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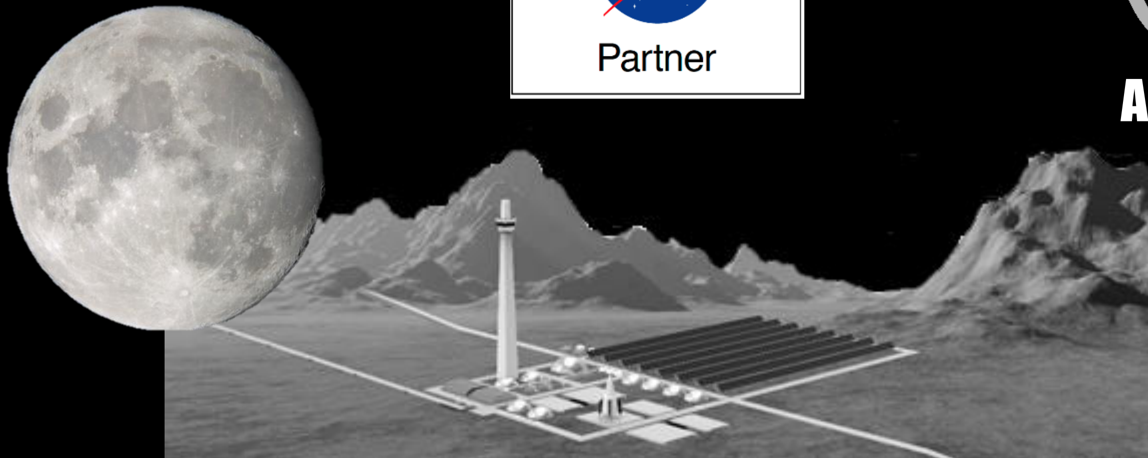

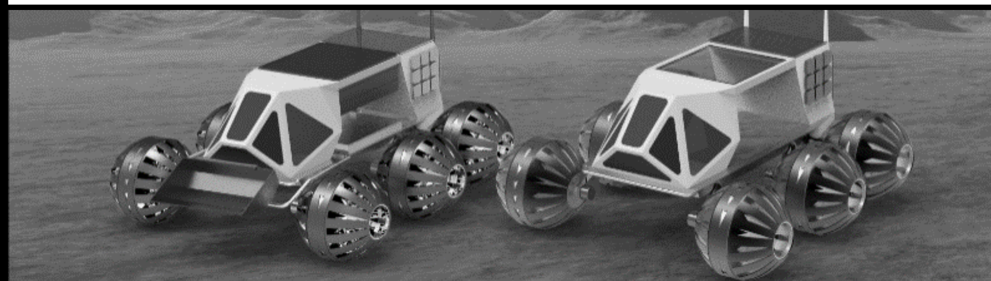

Lunar Mining and Base Construction and Operations Using Teams of Small Robots

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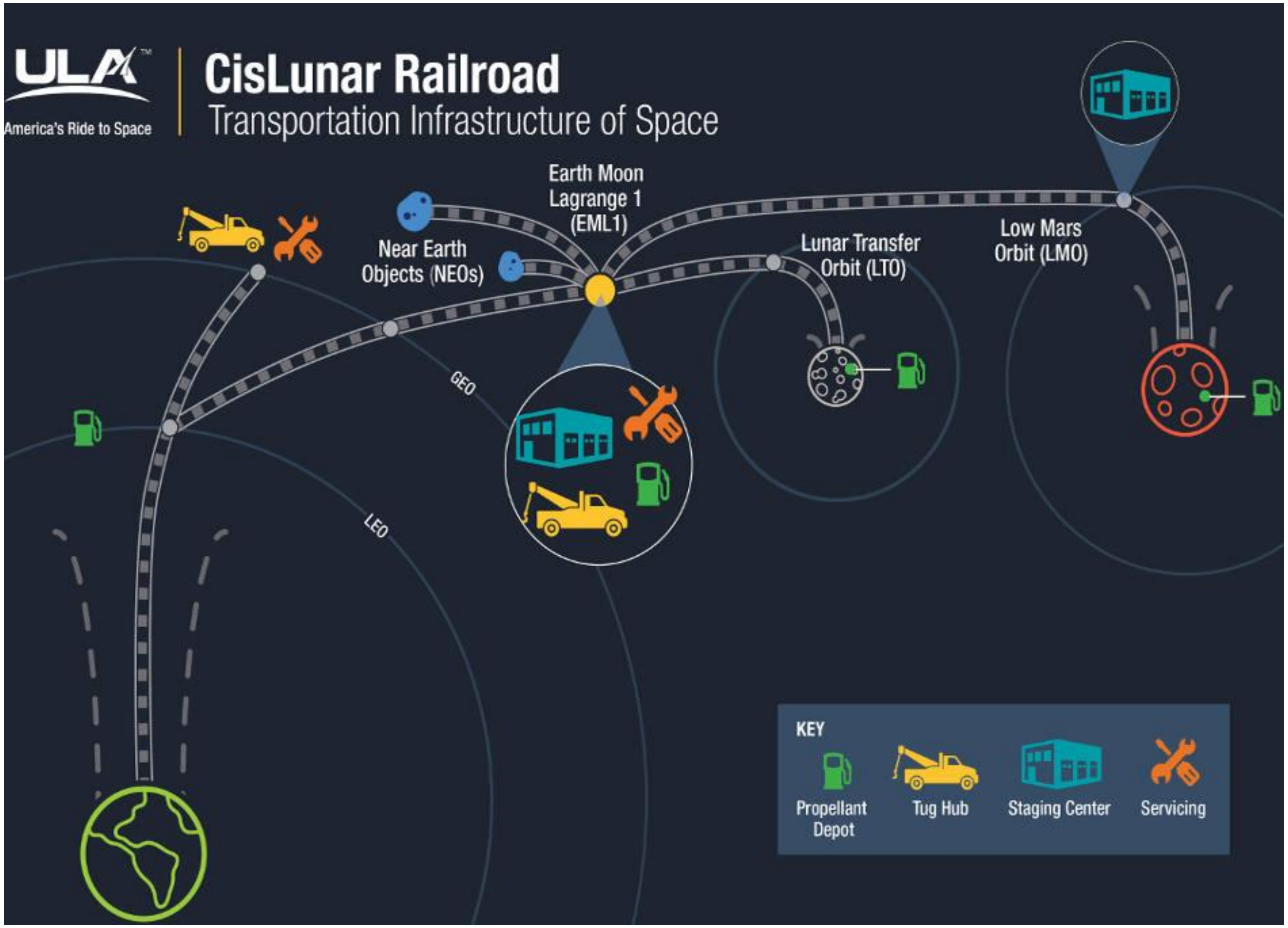
University of Arizona

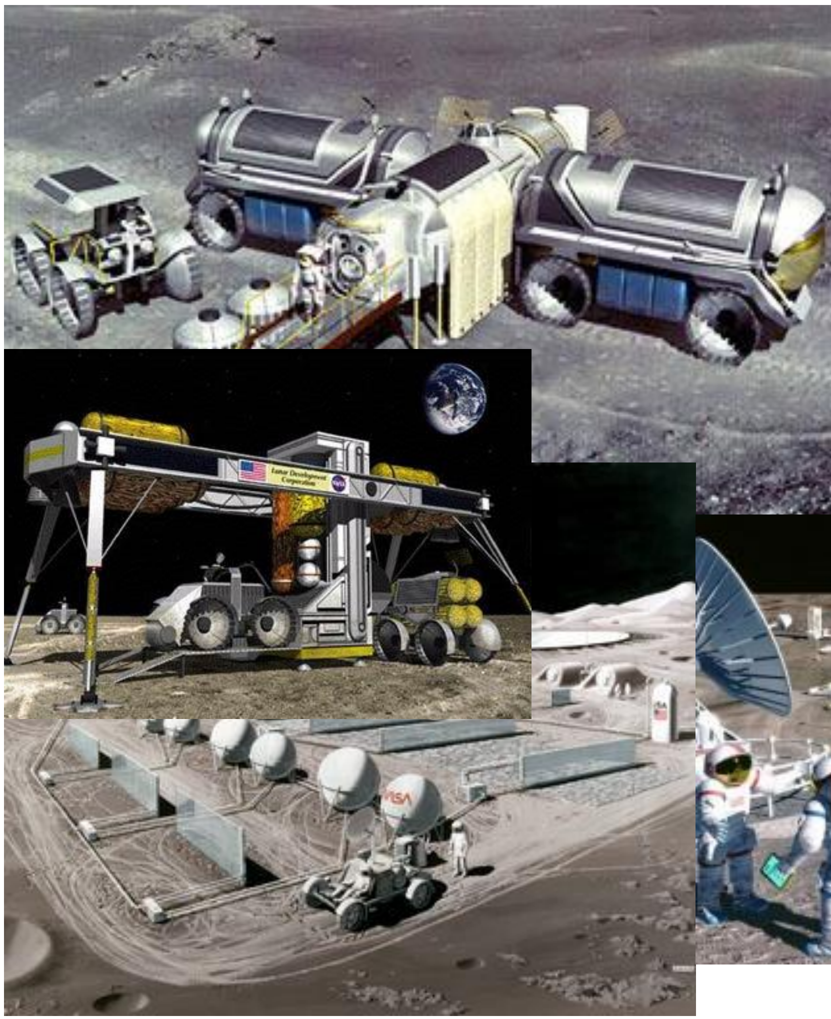
Outline

- Motivation
- Challenges
- Objectives
- Approach
- Simulation Results
- Experiments
- Discussion
- Conclusions

Motivation


ULA
America's Ride to Space
CisLunar Railroad
Transportation Infrastructure of Space
Earth Moon Lagrange 1 (EML1)
Near Earth Objects (NEOs)
Lunar Transfer Orbit (LTO)
Low Mars Orbit (LMO)
GEO
LEO
KEY
Propellant Depot
Tug Hub
Staging Center
Servicing

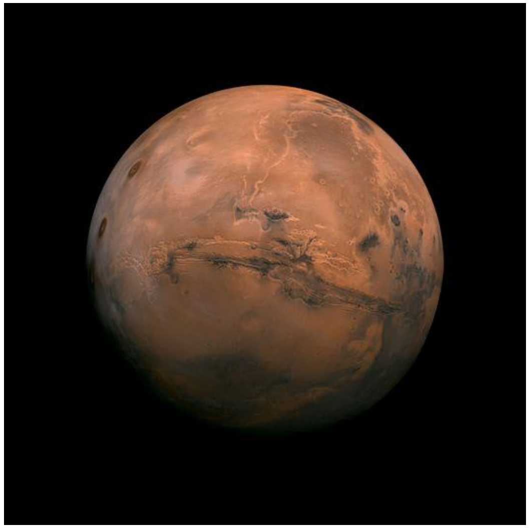
Motivation



- Refueling base at various locations in cis Lunar space
- Water electrolyzed to produce H_2 and O_2
- Fuel and raw material for transport, construction and manufacturing

Export Economies





- Low gravity of the Moon, asteroids and Mars facilitates rise of export economies.
- Substantial reserves of water found
- Matter of extraction and processing.

