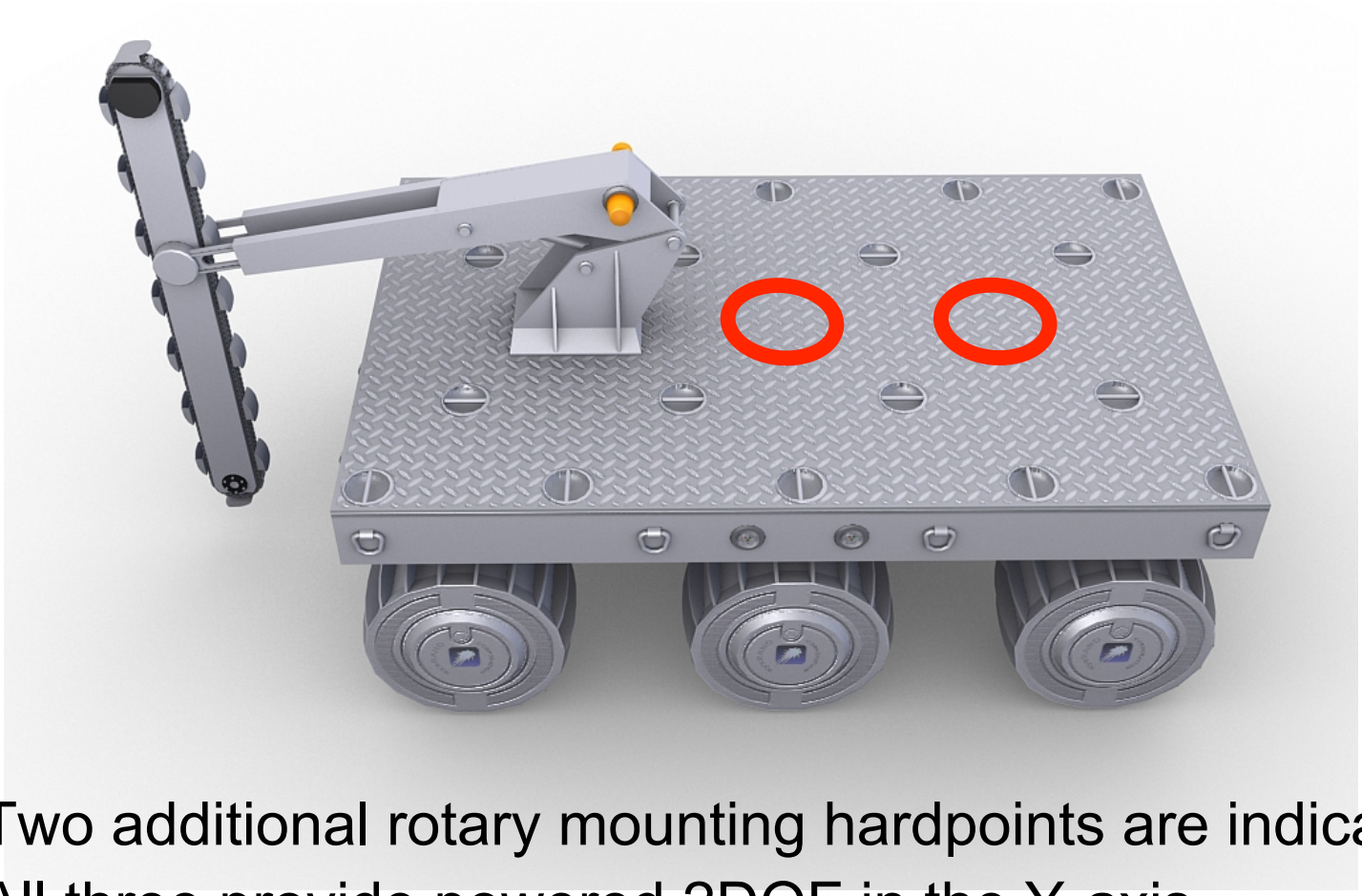
The excavator redrawn to CAD prints.

TUG (Version 3-View 2)



The Turret features a first cut at an extensible arm.

TUG (Version 3-View 3)



Two additional rotary mounting hardpoints are indicated.
All three provide powered 2DOF in the Y-axis.

TUG (Version 3-View 4)

Additional worklamps are now mounted on the sides.

TUG (Version 3-View 5)

The Platform's wide track is conspicuous.

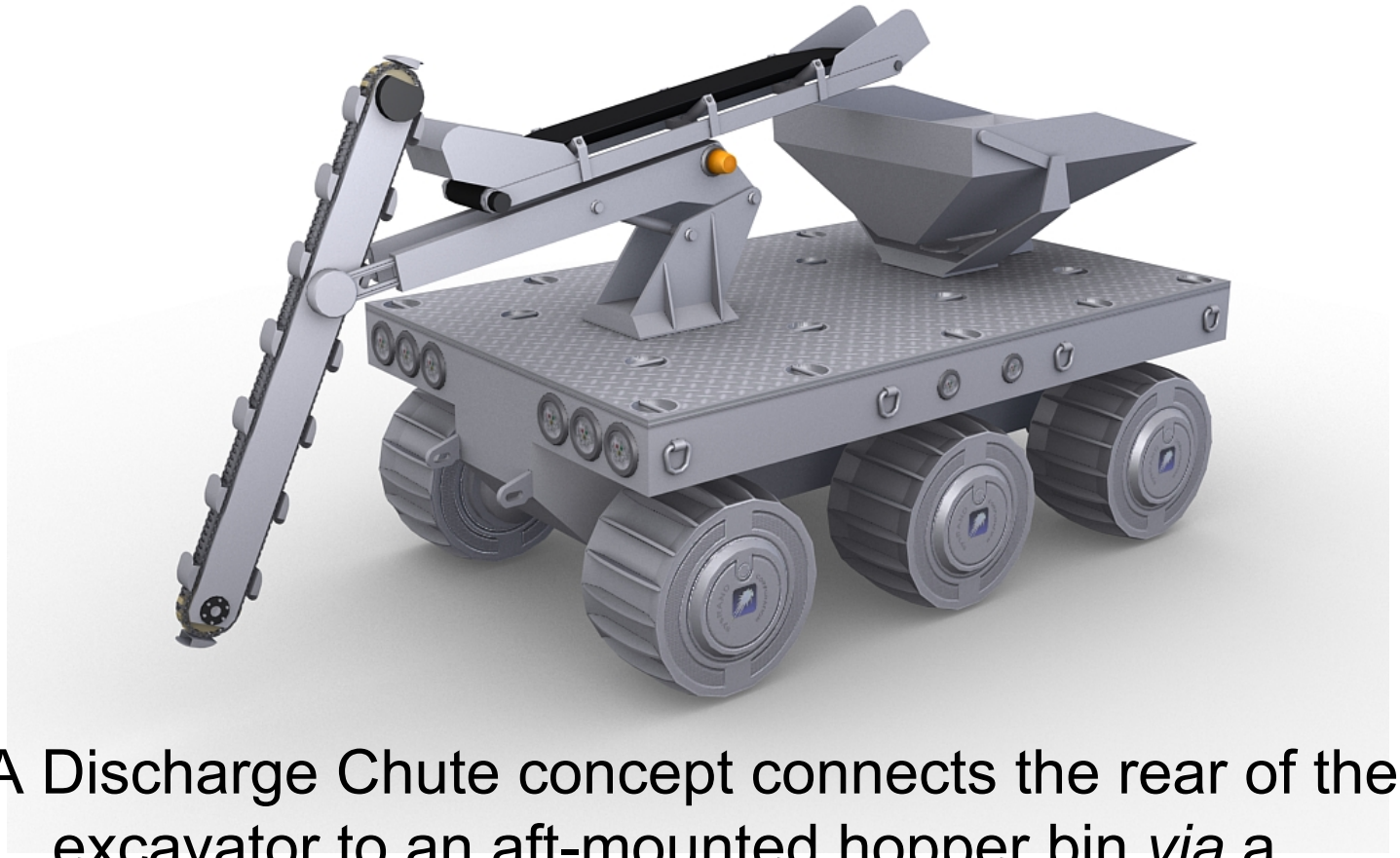
The wide track is expected to provide considerable stability and resistance to roll-over during tool extension.

