CRICKET – Closeout

CRICKET: Cryogenic Reservoir Inventory by Cost-Effective Kinetically Enhanced Technology

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NIAC
NASA Innovative Advanced Concepts

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CRICKET: Standing on the shoulders of giants

- **CRICKET is an evolving architecture**
- **CRICKET builds on other NIAC programs**
- **CRICKET could be started now**
- **CRICKET relies on parallel developments:**
  - Artificial intelligence
  - Autonomous operations of machines and satellites
  - Machine vision
  - Machine navigation
  - Swarm modeling and theory
  - Additive manufacturing (3D printing)
  - Advances in robotics in terrestrial industrial sectors
  - Low cost launch services

OVERVIEW – What we did

- **NASA PROGRAMMATIC CHALLENGE:** Locate hidden water ice in the darkest, coldest places on the moon using dozens of simple, autonomous robots
- **CONCEPTUAL SOLUTION:** Use multiple small, autonomous bots to search for hidden water ice in permanently shadowed regions of the surface of the moon. Bots will locate and tag hidden water ice for follow up missions.
- Technical Basis for proposed solution: use of emerging and maturing technologies - MEMS, Cubesates, Sensor nets, integrated devices – will minimize cost risk and maximize return.
- **Benefits:**
- Cricket will enable human exploration through in situ resource utilization:
- Cricket will demonstrate a distributed constellation to achieve a key NASA goal of novel uses of commercially available technologies
- Cricket will reignite public interest in lunar exploration through a sustained human – and robotic – presence on the moon.
- **Technical Approach**
- The cricket constellation has three members: the "queen"; the "hive" and the "cricket" foragers. The queen transports the hive an its crickets to the moon. The hive lands on the surface and disperses the crickets (there may be more than one species of cricket). The crickets then use the hive as a communications and recharging hub. Each cricket hosts algorithms that allow it to explore its surroundings and monitor its power state – something like a lunar Roomba – and return for recharging. If they are lost due to power or surface condition problems, replacements can carry out the hive tasks. The two most successful types of bio-inspired algorithms (BIAs) are evolutionary algorithms and swarm-based algorithms which are inspired by the natural evolution and collective behavior in animals.
- The evolution of the idea is summarized in Table 1 and Figure 1.
- **NIAC context**
- This system integrates key elements from other NIAC efforts; it uses them and extends them into a meaningful whole

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TABLE 1. Evolution of System Architecture, Targets and Capabilities Over Time

Time Frame	Target	Degree of Specialization	Autonomous Exploration	ISRU	Power	Replicable	Modifiable	System Flexibility	Expandable	System "IQ"
>5 yrs*	Moon	Low	x		Delivered			None		Insect
>10 yrs	Moon, NEO	Med	x	x	Solar			Low		Insect
>15 yrs	Moon, NEO, Mars	High	x	x	Solar, Chem, SC			Med		Insect
>15 yrs	Mars	High	x	x	Solar, Chem, SC, Wind	x	x	Med	x	Dog
>20 yrs	Mercury	Med	x	x	Solar, Chem, SC			Low		Dog
>30 yrs	Titan/Europa	High	x	x	SC, Chem	x		Med	x	Monkey
>35 yrs	Titan/Europa	High	x	x	SC, Chem	x	x	High	x	Human
>40 yrs	Kuiper Belt Objects	High	x	x	Chem	x	x	High	x	Human

* Note that this might be possible using technology available within 5 years. Implementation and demonstration would extend the timeframe towards and beyond 10 years.

Energy Sources for Power are notional and will be considered. Solar arrays will not work well for many targets. Nuclear may not be an option. ISRU may provide the means to extract/store energy. For the foreseeable future, power generation capability may have to be delivered from Earth via the carrier rather than constructed on site.

Chem=chemical energy source
SC=Stirling Cycle

Nuclear power may become acceptable at some point but the design of the system cannot depend on the availability of that power source.

System "IQ" is a heuristic indication of the level of system-wide autonomous problem-solving capability. Some missions will require far more intelligence than others in order to adapt to unforeseen circumstances. Long time lags for signals, complex terrain, unknown surface properties, and cricket adaptability at the target may require a significantly higher level of autonomy than we demonstrated in space. The Worker complement may also have to evolve over time, as there will likely be a shift from surveying to extraction once the ISRU is in full production mode. In order to achieve maximum longevity, it may be useful to design into the system a high degree of modularity so that system resources can be reused and repurposed. Terrestrial applications have demonstrated reconfigurable robots as well.

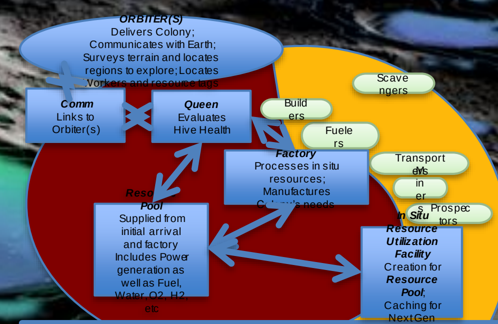
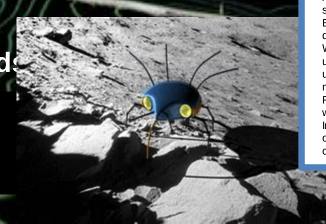


Figure 1. CRICKET final architecture. Intelligence is fractionated among all elements of the system. One or more simple orbiters provide survey data, doppler tracking and location, and Earth-link. Very complex elements, such as the Comm, Power, ISRU and Factory, are delivered as part of the initial colony. Initial worker complement may also be provided. Worker "subspecies" locate, extract and transport material to the ISRU facility. The Factory uses a variety of technologies to convert supplies from the ISRU into workers and facilities using the 3D printers. The Resource Pool includes the initial allotment of prefabricated materials, sensors, power modules, etc. Workers are an element of the Resource Pool. The Factory repurposes and refurbishes the Workers in addition to creating them. The design of worker may change overtime. The Workers produce science data as well as materiel. Information is relayed back to Earth through the Orbiter. The Queen prioritizes the activities of the hive by controlling worker and resource allocations but the actions of individuals are carried out autonomously.



CRICKET: Envisioning an Inspiring Future

- In this study we considered several elements of a future that enables the human race to expand out into the solar system.
- The key ideas are that it will be impossible for us to "conquer" the space environment – we must use the resources available there to make a home for ourselves.
- We won't be able to do it alone
  - Our partners in this adventure will be machine intelligences
  - Some will have direct physical manifestation
  - Some will exert remote control over physical actuators
  - Some will help use plan, discover, map and use
- CRICKET started out by just looking at one element of this system but in order to consider "what" CRICKET was we had to discover the "how" and "why"

CRICKET architecture

Meteors on Demand

Detection of Exospheric Water

"dowsing services" and comm and location relays

Determines where to look from orbit and delivers CRICKET there and provides external services

Blue Origin "Amazon Deliveries" or other routine lunar delivery service

CRICKET sensor bots

Support

Mining and Resource Extraction Robots

Support

Used for

ISRU – water and fuel

Used for

Habitats and resources for Humans

Johns Hopkins Applied Physics Laboratory

CRICKET: What

- The central element of CRICKET is the concept of an autonomous robotic explorer that locates hidden reservoirs of water ice.
- Clearly, this could apply to any of the water worlds in the solar system.
- The study led to many other questions:
  - What had been done before?
  - What would be the role of humans in this effort?
  - What are the obstacles to doing this work?
  - What are the applications on Earth?
- We will show examples of how this sensor would be constructed and how we would use this design concept to build more complex structures.

We review each element in this report

- **Novel on-orbit sensor spacecraft developed for NIAC**
  - Meteors On Demand (MOD)
  - Detection of Exospheric Water (DEW)
- **CRICKET design approach developed for NIAC**
  - Small articulated crawlers
  - The flying cockroach
  - The APL Buckybot (used for NIAC)
- **Mining and resource extraction**
  - A brief mention of current practice and an architecture
- **How ISRU would fit in**
  - Including the value of other NIAC programs to the ideas behind CRICKET
- **How additive manufacturing is used**
  - Other NIAC work
  - How the CRICKET architecture accommodates biomimetic building

The big questions motivate our outward journey

- Are we alone in the Universe?
- If not
  - Where is everyone?
  - What are the obstacles to creating an enduring technological civilization?
- How do we move out from the Earth?
  - Is it possible to colonize space?
- Our first steps require that we are able to develop resources in situ from the many sources in our solar system
- To do that we must locate the resources and develop a safe haven for humans before they can take up permanent residence.

"Conquering the Moon"?

- For centuries man has been engaged in the conquest of…just about everything
- We can choose to "conquer the Moon" by focusing an enormous amount of resources on the problem and reinventing the world or we can build upon the advances that are being made to solve the Earth's problems
- To do that we have to try to think of different ways to approach the problem.

Minimizing human presence to maximize impact

- The lunar environment is hazardous to humans.
- We need a path that ensures that they will be able to avoid exposure to radiation and lunar dust, among others.
- The CRICKET concept started with exploration but the system concept provided the impetus for expanding to the larger problem of ensuring a suitable environment for humans.
- NASA can take advantage of industrially funded developments in robotics to make it possible to go the Moon and stay there.

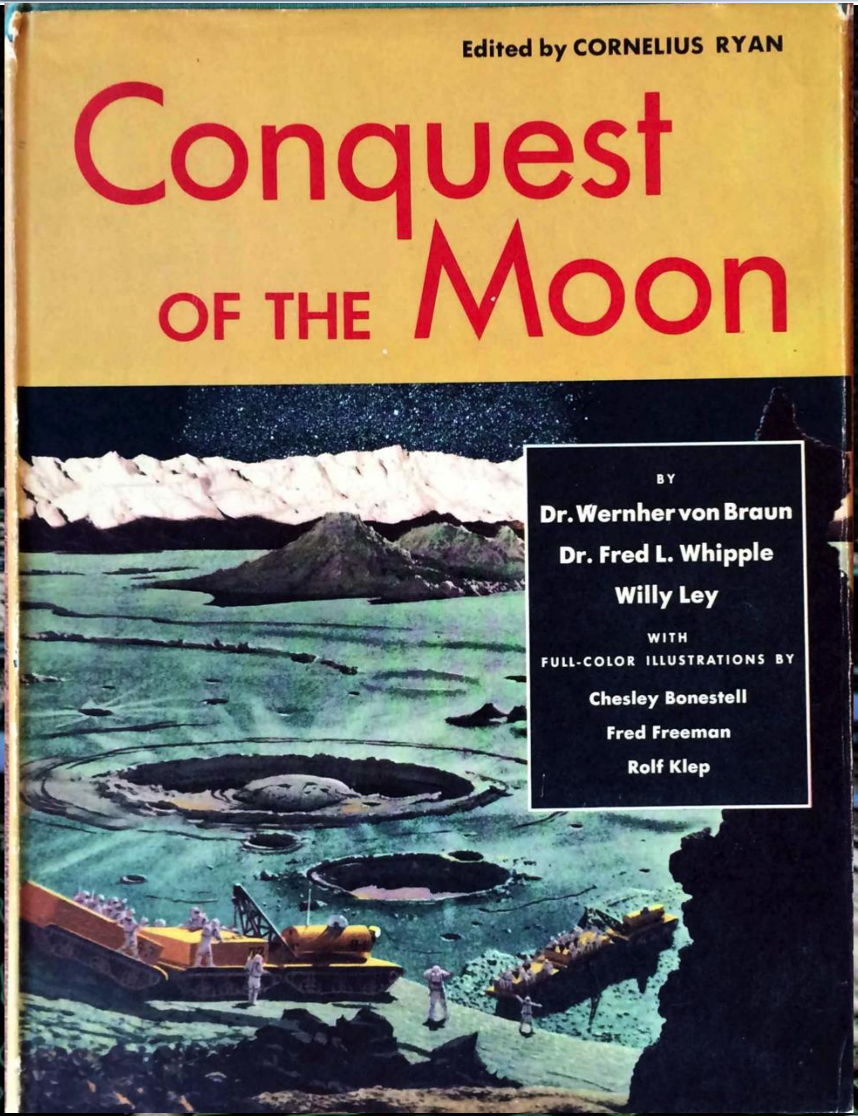
We stand at the threshold of a great adventure

- **Humans became human because they were able to develop partnerships among themselves and with other forms of intelligence**
- **For the first time autonomous robots are within are reach**
  - Powerful CPUs and network capabilities enable us to realistically envision distributed capabilities and fhe development of a “hive mind”
  - Additive manufacturing and resource processing are within our reach – these enable semi-autonomous construction
- The first step –find the water

Human-centric exploitation of the Moon will be complex and complicated

- **Human systems would require a large, complicated system to deliver humans to the Moon and to keep them alive while there – and to return them to Earth**
  - Each of these elements has huge costs that we accept if humans are to conquer the moon
  - Humans must be kept within a narrow temperature and pressure range within a highly constrained, combustion supporting, corrosive atmosphere
  - They must be fed and their waste disposed of and they must be "entertained" by social contact and a sense of purpose during their mission time.
  - This system must be maintained while they are on the lunar surface
  - They must be returned to the Earth
- **Each of these requirements places a burden on the logistical pyramid.**
  - A Saturn 5 massed 2.3 Million kgs to return 3 people and samples to the Earth
  - It was designed to place 41,000 kg in lunar orbit, though

The Dream is alive in CRICKET



Developing a requirements flowdown

- **Take advantage of what the lunar environment has to offer**
  - The Moon's axis tilts only 1.5 degrees from the ecliptic plane (the plane containing the path of the Earth and the Moon around the Sun).
  - Because of this unique geometry, sunlight never shines on the floors of some craters near the Moon's pole
  - These areas are known as Permanently Shadowed Regions, or PSRs.
  - Water will be stable there.

1952

More rock samples from the moon will be brought back to earth. The composition of the rocks is important in determining where the permanent lunar colony shall be constructed.
—*Hamilton Standard*

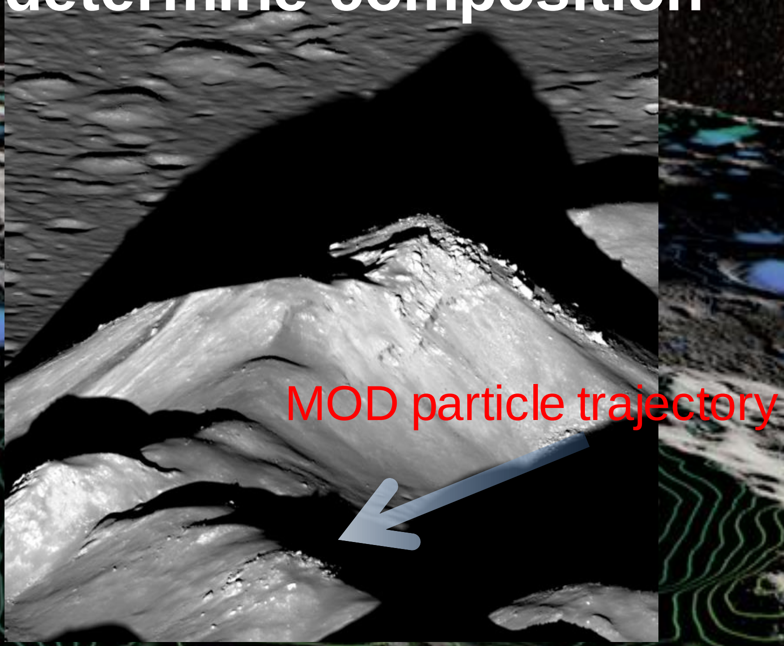
What are the irreducible minimum requirements for locating water on the moon?
Must we use humans?
How much can be done from a combination of autonomous systems operating on-orbit and on the ground?

Locating resources: MOD, DEW and CRICKET

- **APL has developed three new concepts that can be used to probe the lunar subsurface environment to look for water.**
- **MOD or Meteors on Demand uses a coil gun to deliver a tiny surface impactor into the lunar regolith**
  - The orbital velocity of the MOD cubesat “creates” the impactor energy
  - The coil gun is used to aim the impactor at a particular location
  - Provisional patent in process
- **DEW or Detecting Exospheric Water detects the water plume produced by the micrometeor impacts**
  - DEW sensor was proposed to NASA Matisse program
  - In the CRICKET project architecture, DEW would follows behind MOD to detect water plumes and locate water rich areas
- **CRICKET is the overarching, modular architecture of surface assets that locate and exploit lunar water.**

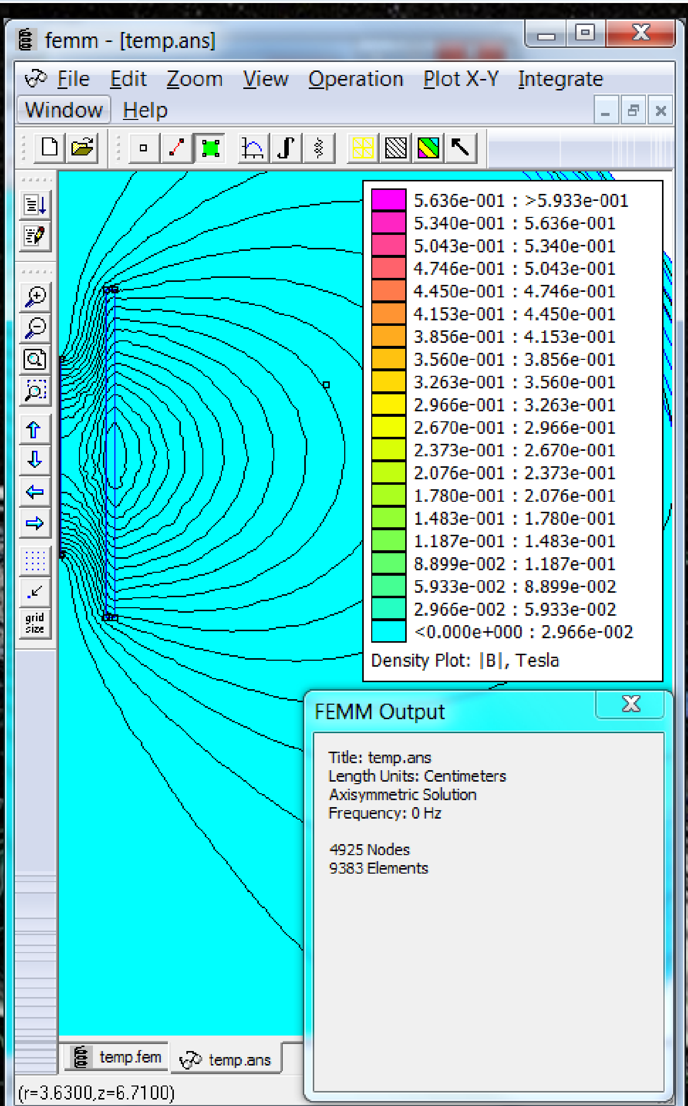
Meteors on demand enables sampling of inaccessible areas

- Remote sensing requires access and illumination
- Sampling in the darkest most inaccessible regions and determining the form and composition is a challenge.
- MOD provides a means of doing so.
- MOD launches a micrometeor to impact the crater wall to products a plume to determine composition



MOD design effort

- Did a full system analysis
  - Launch mechanism for the particles
  - Orbital dynamics
  - Meteor ablation characteristics for an atmospheric re-entry
  - Comm link budget and ground system design
- Designed a CubeSat proof of concept



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MOD uses a coil gun…can use solar arrays on a cubesat for power

Coil design and timing

Handling microgram particles

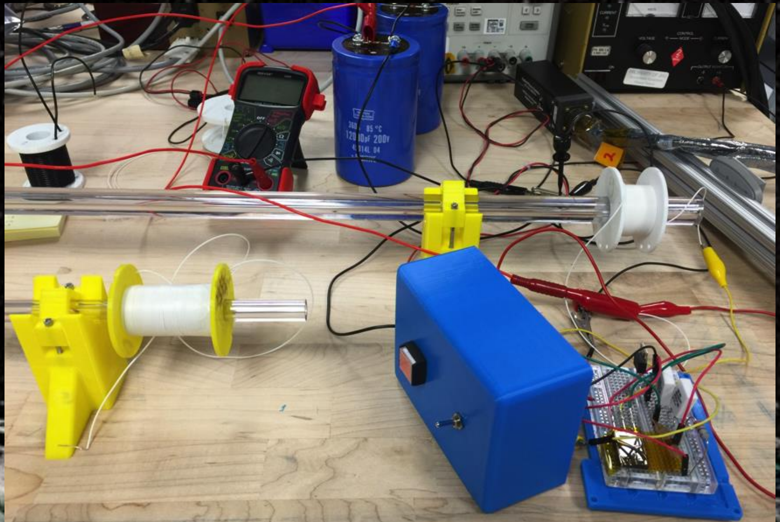
0.1 mm = 10micrograms

1 mm= 0.01 grams

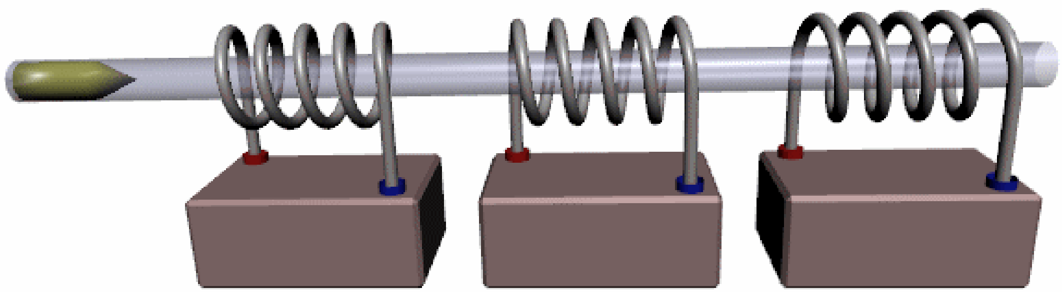
Energies are reasonable:

0.1mm = <2J @ 3km/s

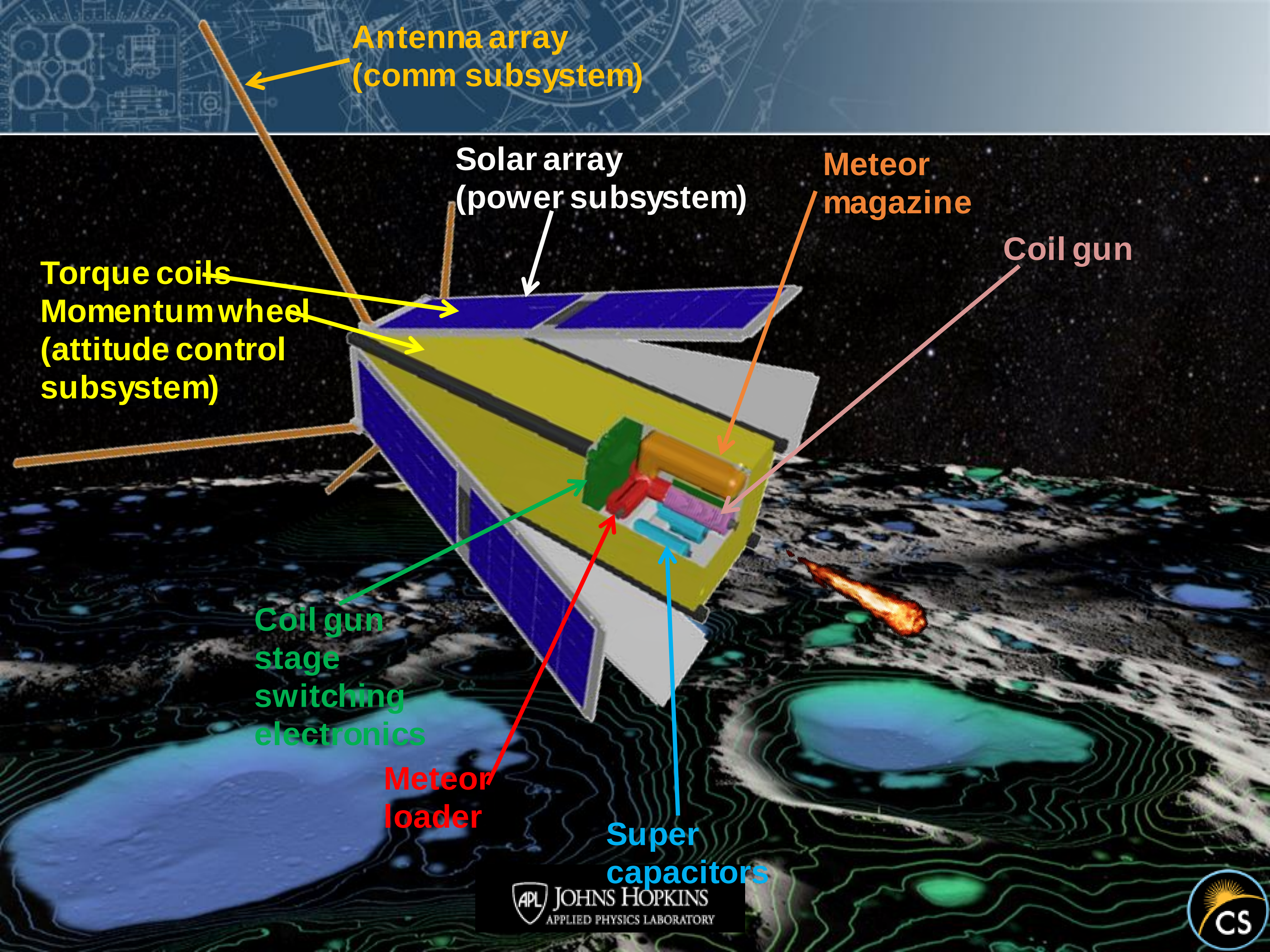
The MOD advantage is that thousands of points on the lunar surface can be sample – including areas that are not generally accessible to remote sensing



Benchtop test and development



Coil gun animation – view in slideshow mode


Antenna array
(comm subsystem)
Solar array
(power subsystem)
Meteor
magazine
Coil gun
Torque coils
Momentum wheel
(attitude control
subsystem)
Coil gun
stage
switching
electronics
Meteor
loader
Super
capacitors
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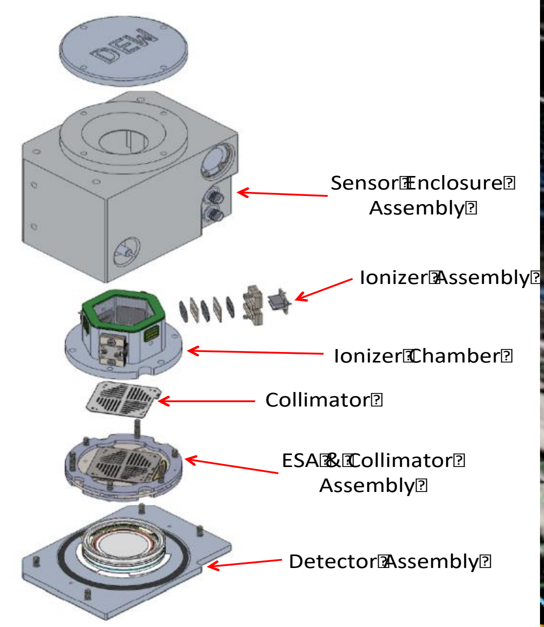
DEW – detects the plume using a miniature mass spectrograph tuned to water

- We have built and demonstrated a system that is very simple and can be built to detect particular molecule.
- For the DEW Matisse proposal we took this idea and applied it to a particular science problem.
- For the CRICKET NIAC concept DEW would detect water and that information would be used to indicate areas, in concert with information from the other “dowser” satellites (radars, imagers, etc) to decide where to send CRICKET teams.

- CANARY-heritage instrument that is optimized to detect neutral water and OH
  - Water molecule enters, is ionized, passes through ESA if right charge to mass ratio.
  - Low noise
  - High sensitivity
- Capability and accommodation
  - Accommodation:
    - FOV in ram direction
  - Mass: 1-3 kg
  - Power: <3 W
  - Volume: 3000 cm^3
  - Cost: $3-4 M



CRICKET areas of interest

- **The CRICKET "ecology" grew out of the desire to produce a system of systems that could grow, starting today, into a viable system that would enable a large, robust, complex human presence on the Moon in 30-40 years.**
- **The principal drivers are;**
  - Detecting resources
  - Locating them for other services
  - Extraction
  - Transportation
  - Processing
  - Storage
  - Fabrication

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Our robotic explorers, to date, have not changed (except in price)

In 1955, a 14-year-old with ambitions to go to the moon built a robot he named Gismo, winning the Industrial Arts Competition run by the Ford Motor Company. Gismo walked, talked and waved his arms, and he cost $15 to make. He was one of 72 examples of craftsmanship by teenagers on display at the Waldorf-Astoria. Photo: Neal Boenzi/The New York Times

http://scienceblogs.com/startswithabang/2012/08/06/this-is-why-we-must-invest-in-ourselves/

Mars Rivers require huge expensive teams to explore a tiny fraction of Mars the same way Gismo worked in 1955

CRICKET assumes that current trends will continue

- **Improvements in:**
  - Cognitive neural networks
  - Neuromorphic programming
- **A NASA vision that included a return to the Moon would profit by the incorporation of developments in computational cognition into their exploration roadmap.**
- **NASA need not push these efforts as commercial efforts and DARPA are already investing.**
- **The DARPA SyNAPSE program (http://www.artificialbrains.com/darpa-synapse-program) worked to simulate a cat brain.**
- **Neuromorphic programming is thought to be scalable implying that at some point in the future (perhaps 20 years) complexity should approach human levels.**

Application of Swarm Intelligence

- **Swarm intelligence is the functionality engendered by designing algorithms or systems that take advantage of the collective behavior of a number of agents to solve a problem.**
- **Swarm intelligence is demonstrated in the emergent behavior of social insect colonies (e.g. termites) and other animal societies.**
- **Advantages are:**
  - Decentralized
  - Individuals are simple and autonomous
  - System is scalable (new elements can be added without problems)
  - Simple rules produce complex, emergent behaviors
  - Cooperative behaviors emerge
  - Local communication and control, only, are required.