Performa… …pellant)

- **Delta-v**

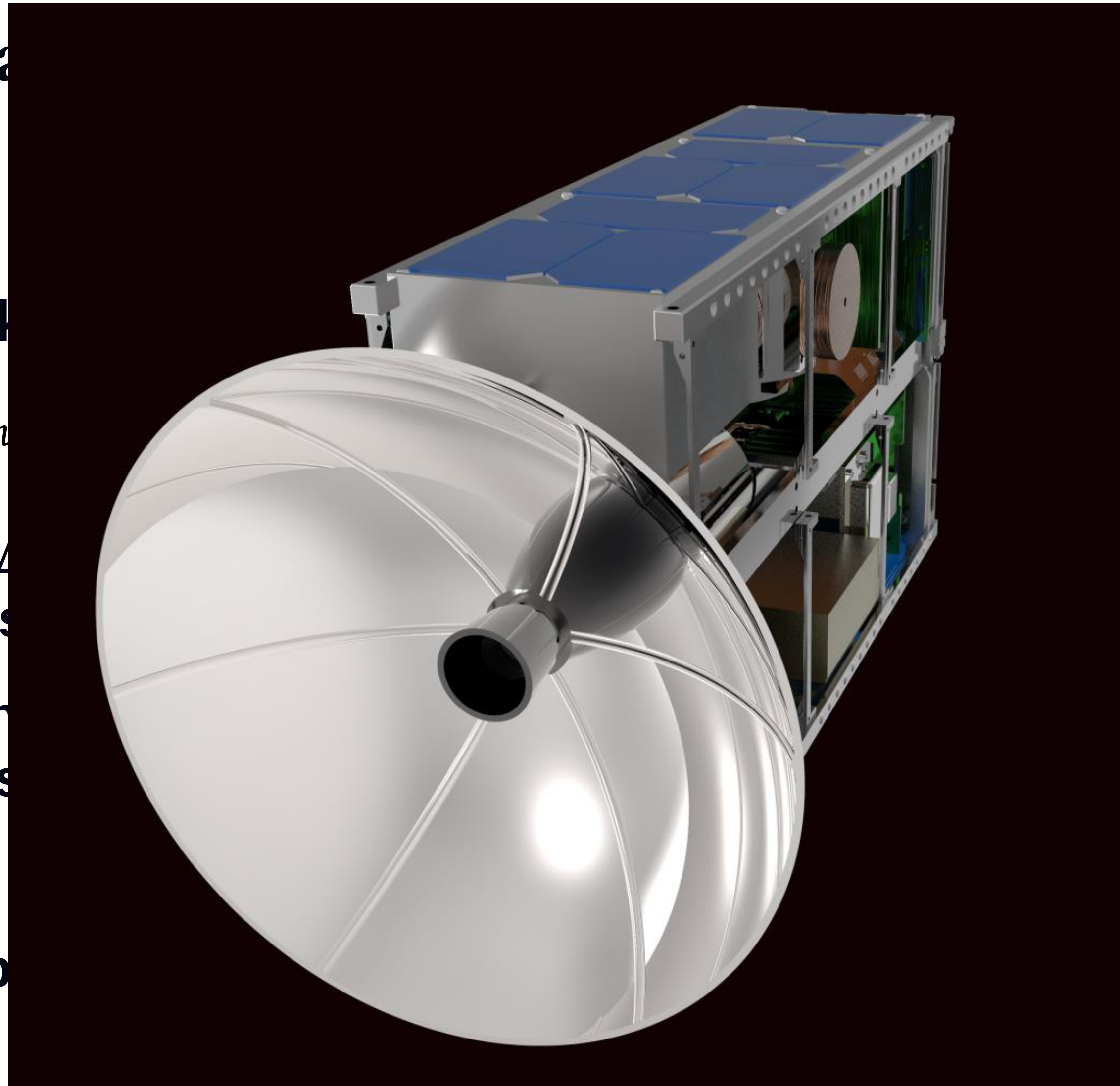
- **Tsiolkovsk…**

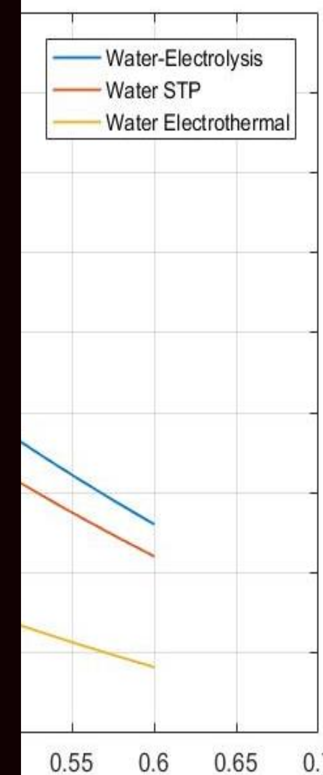
Δv …

- **Maximum Δ… 0.3 dry mas…**

- **It approach… electrolysis… systems**

- **Offer a sup… than water… propulsion…**





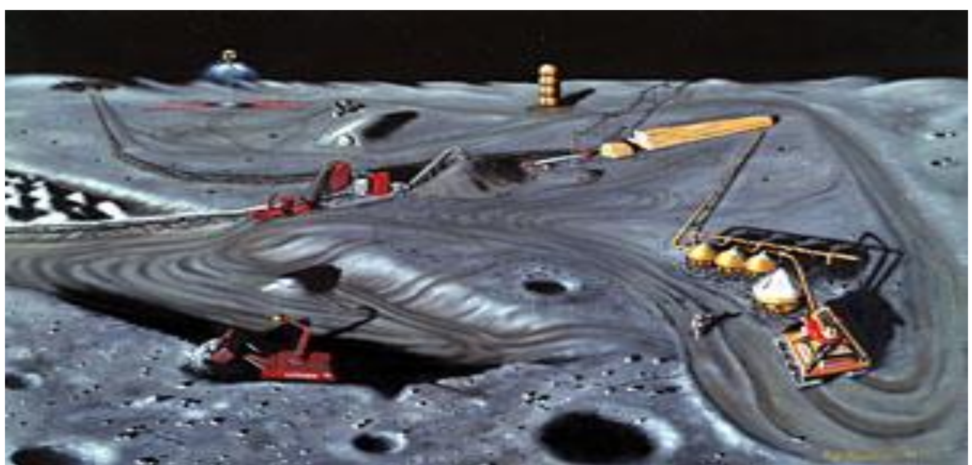
Multifunctional Materials - Water

- "Near Universal" Solvent
- Propellant
- Energy Carrier
- Hydrogen Storage
- Radiation shield
- Thermal storage device
- Coolant
- Life-support
- Needed for metal refining

Base Construction and Operation

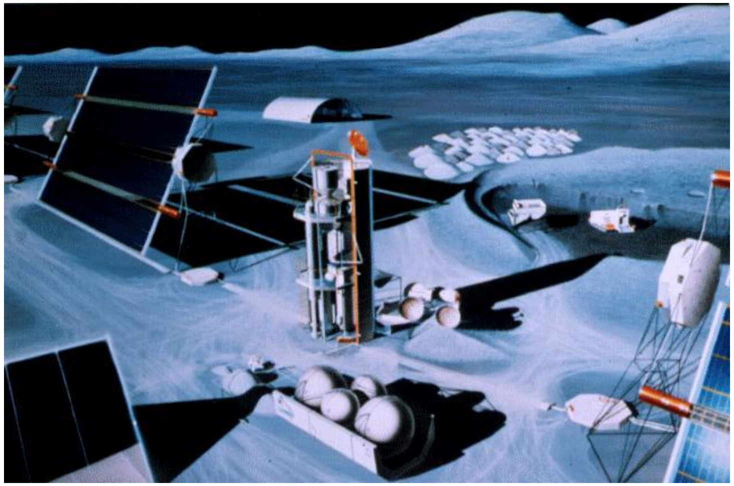
- Terrain preparation
- Facilities construction
- Water, oxygen, fuel production
- Metal extraction and refining

} Excavation



Key to Base Operation

- Autonomous Control
  - Unstructured environments
  - Minimal supervision and task decomposition
  - In-situ adaptation
- Multiple robots - increases
  - Parallelism
  - Redundancy
  - Robustness
  - Simplicity