TUG (Version 3-View 6)

That the flashing yellow hazard lamps could be sheared off became clear in this rendering.

Note clearance to avoid high-centering.

TUG (Version 3-View 7)

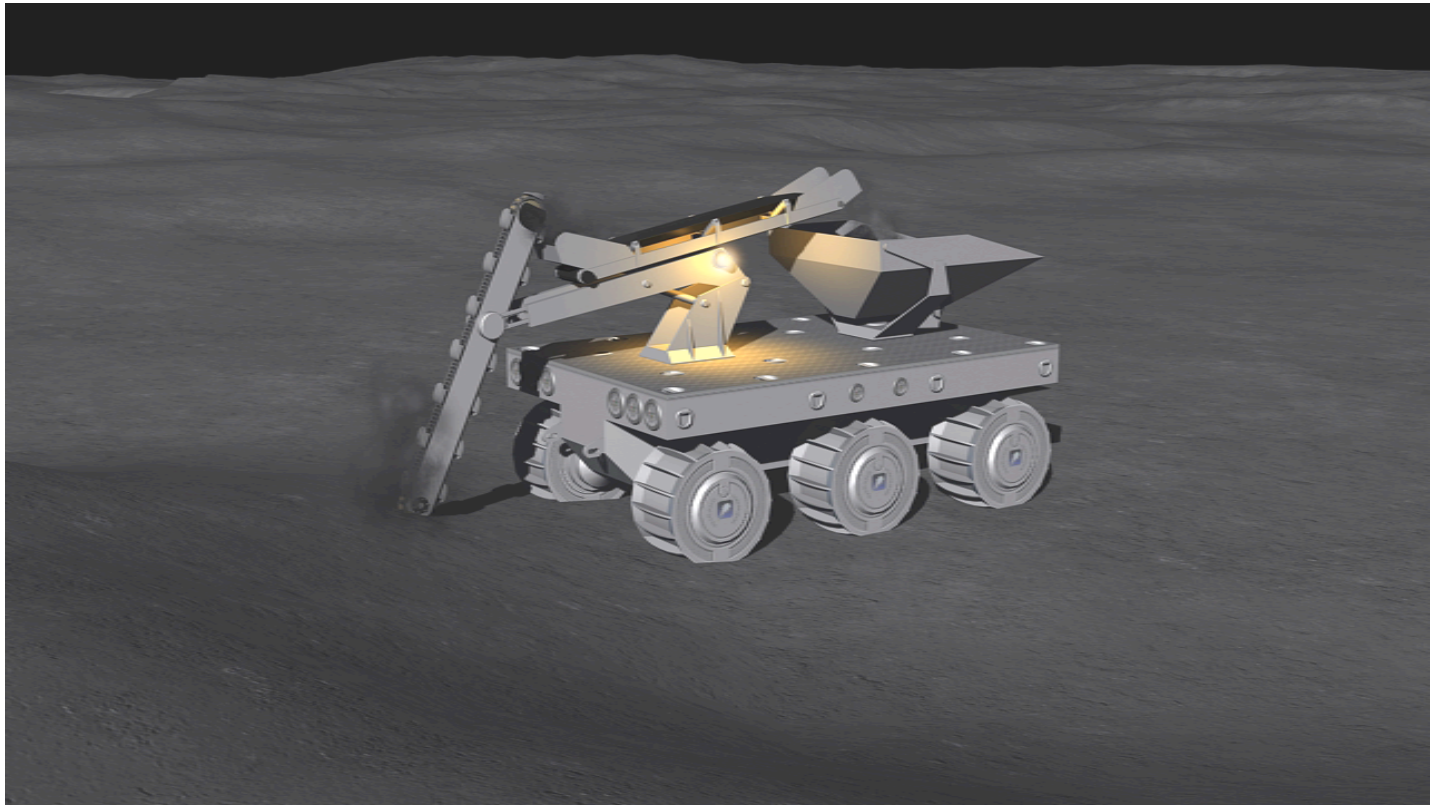


A Discharge Chute concept connects the rear of the excavator to an aft-mounted hopper bin *via* a conveyor belt.

TUG (Version 3-View 8)

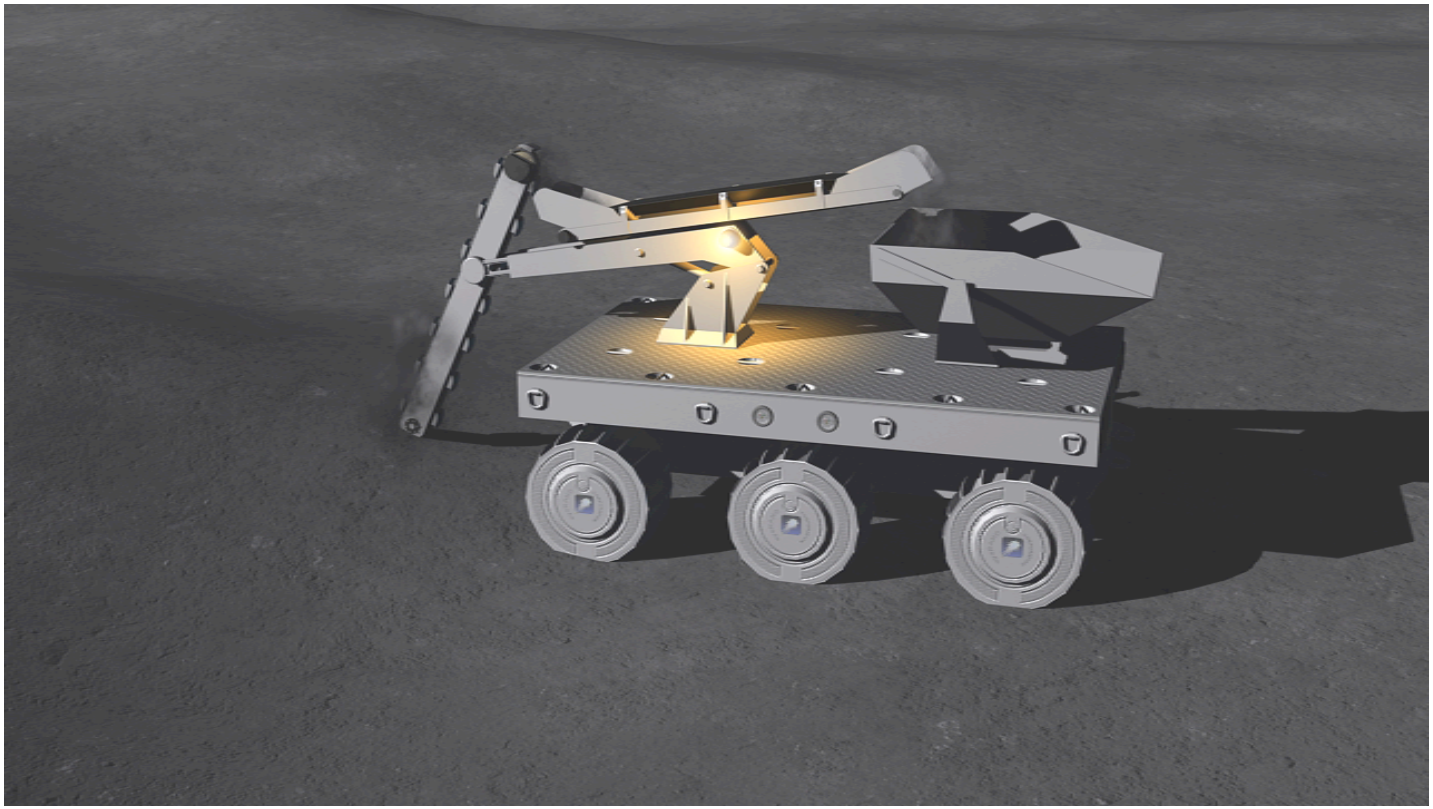
This vantage point highlights the constraints and conflicts of the discharge chute and hopper bin.