Thesis: Break away from current Human-centric concepts

- The rise in CPU power, artificial intelligence, understanding swarms and 3D printing enables us to change the way we do things.
- We can use semi-autonomous and autonomous agents to prepare the way for an permanent human settlement on the moon.
- We need not think of this as another MvMurdo station where human presence relies on "conquering" the environment and the continuation of a large supply chain back to Earth.

McMurdo trash dump – the lunar analog would be a resource

McMurdo – the end of a long supply chain showing that indigenous support for human exploration grows exponentially with the number of explorers and the length of sty

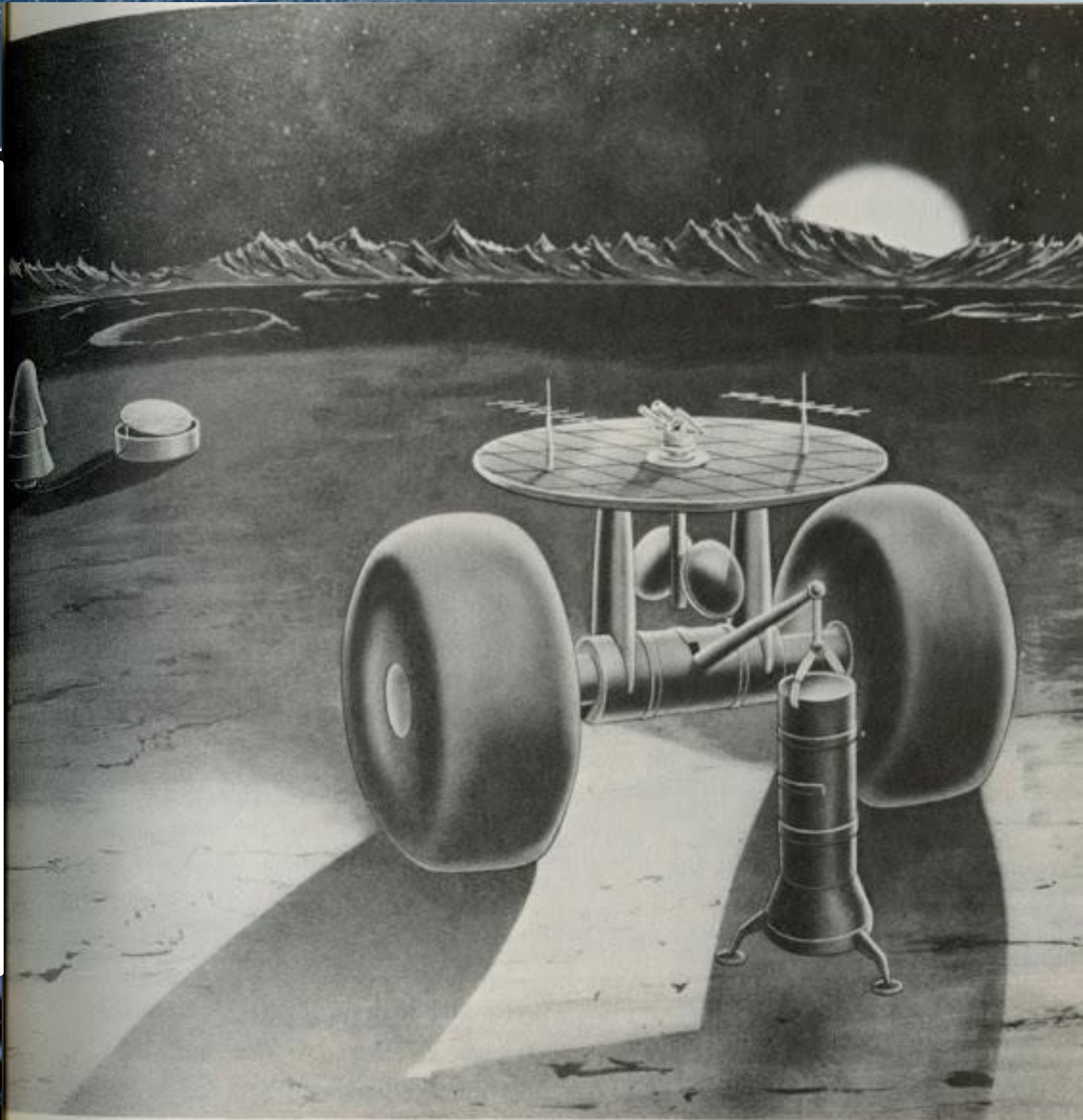
The idea of robotic explorers has been around for over half a century.

NASA has done little to develop the concept of autonomous exploration.

If failure is not an option then risk is to be avoided.

This is certainly true for a single rover.

An architecture that uses many inexpensive bots is more robust against the loss of a single bot.



Self-propelled, automatic lunar rover fitted with solar-cell collector, radar, radio, and laboratory capsule used for sampling of soil.

Biomimicry as a model for cricket construction

Cricket would use the principles observed in nature to develop structures from material.
There are two approach:

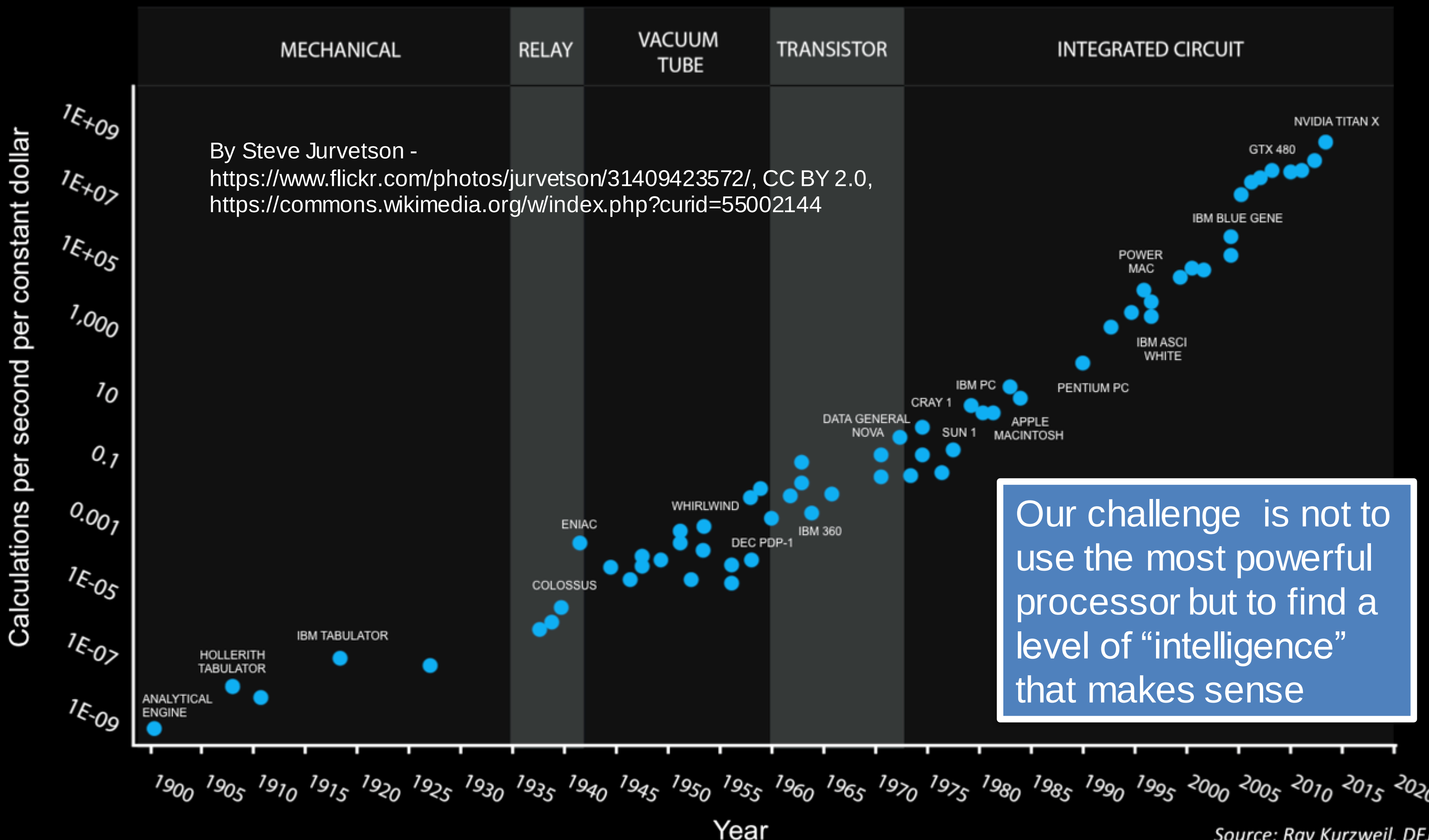
regular, repeated structures that map to a plan

"organic" structure that grows over time based on simple rules with no plan

Movement of material in a biological system by a network enables movement of material over distance greater than that possible by diffusion.
Almost all biological transportation networks are produced as the result of self-organized (SO) morphogenetic
processes whereby the growth is driven by locally available information, in the absence of a preexisting master plan of the network

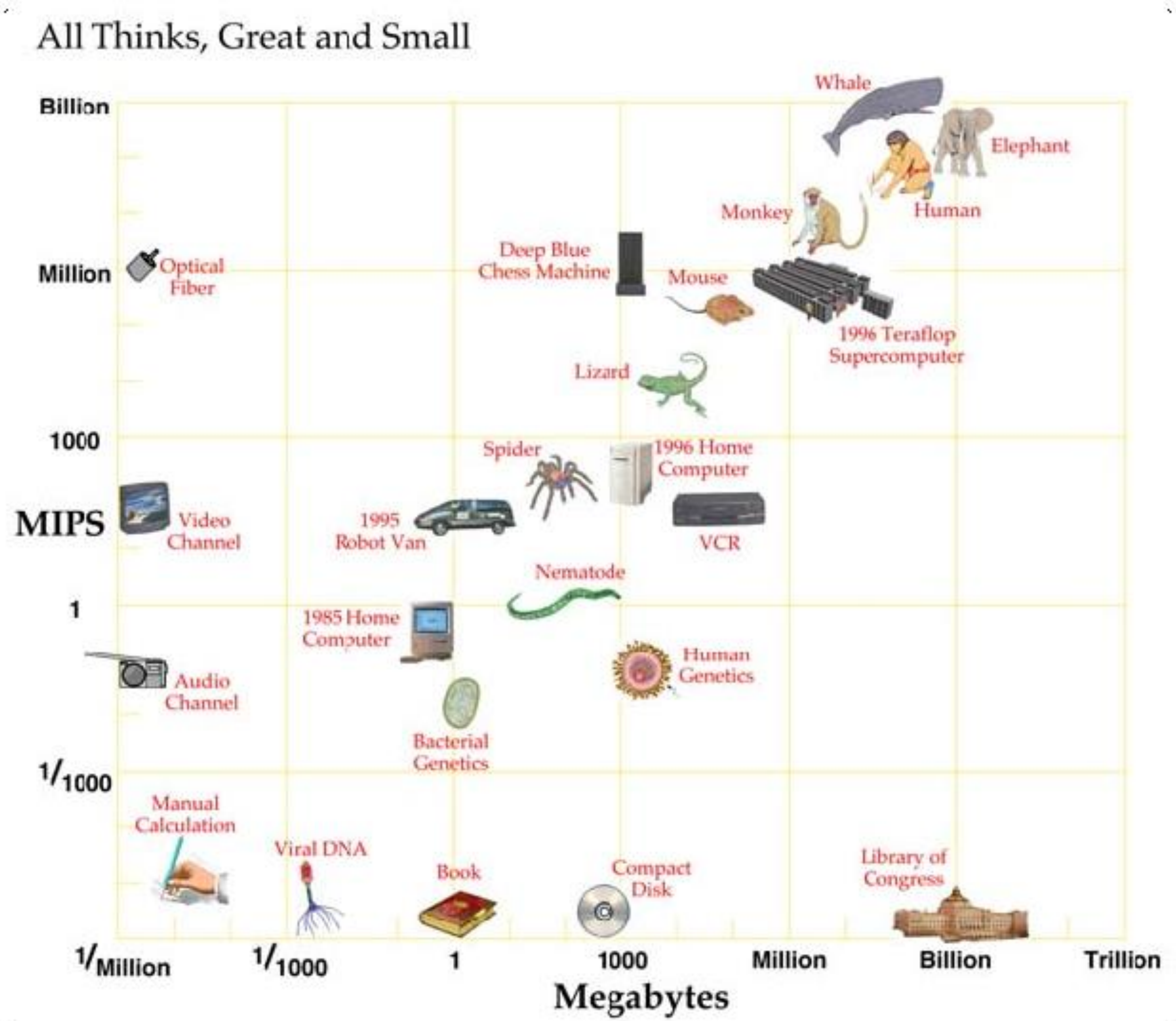
S. Camazine, J.-L. Deneubourg, N. R. Franks, J. Sneyd, G. Theraulaz, and E. Bonabeau, Self-organization in Biological Systems (Princeton University Press, Princeton, NJ, 2001), p. 538.

120 Years of Moore's Law



By Steve Jurvetson - https://www.flickr.com/photos/jurvetson/31409423572/, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=55002144

Our challenge is not to use the most powerful processor but to find a level of "intelligence" that makes sense

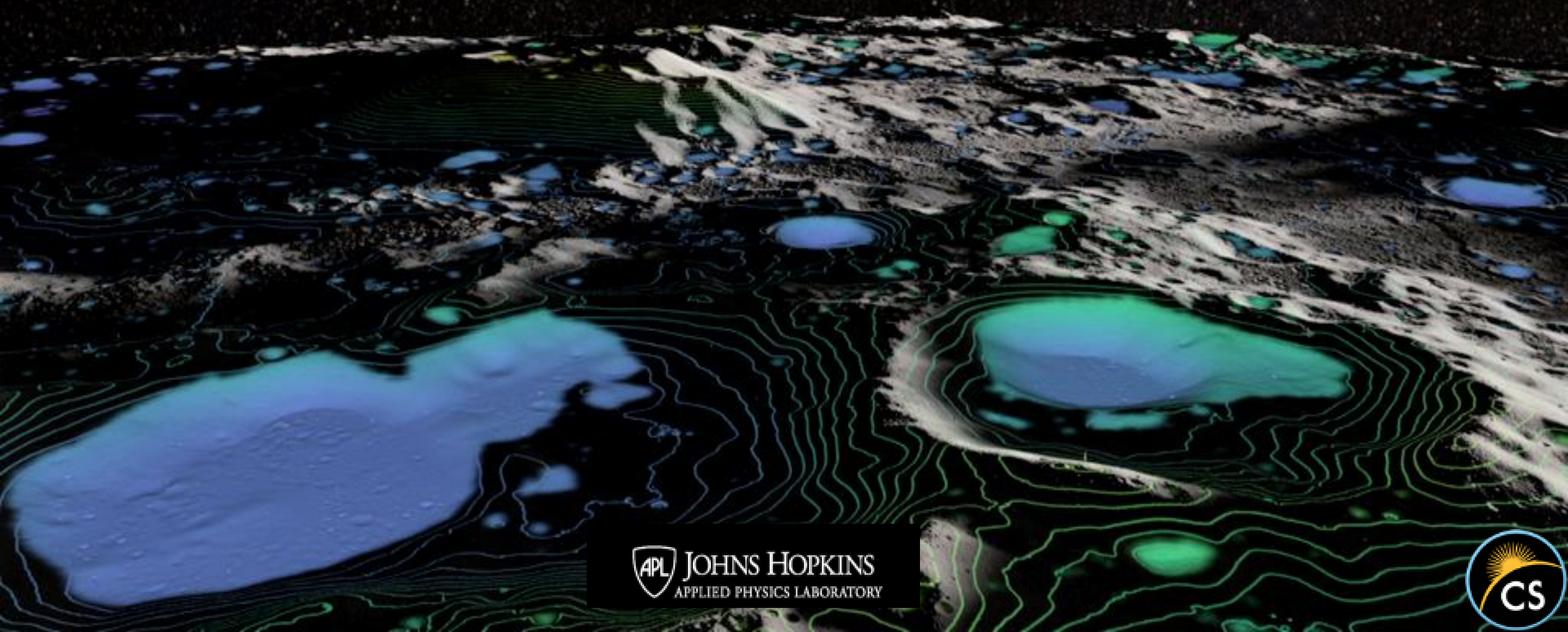


MIPS and Megabytes. to mimic their behavior. Note the scale. Entities rated by the computational power and memory of the smallest universal computer needed is logarithmic on both axes: each vertical division represents a thousandfold increase in processing power, and each horizontal division a thousandfold increase in memory size. Universal computers can imitate other entities at their location in the diagram, but the more specialized entities cannot. A 100–million–MIPS computer may be programmed not only to think like a human, but also to imitate other similarly–sized computers. But humans cannot imitate 100–million–MIPS computers––our general–purpose calculation ability is under a millionth of a MIPS. Deep Blue's special–purpose chess chips process moves like a 3–million–MIPS computer, but its general–purpose power is only a thousand MIPS. Most of the non–computer entities in the diagram can't function in a general–purpose way at all. Universality is an almost magical property, but it has costs. A universal machine may use ten or more times the resources of one specialized for a task. But if the task should change, as it usually does in research, the universal machine can be reprogrammed, while the specialized machine must be replaced.

From an early paper Moravee, H.,(1998) When will computer hardware match the human brain?, J. Evol. Tech. http://www.jetpress.org/volume1/moravec.htm

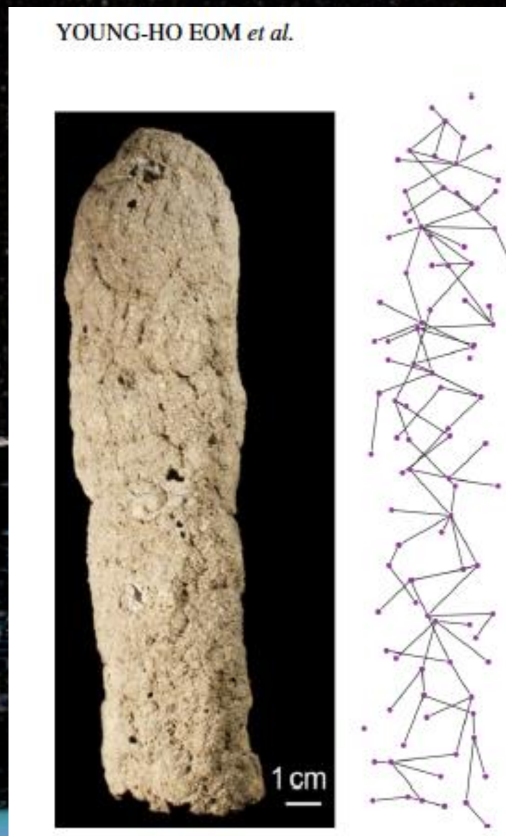
The challenge is that we still don't have true intelligence

- **Simulations of animals, even very simple ones, have not been successful at providing generalized intelligence but they are able to perform simple repetitive functions in a hostile environment far better than a human can.**



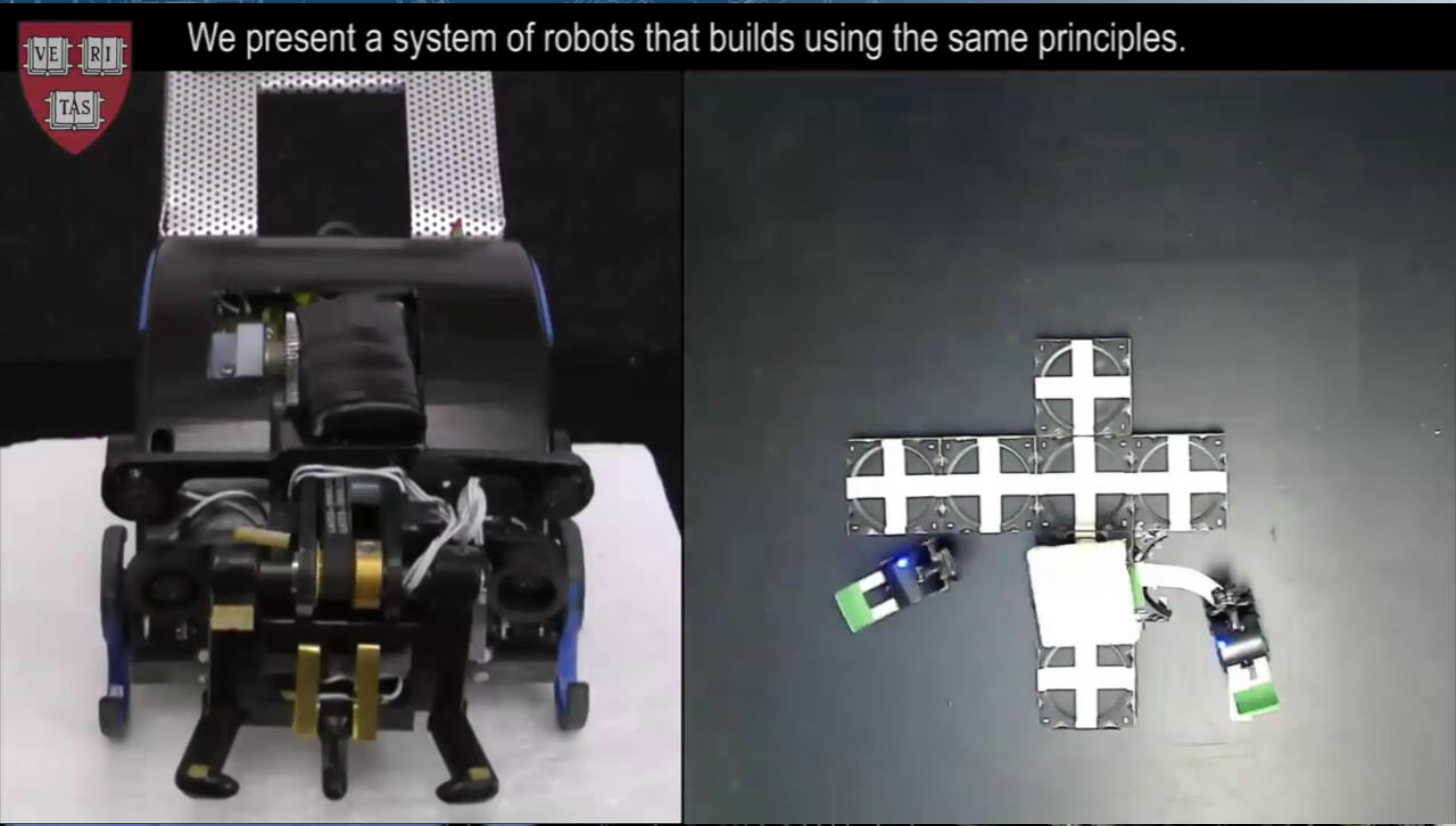
Termites build complex structures without a master plan

Termite mound building can be modeled as a network that exhibits particular rule-based behaviors.



Network-based model of the growth of termite nests
Young-Ho Eom, Andrea Perna, Santo Fortunato, Eric Darrouzet, Guy Theraulaz, and Christian Jost
Phys. Rev. E 92, 062810 – Published 9 December 2015

Termite like behavior (movie)



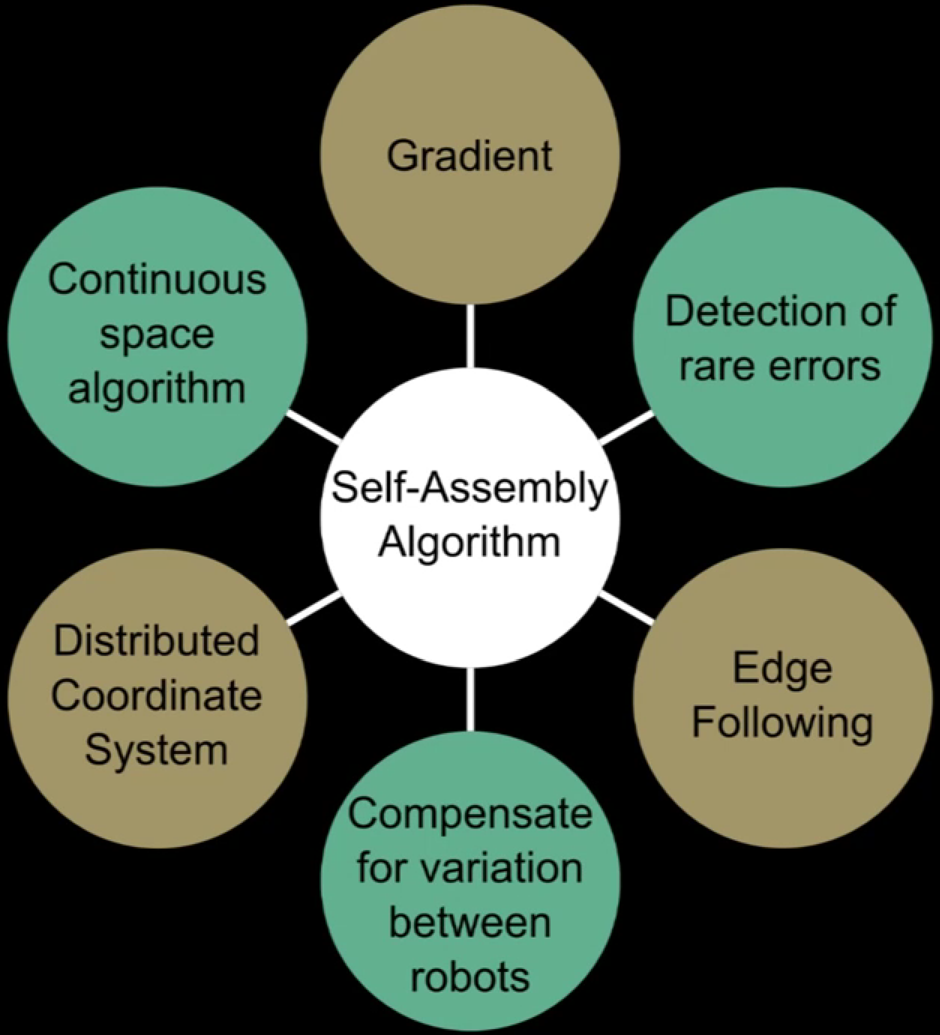
https://www.youtube.com/watch?v=LFwk303p0zY

Small agents of low intelligence work independently to

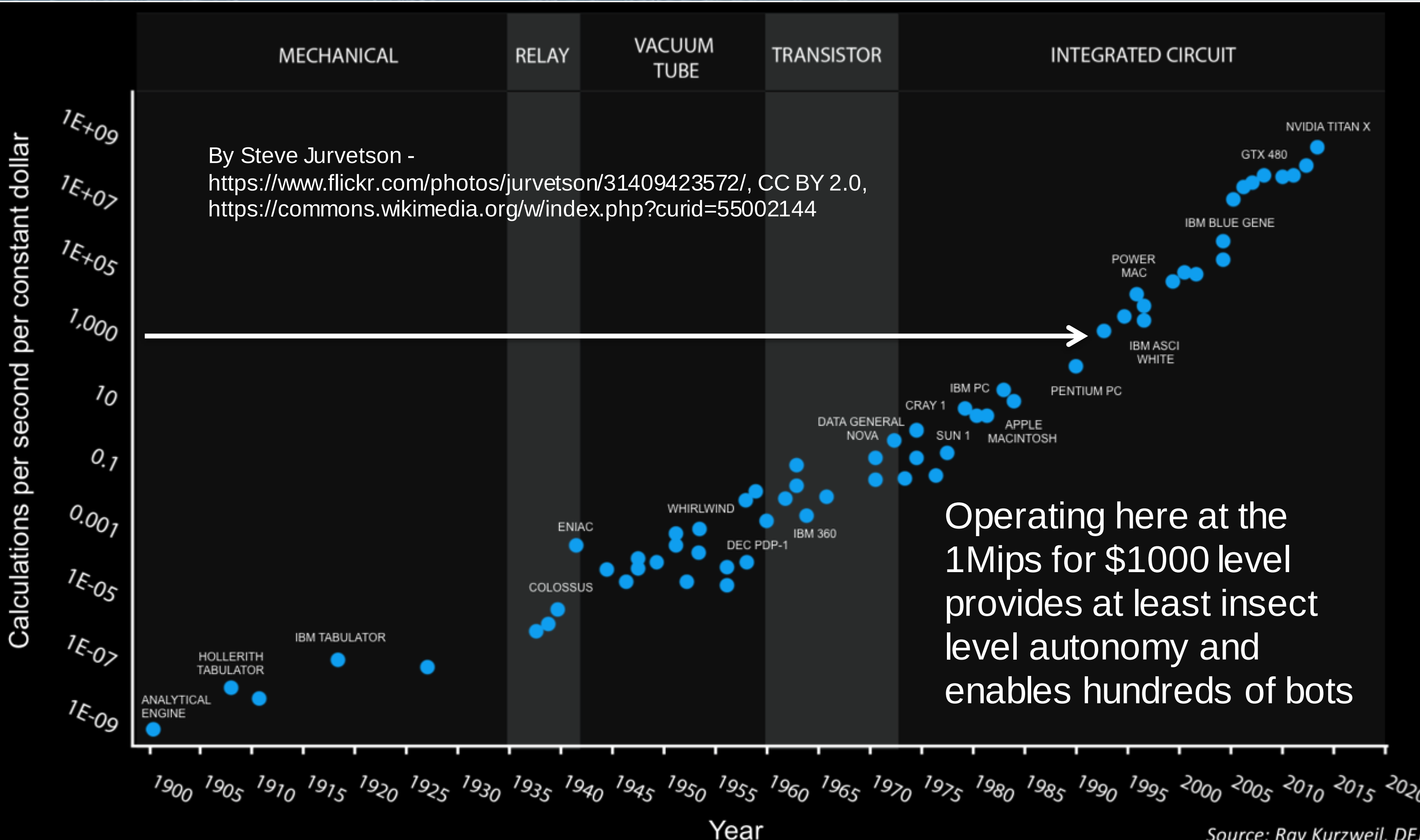
https://commons.wikimedia.org/wiki/File:Todd_Huffman_-_Lattice_%28by%29.jpg