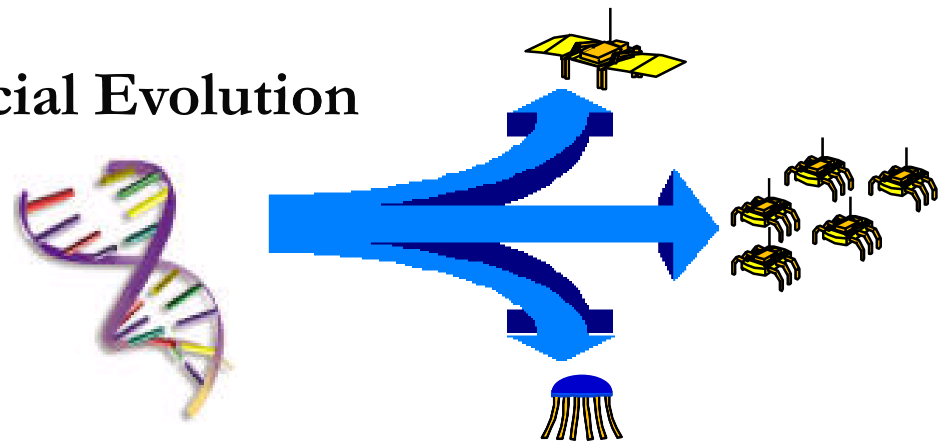


- Control development
  - Decentralized, adaptive, robust, no onsite support

Evolvable Systems

Space Systems Design Goal:
Meet Requirements

Artificial Evolution

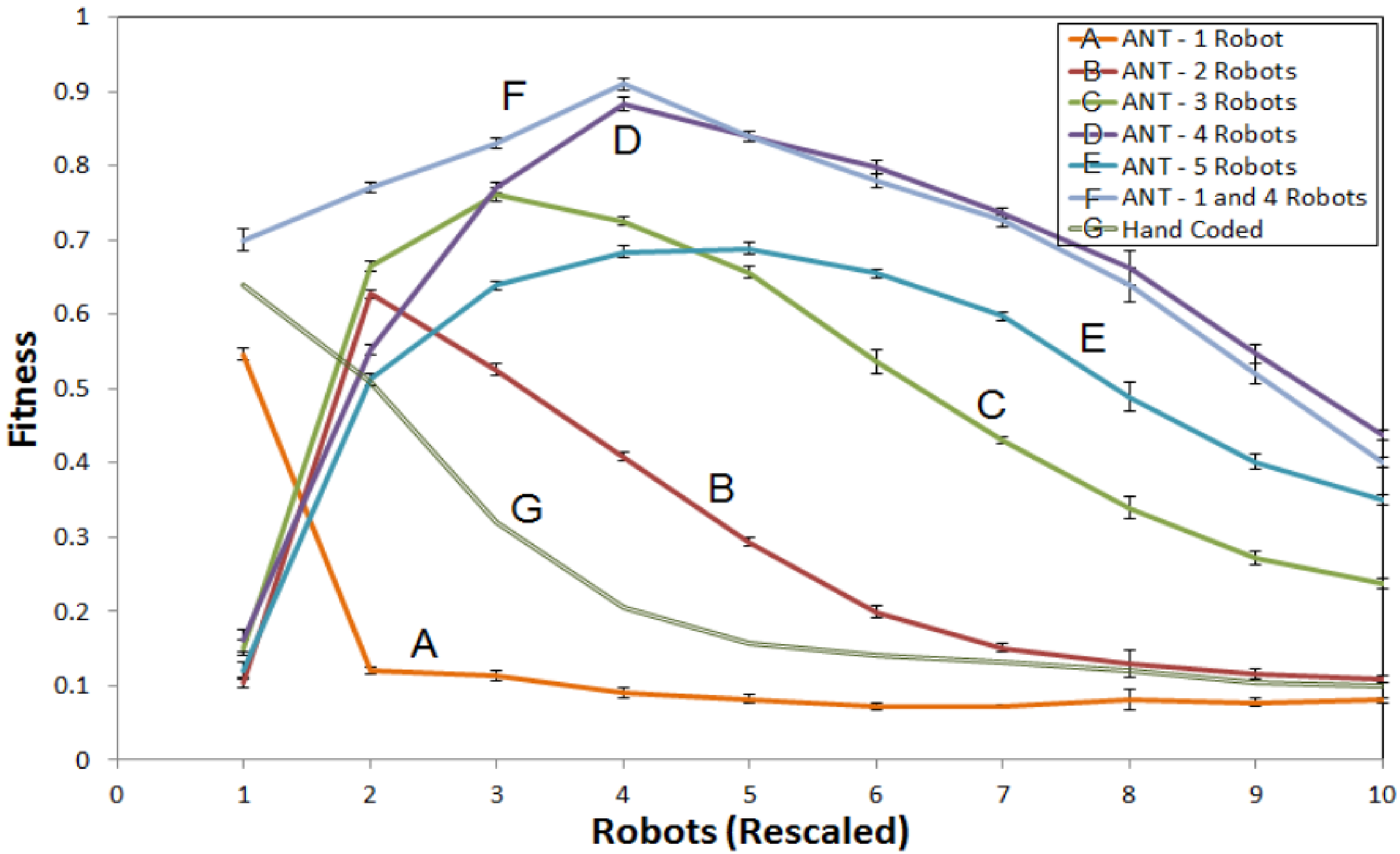


JPL

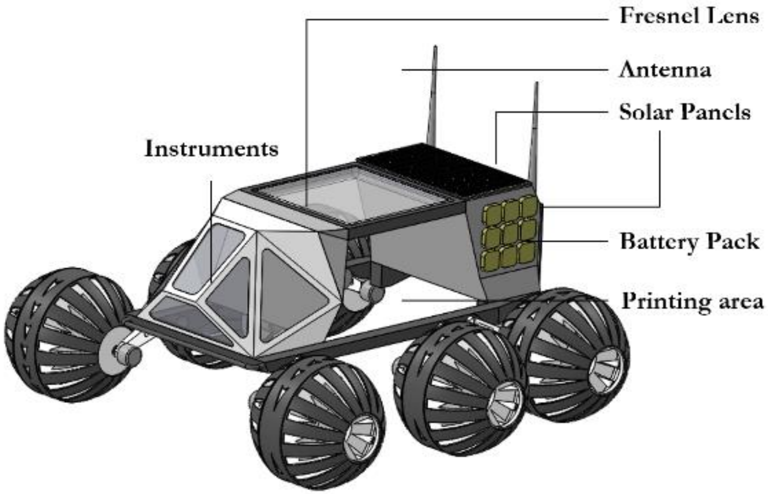
The Engineering Model: Social Insects

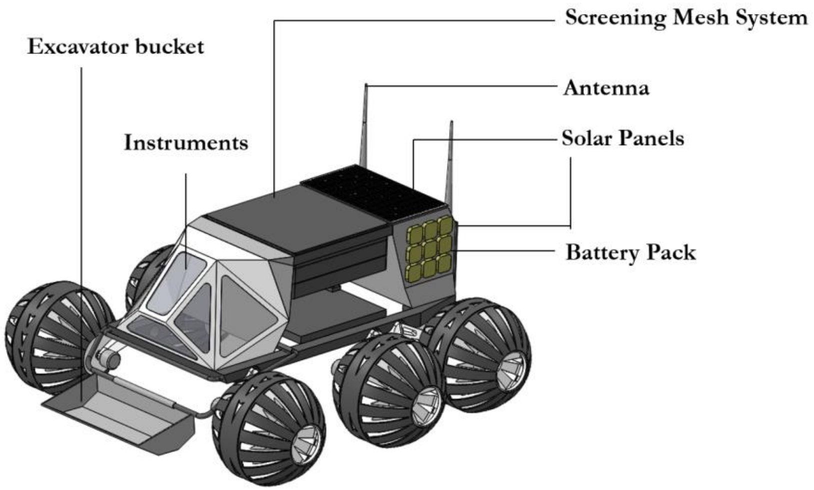
- “Whole greater than the sum of the parts” -Koffka
- Solve a complex task using many individuals.
- Individuals are simple, low-cost, disposable.
- They have survived for 400+ million years

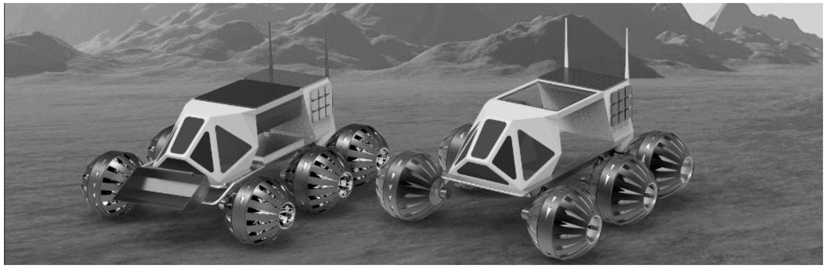
Teams of Autonomous Robots for End to End Operations



Robot Teams


Fresnel Lens
Antenna
Solar Panels
Instruments
Battery Pack
Printing area


Screening Mesh System
Excavator bucket
Antenna
Solar Panels
Instruments
Battery Pack