TUG (Version 3-View 9)



A still shot from an animation of a simulated TUG in the Lunar ISRU context.

TUG (Version 3-View 10)



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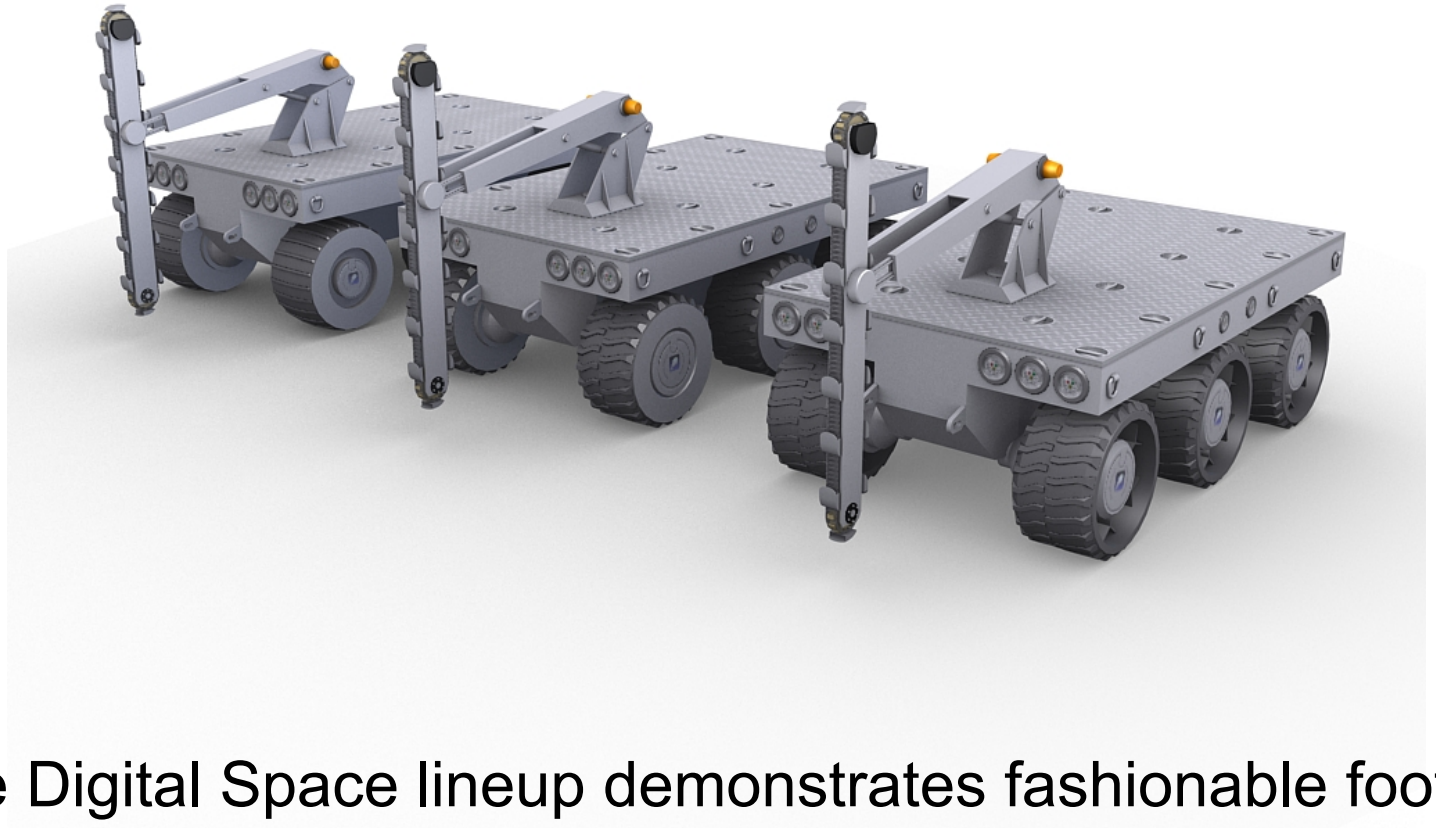
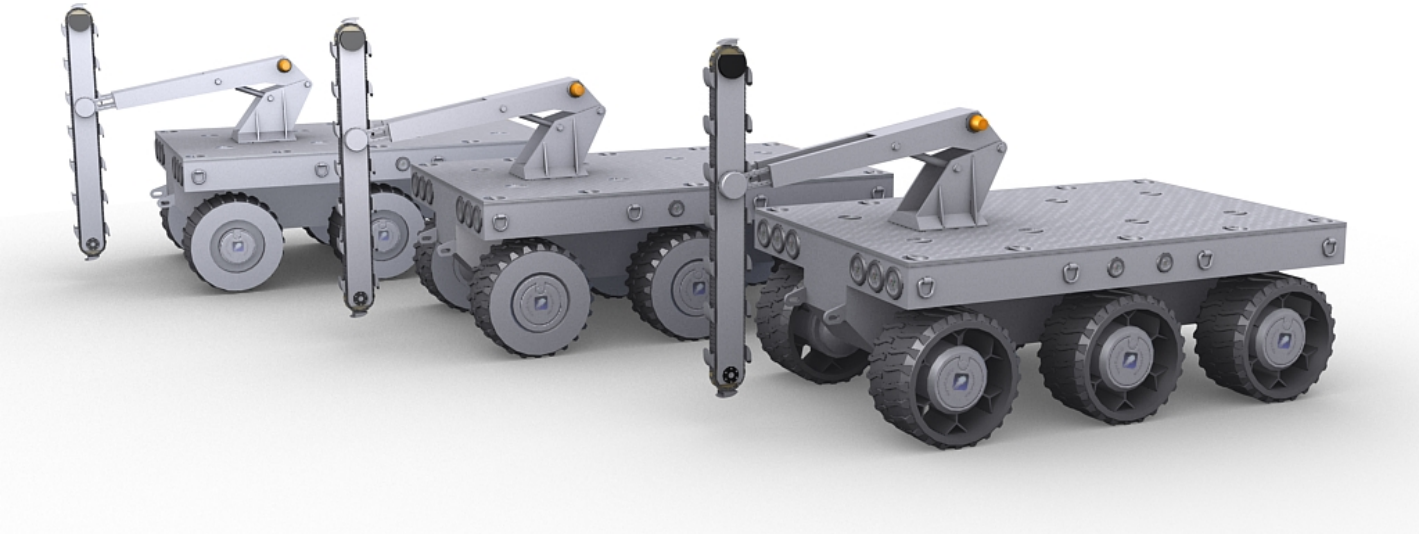
TUG (Version 3-View 11)



The Digital Space lineup demonstrates fashionable footwear.

TUG (Version 3-View 12)



Some yellow plastic and LEGO has a new series.