Collective behavior (movie)

It relies on additional strategies to operate in large groups of error-prone robots.



https://www.youtube.com/watch?v=xK54Bu9HFRw



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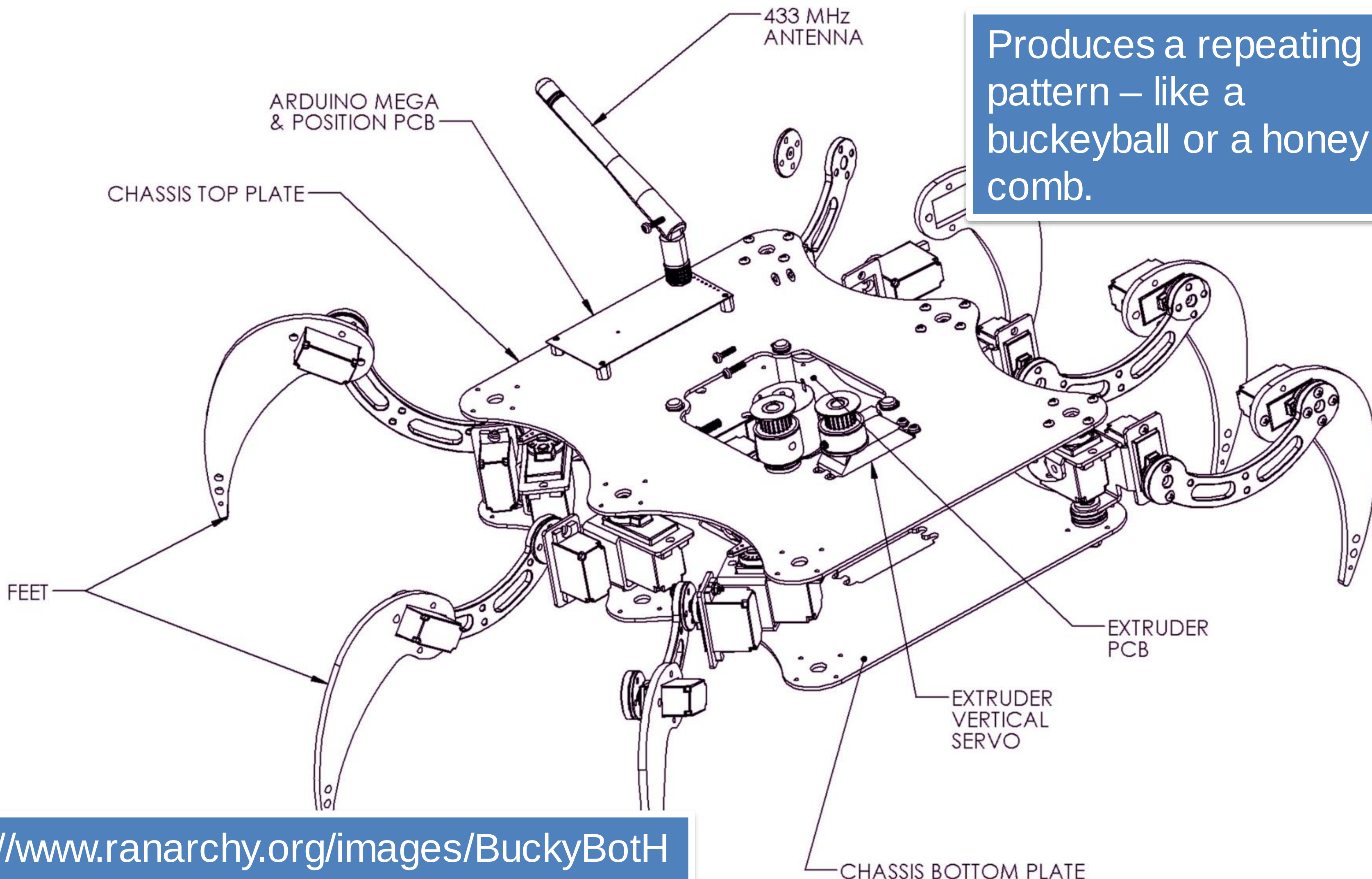
Operating here at the 1Mips for $1000 level provides at least insect level autonomy and enables hundreds of bots

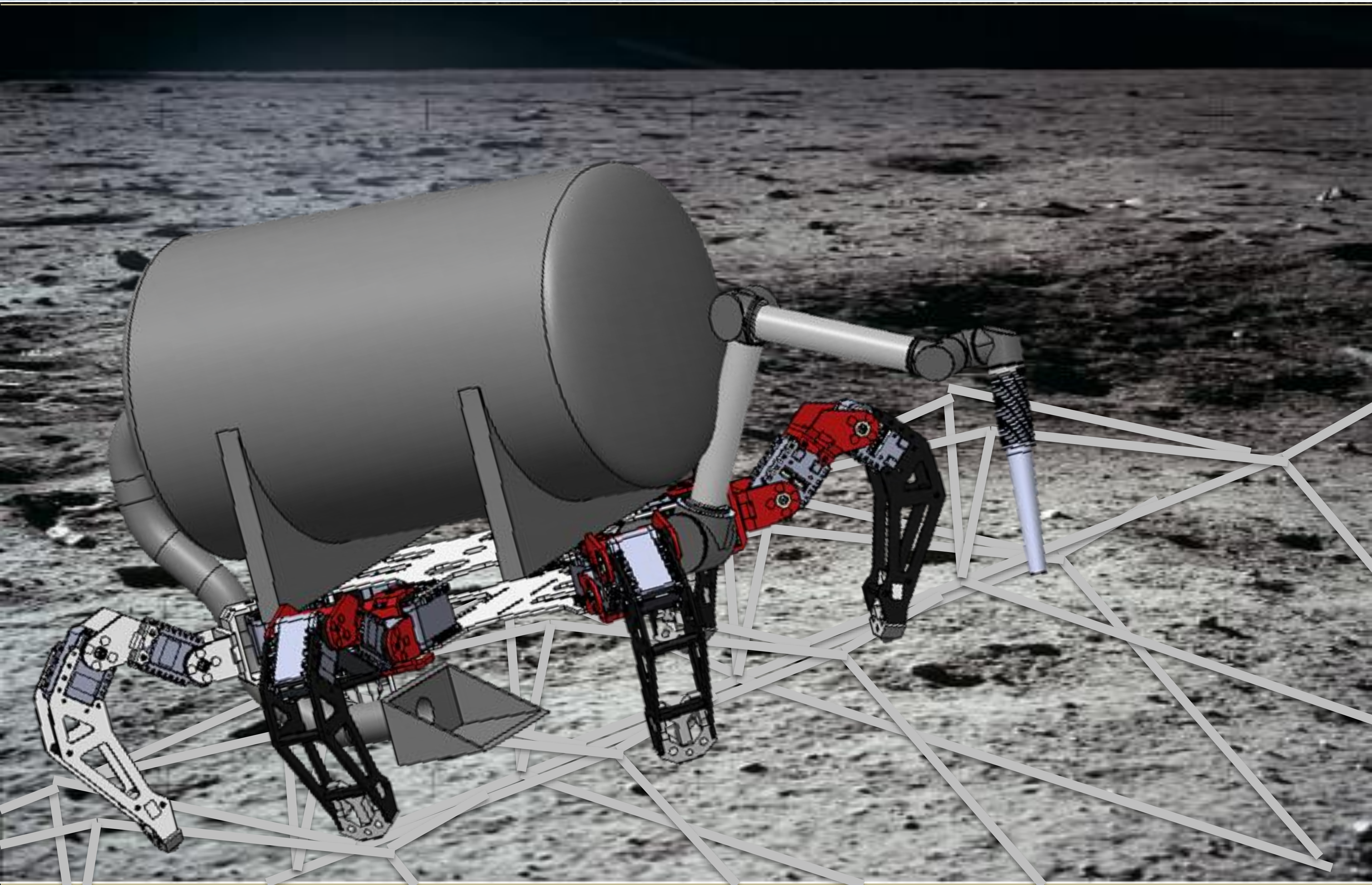
Philip Cox's Buckbot was posited as a way to create a structure using simple elements



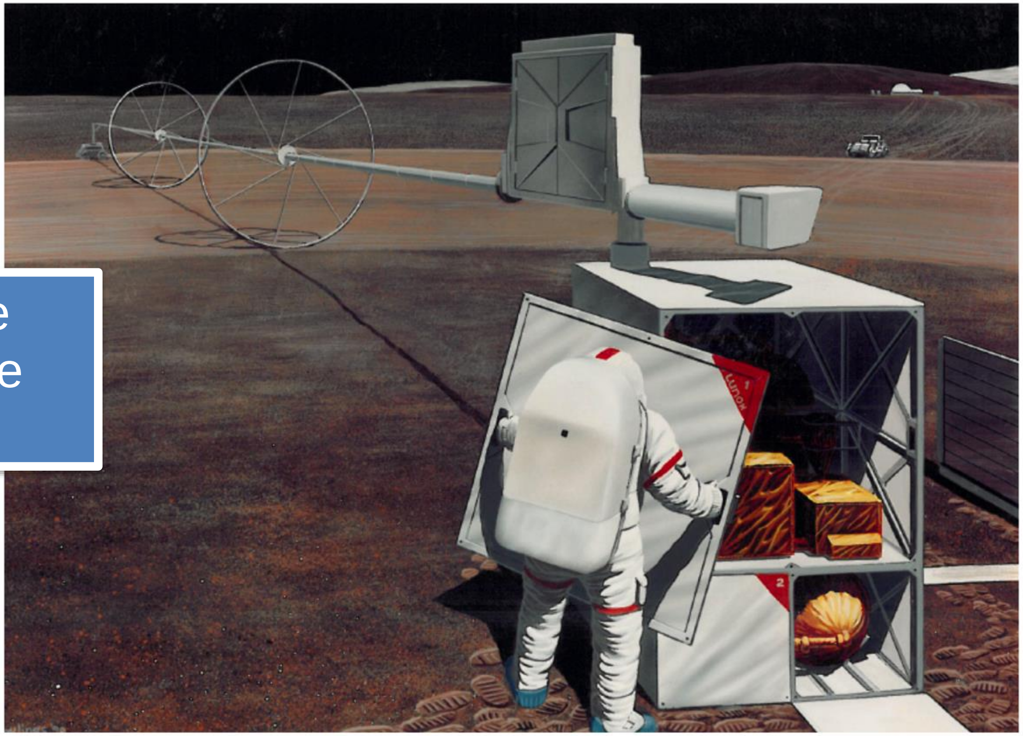
Produces a repeating hex pattern – like a buckeyball or a honey comb.

http://www.ranarchy.org/images/BuckyBotHexaPod2.jpg

CRICKET Spiderbots are used to create 3D structures



Human intensive mining and exploration will be difficult to achieve even if maps to our expectation of the "future"



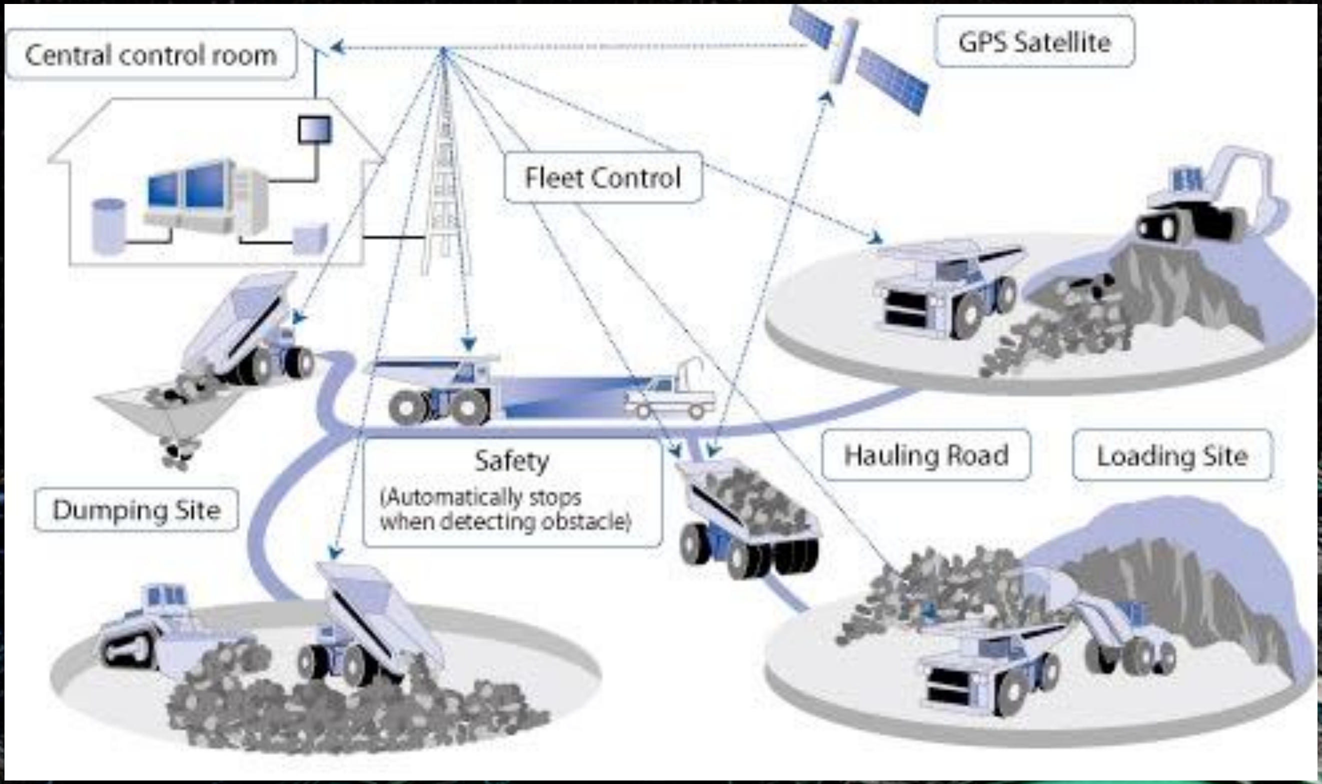
Can we take the human out of the loop?

Fig. 12.37 Lunar pneumatic mining with a production-scale system: LUNOX Pilot Plant. NASA image: S91-25382 created by Pat Rawlings.

The problem has well defined elements

- **We understand how we would extract materials from the surface and process them to create the materials needed to support our existence.**
  - In the discussion that follows, we identify the key elements in Earth systems for material identification and extraction
  - We show that robotic mining and autonomous operations are well advanced in all phases of Earth mining.
  - The system used depends on the type of extraction effort one is faced with
    - Extraction is accomplished via tunnels or open face mining
- **Can the problem be made more manageable by breaking it into constituent elements?**
- **Our focus is on examining site exploration and assessment (see discussion below)**

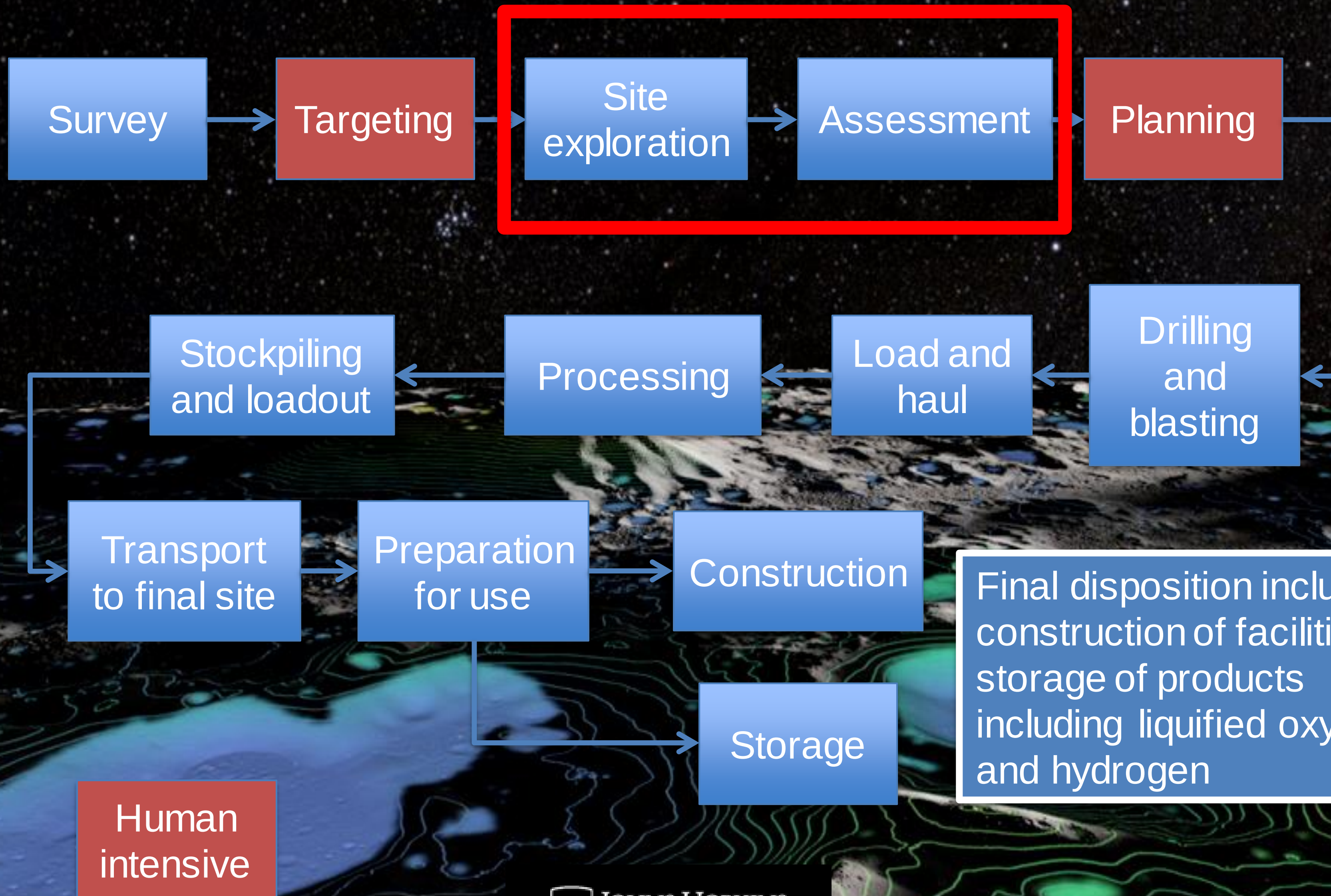
Mining – extraction of material for ISRU



On Earth, robotic mining is already being carried out.

http://adrianboeing.blogspot.com/2012/09/mining-robotics-overview-survey.html

CRICKET functions…and flow to production



Final disposition includes construction of facilities and storage of products including liquified oxygen and hydrogen

Terrestrial mining is largely automated


Completely autonomous truck

Human intensive mining functions are being auto

- Exploration
- Cutting
- Drilling
- Rock support
- Excavation
- Crushing and Screening
- Stacking and reclaiming
- Loading and unloading
- Transport networks
- Refueling

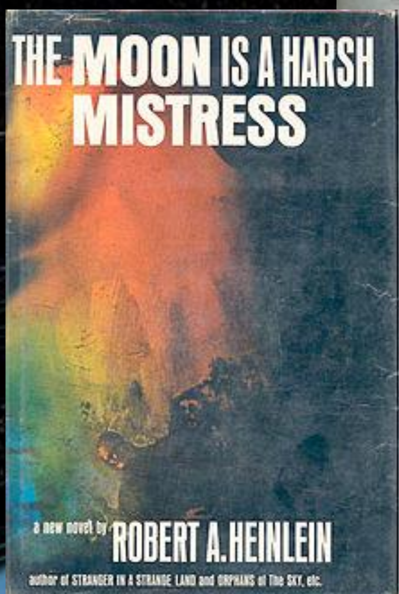
https://www.robots.com/articles/viewing/robofuel-for-automated-robotic-refueling

A issue is that “the moon is a harsh mistress”

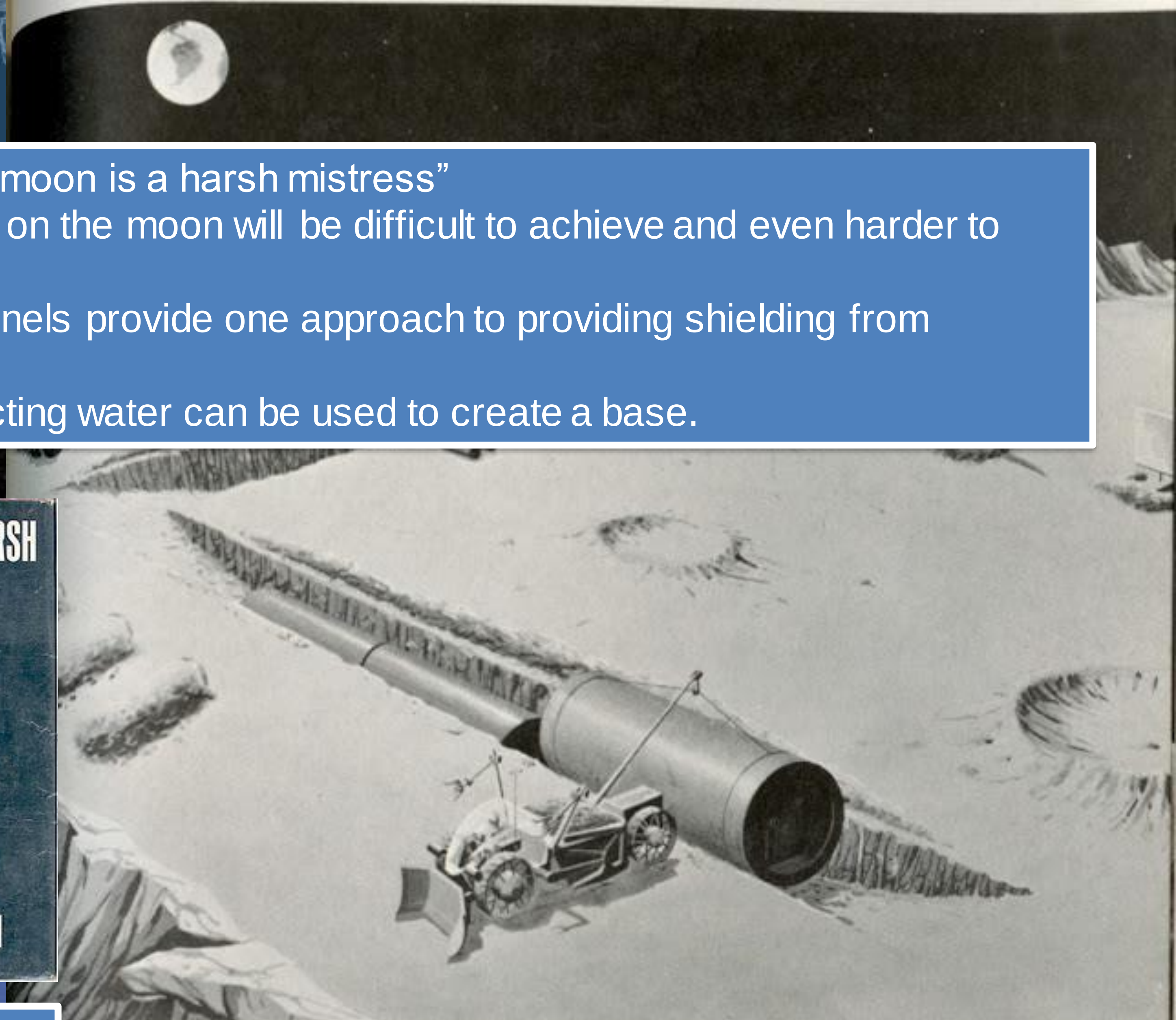
A human presence on the moon will be difficult to achieve and even harder to maintain.

“Cut and cover” tunnels provide one approach to providing shielding from radiation.

The tools for extracting water can be used to create a base.



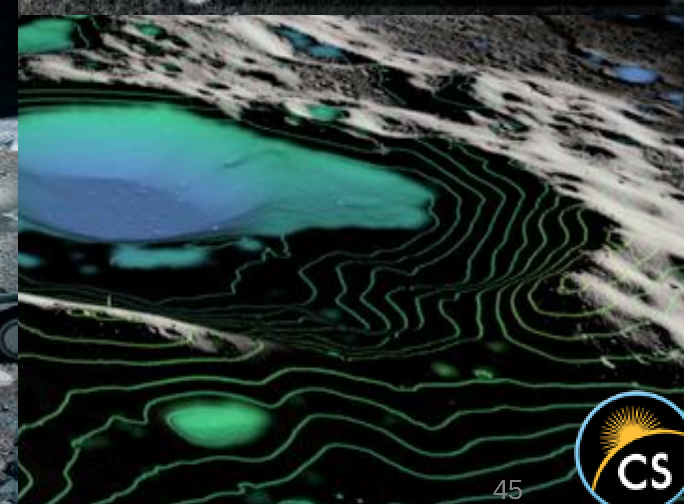
Published 1966



Scientists differ on whether sites should be underground in a lunar crater or "ocean" or if they should be blasted out of the sides of mountains.

—*Martin*

A much more sophisticated imagined lunar base buried in the regolith



http://www.esa.int/spaceinimages/Images/2013/01/Lunar_base_
made_with_3D_printing

https://www.youtube.com/watch?v=E-lq2ErdlXY

NIAC funded work shows that 3D printing can be used to create habitats

https://3dprint.com/30302/3d-printing-on-moon-mars/

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http://www.businessinsider.com/berok-khoshnevis-nasa-to-3d-print-houses-mars-2016-7

Behrokh Khoshnevis, a professor of engineering at the University of Southern California, has developed a method he calls Contour Crafting that would allow humans to easily build houses on other planets. Contour Crafting uses a giant robot to layer concrete to build houses. The 3D-printing method ensures all the conduits for electrical, plumbing and air-conditioning are set up once the house is complete.

3D Printing using regolith prepares the surface for humans

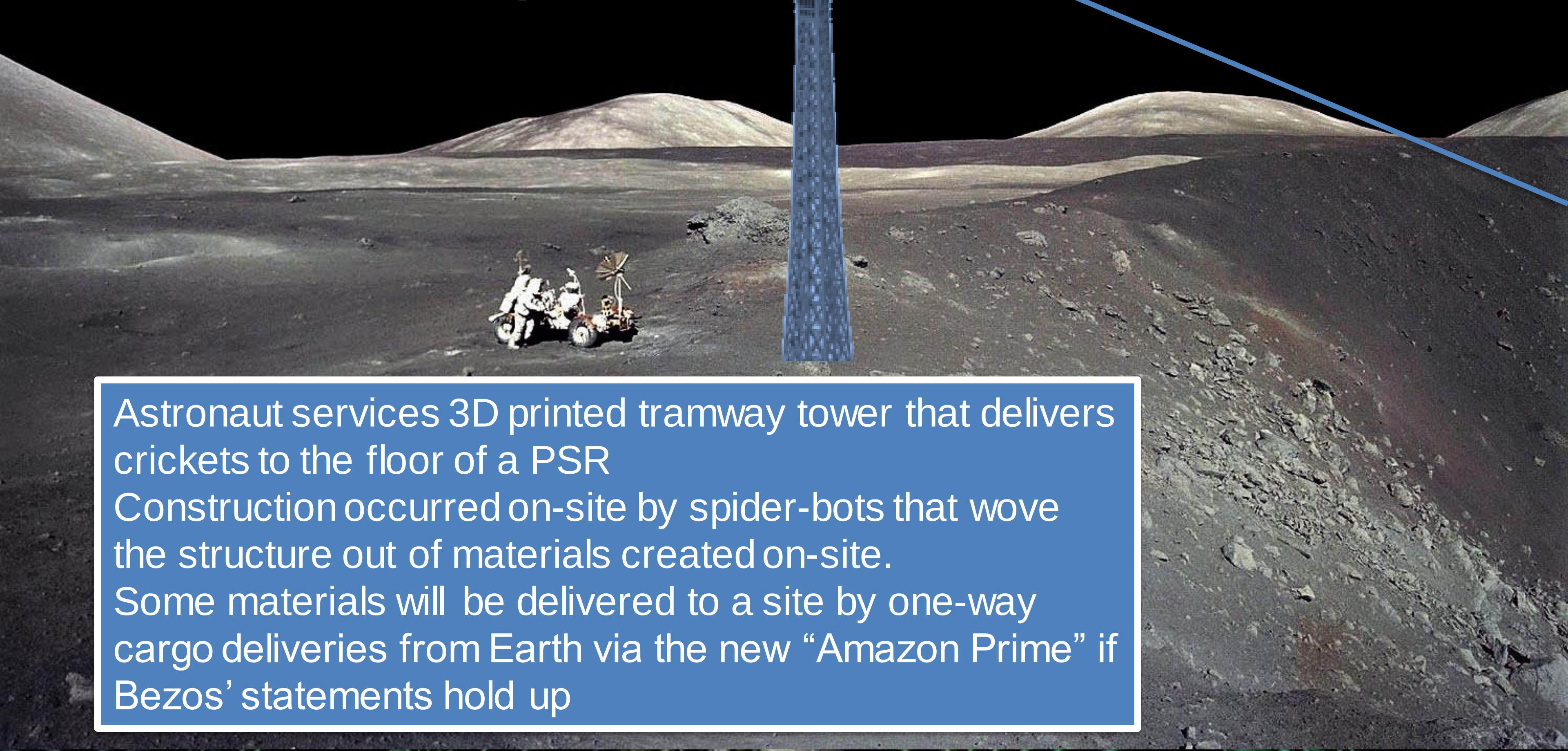
https://lunarscience.nasa.gov/wp-content/uploads/2013/02/lunarbase3dprinting.jpg

Combine this with other robotic capabilities

- The ability to construct “Lego bricks” on site would enable the creation of structures that can be extended more readily and be constructed in shapes that are not limited by the extrusion process.
- Using modular components to construct a repeating pattern is within the capability of robots today.
- One on-site use would be to use simple bots to assemble site-manufactured components.
- Note that not all materials can or should be made on-site.
- It is more cost-effective to rely on delivery of key components from Earth
- We note that the delivery vehicle could be cannibalized for use to support the site build-out.