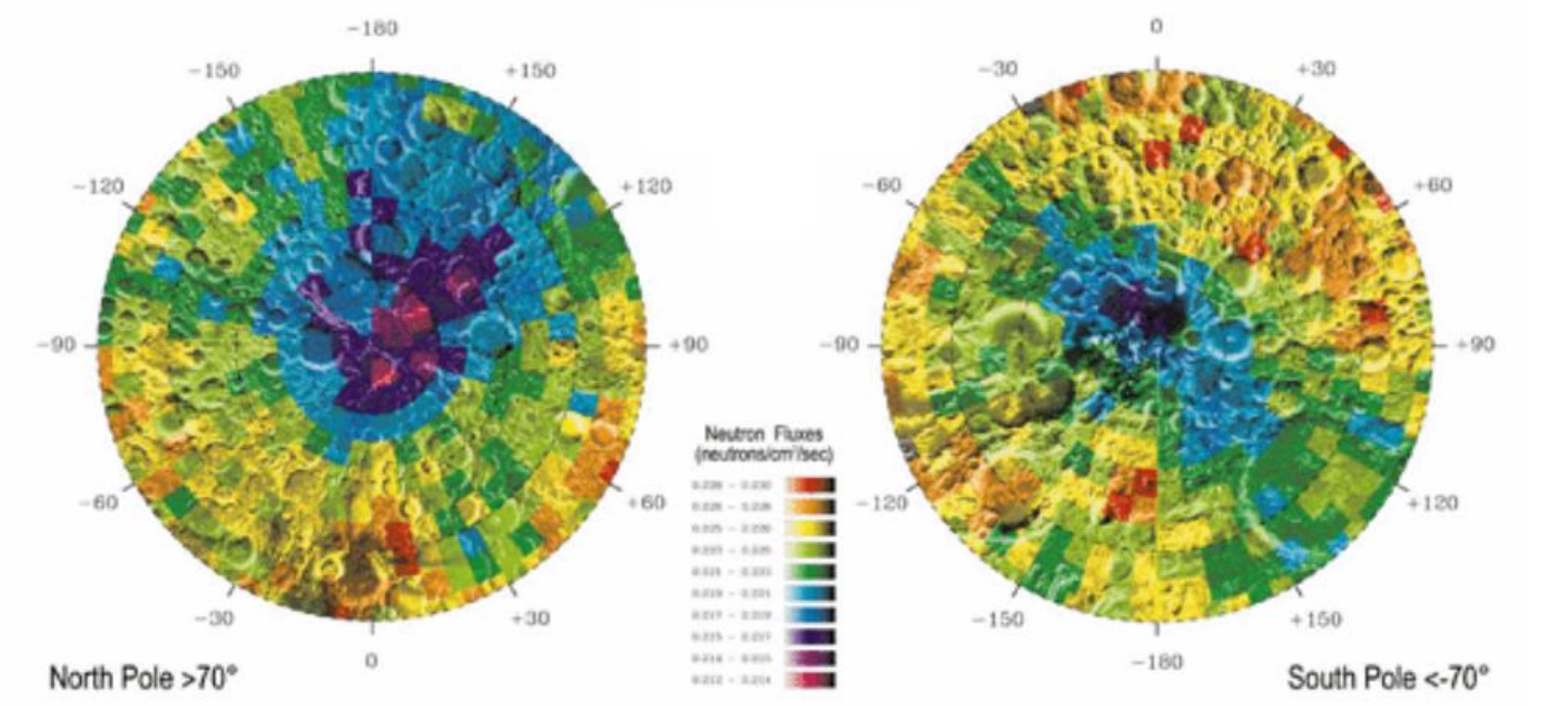
Additive Manufacturing Off-world

Technique	Print Mech	Materials	Support Structures	Post-Processing	Mars/Moon Use
Vat Photo-polymerization (VP)	Light Source (Directed Laser)	Light activated polymers	Yes	Yes	No
Material Jetting (MJ)	Resin Dispensing Printhead (Gantry)	Thermoset photopoly mer resin	Yes	Yes	No
Binder Jetting (BJ)	Binding agent dispensing printhead (Gantry)	Metals, sands, ceramics	No	Depends on application	Yes
Material Extrusion (ME)	Extrusion nozzle (Robotic or Gantry)	Wide range of thermo-plastics, cement paste, rubber, food pastes	In some cases	Depends on surface finish required	Yes
Powder Bed Fusion (PDF)	Laser or electron beam	Metals, Ceramics, Nylon	No	Depends on surface finish required	Yes

Objective

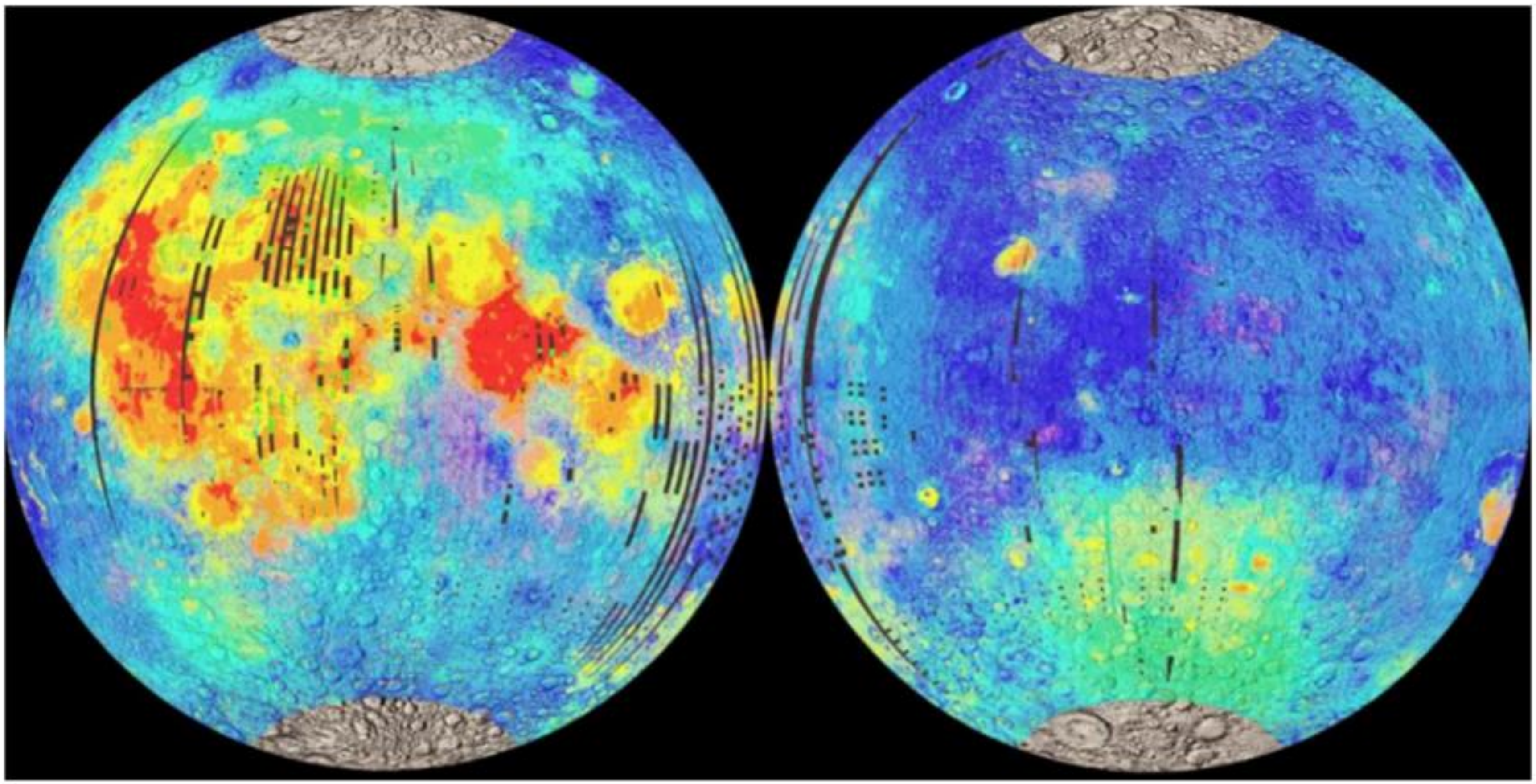
- Develop an energy model for the construction and operation of a mining base. Compare overall feasibility of developing a base on the Moon and outline the need for new technology.

Water Ice or Hydrate Deposits on the Moon



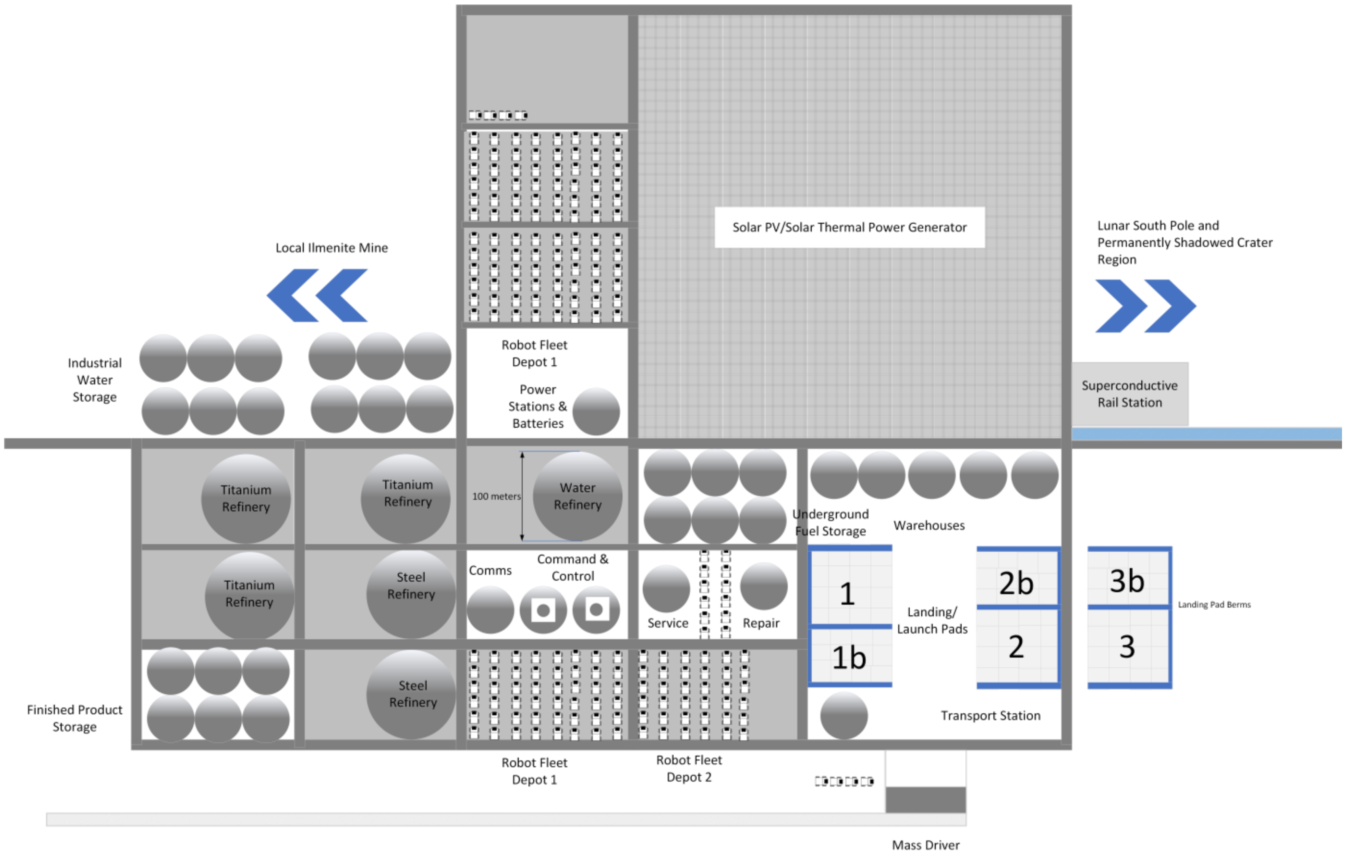
LCROSS Data, NASA Ames

Ilmenite Deposits on the Moon



(Spudis/LPI, 2002)