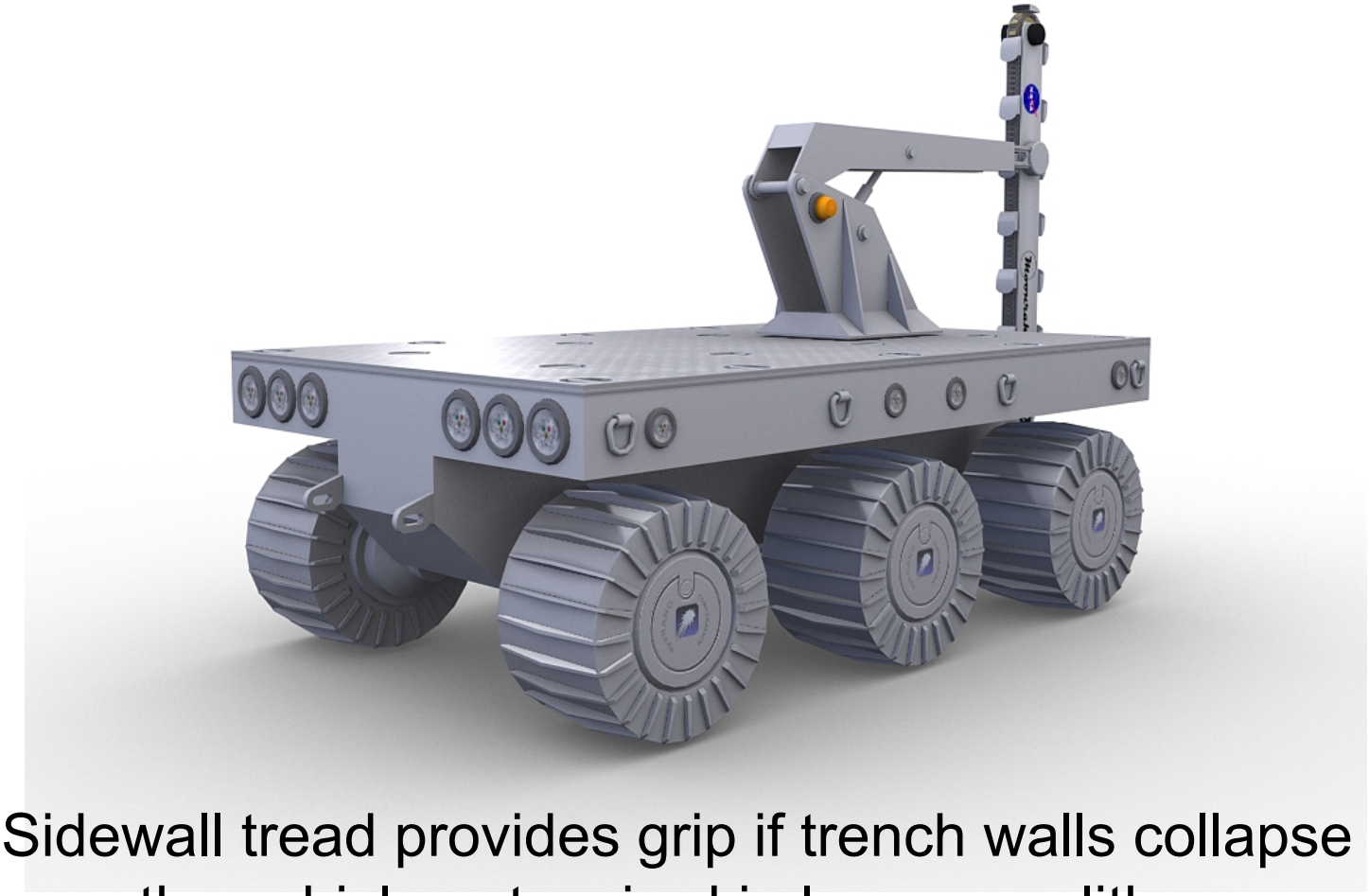
TUG (Version 4-View 1)

Additional LEDs mounted on the deck edges help others to better see the TUG's eight foot extent.

TUG (Version 4-View 2)

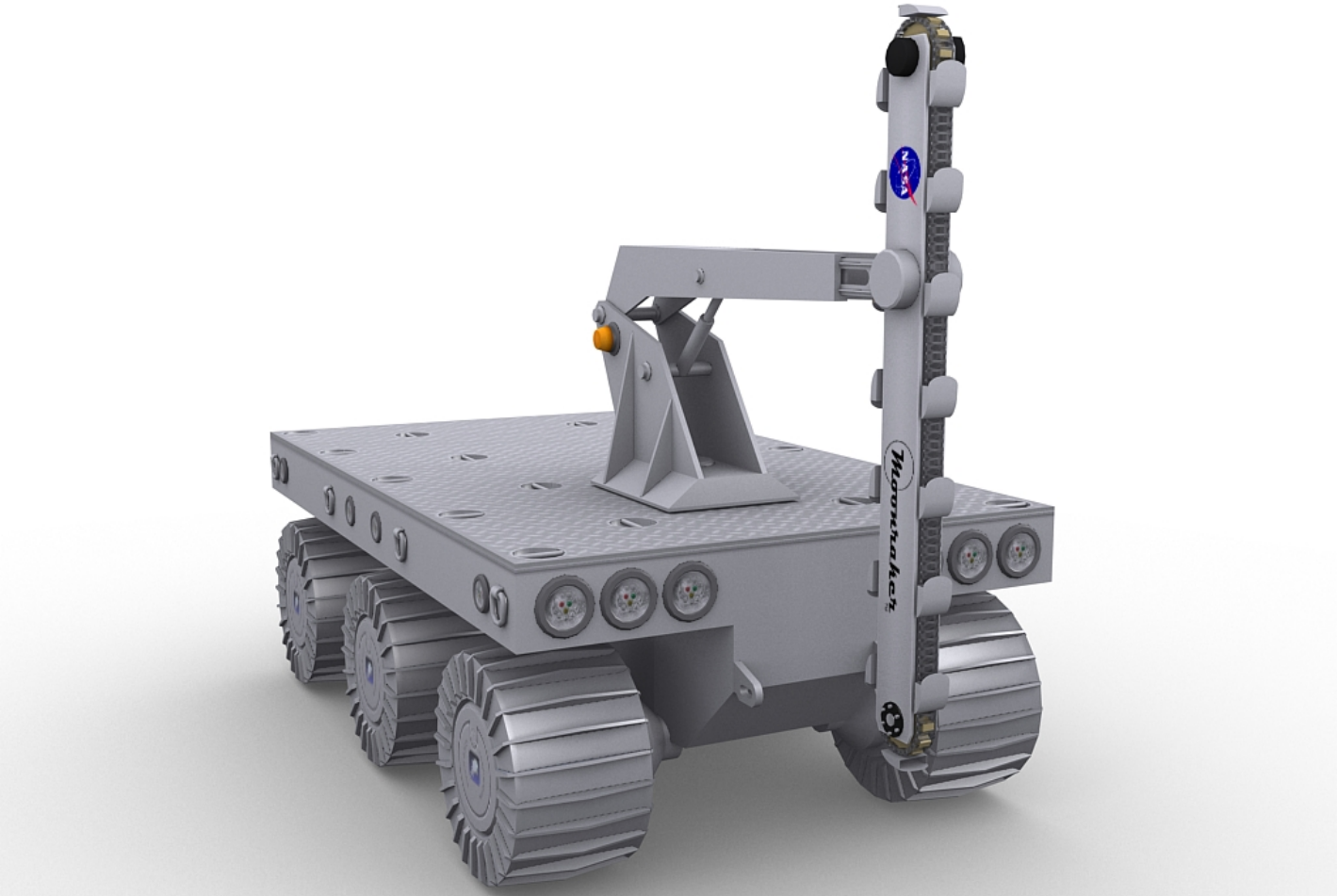
Solid wheels provide volume to accommodate a wheel's motor, brake, and clutch.