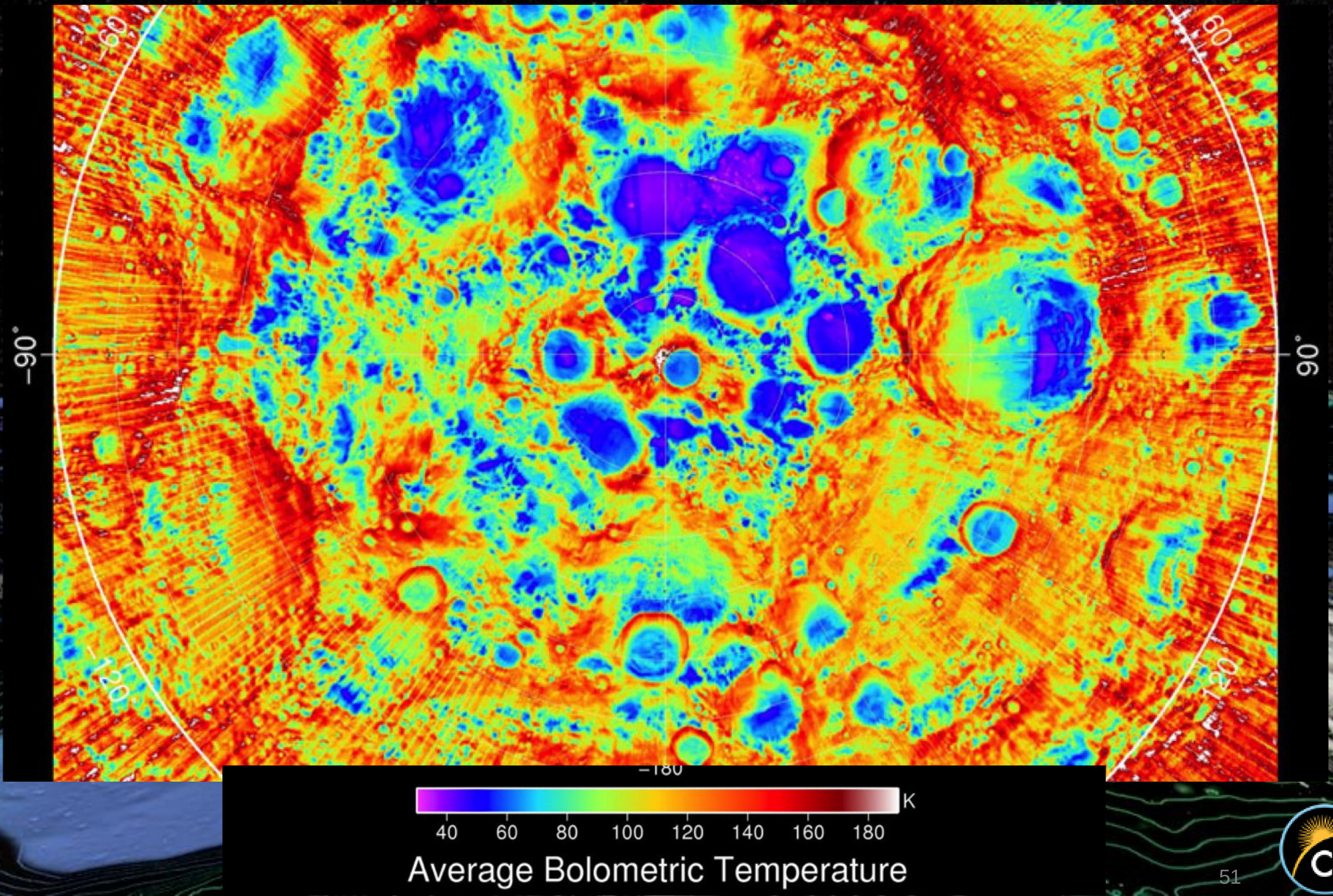
We Can Use the Moon

- **The Moon is nearby and has the characteristics of objects much more difficult to access that may be more interesting but we will have to go there in a way that can sustain our presence**

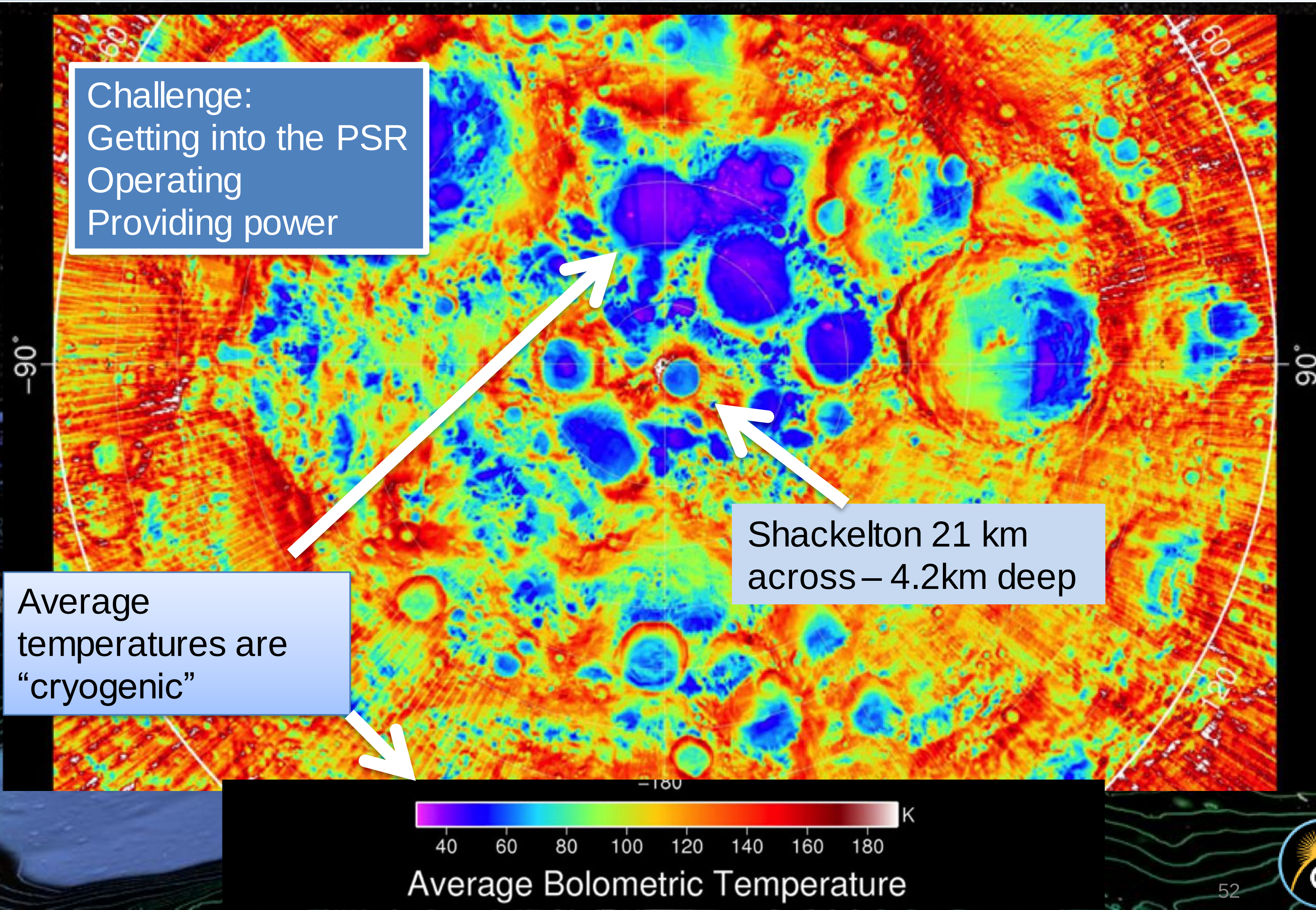


Astronaut services 3D printed tramway tower that delivers crickets to the floor of a PSR
Construction occurred on-site by spider-bots that wove the structure out of materials created on-site.
Some materials will be delivered to a site by one-way cargo deliveries from Earth via the new “Amazon Prime” if Bezos’ statements hold up

The Availability of Water Ice is Dictated by Solar Insolation



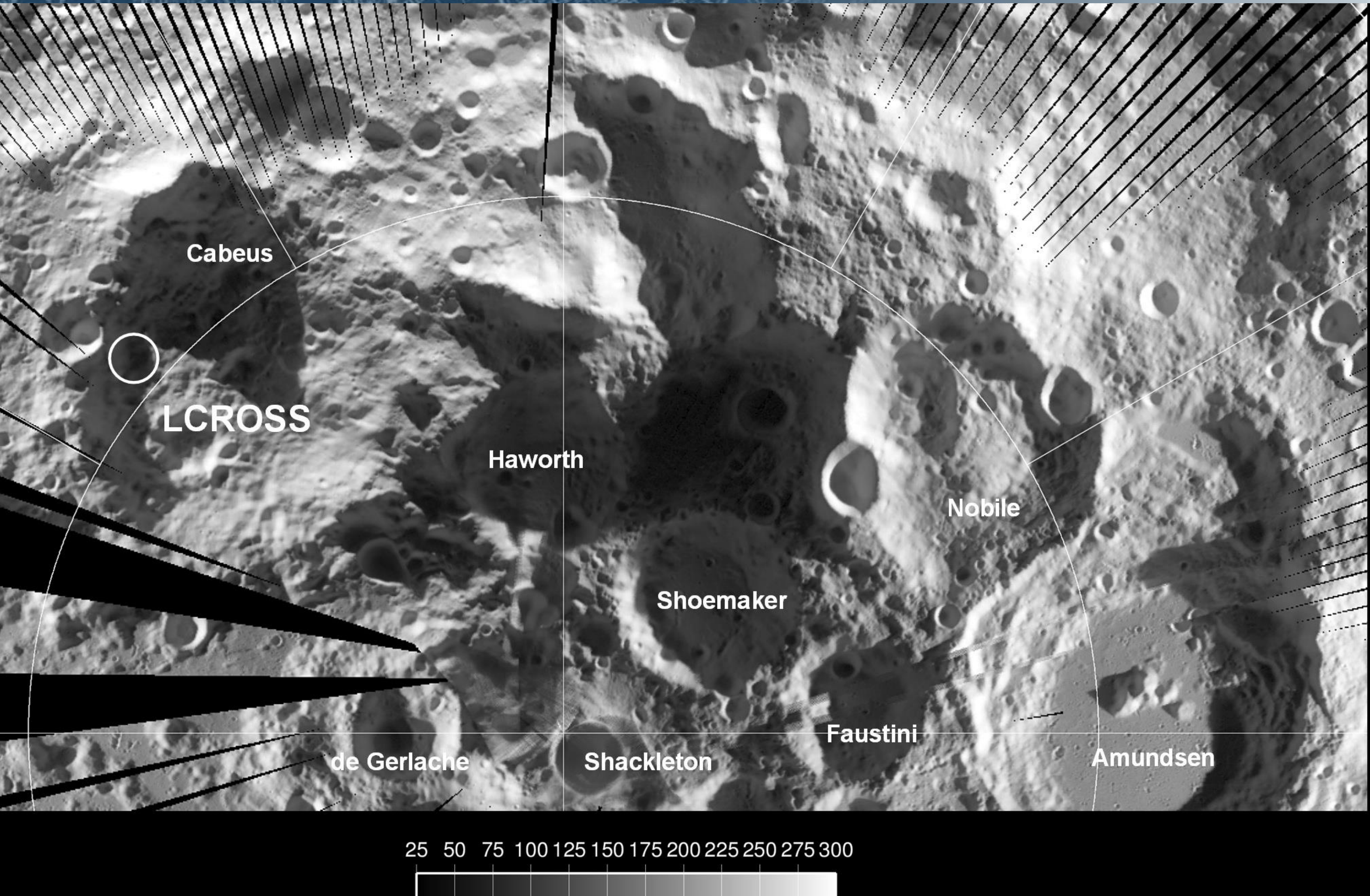
The Approach is Dictated by Solar Insolation



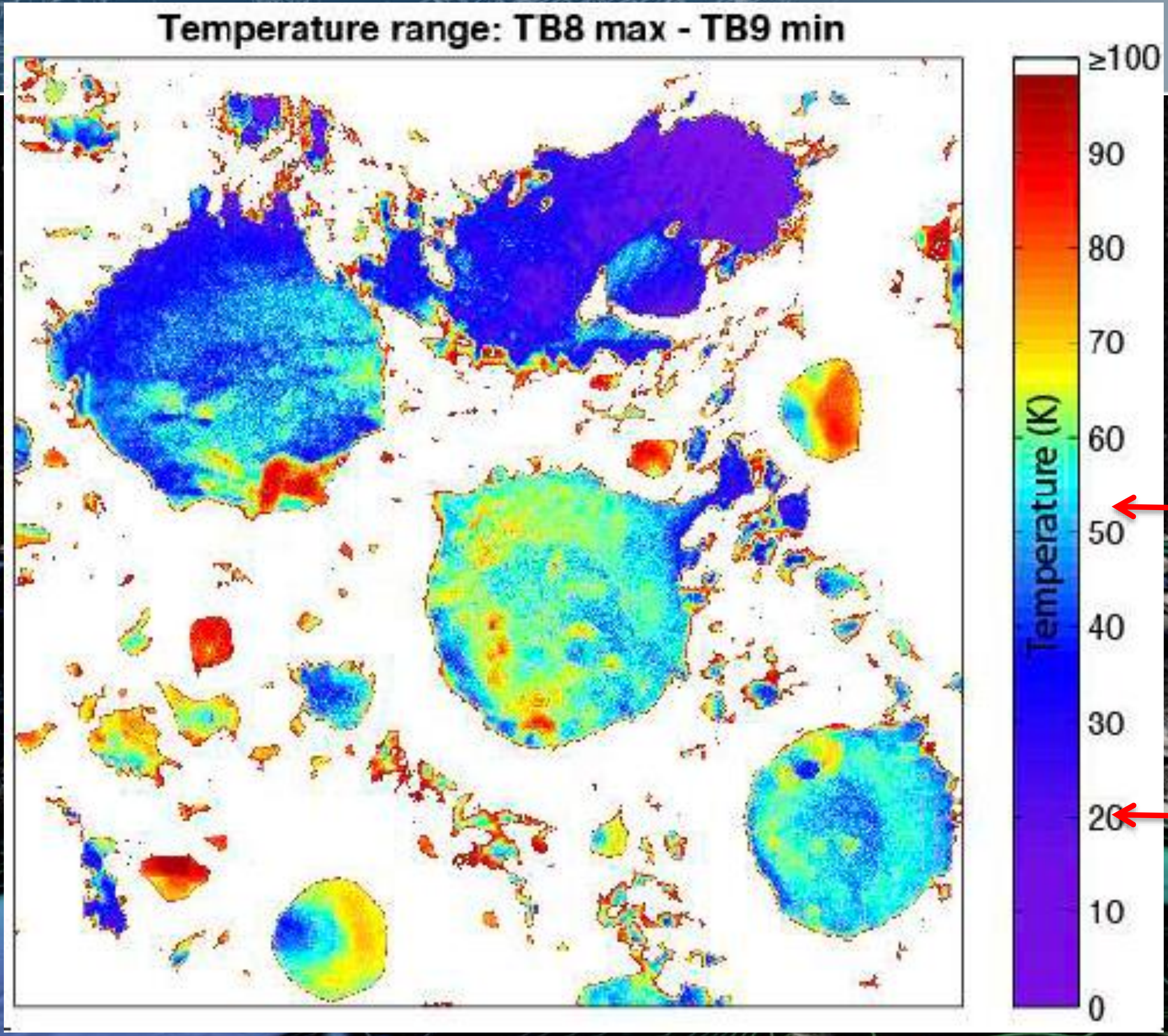
Challenge:
Getting into the PSR
Operating
Providing power

Shackelton 21 km across – 4.2km deep

Average temperatures are "cryogenic"



Diviner Channel 8 Brightness Temperature Map (K)



LH2 at 20K
LO2 at 54K

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The Environment is Challenging

- Temperatures in the craters containing the PSRs range from extremely low (into the superconducting realm) to cold but manageable
- The subsurface lunar regolith provides a relatively stable temperature in the regions where sunlight does fall on the surface
- Getting the our prospectors into (and possibly out of) the PSRs is a challenge.
  - Retrieval and relocation solutions provide an opportunity to expand the scope of our approach
- Mobility and power limit the life of the CRICKETS
- We can remove or ameliorate some of these constraints by taking advantage of the site geometry.

LRO observations of PSR

Developing a Requirements Flowdown

- **The current activity is focused on developing a requirements flowdown**
- **Describe 4 stages of evolutionary development**
  - Initial reconnaissance and mapping
  - In situ resource utilization
  - Development
  - Sustainment – goal to support human presence
- **Evolutionary architecture more broadly applicable**

"Bookends" to the study

1. **Focus on how the lowest level architectural element (individual crickets) can provide requirements flow-up that informs requirments flowdown**

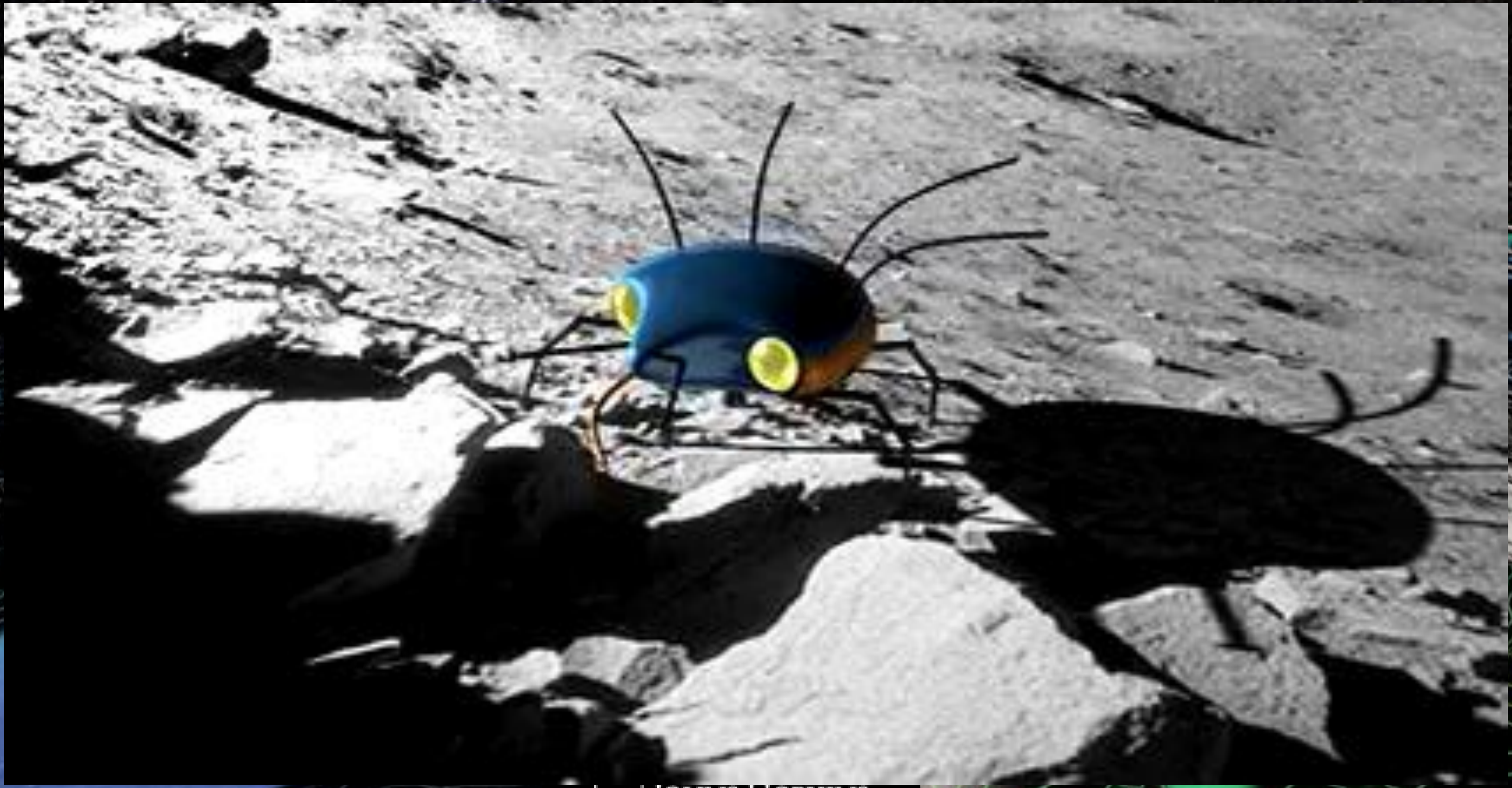
   - Outline an approach to establishing a requirement on number of crickets, N
   - *A means to establish N informs design requirements for the landed package (payload) and orbit-to-surface delivery system*

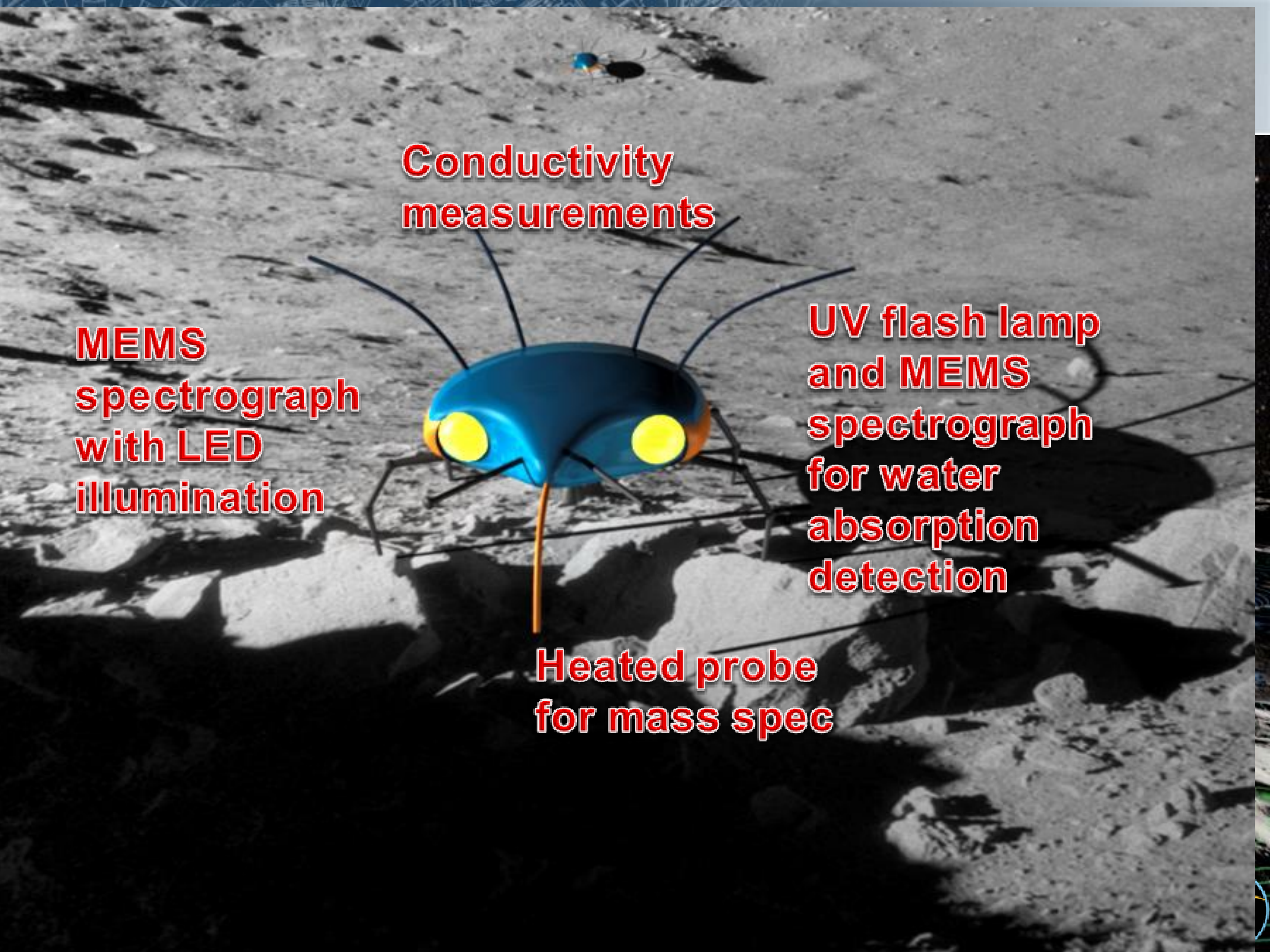
1. **Consider other NIAC concepts as contributors to the broader architecture**

   - Conceive an integrated broader architecture comprised of CRICKET and other NIAC concepts
   - *Suggests a way for NASA to leverage multiple investments toward an advanced concept greater than the sum of its parts*

A simple cricket exploring

Initial concept
- Delivery of the payload to the crater edge – into sunlight
- Dispersal of individual crickets into the PSR
- Mapping and exploration of the area



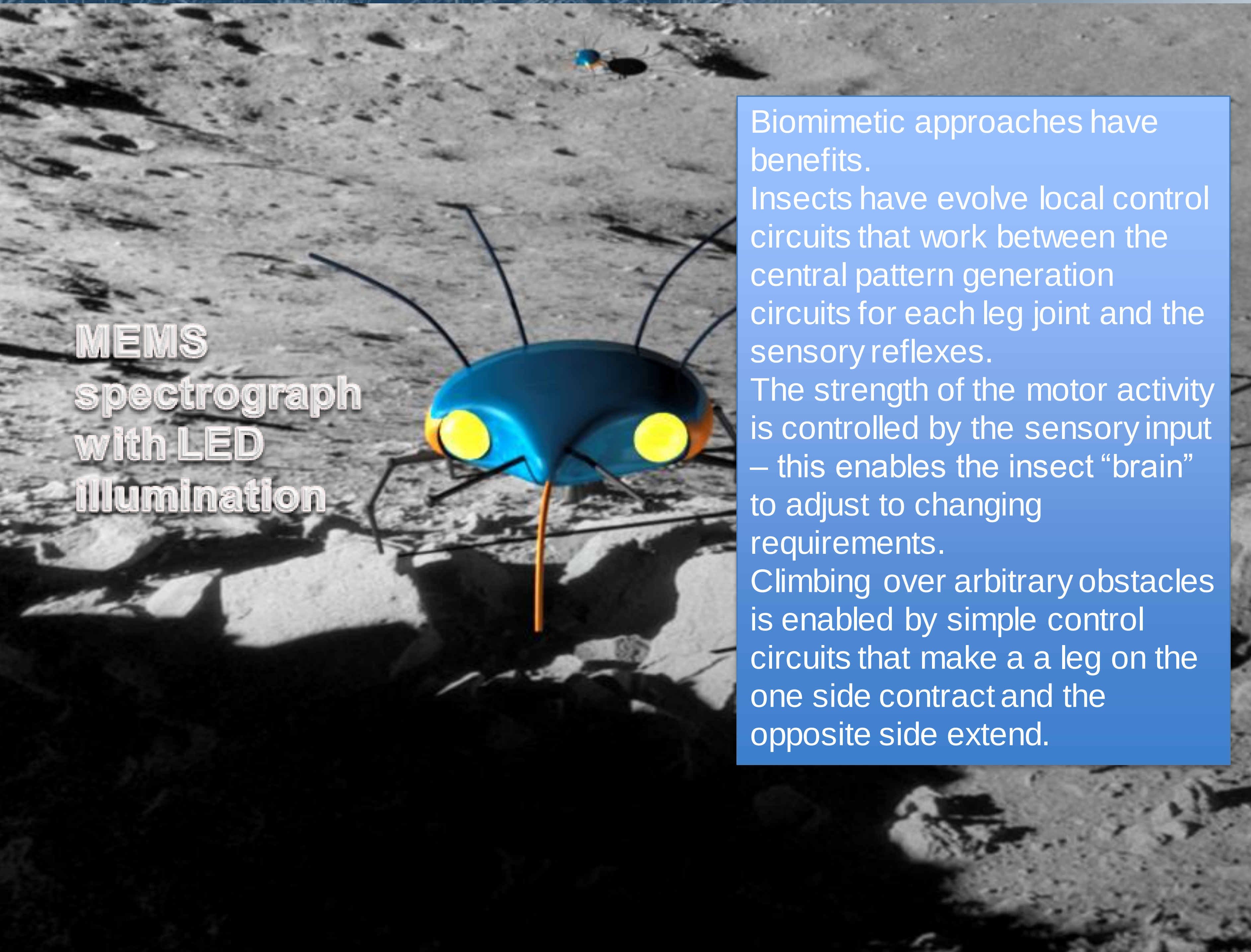

Conductivity
measurements
MEMS
spectrograph
with LED
illumination
UV flash lamp
and MEMS
spectrograph
for water
absorption
detection
Heated probe
for mass spec

Initial Design Considerations

- **CRICKET uses reasonable extrapolations of existing cubesat and/or commercial technology.**
- **An orbiter provides the very low-rate communication back to Earth and delivers a "queen" to orbit around the moon.**
  - The "queen", a carrier, based on cubesat delivery technology, carries the "crickets" to the surface and provides a reference location.
  - The carrier delivers dozens of "crickets" to an area deemed likely to contain ice in permanently shadowed regions.
  - The "crickets" are located on the surface by detecting the Doppler of a low-power beacon "chirp" from the orbiter and/or carrier.