Mining Base – 100 tons of H_2O, Ti, Fe day

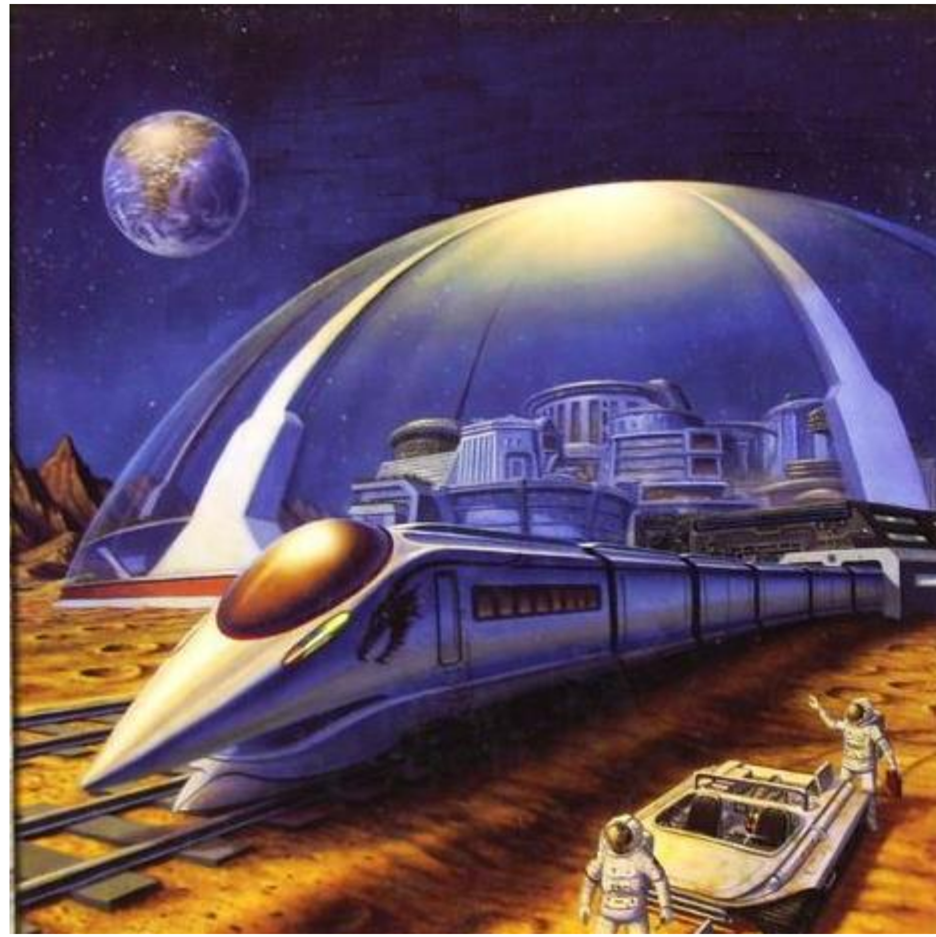


Mass Driver for Material Export

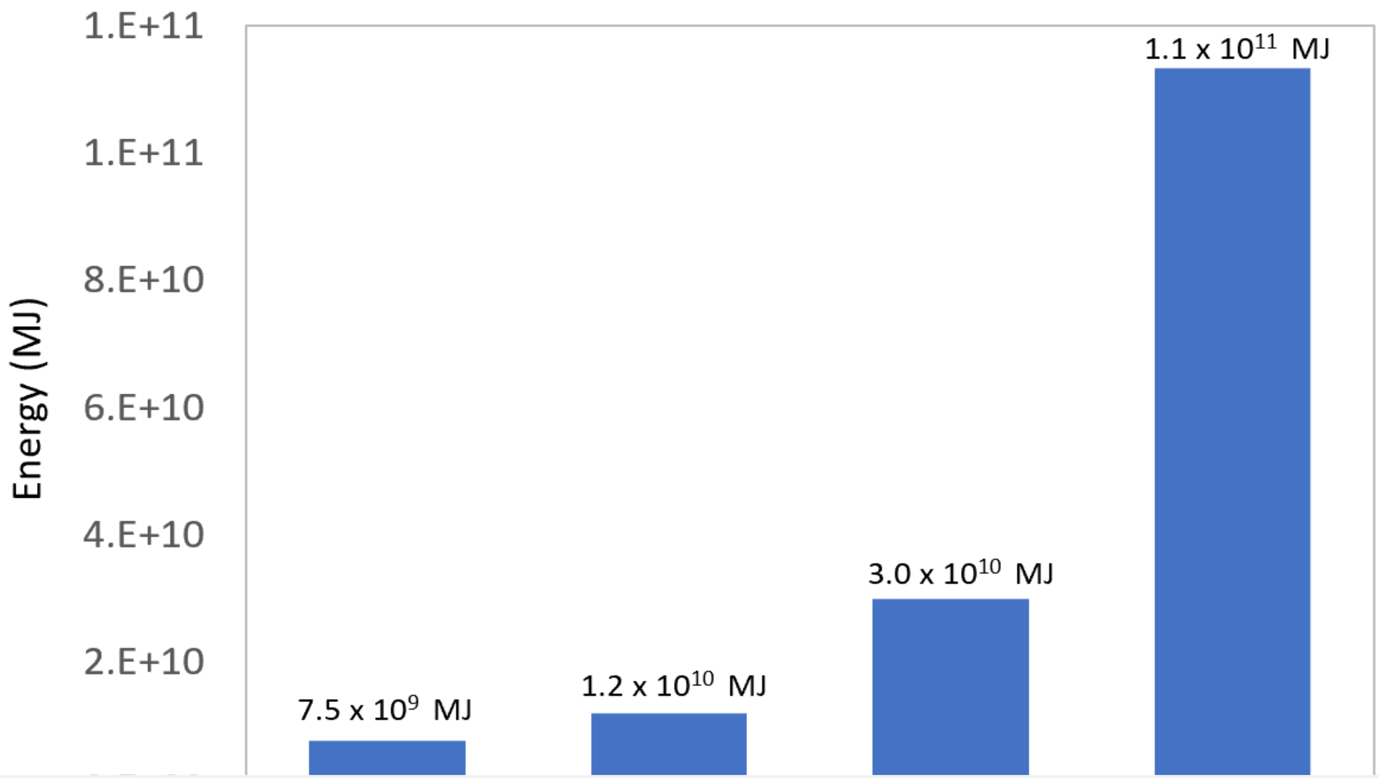
- Utilize solar energy to power mass driver using electro-magnets.
- Potential for efficiency improvement using superconductors.
- Avoid use of fuel produced.
- Export material then needs to be caught.

Maglev Train – Raw Material Transport

- Exploit cold temperatures to use superconductive magnets to transport ice from PSRs/poles to mid-latitude region.
- Need to build elevated rail-line to enable smooth transport at high speeds
- Serve as transport backbone to other development activity