TUG (Version 4-View 3)



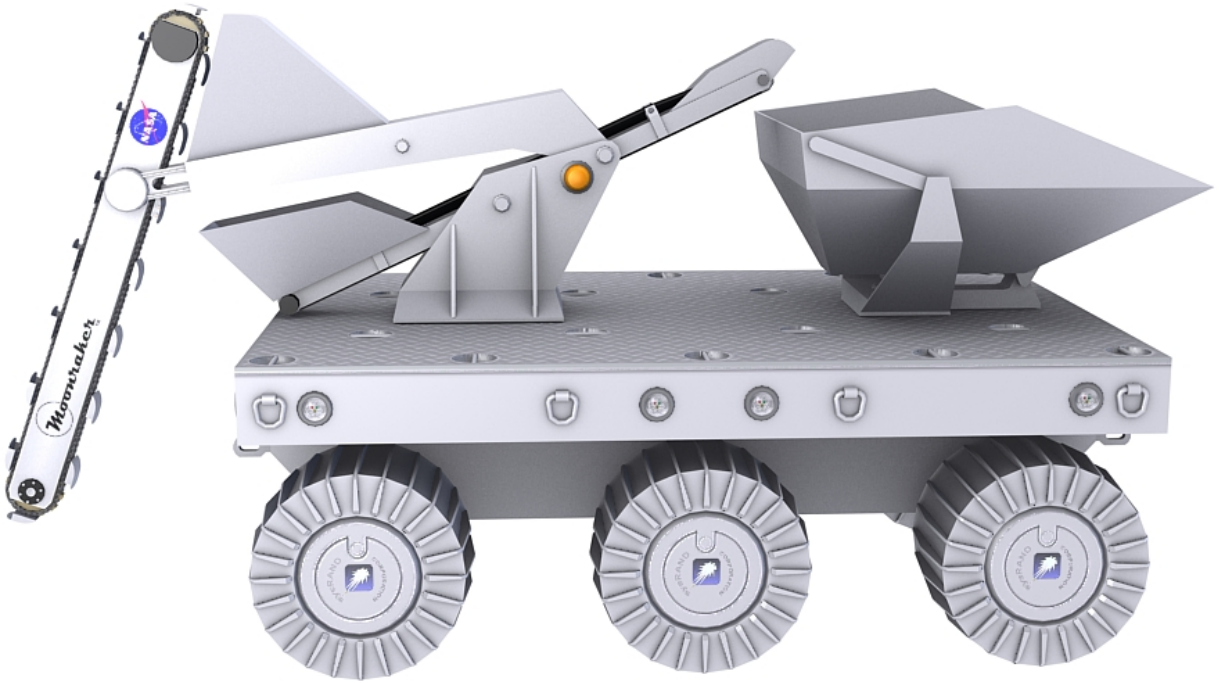
Sidewall tread provides grip if trench walls collapse or the vehicle gets mired in loose regolith.

TUG (Version 4-View 4)



The fine details of the excavator are more accurately rendered here.

TUG (Version 5-View 1)



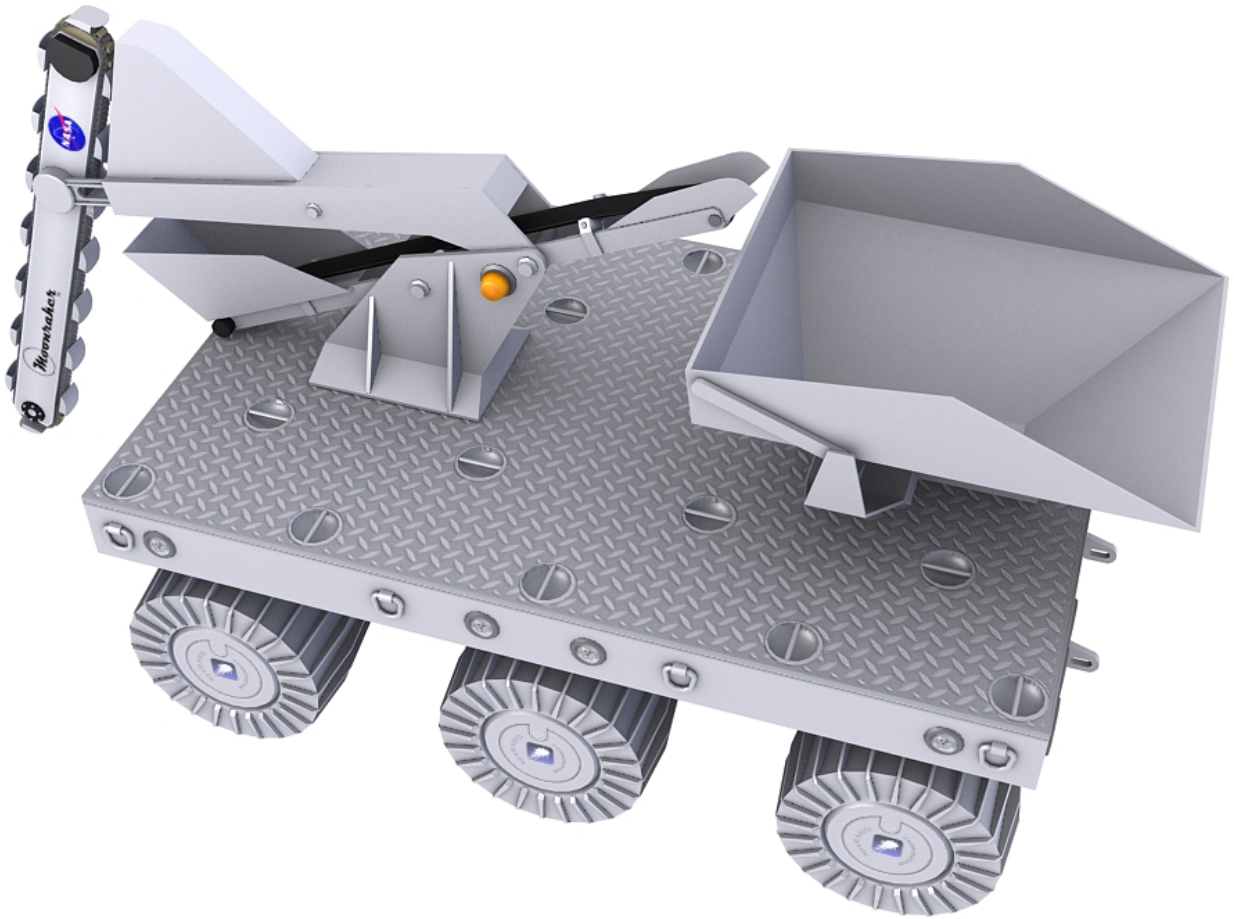
The flashing hazard lamps have been relocated.

The Hopper rotates and slides fore and aft to track the Discharge Chute.

TUG (Version 5-View 2)

An Imposing Aspect

TUG (Version 5-View 3)