CRICKET Instrumentation

- **Each cricket carries a tiny SWIR and Far Ultraviolet MEMS spectrograph, Xenon lamp, heating element “proboscis” and “whiskers” for characterizing the surface and subsurface conductance.**
  - Simple “eyes” tell the cricket its illumination level and a nulling circuit drives it toward darkness.
  - Simple robots with such primitive sensor-driven behavior have been well understood for decades, and their use in numbers to perform collective missions has been a topic of recent research [Braitenberg and more].
  - The heated proboscis measures the surface and subsurface thermal conductivity as well as presence of water.
  - Each cricket measures the reflected spectrum seen by the spectrograph from the miniature xenon flash lamp and compares it to a template to determine whether water ice or water has been found; positive detections are transmitted and tagged by location.
  - Once their state is queried by the overflight of the orbiter they return to their search for another random corner to hide in. Eventually the crickets run out of propellant/energy and/or freeze to death.



Biomimetic approaches have benefits.

Insects have evolve local control circuits that work between the central pattern generation circuits for each leg joint and the sensory reflexes.

The strength of the motor activity is controlled by the sensory input – this enables the insect “brain” to adjust to changing requirements.

Climbing over arbitrary obstacles is enabled by simple control circuits that make a a leg on the one side contract and the opposite side extend.

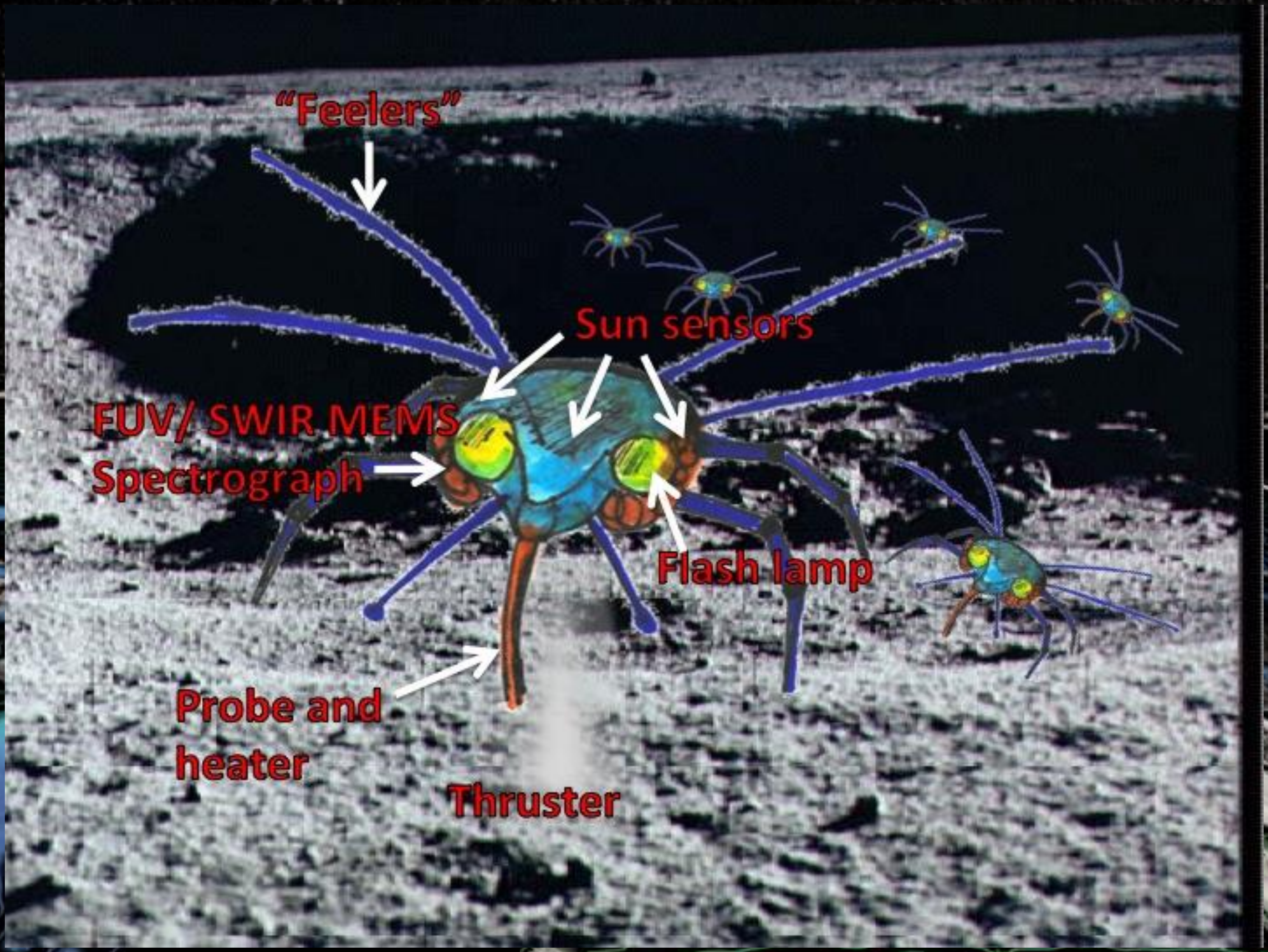
The PSRs can be made accessible

- The bottom line: be in harmony with th lunar environment – don't "conquer" the moon
- The challenge is to take advantage of the terrain to produce power in the illuminated regions while operating mappers in the PSRs
- We are examining approaches for survival over the extremes of temperature
- This includes taking advantage of the thermal conductivity of the regolith to use as a heat pump for power generation.

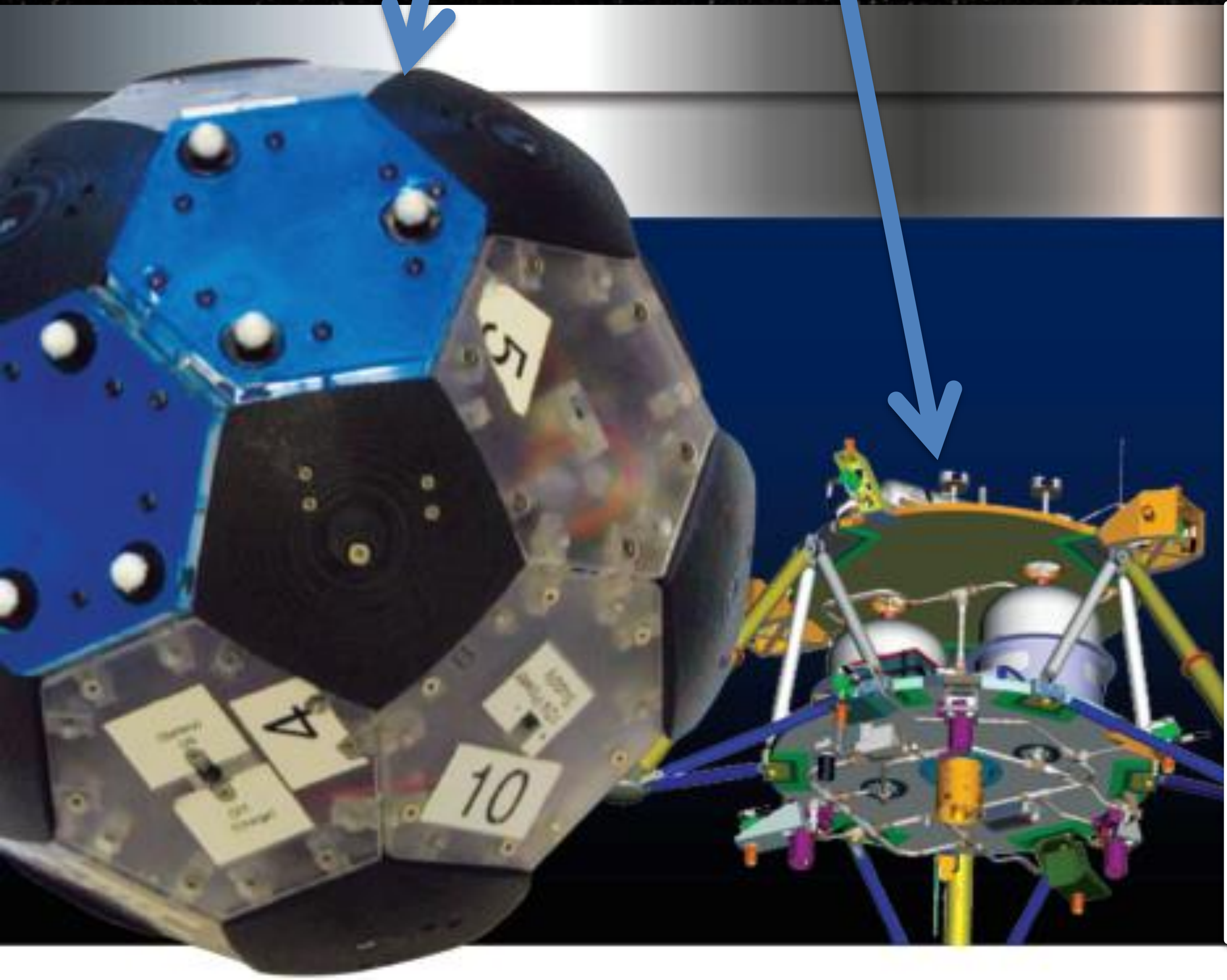
Why do we do solid modeling of concepts?

- The goal is to establish what a reasonable design might look like.
- For example, one of the primary issues is going to be power (and the associated issue of dealing with the low temperatures).
  - Batteries are not very efficient
  - Can we use a fuel cell to store energy?
  - If so what are the packaging issues?
- The goal is to explore the areas in the solution space that need to be addressed
- Ideally we'd develop a technology roadmap

Mobility on the surface will have a variety of solutions



Buckybot and lander for delivering the system



Development of a delivery system for a large number of bots to an area for exploration.
Use of a standard rack that can carry many mass produced bots enables us to effectively explore key areas.

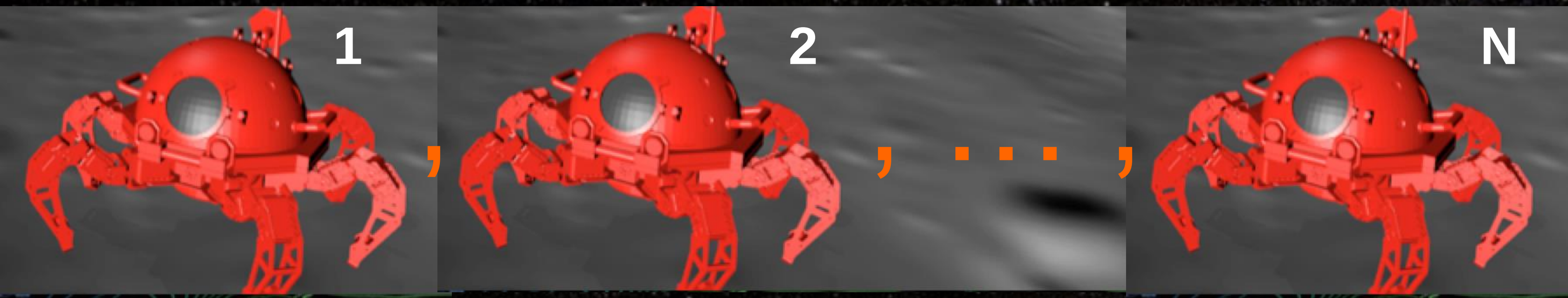
APL's buckybot uses actuators to move

Buckybot is a new mobile robotic platform based on a truncated icosahedron.

- It is stable on any of its 20 hexagonal faces.
- 12 linearly actuated pentagonal faces enable it to roll from any orientation in any direction.
- Pentagonal faces are rounded to prevent Buckybot from resting on a single actuator.
- Buckybot moves by extending a single pentagonal face until the center of mass shifts to tip onto an adjacent hexagonal face.
- The APL Buckbot can actually climb stairs – or rocks!

From Grande et al, APL Tech Digest, 32, #3, 605, 2013

How Many Crickets to Explore an Area?



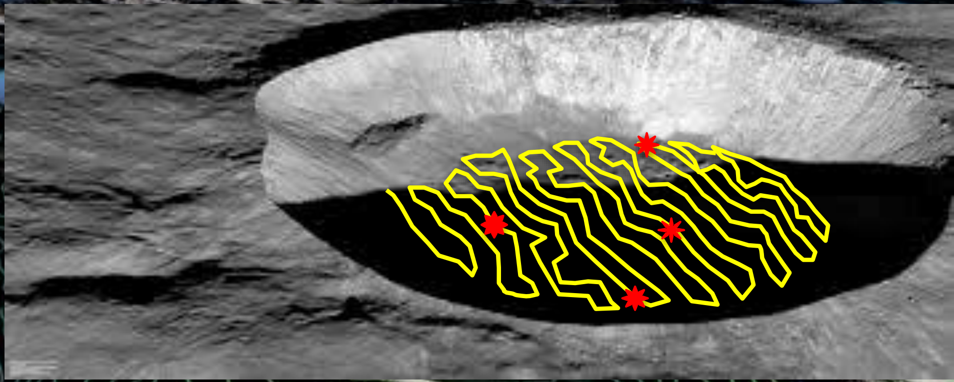
- **Fundamentally, the PSR prospecting task at the level of individual crickets can be considered an area coverage task**

- …a classical problem in mobile robot path planning with applications to lawn mowing, snow removal, mine clearing, sensor-based surveying, search-and-rescue, and agricultural harvesting

- **Knowing the sufficient number of crickets, N, required to fully prospect in PSR-of-interest, R, in mission duration, T, would inform the design requirements for the landed payload design and payload delivery system**

Area Coverage

- **Classical problem in mobile robot path planning with applications to lawn mowing, snow removal, mine clearing, agricultural harvesting, search-and-rescue, sensor-based surveying, and more**
- **Knowing the sufficient number of crickets, N, required to fully prospect in PSR-of-interest, R, in time period, T, would inform the design requirements for the landed payload design and payload delivery system**
- ***Many algorithms exist for single and multi-robot systems; and many offer theoretical guarantees on coverage completeness and efficiency***



Sampling of vast open literature on robotic Area Coverage algorithms

1. A. Khan, I. Noreen, Z. Habib, "On Complete Coverage Path Planning Algorithms for Non-holonomic Mobile Robots: Survey and Challenges," Journal of Information Science and Engineering, 33(1), pp. 1016-2364, 2017.

2. D. Jia, M. Wermelinger, R. Diethelm, P. Kr¨usi, M. Hutter, "Coverage Path Planning for Legged Robots in Unknown Environments," IEEE Intl. Symp. on Safety, Security and Rescue Robotics, Lausanne, Switzerland, Paper MoC1T.3, Oct. 2016.

3. E. Galceran and M. Carreras, "A Survey on Coverage Path Planning for Robotics," Robotics and Autonomous Systems, 61(12), pp. 1258–1276, Dec. 2013.

4. P. Fazli, A. Davoodi and A.K. Mackworth, "Multi-robot repeated area coverage," Autonomous Robots, 34, pp. 251–276, 2013.

5. M.A. Habib, M.S. Alam, and N.H. Siddique, "Optimizing Coverage Performance of Multiple Random Path-planning Robots," Journal of Behavioral Robotics, 3(1), pp. 11-22, 2012.

6. B. Ranjbar-Sahraei1, G. Weiss and A. Nakisaei, "A Multi-Robot Coverage Approach based on Stigmergic Communication," Proc. 10th German Conference on Multiagent System Technologies, Trier, Germany, pp. 126-138, Oct. 2012.

7. H. Choset, "Coverage for robotics – a survey of recent results," Annals of Math. and AI, 31, pp. 113-126, 2001.

8. K.R. Guruprasad, Z. Wilson and P. Dasgupta, "Complete Coverage of an Initially Unknown Environment by Multiple Robots using Voronoi Partition," Intl Conf. on Advances in Control and Optimization in Dynamical Systems, Bengaluru, India, Feb. 2012.

9. C. Pinciroli, V. Trianni, R. O'Grady, G. Pini, et al, "ARGoS: a modular, parallel, multi-engine simulator for multi-robot systems," Swarm Intelligence, 6, pp. 271–295, 2012.

10. E. Tunstel, J.M. Dolan, T. Fong and D. Schreckenghost, "Mobile Robotic Surveying Performance for Planetary Surface Site Characterization," In Performance Evaluation and Benchmarking of Intelligent Systems, Springer, 2009.

11. J. Mason and R. Menezes, "Autonomous Algorithms for Terrain Coverage: Metrics, classification and evaluation," IEEE Congress on Evolutionary Computation, Hong Kong, 2008.

12. E. Garcia and P. Gonzalez de Santos, "Mobile Robot Navigation with Complete Coverage of Unstructured Environments," Robotics and Autonomous Systems, 46(4), pp. 195–204, 2004.

13. M.A. Batalin and G.S. Sukhatme, "Spreading out: A local approach to multi-robot coverage," Intl. Symp. on Distributed Autonomous Robotic Systems, 5, pp.373–382, 2002.

1. S. Koenig and Y. Liu, "Terrain Coverage with Ant Robots: A Simulation Study," AGENTS '01 Proc. 5th International Conference on Autonomous Agents, Montreal, Quebec, Canada, pp. 600-607, 2001.

Simulation-based experimentation can prescribe N

- One or more existing coverage algorithms can be used for prospecting experiments by various numbers of crickets
- E.g., a representative study [13] showed that for a given area and set of coverage algorithms, full coverage is achieved by at least 7 robots.
- Some algorithms are designed for more constrained cases in which the terrain traversability must be considered (and assuming traversability can be adequately discerned by perception systems) and for which the locomotion mechanism is legged rather than wheeled [2]
- Relevant comprehensive performance metrics [10] accounting for other mission factors of interest can also be brought to bear on the choice of N when >N crickets do not increase total coverage or when minimum time is not a goal.

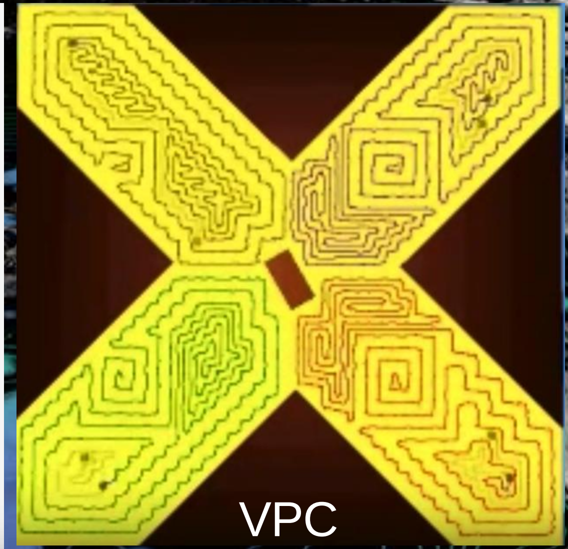
- Simulation studies can be focused to predict outcomes for particular PSR prospecting ConOps for a CRICKET mission.
- A simulator for which a set of motion behaviors are encoded for area coverage can be used to run experiments that simulate teams of crickets of increasing numbers prospecting in PSRs of different areal extents.
- For a set of particular PSRs, experiments can be run to predict the number of crickets, N, needed to cover the surface area of each PSR as well as the times it would take to complete the coverage tasks

Candidate Algorithms & Simulator

- **Stigmergic Coverage (StiCo) [6] – simplest end of algorithm spectrum, and robust**
- **Voronoi Partition Coverage (VPC) [8] – area boundary presumed known**

- **Existing multi-robot sims. can be configured as the experimental test bed, e.g., ARGoS [9] – open-source and freely available**

https://www.youtube.com/watch?v=DOlyqDN2a9o&feature=youtu.be



https://www.youtube.com/watch?v=2XDIpCRCPM4

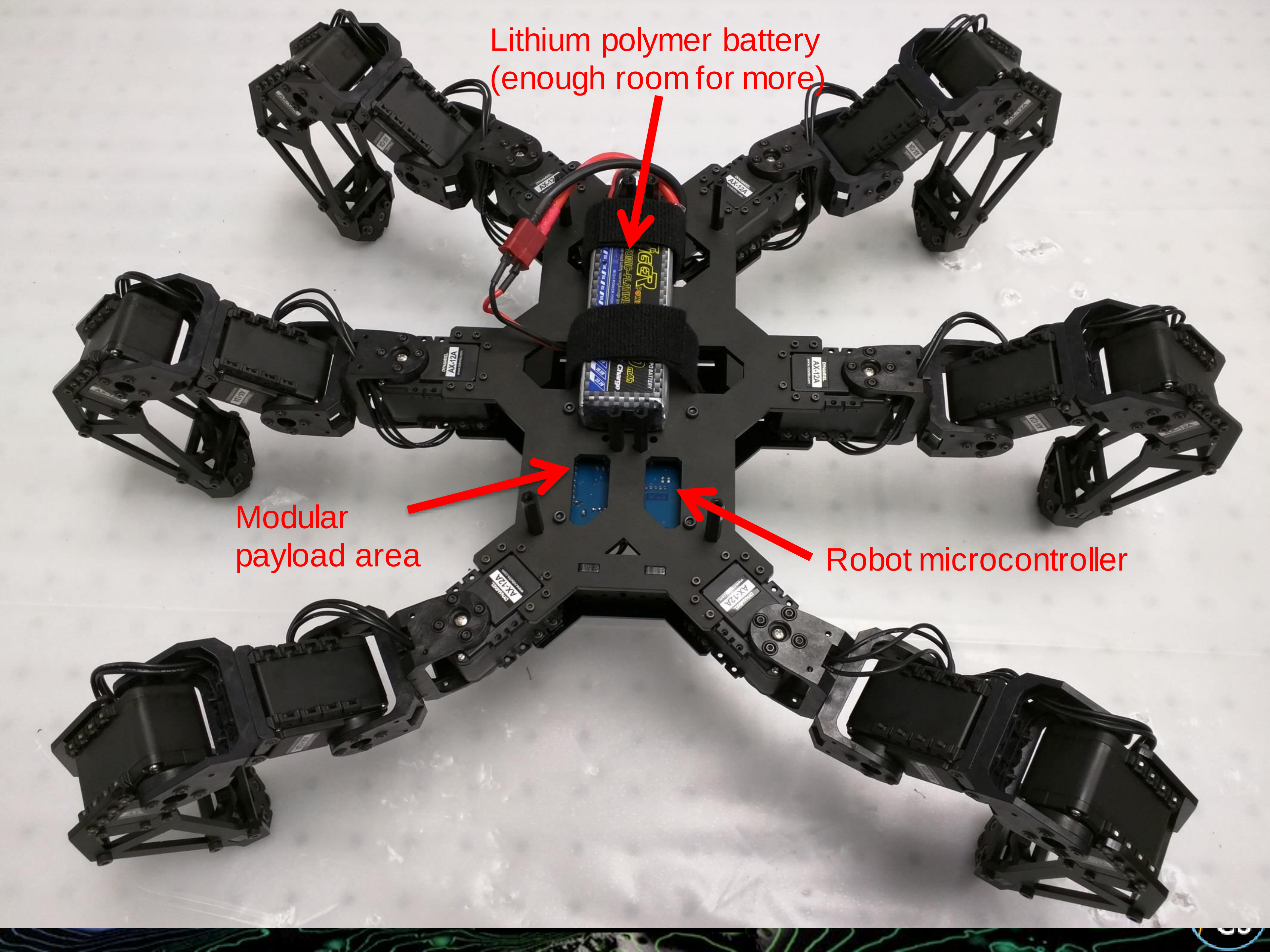
http://www.argos-sim.info/index.php

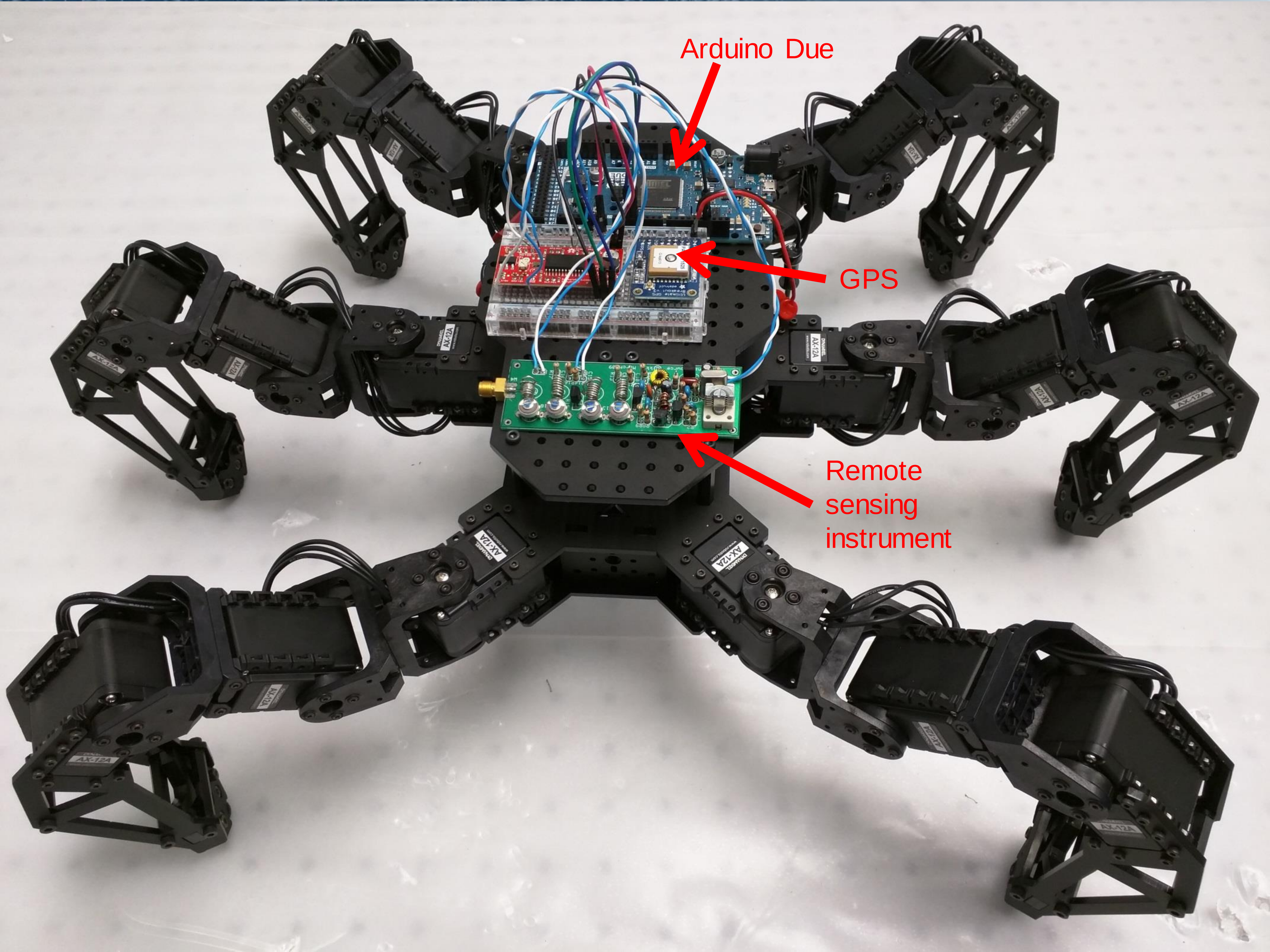
Survey Robots locate resources

- Survey robots stay in the permanent shadow regions scanning for water ice with a ground penetrating radar
- They rely on hybrid a fuel cell and battery power system.
- Most of its energy is supplied by the rover bot to be able to operate in permanent eclipse
- Each survey robot is imaging and mapping
- RFID tags are dropped and surveyed from orbit by overhead asset looking at doppler on signal to determine location.
  - A biomimetic analogy

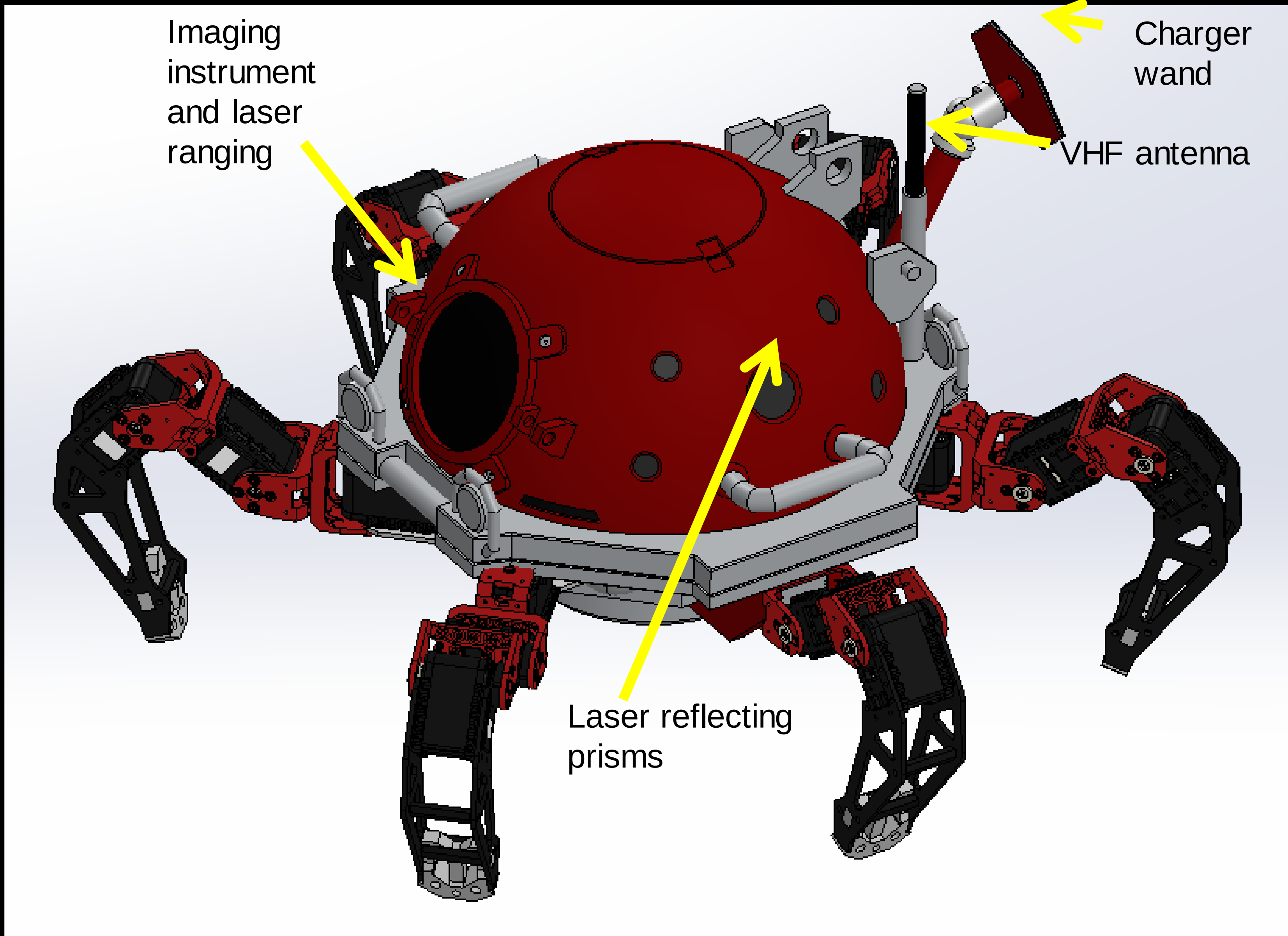
We Develop a Modular Lunar Robot Architecture – Starting with a COTS Bot