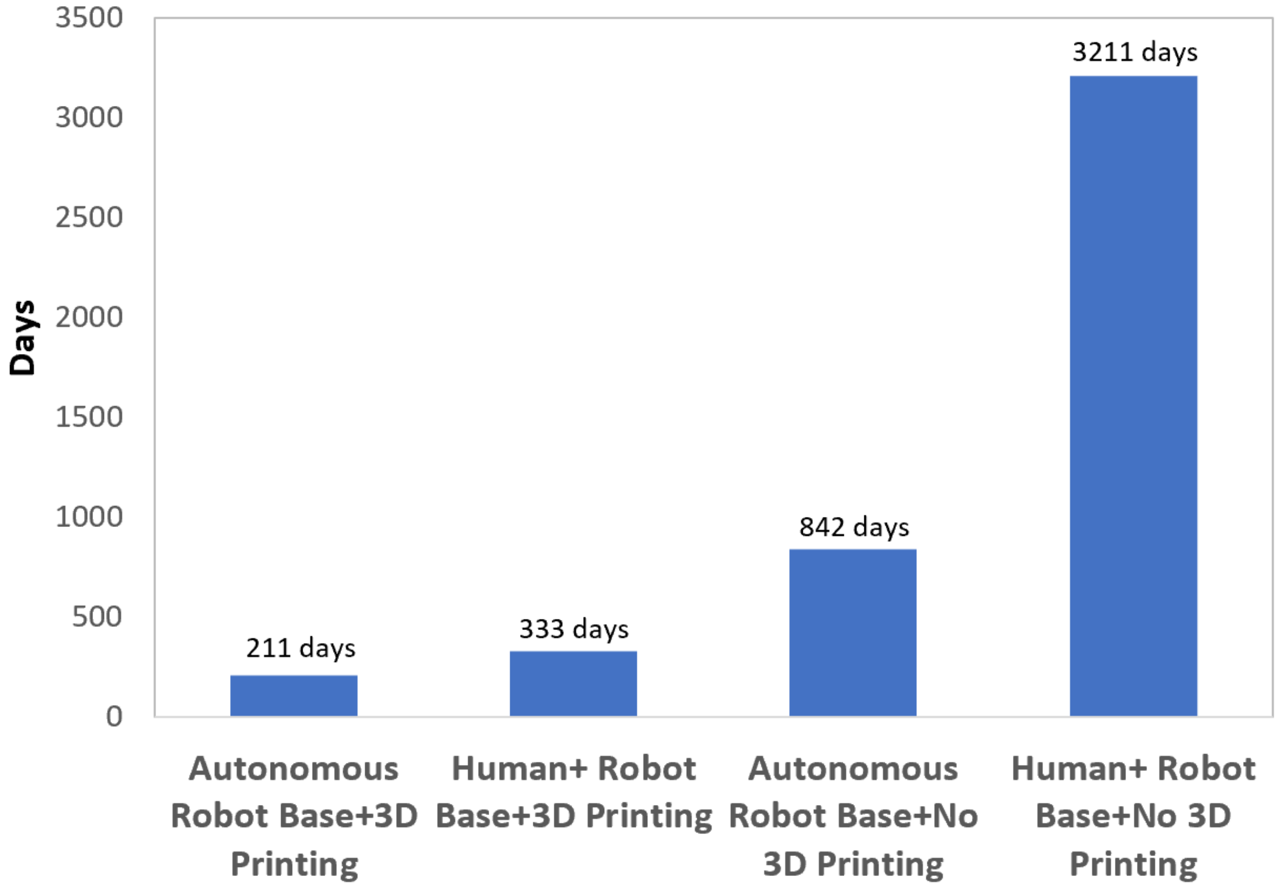


Energy Model Summary - Moon

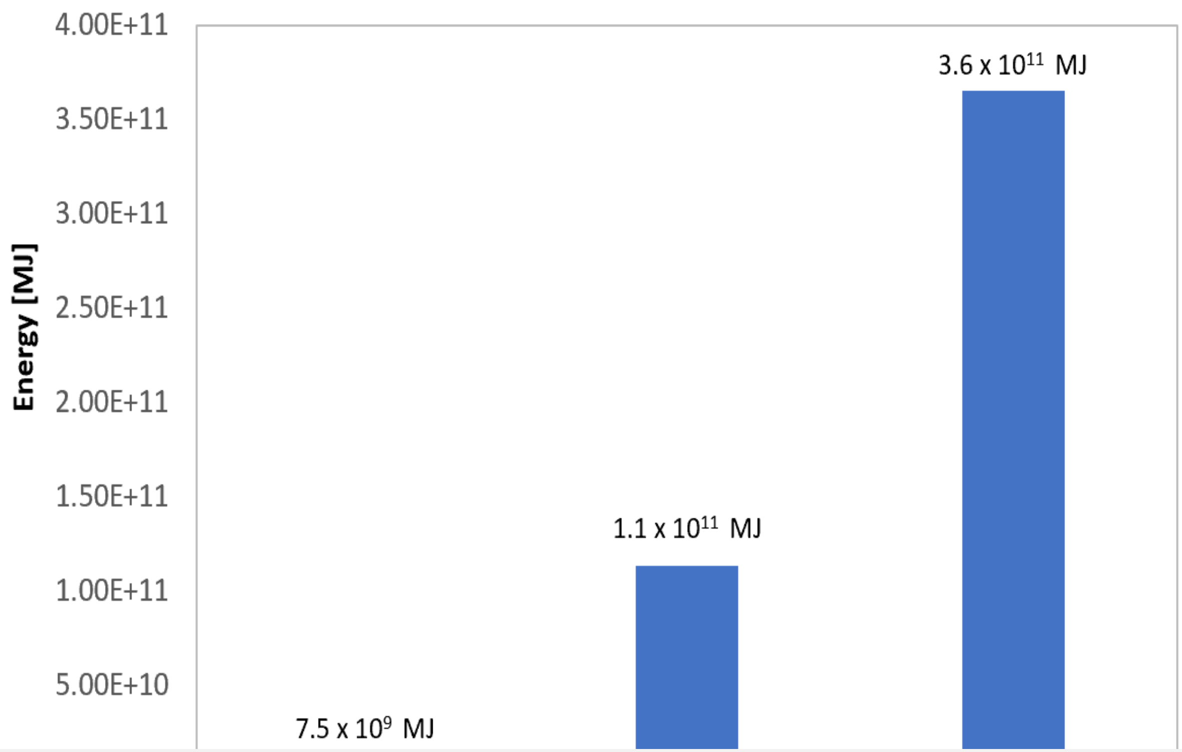


Ensuring a robot base built using 3D printing results in 15-folds energy savings in terms of construction.

Time Taken to Complete Base

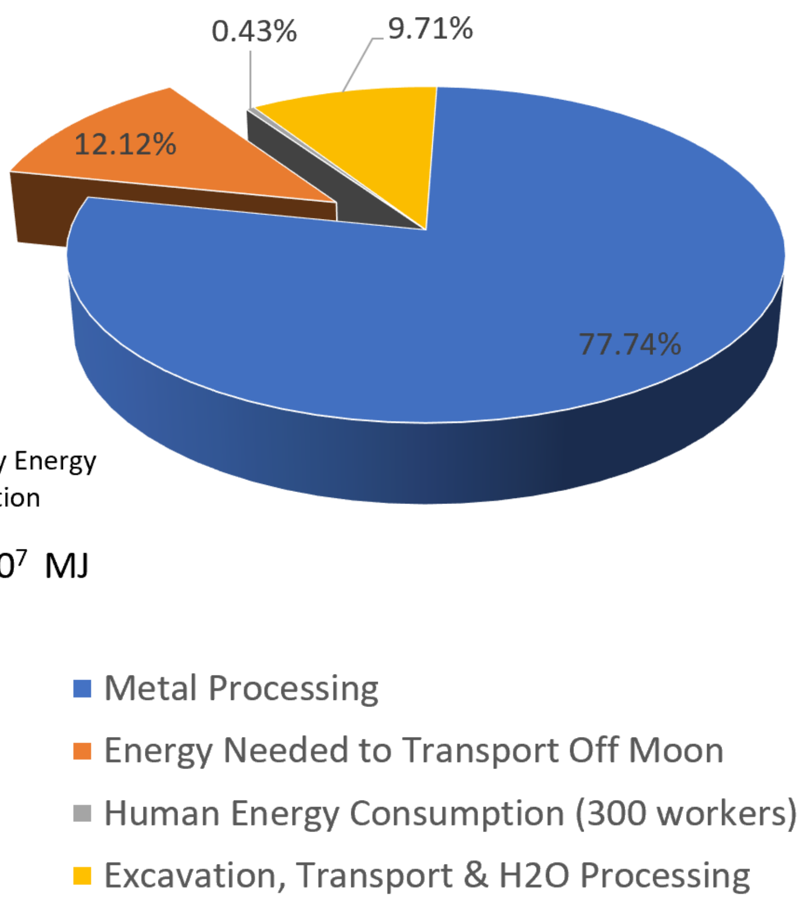


Infrastructure Requirements



Bigger infrastructure investment needed on the Moon to get water ice to mid-latitudes for processing.

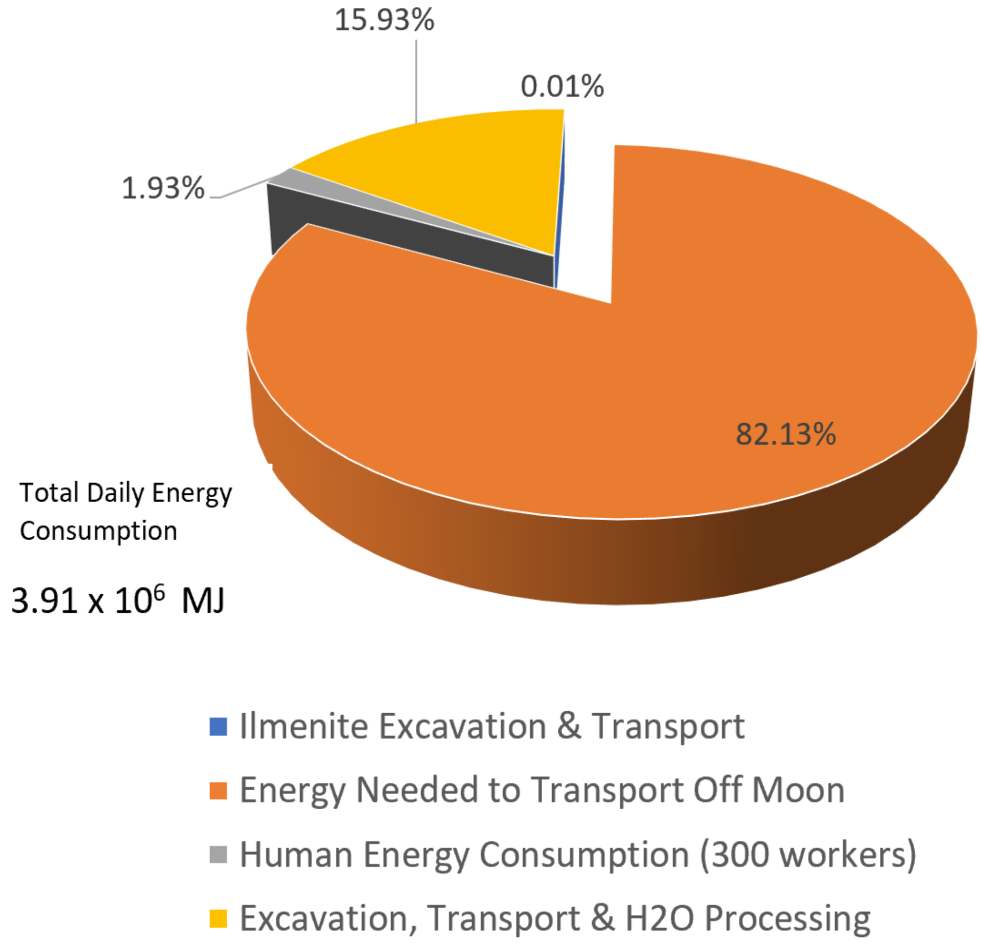
Energy Required for Base Operations



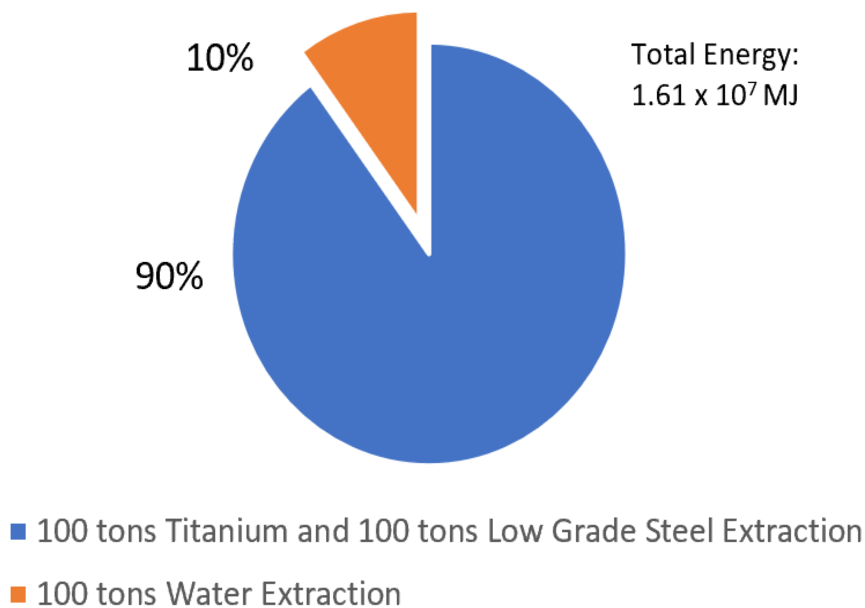
Total Daily Energy Consumption

1.76×10^7 MJ

Energy Required for Base Operations – Raw Export



Water Extraction vs Metal Extraction

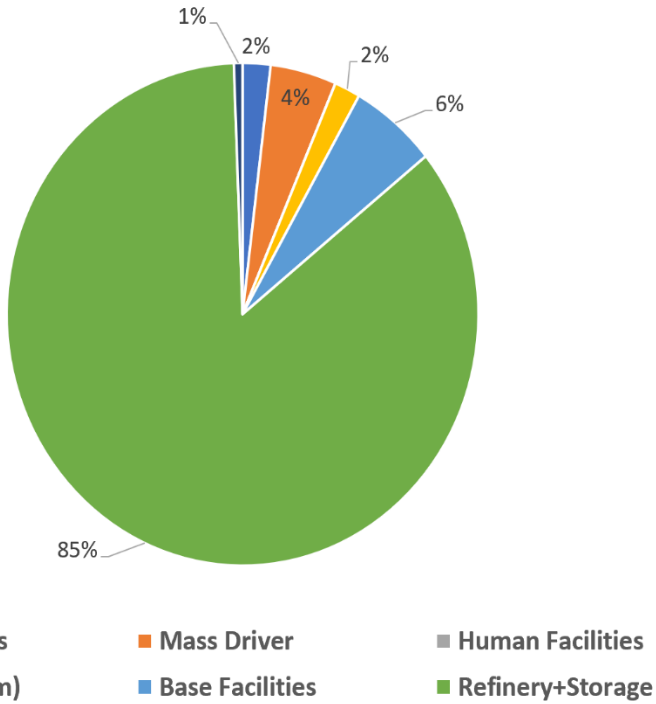


With the right infrastructure, water extraction expected to be low-cost compared to metal extraction on the Moon.