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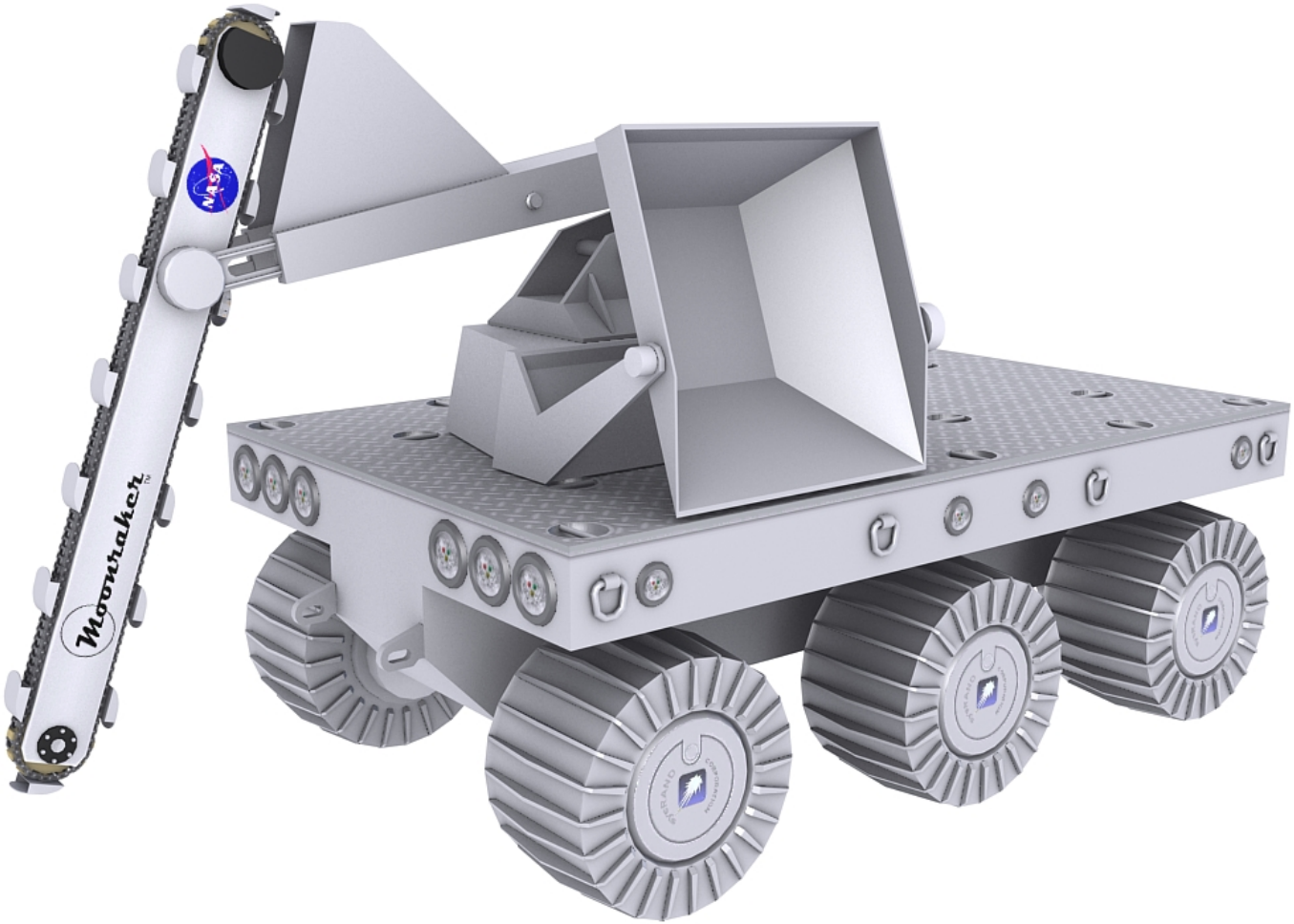
TUG (Version 5-View 4)

A creative suggestion from DS stacks the turret atop a rotating hopper for a compact configuration.

TUG (Version 5-View 5)

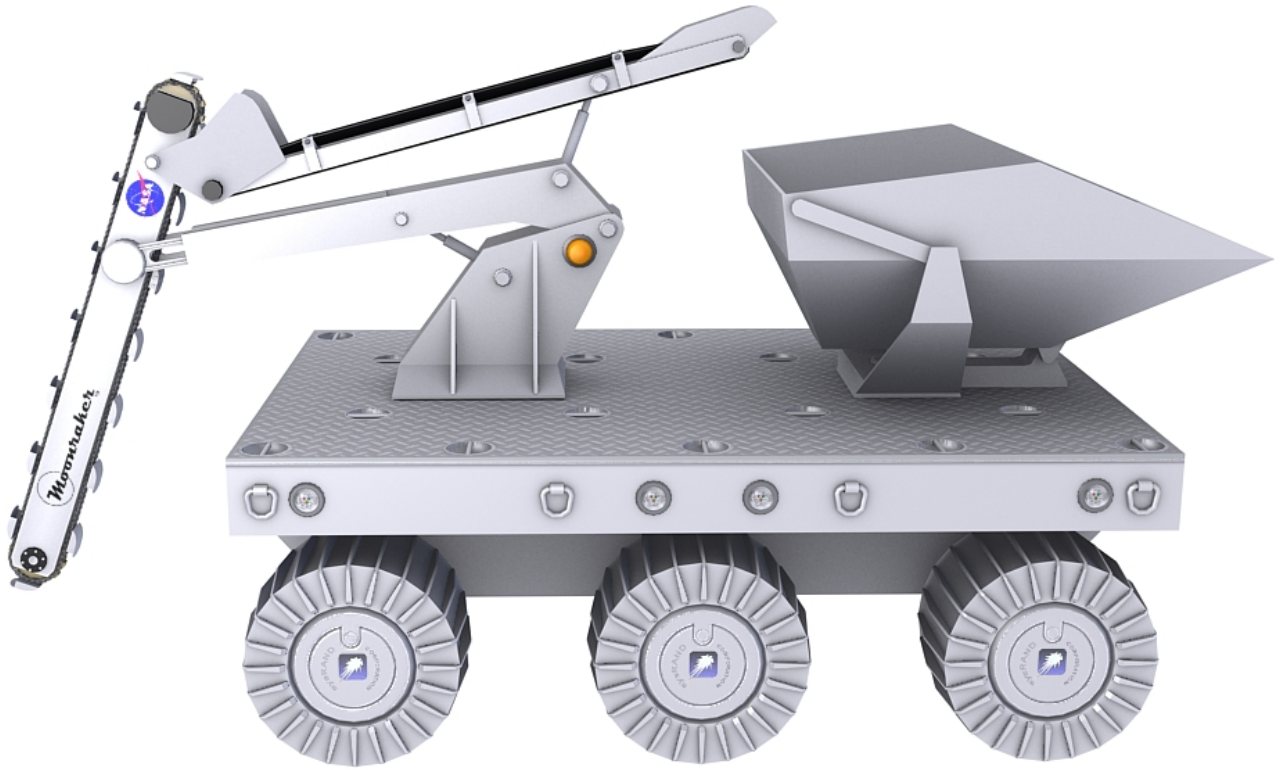
The hopper can be positioned in a continuous arc.

TUG (Version 5-View 6)



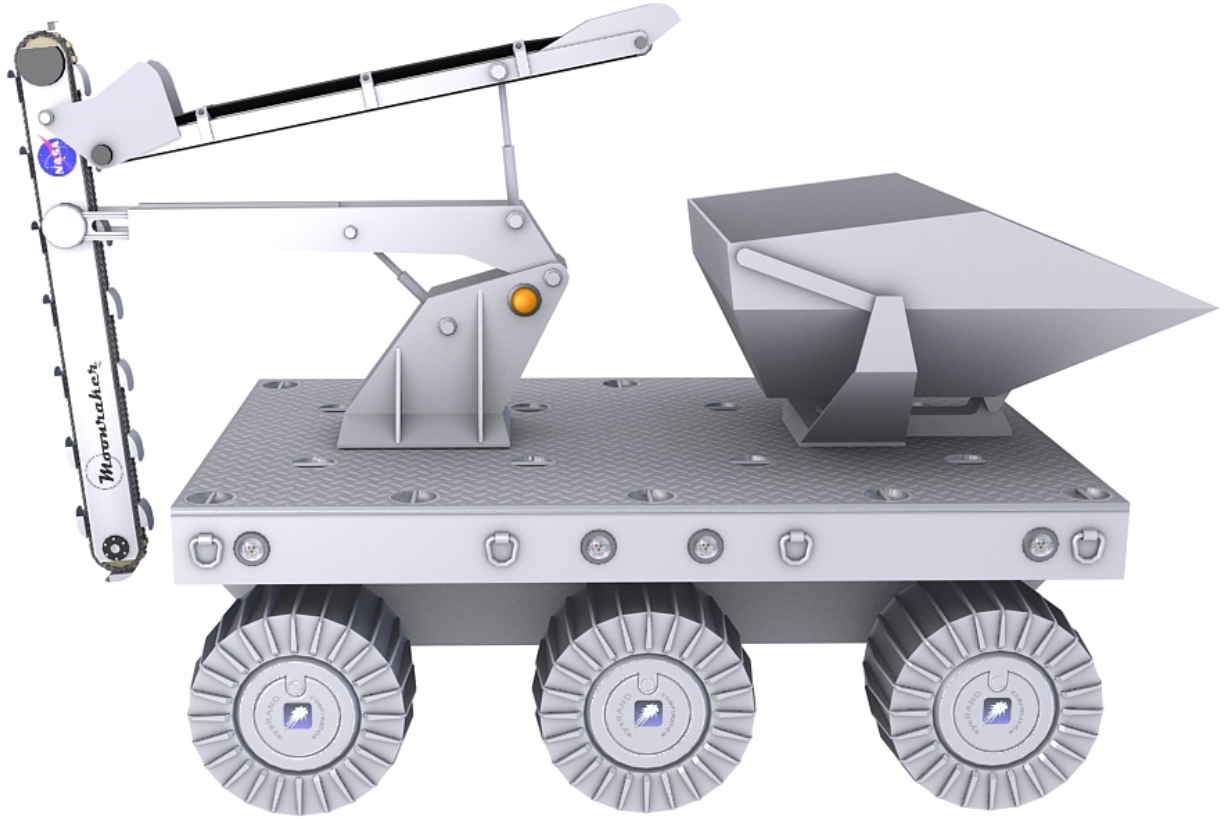
This hopper configuration can dump to the side.