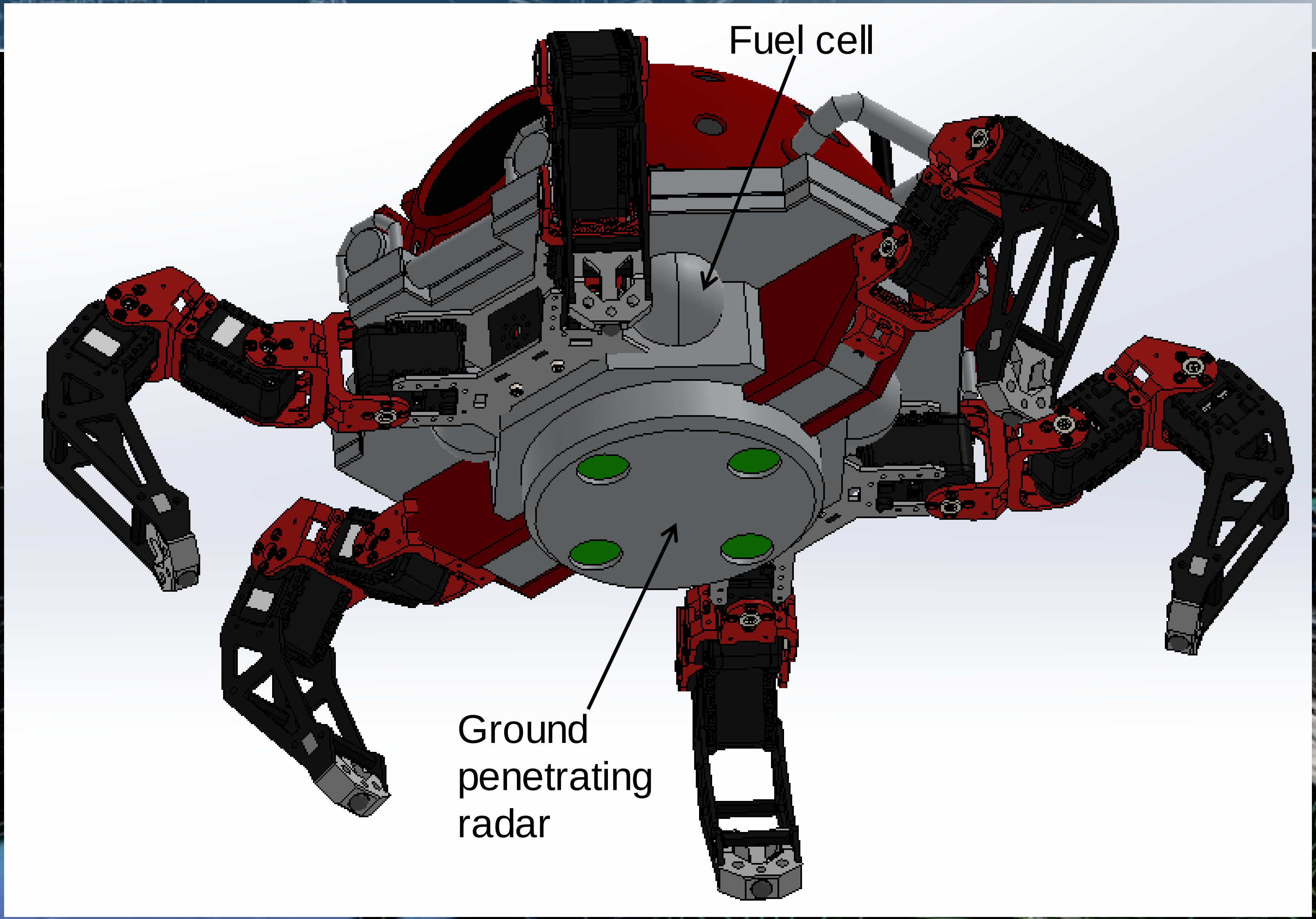
- COTS design
- CAD model available
- Gait can be modified
- Body chassis has symmetric form factors
- All legs and joints are identical
- “Swapable” multi-level platforms organized into
  - subsystem avionics,
  - electrical power subsystem,
  - guidance navigation & control,
  - communications,
  - payload, etc.
- Simple archetype for functional system for lunar needs


Lithium polymer battery
(enough room for more)
Modular
payload area
Robot microcontroller


Arduino Due
GPS
Remote
sensing
instrument

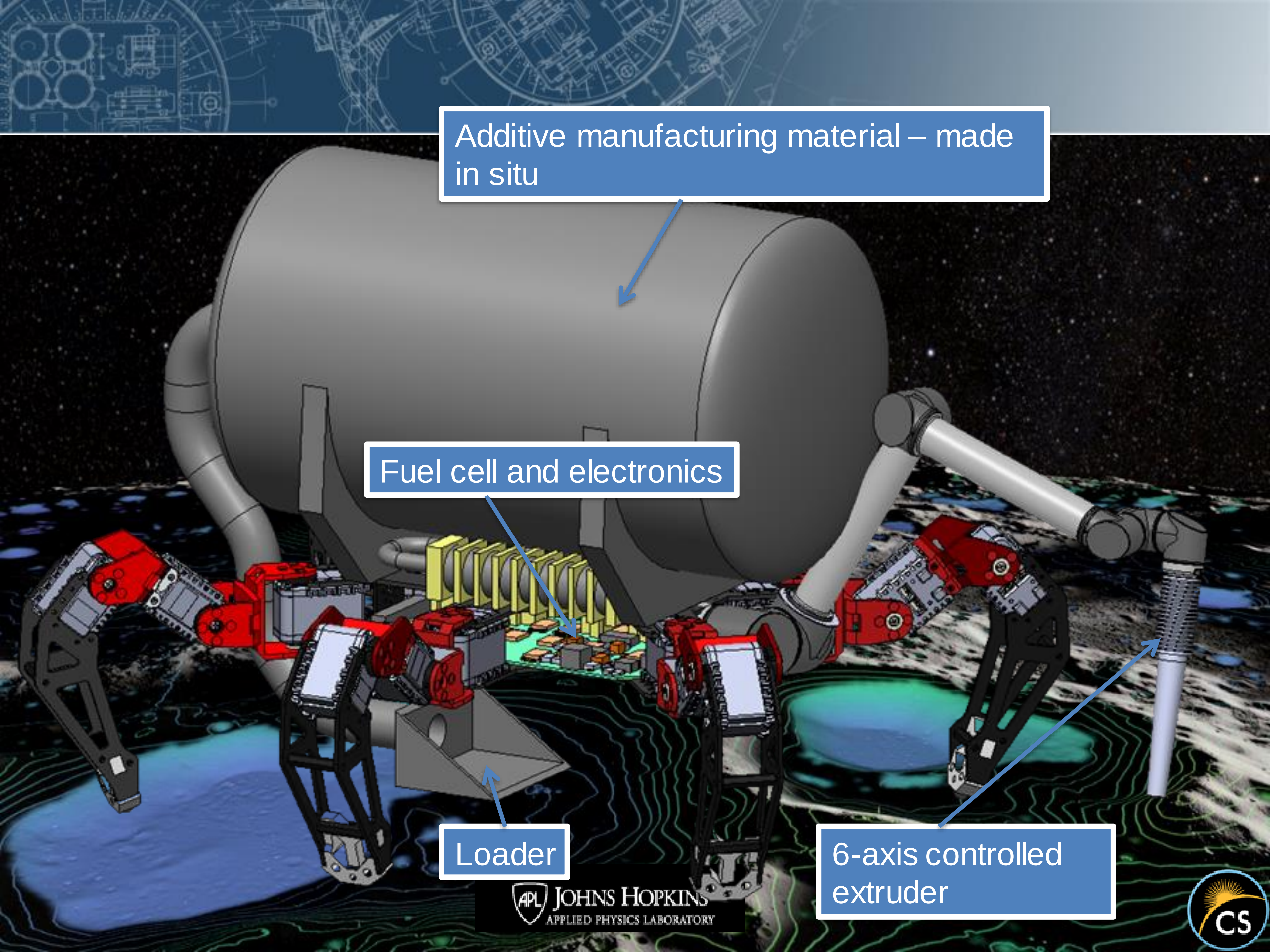
“Pillbugs” are designed to roll and clamber

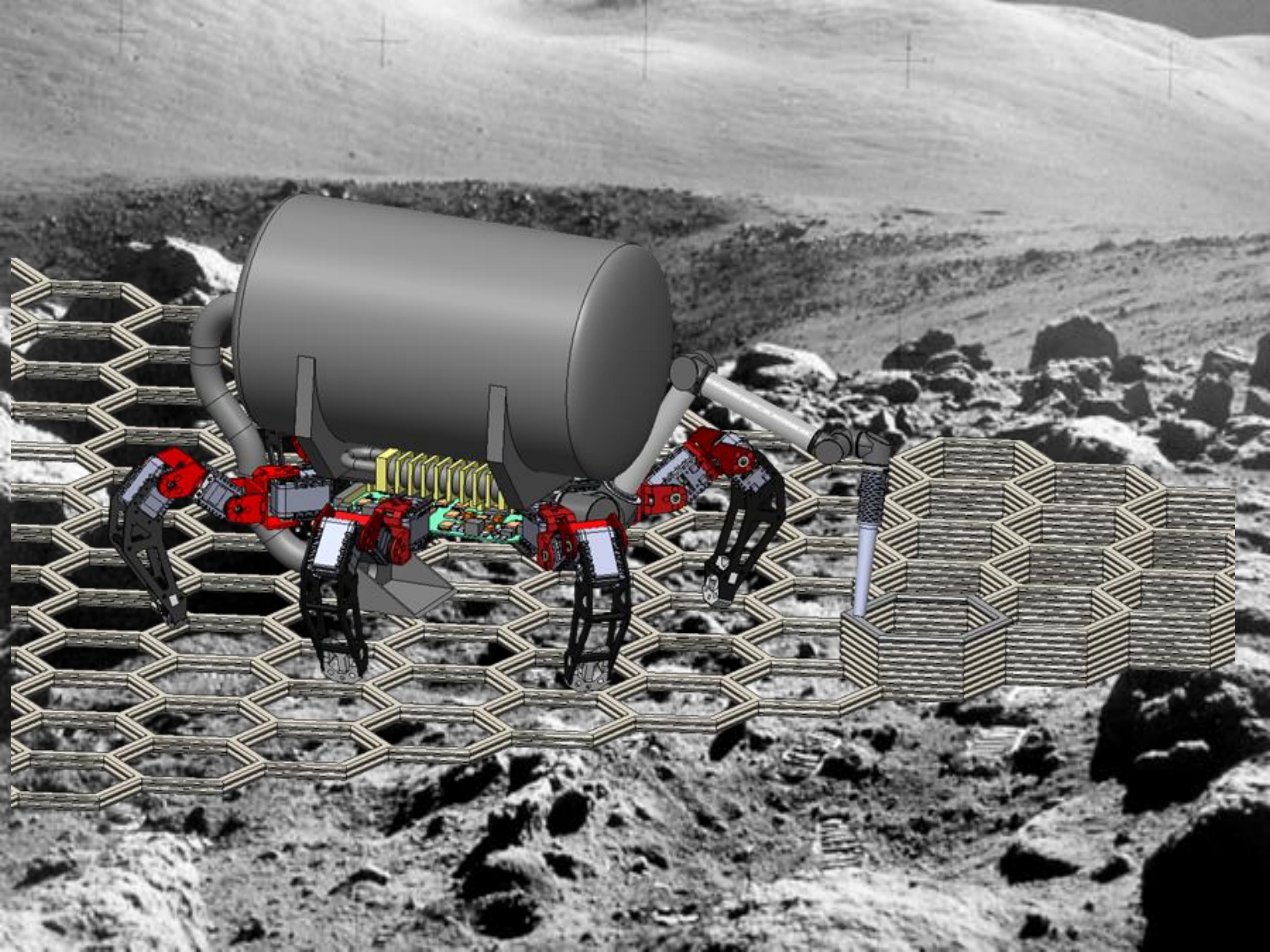


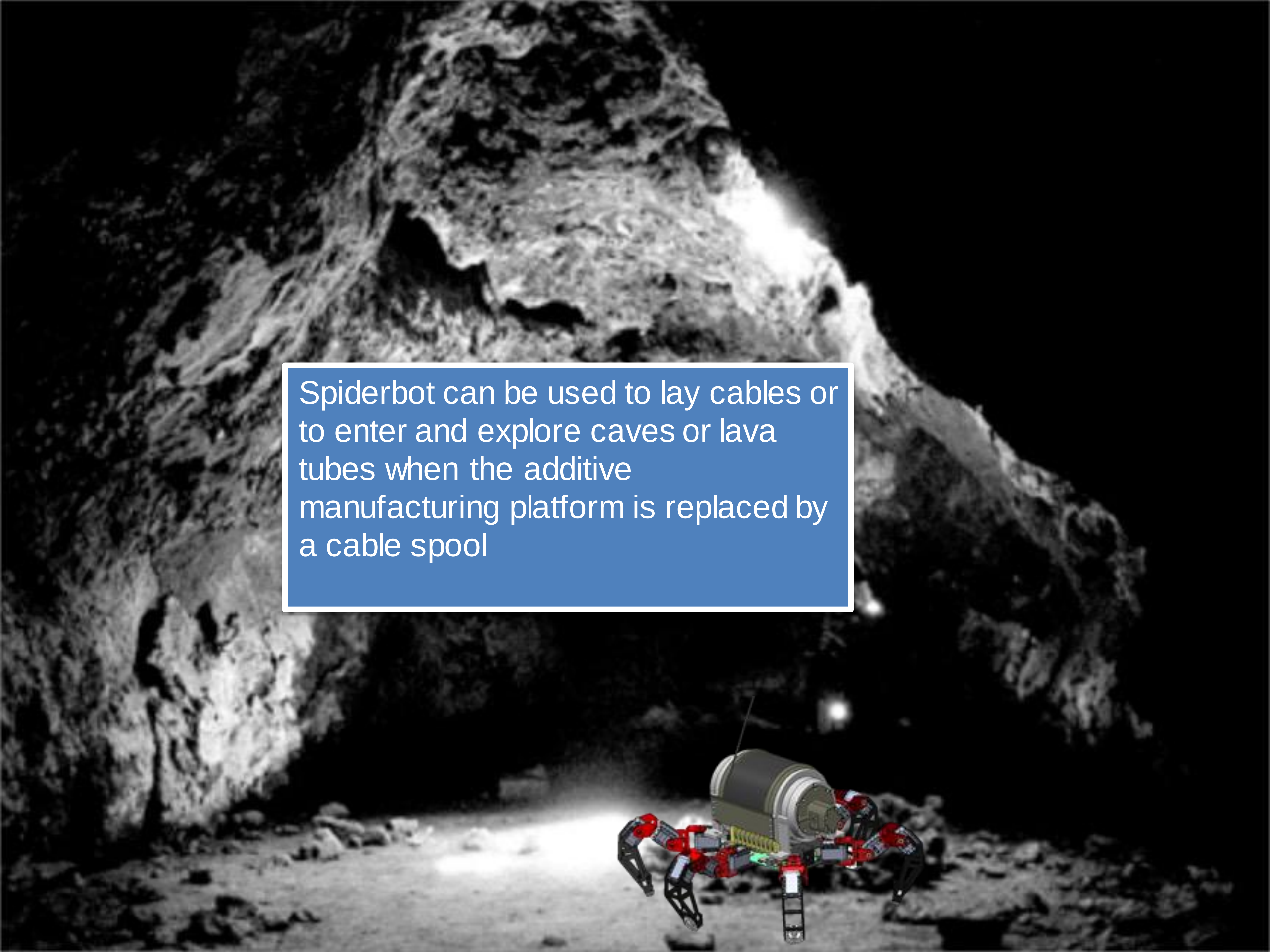

Fuel cell
Ground penetrating radar

CRICKET Spiderbot Concept

- As we've discussed, additive manufacturing is a powerful tool for some types of structures.
- For the CRICKET problem, several other kinds of structures were identified that are not readily served by the fixed point extruder model.
- To construct towers for comm relays and other support items a mobile constructor would be desirable.
- The following charts illustrate how the CRICKET chassis would be used to support a container of the additive manufacturing matrix with extruders and manipulators.
- The grasping manipulators enable the CRICKET spiders to weave their structures from within or on top of the structure.

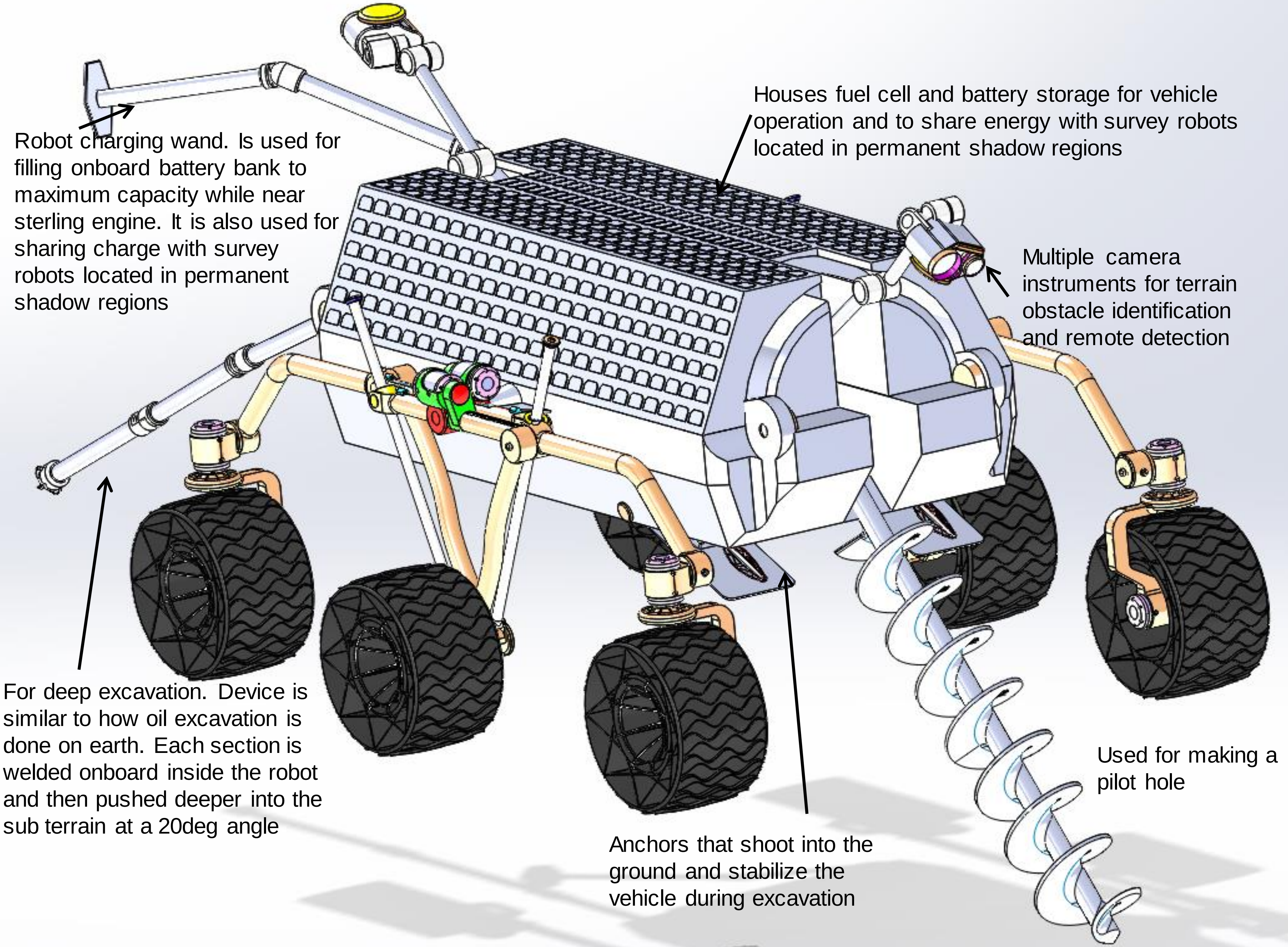

Additive manufacturing material – made in situ
Fuel cell and electronics
Loader
6-axis controlled extruder
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY
CS




Spiderbot can be used to lay cables or to enter and explore caves or lava tubes when the additive manufacturing platform is replaced by a cable spool

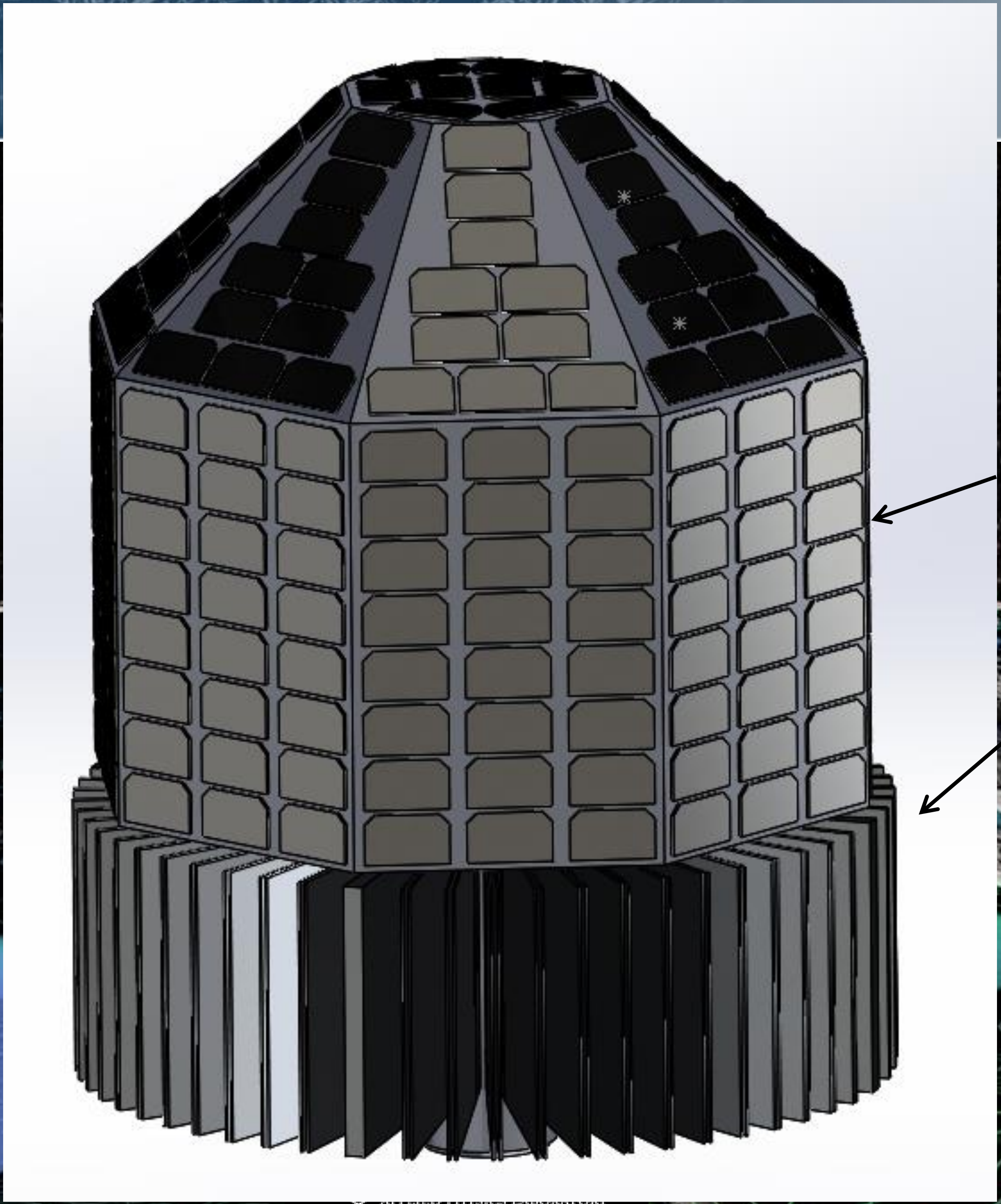
Power Supplier/Excavator Rover

- The rover routinely goes back and forth between the stirling engine and the surveyor robots to transport stored electrical power
- The rover has a dedicated electrical power subsystem that stores solar energy for it to operate while conserving electrical power saved from the stirling engine for use by the surveyor robots
- When the surveyor robots discover water ice, the rover plays the role of excavator and sample carrier


Robot charging wand. Is used for filling onboard battery bank to maximum capacity while near sterling engine. It is also used for sharing charge with survey robots located in permanent shadow regions
Houses fuel cell and battery storage for vehicle operation and to share energy with survey robots located in permanent shadow regions
Multiple camera instruments for terrain obstacle identification and remote detection
For deep excavation. Device is similar to how oil excavation is done on earth. Each section is welded onboard inside the robot and then pushed deeper into the sub terrain at a 20deg angle
Used for making a pilot hole
Anchors that shoot into the ground and stabilize the vehicle during excavation

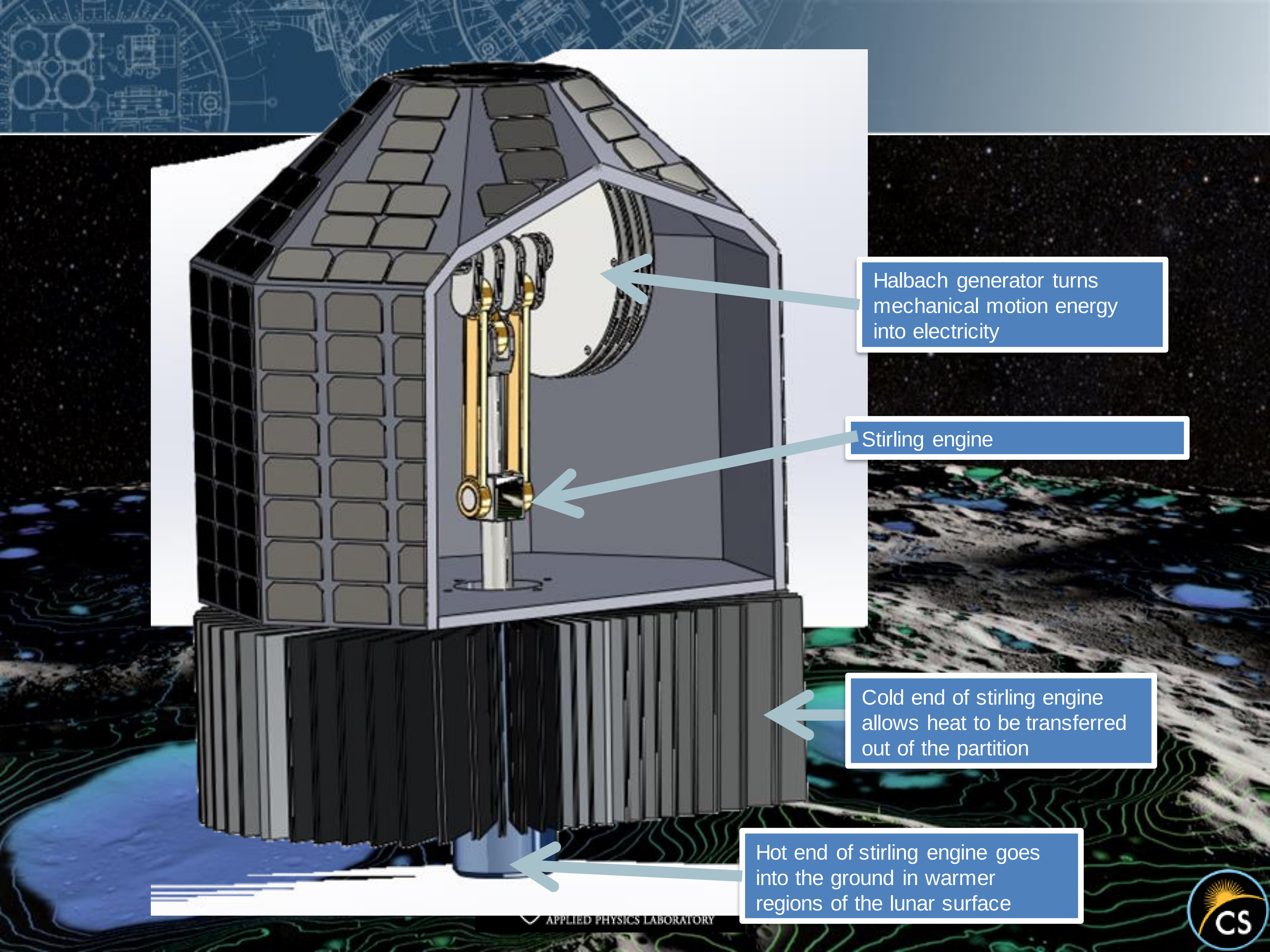
Stirling Cycle Engine

- This Stirling engine utilizes the temperature difference between the cold sky scene and the warmer periodically sunlit lunar surface when in darkness.
- When illuminated (note that the areas around PSRs will be exposed to sunlight at times) the Stirling engine produces power from heat absorbed.
- The Stirling engine system stores its energy in a large energy storage system.
- The rover docks with the charging wand when needed.