Energy Consumed for Construction – Robot base

Total Energy Needed for Construction

7.5 x 10^9 MJoules

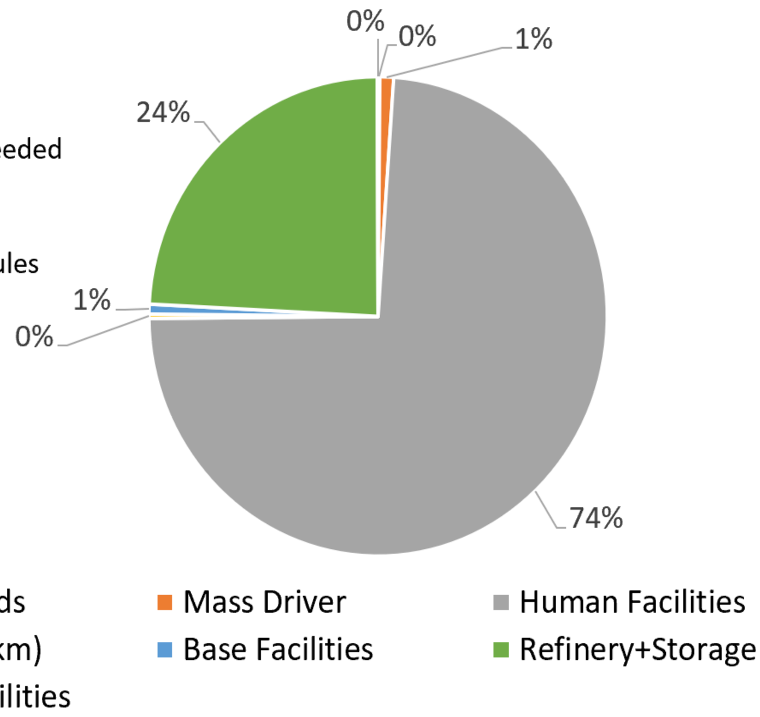


For a robot base, big energy consumer is the construction of the refinery and storage space

Energy Consumed for Construction – Human Base

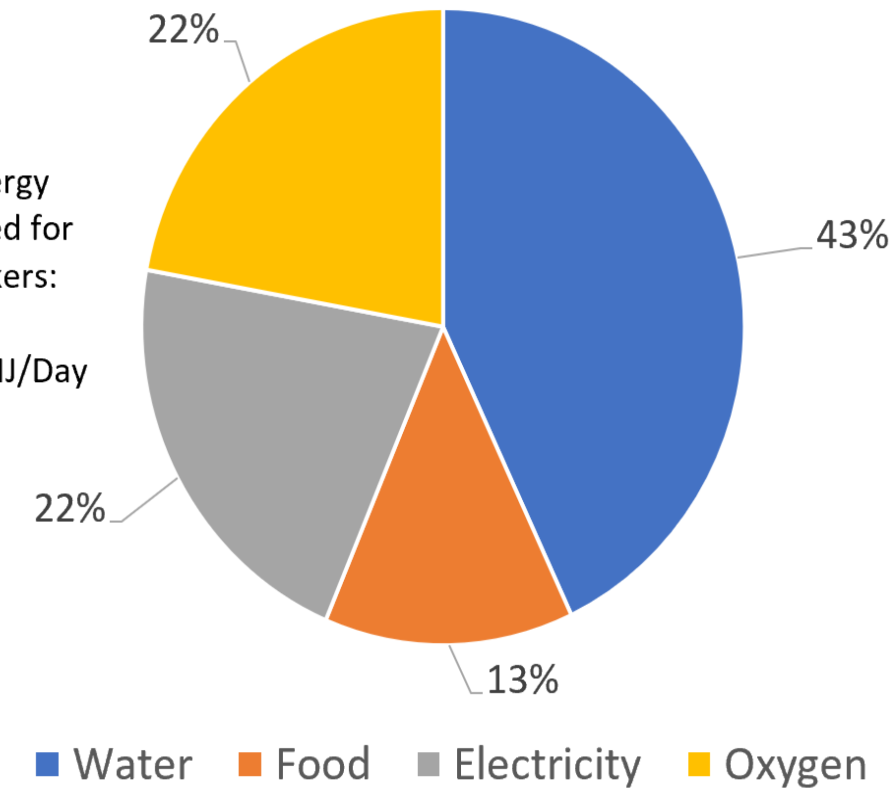
Total Energy Needed for Construction

1.11 x 10^{11} MJoules



For a human base, biggest energy consumers are human facilities and life-support infrastructure

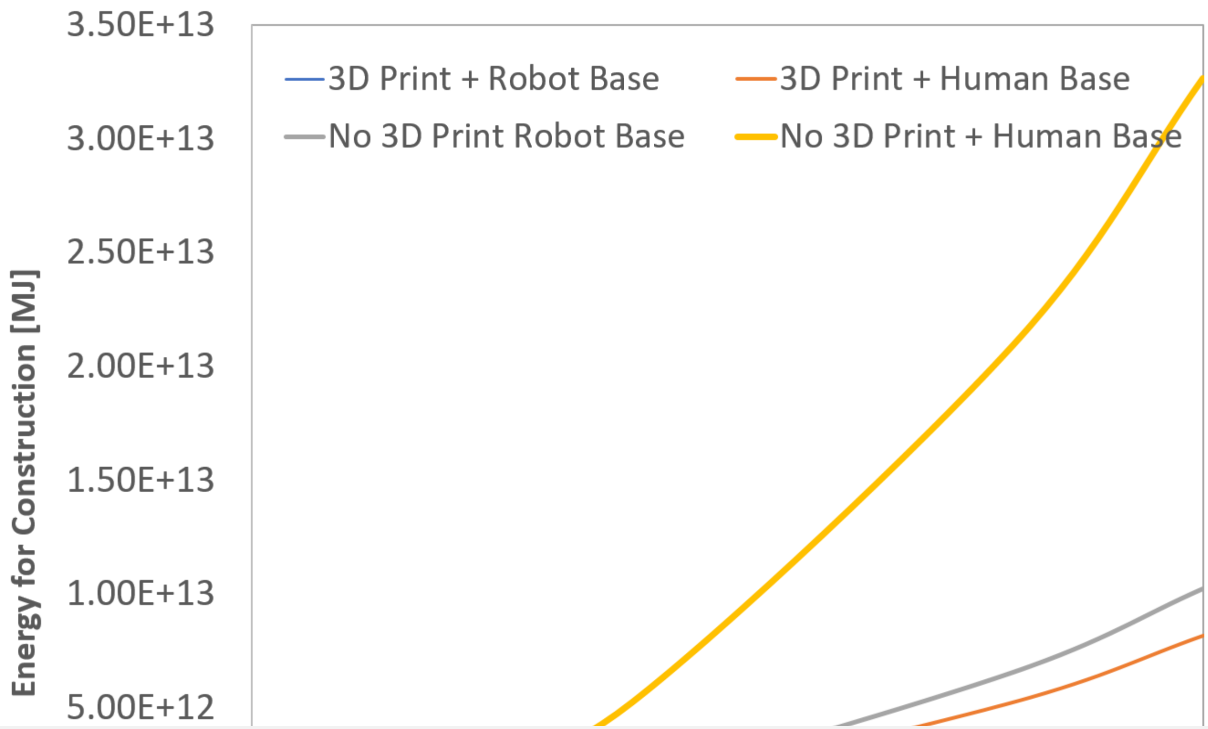
Distribution of Operating Energy Consumed by Human Workers



Total Energy Consumed for 300 workers:

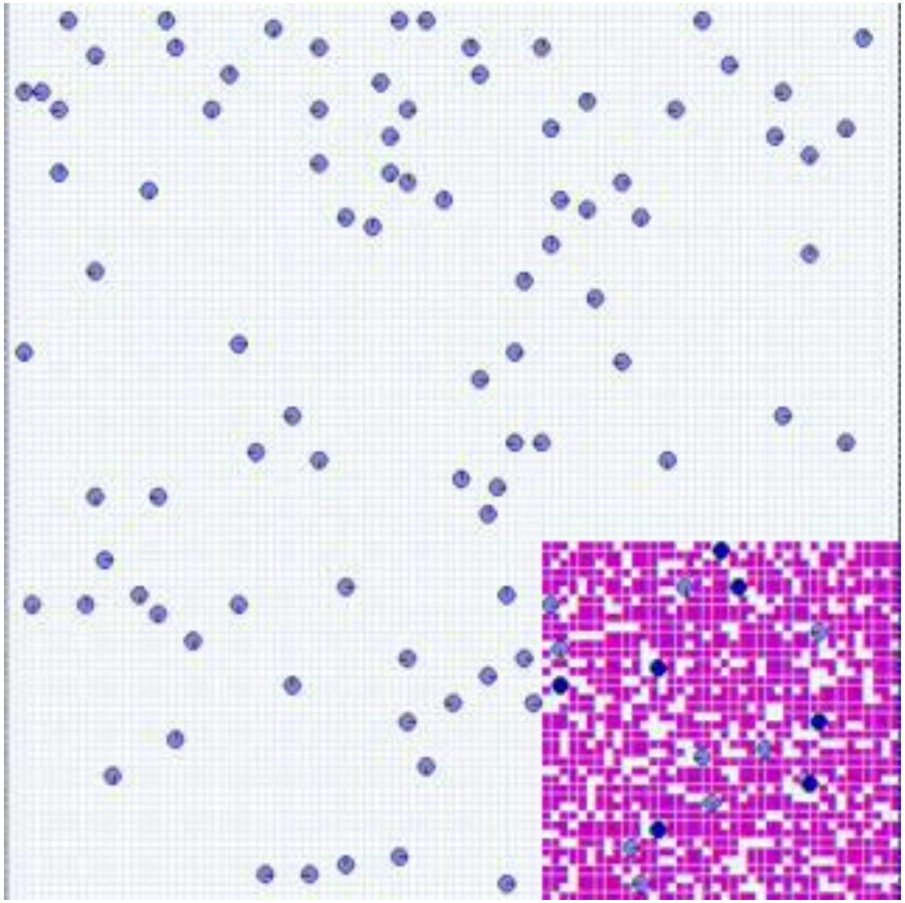
75,340 MJ/Day

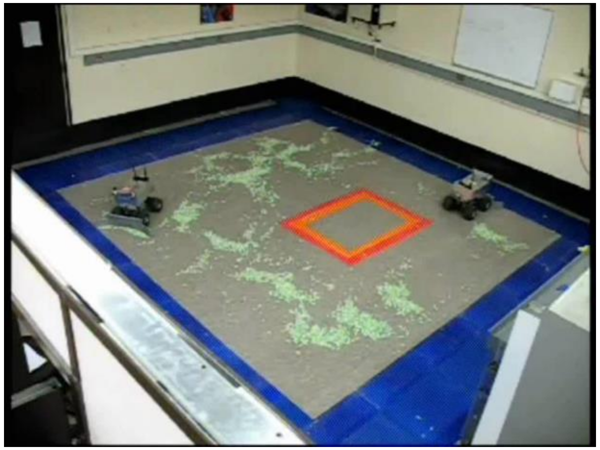
Scaling Up Export of Materials



3D Printing and Running a Robotic Base most scaleable, avoids exponential "blow-up" in resources needed.

Laboratory Experiments





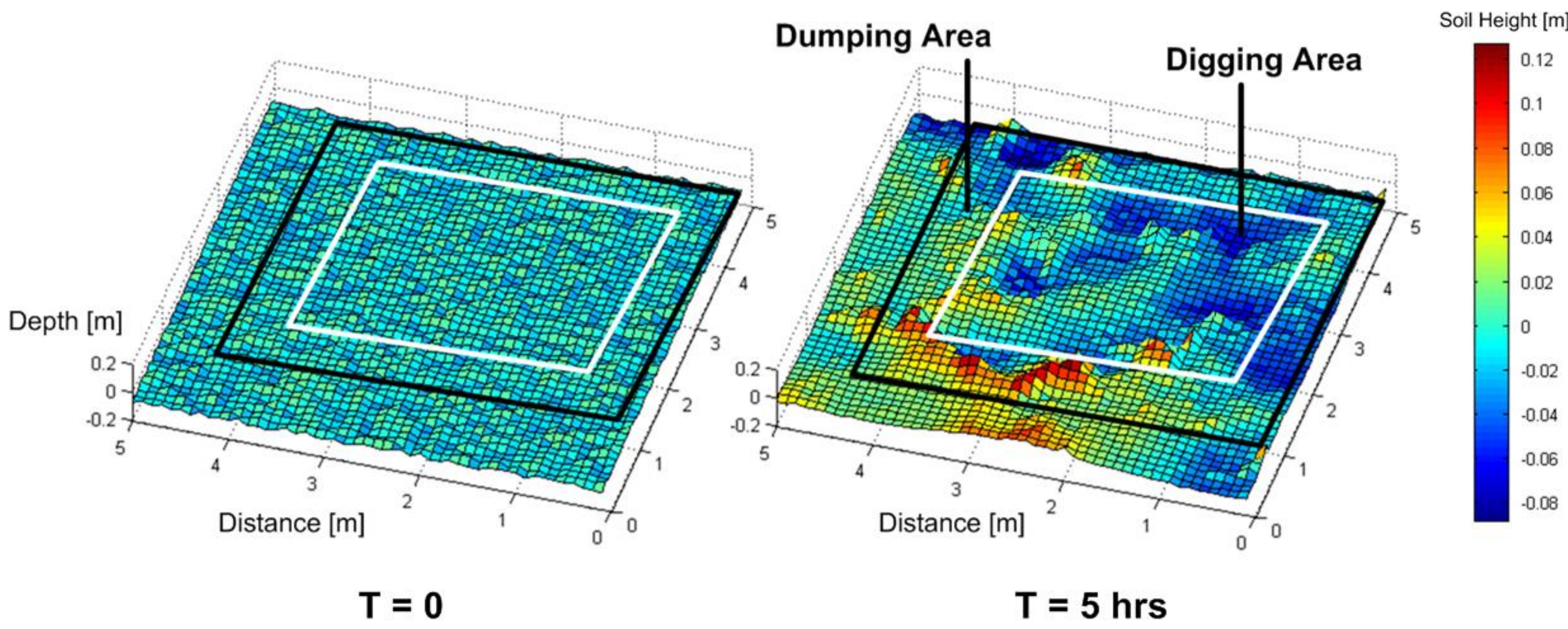
Robust system with imperfect individuals…

High Fidelity Simulations

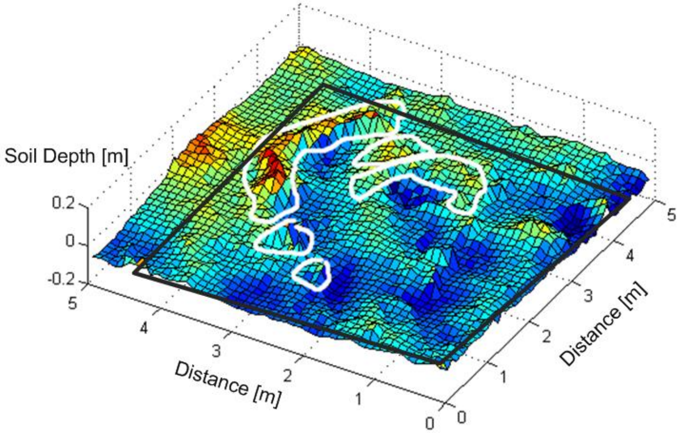
Robust system with imperfect individuals…

Field Experiments

1 - Wireless Radio
2 - LED Light Beacon
3 - Camera
4 - Laser Range Finder
5 - PC-104 i386 Computer
6 - Electronics
7 - Pan Tilt Unit
8 - 2-Axis Accelerometer
9 - Sonars
10 - Blade 1-DoF Actuator
11 - Blade Force Sensor
12 - Bulldozer Blade



Multirobot Excavation in Controlled Environment..



Multirobot Excavation in Controlled Environment..

UNAMEEP

- Large Excavation Platform

Demonstrate excavation outside of controlled field tests.

ARGO

8 wheel field ready amphibious wheel platform for dev. of the Muskateer rovers

Multirobot Excavation in the field..

Multirobot Excavation in the field..

Berms

Road Way

Multirobot Excavation in the field..


N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241325
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241340
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X (UTM)
Porthos 2010-02-10
Porthos 2010-02-09
Aramis 2010-02-10
Aramis 2010-02-09
Landing Pad Boundary
Athos

Landing Pad…

Discussion

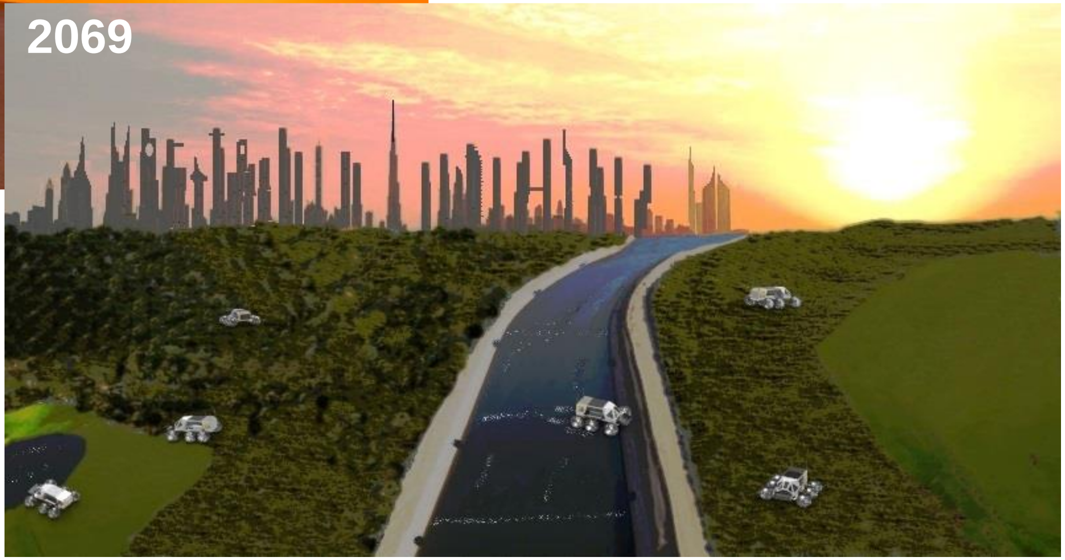
- Game-changing benefits from 3D printing and total end-to-end autonomy using teams of robots
- End to end robotic construction and operation of mining base possible.
  - Modelled from social insect colonies
  - Robust results from teams of “mediocre individuals.”
  - Exploit energy advantage of low-gravity, particularly the Moon.
- Scaling up shows human base very energy intensive.

Discussion: Moon

- Important barrier for the Moon is extracting water ice from the PSRs.
  - How big are the reserves ?
  - Feasibility of Maglev rail line.
- Otherwise a significant game-changer than depends on very good water recycling capability.
- Use of robots on the Moon to construct and run the base is a good fit due to expected health hazards of having humans on the Moon for prolonged time.
  - Low gravity

Discussion

- Big benefits come from Earth applications…



Conclusions

- Identified role of multirobot systems to perform tasks too expensive and dangerous for humans.
- Energy model shows game-changing benefit from 3D printing and autonomy.
- 10 years of laboratory to field experiments identify pathway for future development.
- Extended duration operation needs further R&D
- Transformational applications on Earth

Future Work

- Extended comparison with mining base on Phobos and Deimos.
- Automated design approach to mining base development that enables scalability
- Develop a holistic energy-cost model that identifies optimal locations to mine critical resources.

Thank You!

Questions ?