TUG (Version 5-View 7)



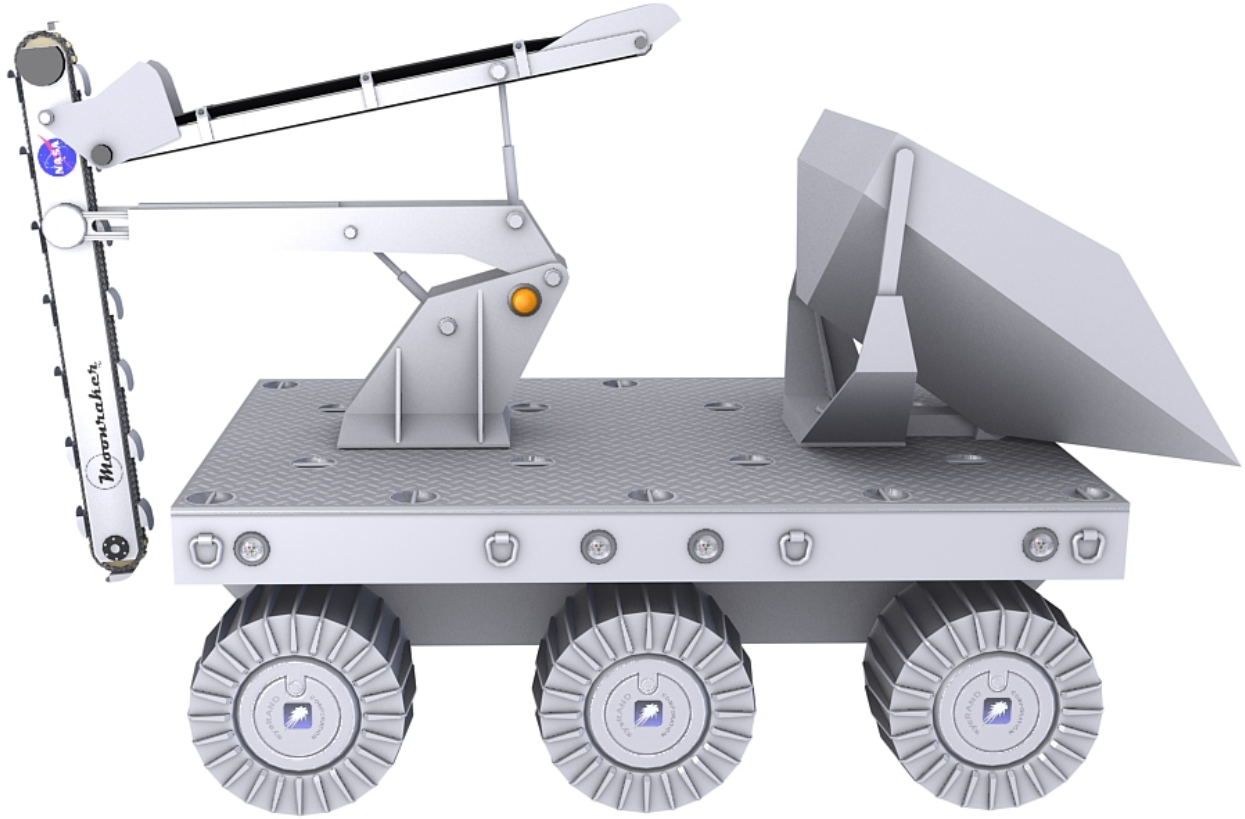
Another Discharge Chute concept attaches a conveyor above the turret arm.

TUG (Version 5-View 8)



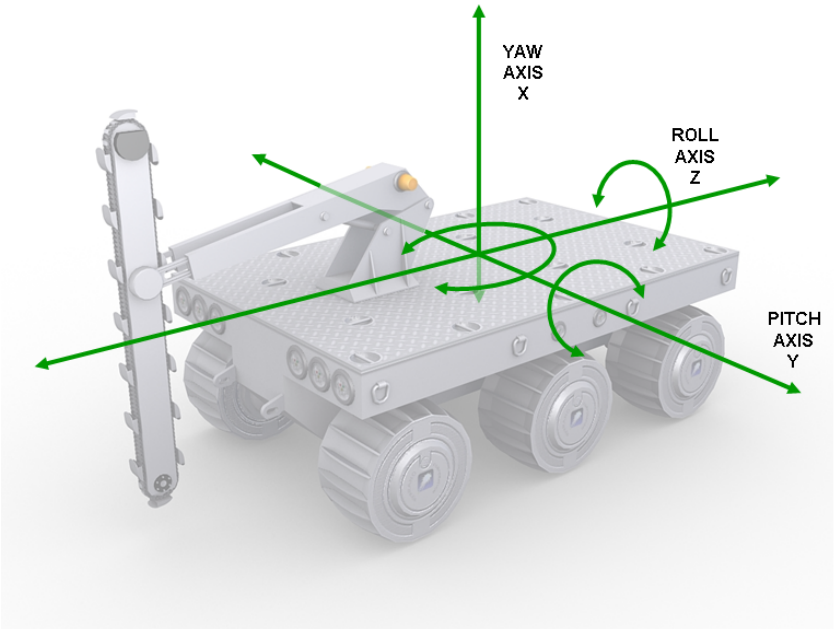
The conveyor is a follower, operating in the same plane as the excavator.

TUG (Version 5-View 9)



The hopper can dump to the rear or side. A side position offers a continuous dump mode.