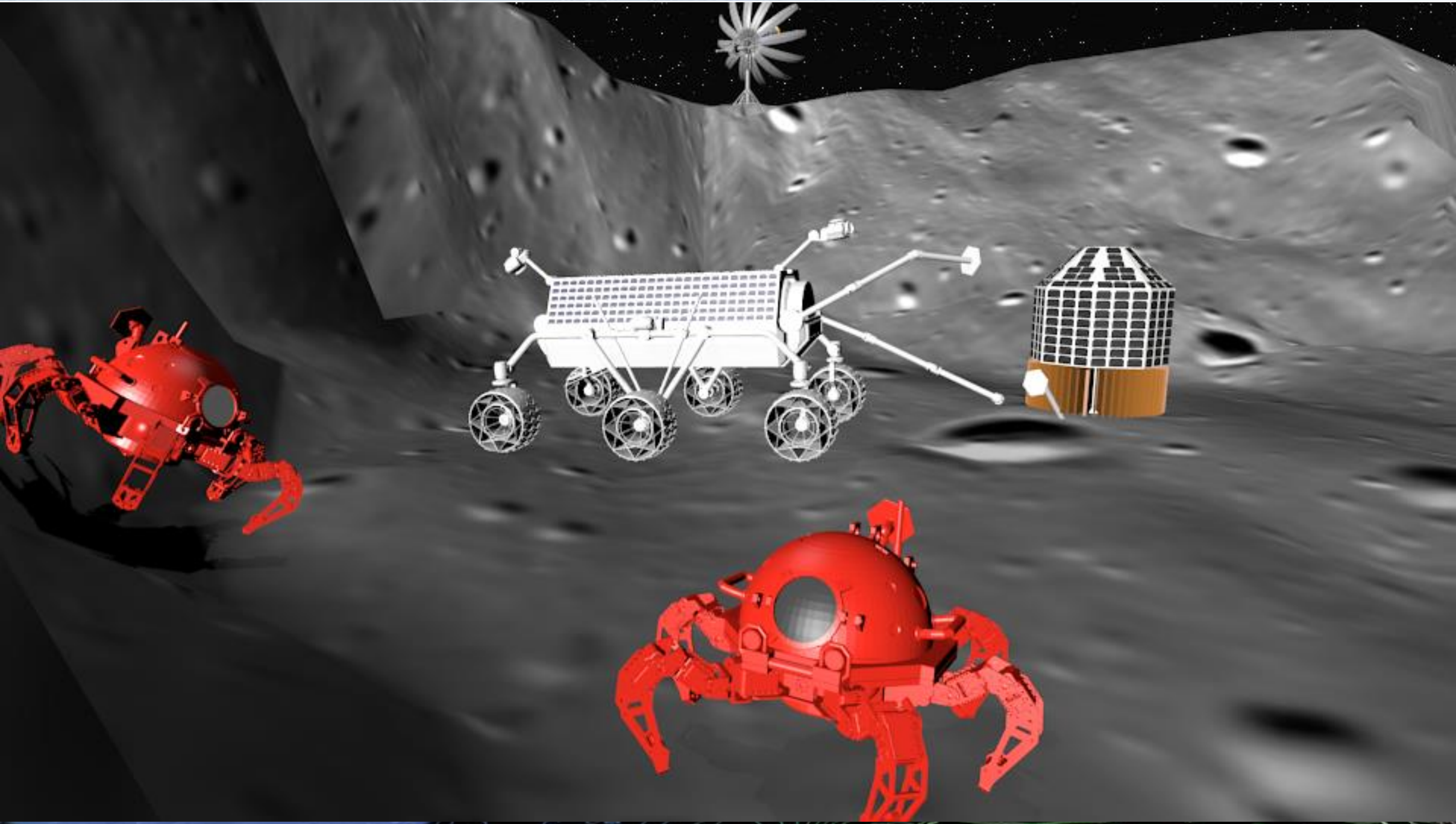


Stirling engine enclosure

Heat exchanger/ sink

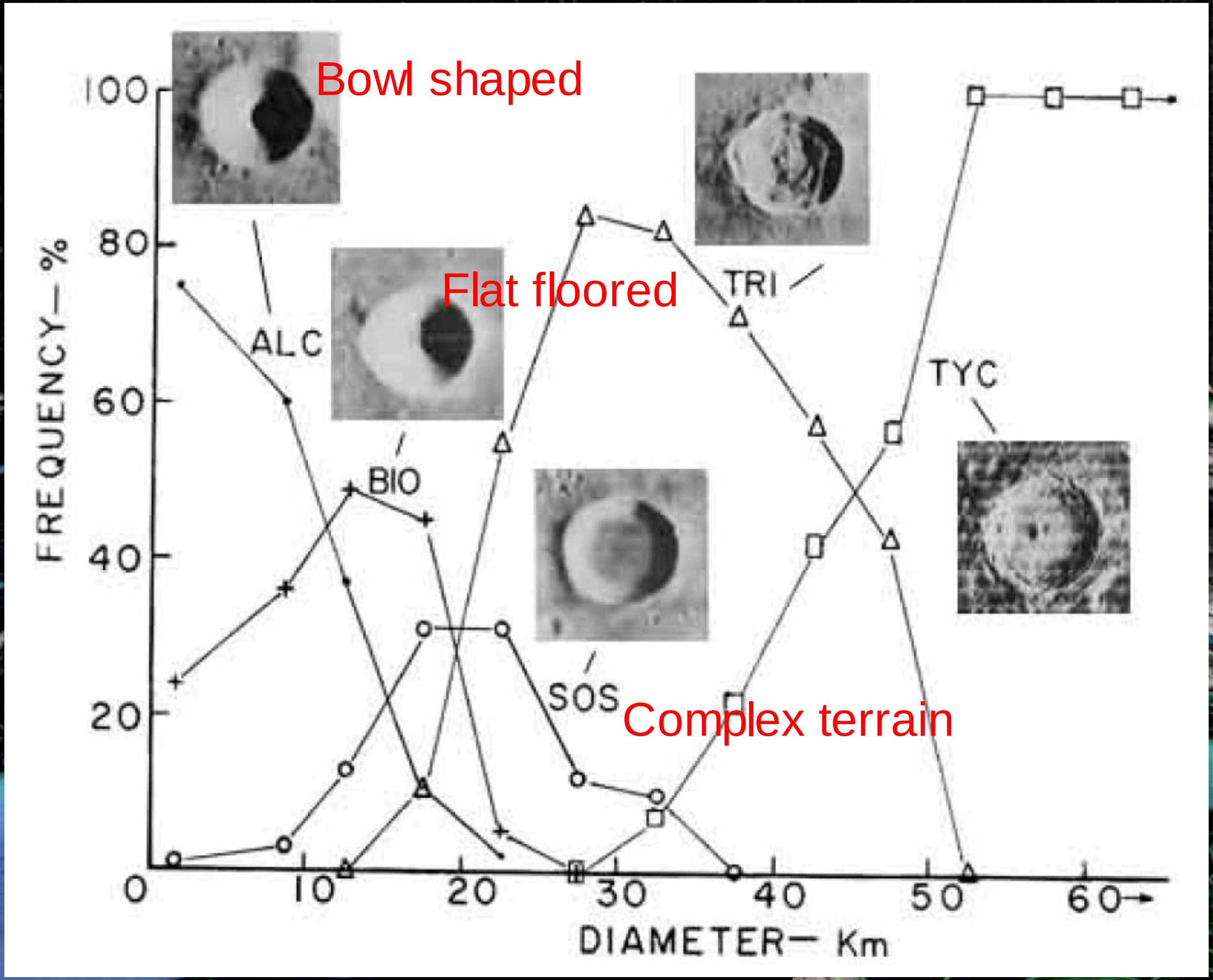

Halbach generator turns mechanical motion energy into electricity
Stirling engine
Cold end of stirling engine allows heat to be transferred out of the partition
Hot end of stirling engine goes into the ground in warmer regions of the lunar surface
APPLIED PHYSICS LABORATORY

A view from inside a crater showing some of the elements



Comm Link on the Crater Rim

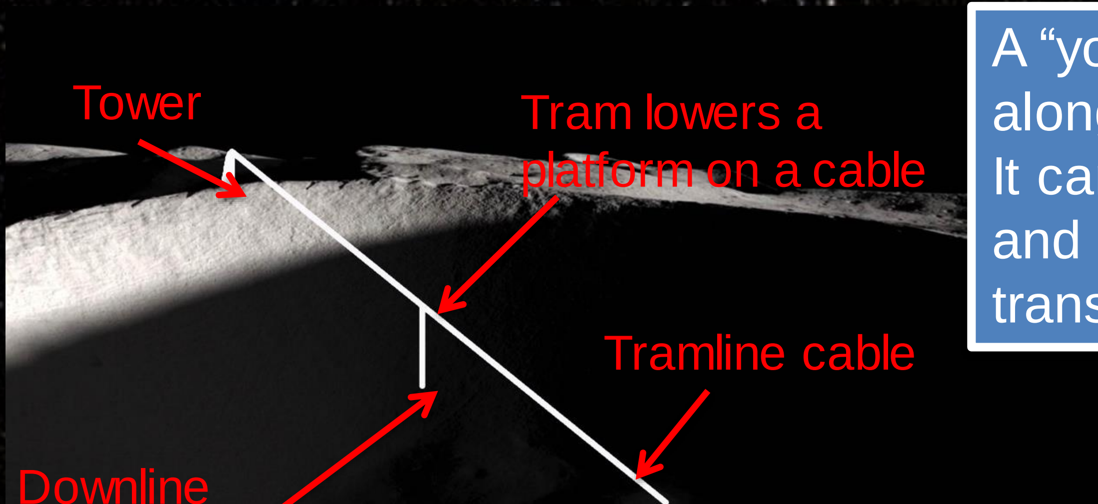
Size and surface topography are inter-related



Transport can be addressed in novel ways

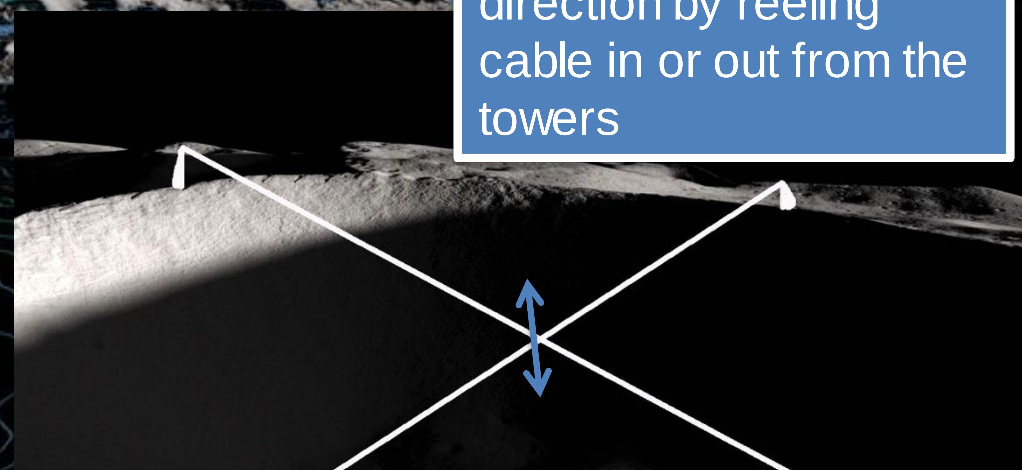
- The terrain is steep with a typical height to diameter ratio of 1:5
- Block size, distribution and roughness vary depending on crater diameter (type)
- “Jack and Jill” deliver in which APL Buckybots or Pillbugs roll down hill
- “Yoder” and “skycam” to deliver more complex shapes to the bottom of the crater

Moving material, equipment and sensors



A “yoder” moves along a 2D plane. It can lift payloads and perform transects.

A “skycam” moves in 3D. It can also lift payloads and provide mapping of the entire crater.



Using four towers the system can move up or down and in any direction by reeling cable in or out from the towers

Tether and space elevator community are working to develop the cables

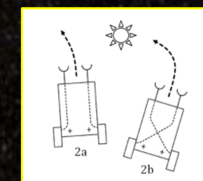
Cricket motion behaviors

Example characteristics:

- **Each cricket seeks (most) shadowed regions of PSR**
- **Cricket-cricket collisions avoided "repulsion" from cricket-LED illumination**
- **Area coverage facilitated by insect-like stigmergic behavior ("pheromones" as implicit coordination, e,g., StiCo)**
- **Low power state triggers taxic behavior toward Power rover**

Feasible implementation & experimentation:

- **Behaviors can be minimal and simplistic, e.g., Braitenberg vehicle search, dark-seeking, & light-fleeing behaviors fused with water-sensing**

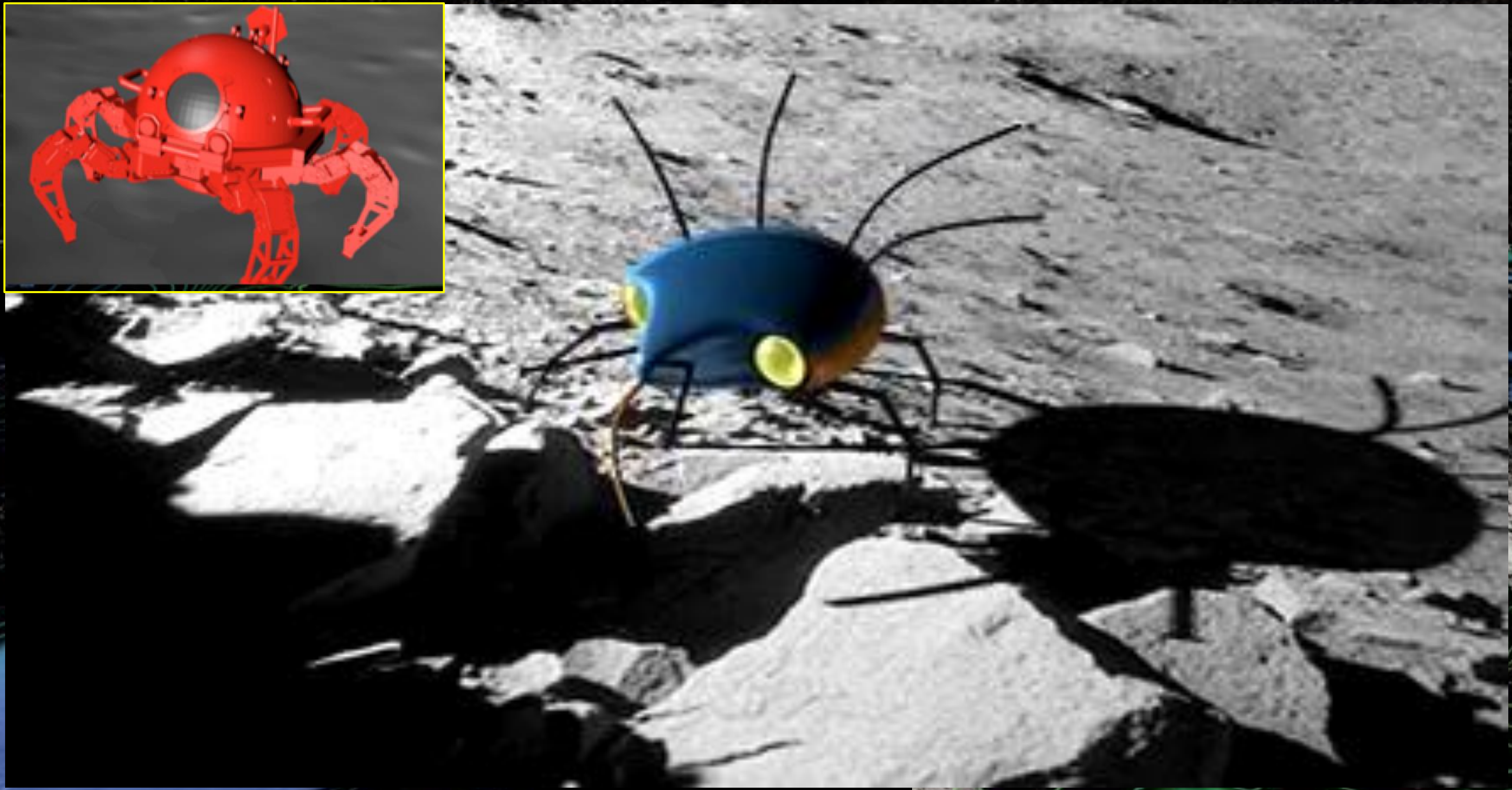


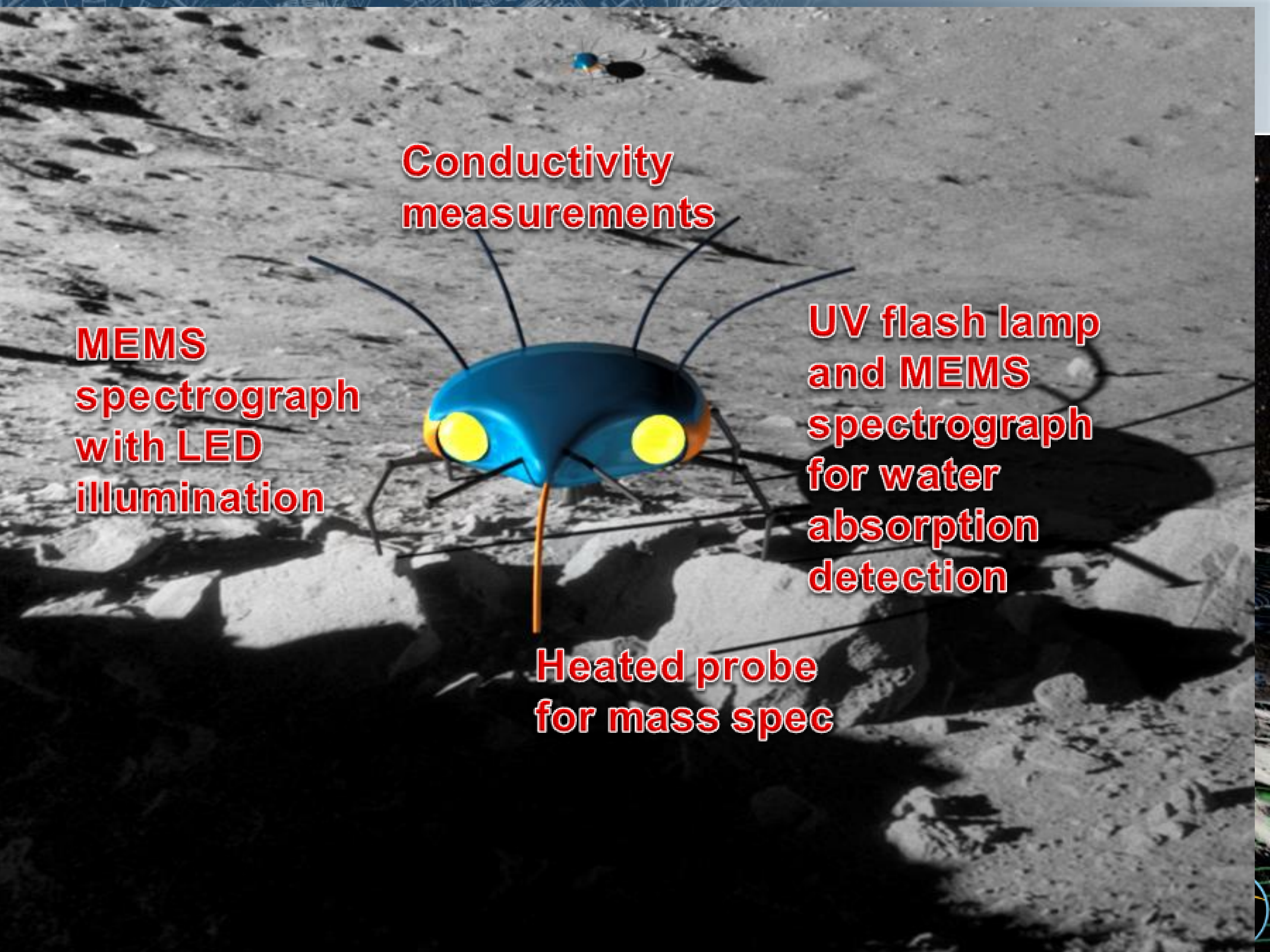
- **Individual cricket capability can be demo'd via 3D physics-based simulation or prototype**
- **Dozens of crickets can be simulated (modeled as pillbugs) to demo capability for prospecting**

This explores a fundamental premise regarding what could dozens of simple autonomous robots do toward covering particular PSRs or craters of known size and how many are sufficient if less than dozens.

A simple cricket exploring

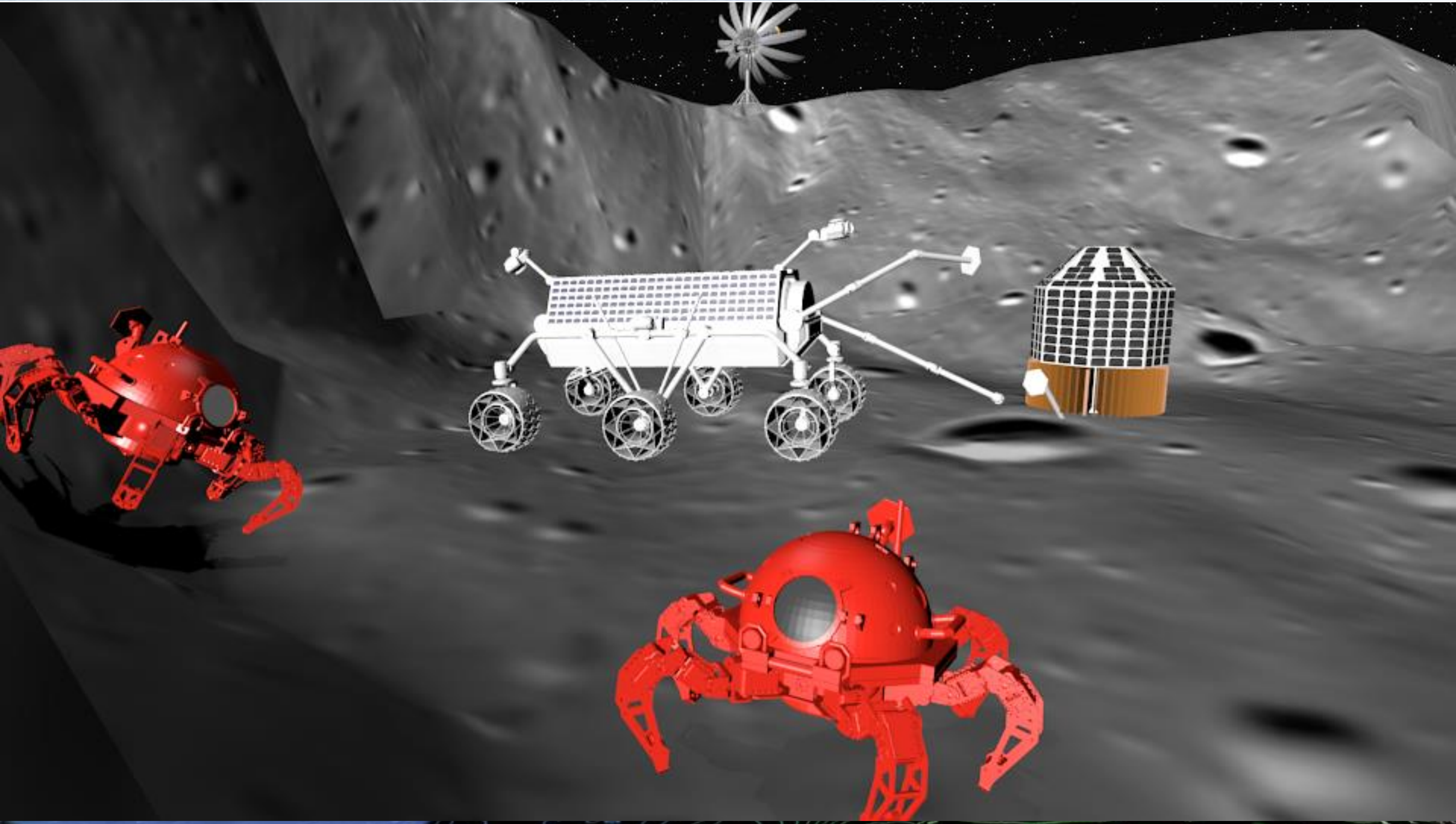
- **Initial concept**
  - Delivery of the payload to the crater edge – into sunlight
  - Dispersal of individual crickets into the PSR
  - Mapping and exploration of the area



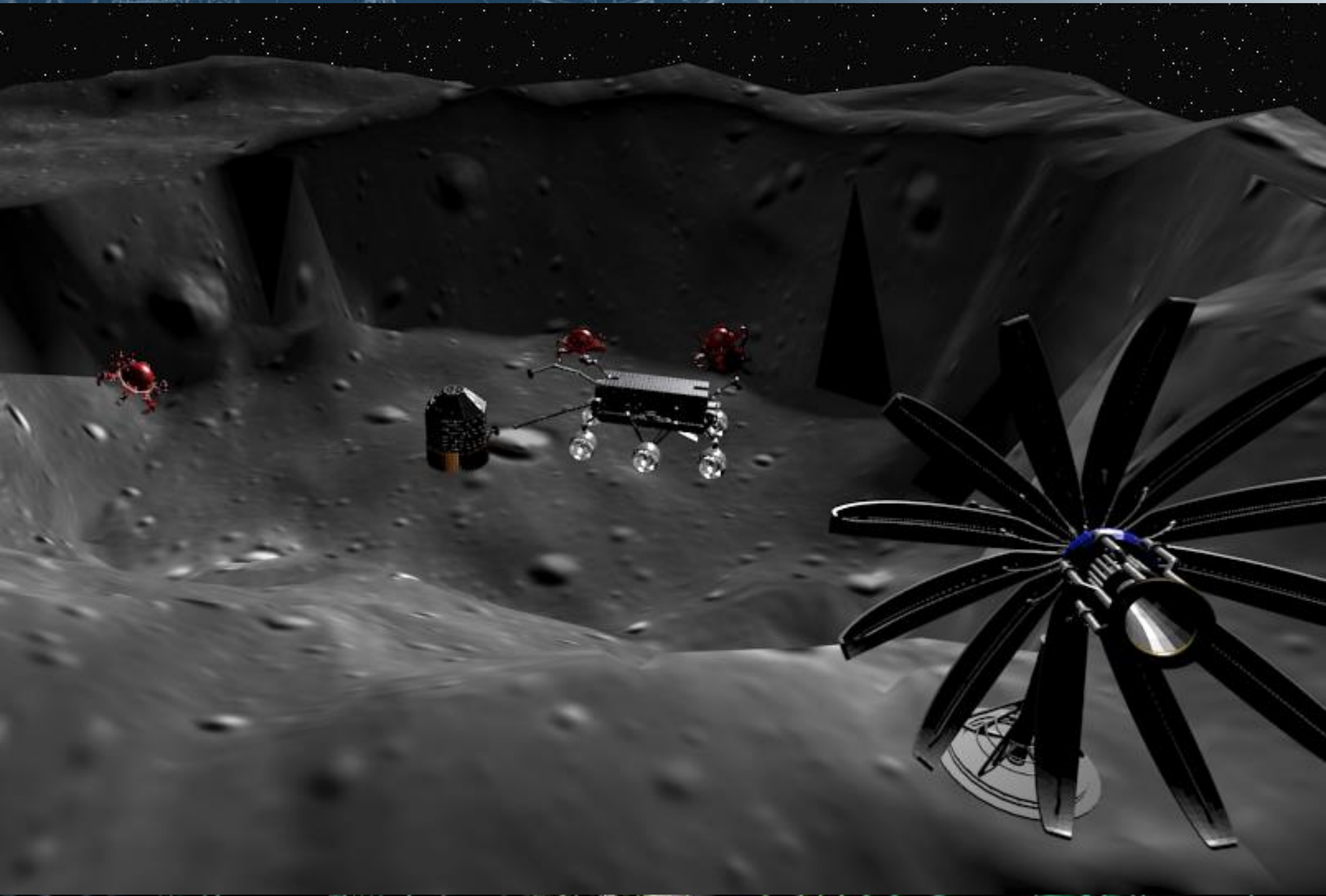

Conductivity
measurements
MEMS
spectrograph
with LED
illumination
UV flash lamp
and MEMS
spectrograph
for water
absorption
detection
Heated probe
for mass spec

CRICKET Oscar Mike

A view from inside a crater



Comm Link on the Crater Rim

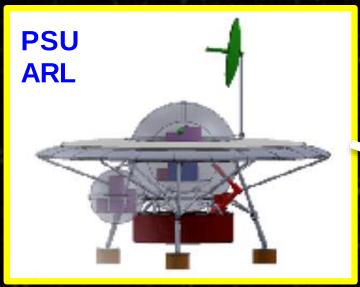


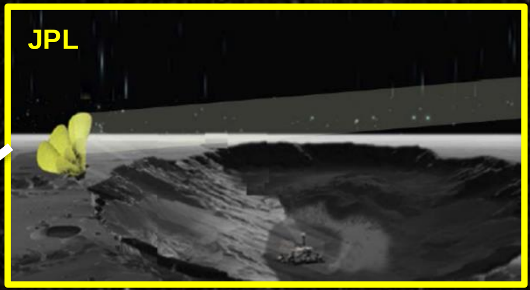
Space Tether Tech Would be Applied to this Problem

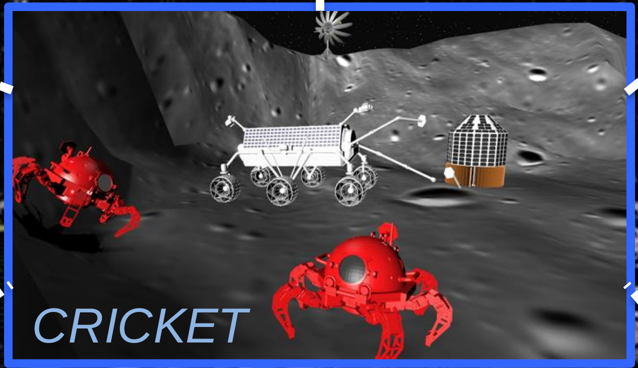
- **M5 cable from tower to tower will work**
  - 10 km length = 10 kg
  - Payload capacity = 2000kg.
- **Proposed materials include Kevlar, ultra high molecular weight polyethylene, carbon nanotubes and M5 fiber.**
- **M5 is a synthetic fiber that is lighter than Kevlar or Spectra.**
- **According to Pearson, Levin, Oldson, and Wykes in their article "The Lunar Space Elevator", an M5 ribbon 30 mm wide and 0.023 mm thick, would be able to support 2000 kg on the lunar surface.**
- **It would also be able to hold 100 cargo vehicles, each with a mass of 580 kg, evenly spaced along the length of the elevator. Other materials that could be used are T1000G carbon fiber, Spectra 2000, or Zylon.**

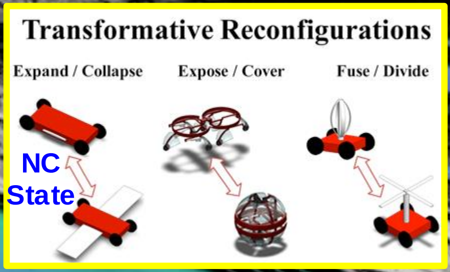
See https://en.wikipedia.org/wiki/Space_tether

There are many related NIAC projects that fit into the CRICKET shema









What other NIAC concepts might contribute to the broader architecture allowing leverage of multiple investments toward an advanced concept greater than the sum if its parts?