The TUG's Major Axes

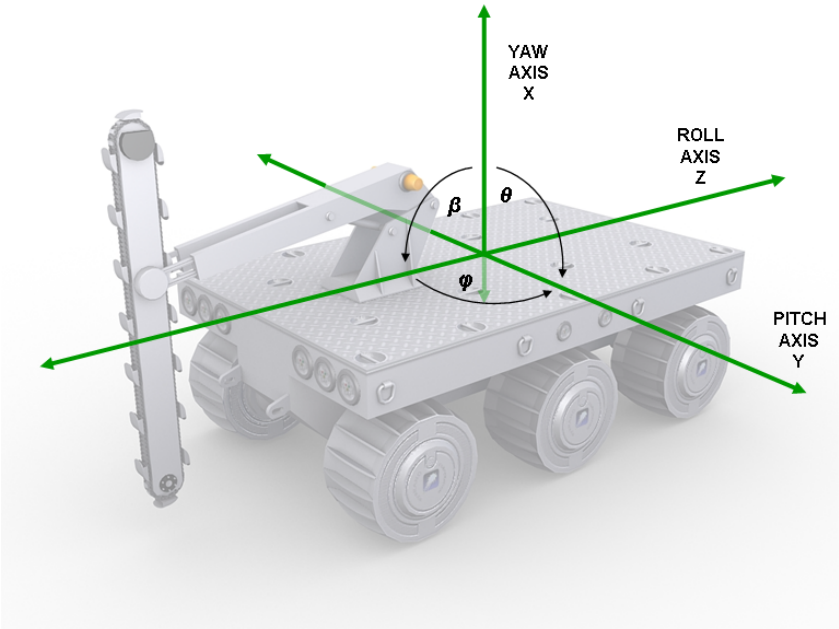


The Platform's Major Axes align with conventional aircraft and ship axes:

ROLL	(R)
PITCH	(P)
YAW	(Y)

The Roll axis describes the platform's direction of travel.

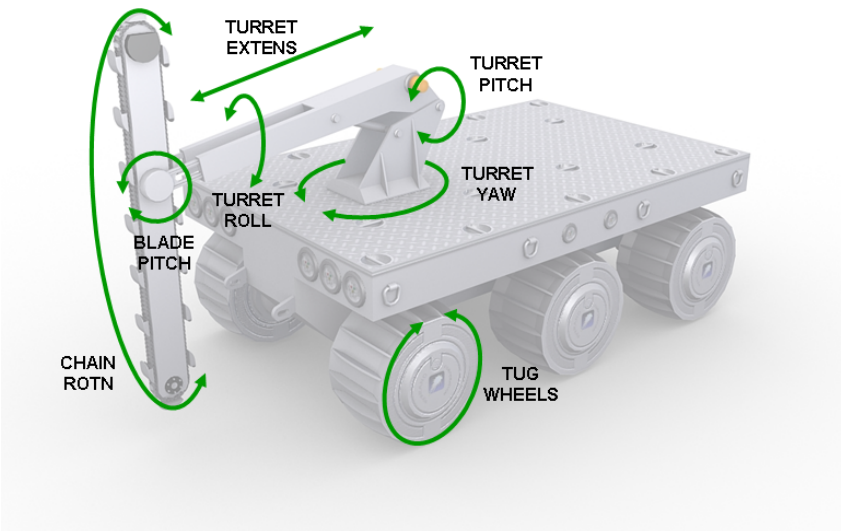
The TUG's Polar Angles



The notation for polar angles are:

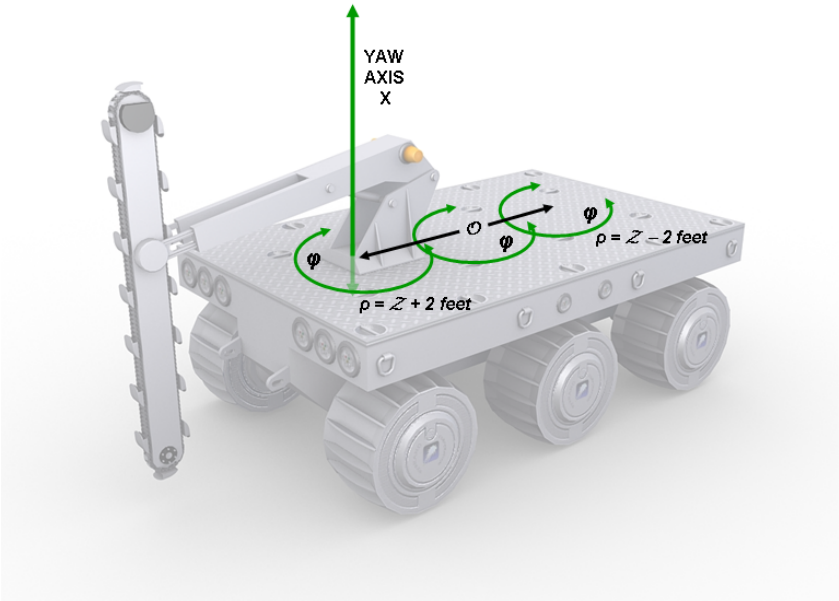
ROLL	θ
PITCH	β
YAW	φ

The TUG Coordinate Reference Frame



The Integrated Tool and TUG delivers 12DOF to the Excavator Blade tip.

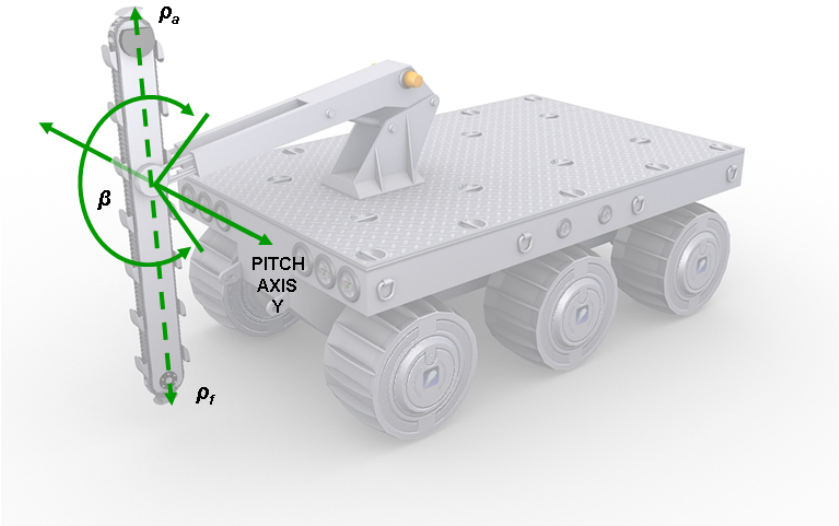
Modular CRF



The center hardpoint is the vehicle's Coordinate Reference Frame origin.

The forward and aft hardpoints have a Z-axis offset of 24 inches.

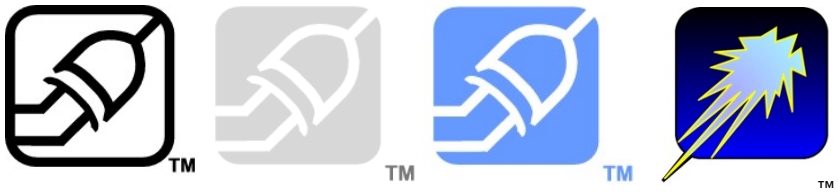
Excavator Blade CRF

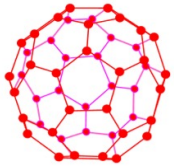


The Nose and Aft of the Blade are referenced to the Module boundary of the Turret-to-Blade Interface.

We acknowledge the tremendous contribution of Bruce and Ryan at Digital Space for their faithful rendering, creative gap-filling, and *ad hoc* engineering. We appreciate that they can operate independently when we are absorbed in other aspects of the project, and bring new ideas forward.

A Sketch of *sys*RAND





- Incorporated 14 Dec 1989 in Colorado
- Started as a systems consultancy, work with oil, industrial, avionics, and systems manufacturers
- 1998 downturn: product development increasingly moved offshore along with manufacturing (the IT bust)
- 2001: entered space industry with a paper on ISRU applications of Silicon
- 2004: assembled and managed a winning $14.3M NASA ISRU contract for Colorado School of Mines
- 2006: awarded existing NASA and AF SBIRs, where both advanced to Phase 2
- Today, we actively develop technologies in two domains:
  - Foundational Systems and Tools
  - Translating Low-Energy Industrial Processes to Space-based ISRU
- Our new facility at Centennial Airport combines our offices and laboratory facilities into a suite which includes an integration bay and technical library