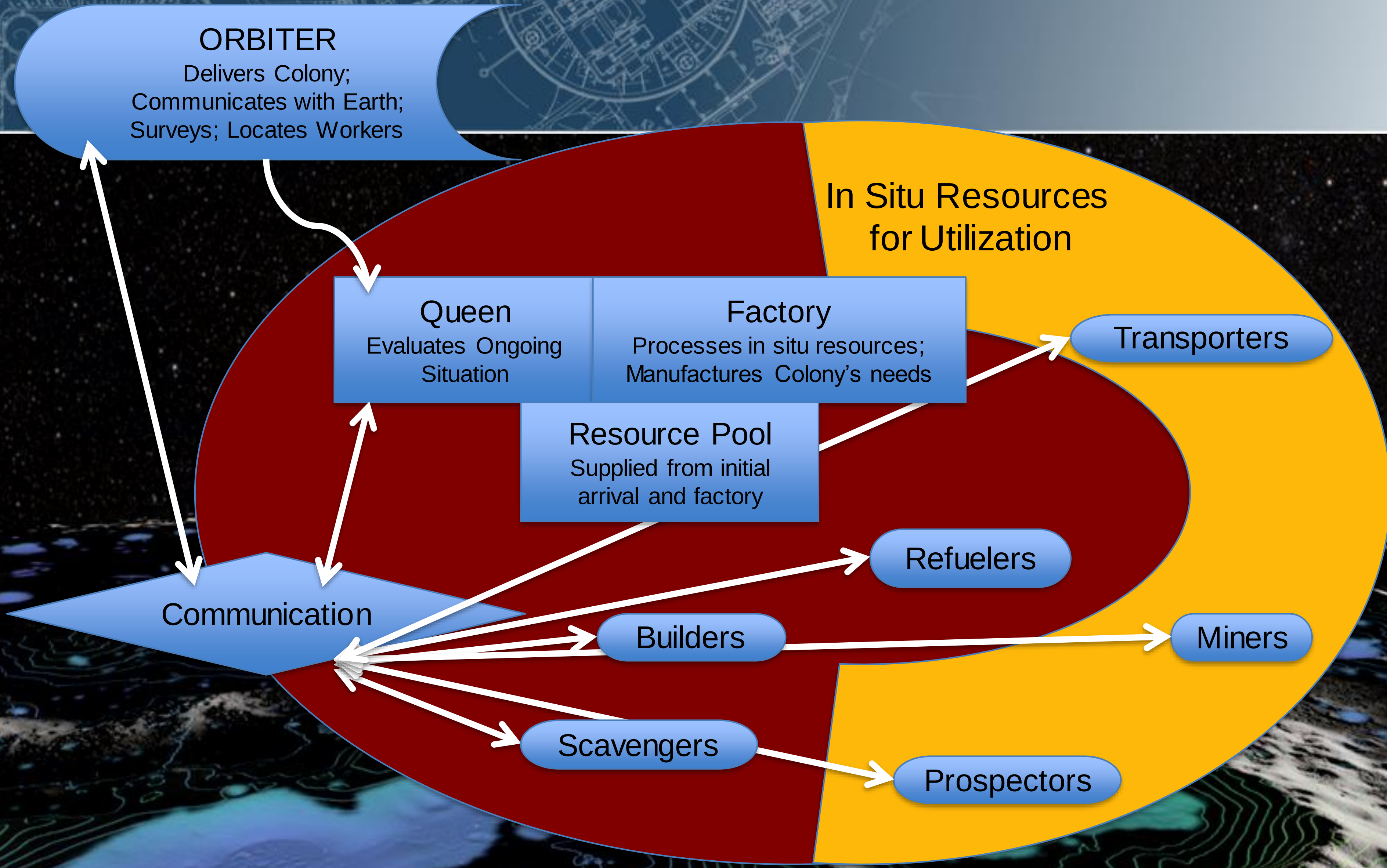
GOAL: A Fully Functioning "Ecosystem"

- **The CRICKET concept is illustrated on the chart below**
- **The workers may consist of:**
  - Transportation: delivers workers to a site, transports raw matter to ISRU site
  - Propector: surveys terrain, investigates and characterizes the target area, marks sites for Miners with taggants
  - Miners: extracts raw material, capable of exposing material for characterization by prospectors.
  - Fuelers: refuel/recharge workers, provide fuel for new queen for dissemination of new colony (late phase of architecture)
  - Scavengers: recover high value resources from "dead" workers
  - Builders: fabricate structures to house/protect/support the ISRU, Factory, Power and Comm functions using materials delivered with initial colony or manufactured or extracted on-site.
- **Each element is simple, can be reused and is replicated many times over.**
- **Eventually, it may even prove practical to have many elements manufactured in situ.**

- Factory: manufacturing structural elements and components for the bots
- ISRU: resource extraction and refinery
- Power: the power generation and distribution network
- Communications: link between the “queen” and the orbiter
- Orbiter: delivers the initial colony to the target, provides survey information and updates, may provide location of workers.
- Workers: locate, characterize, extract, and transport raw materials
-

CRICKETS are Broadly Applicable

- **One of the more important steps is to define how the environment is characterized.**
- **There are still many open questions about the structure and evolution of solar system objects that have implications for how and where resources are to be found.**
- **Notionally the Prospectors would have all five senses distributed over many different subspecies of Prospectors.**
  - Hearing: seismic detection and characterization
  - Taste: conductance measurements, in situ chemical analysis
  - Smell: MEMS mass spectrograph (detection of OH, H2O, methane, etc),
  - Touch: surface characterization (including trafficability), hardness
  - Sight: MEMS spectrographs for OH, H2O etc



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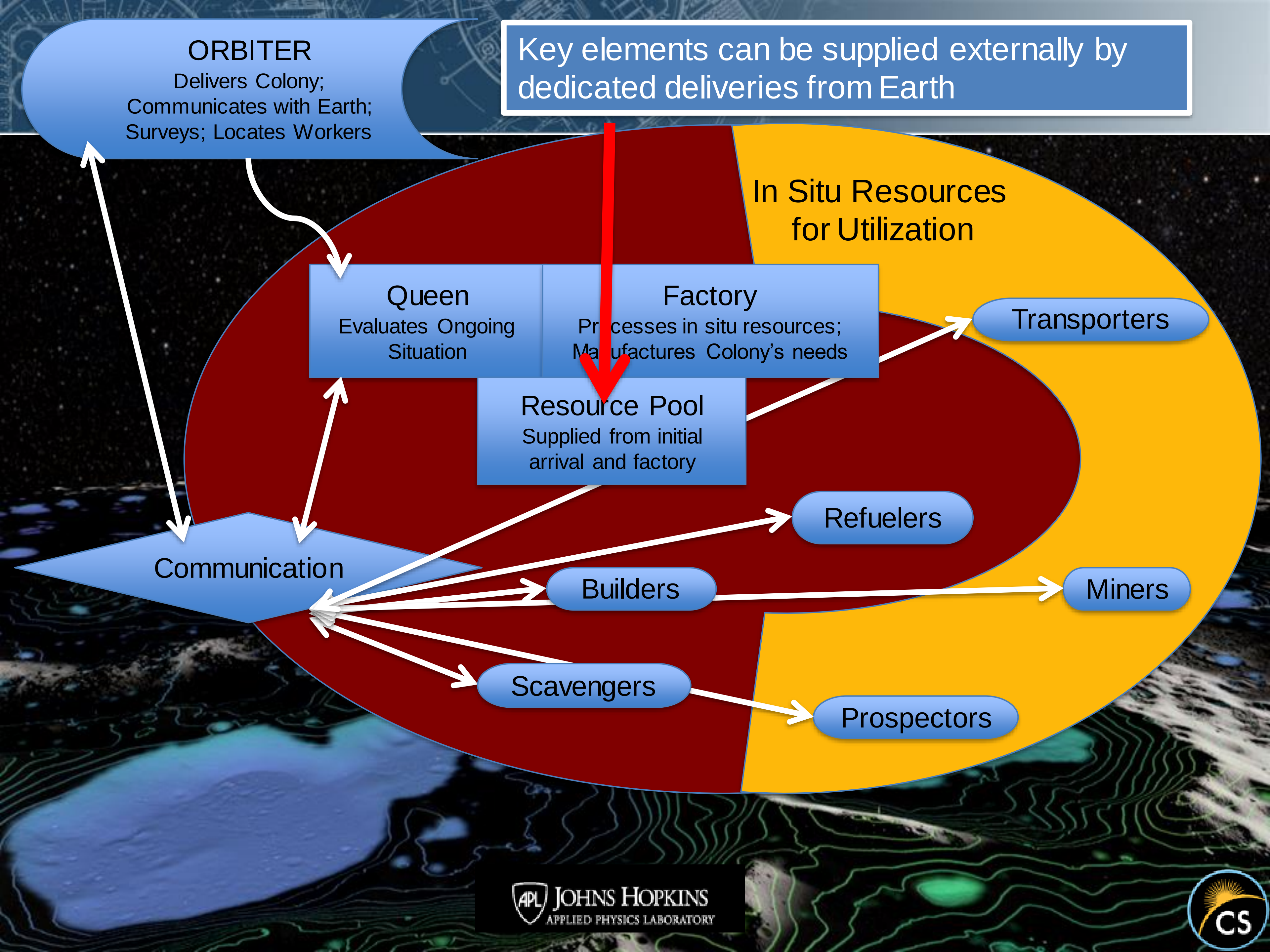
ORBITER
Delivers Colony; Communicates with Earth; Surveys; Locates Workers
Key elements can be supplied externally by dedicated deliveries from Earth
In Situ Resources for Utilization
Queen
Evaluates Ongoing Situation
Factory
Processes in situ resources; Manufactures Colony's needs
Resource Pool
Supplied from initial arrival and factory
Transporters
Communication
Refuelers
Builders
Miners
Scavengers
Prospectors
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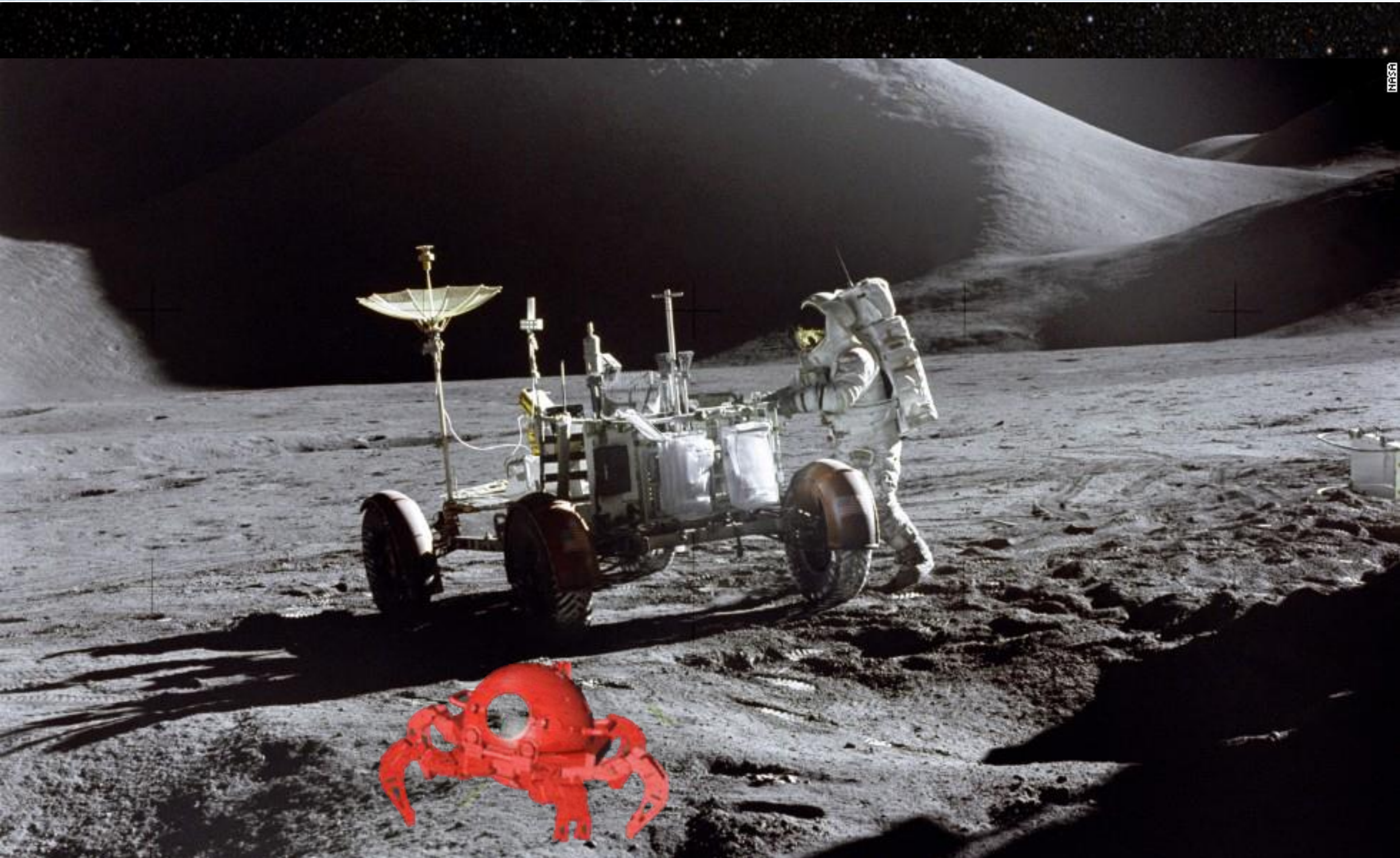
The human-robot partnership provides a path for exploring difficult terrain



CRICKET also can incorporate other aspects of NIAC funded research

- Setting ISRU on the moon as a goal enables us to design an ecosystem around that element
- All of the other elements of a system that can expand to meet evolving capabilities and requirements appears to be on the horizon.
- Even difficult problems, like storing LOX and LH2, can be surmounted by using the lunar environment to our advantage.

Advanced concept relationships – 1/2

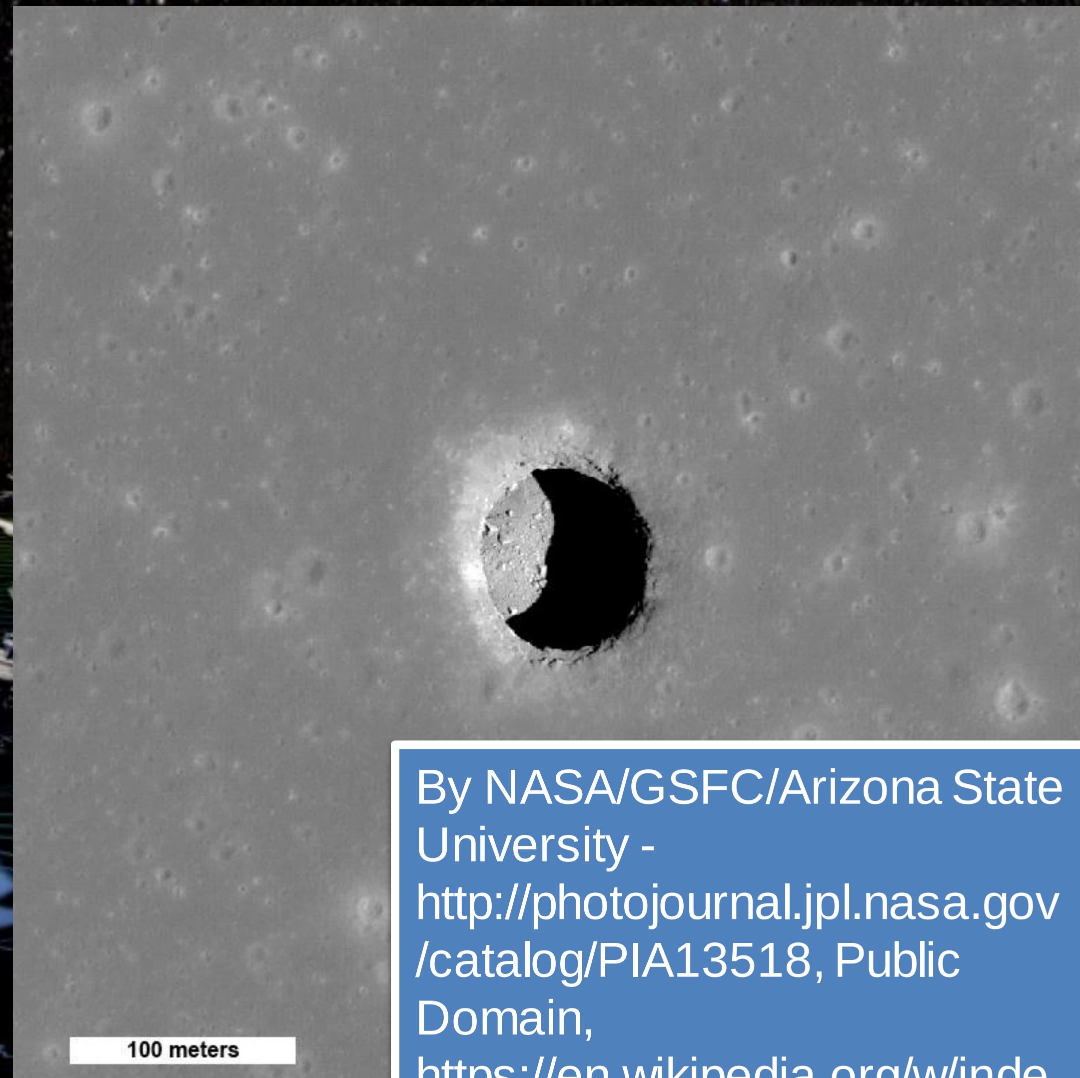
NIAC Project	Description	CRICKET Relationship
SCEPS – Non-Radio-isotope Power Systems for Sunless Solar System Exploration Missions	Power solution in the form of a metal-combustion engine and Stored Chemical Energy Power System as non-solar power sources for use in PSRs or at extreme distance from the sun.	Alternative power source or supplemental to the baseline Stirling engine
Trans-Formers for Lunar Extreme Environments: Ensuring Long-Term Ops in Regions of Darkness and Low Temperatures	Steerable heliostats that reflect sunlight into PSRs warming and powering solar-powered robots that prospect/excavate lunar volatiles in icy regolith for liquid hydrogen and oxygen via ISRU.	Alternative/supplemental means for dealing with darkness, cold, and solar power in PSRs
Low Power Micro-robotics Utilizing Biologically Inspired Energy Generation	Advancement and integration of low power electronics & mobility with microbial fuel cell power generation for a target ~1kg robot. Fuel cell charged a super cap, discharged to activate a robotic locomotion system.	Alternative means to power crickets

Advanced concept relationships – 2/2

NIAC Project	Description	CRICKET Relationship
Cavehopping Exploration of Planetary Skylights and Tunnels	Robotic exploration and search for life in subsurface voids such as skylights and caves	Also targets robotic operation in PSRs, but of a different variety Use APL Buckybot.
Enabling All-Access Mobility for Planetary Exploration Vehicles via Transformative Reconfiguration	Explores reconfigurability to enable mobility across diverse, uncertain terrains. Assessing relevant technologies and developing proof-of-concept prototypes.	The “pillbug” cricket configuration is similar to a form of reconfiguration being explored
ISRU-Based Robotic Construction Tech. for Lunar and Martian Infrastructures	Construction architecture and technology for rapid buildup of a lunar base leveraging maturing NASA technology development systems. Focused on various structures via ISRU.	Solutions could apply for install and movement of material and equipment (e.g., yoder, skycam)

APL Buckybot Hybrid with NAIC research could enable exploration

- Low-cost autonomous exploring robots, like our crickets, could provide access to dangerous areas.
- These robots could characterize the environment and resources in the lava tube.



By NASA/GSFC/Arizona State University - http://photojournal.jpl.nasa.gov/catalog/PIA13518, Public Domain, https://en.wikipedia.org/w/index.php?curid=52638301

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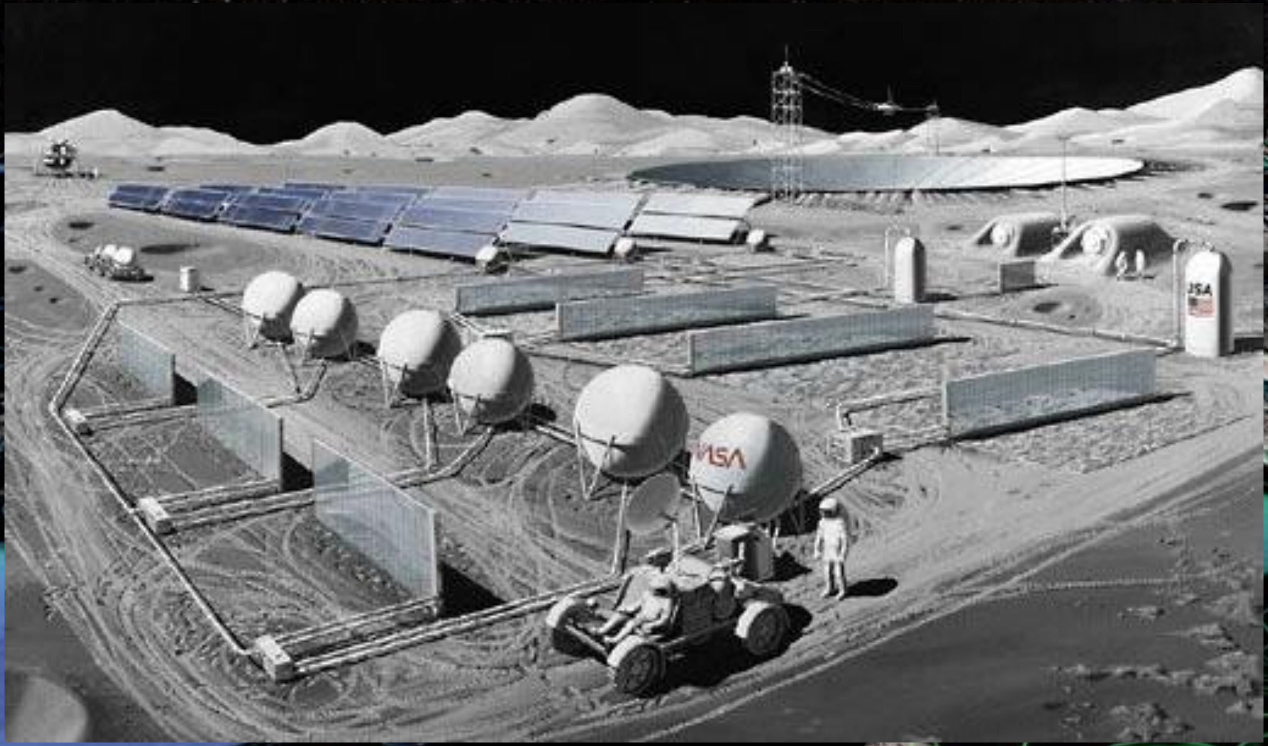
The cricket architecture would support human presence

NASA concept of a south pole base with liquid oxygen and hydrogen storage
Autonomous mining techniques would enable extraction of the raw materials with minimal human intervention



Thinking in terms of evolution of a system

- Start with an accessible object where human presence and/or intervention may be practical
- Develop the mission requirement flowdown to enable resource utilization then, possibly, human presence

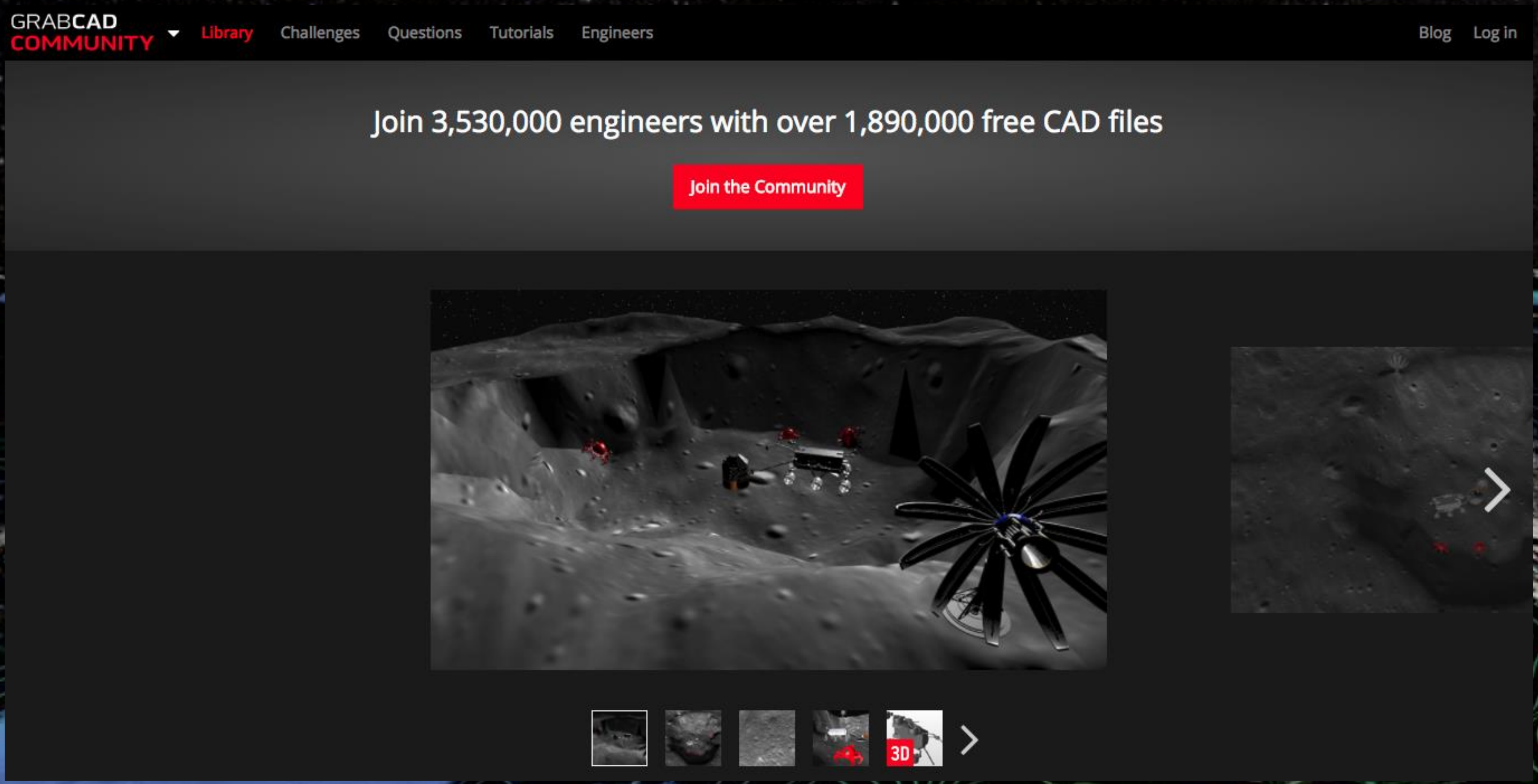
Time Frame	Target	Degree of Specialization	Autonomous Exploration	ISRU	Power	Replicable	Modifiable	System Flexibility	Expandable	System "IQ"
>5 yrs*	Moon	Low	x		Delivered			None		Insect
>10 yrs	Moon, NEO	Med	x	x	Solar			Low		Insect
>15 yrs	Moon, NEO, Mars	High	x	x	Solar, Chem, SC			Med		Insect
>15 yrs	Mars	High	x	x	Solar, Chem, SC, Wind	x	x	Med	x	Dog
>20 yrs	Mercury	Med	x	x	Solar, Chem, SC			Low		Dog
>30 yrs	Titan/Europa	High	x	x	SC, Chem	x		Med	x	Monkey
>35 yrs	Titan/Europa	High	x	x	SC, Chem	x	x	High	x	Human
>40 yrs	Kuiper Belt Objects	High	x	x	Chem	x	x	High	x	Human

Why do we do solid modeling of concepts?

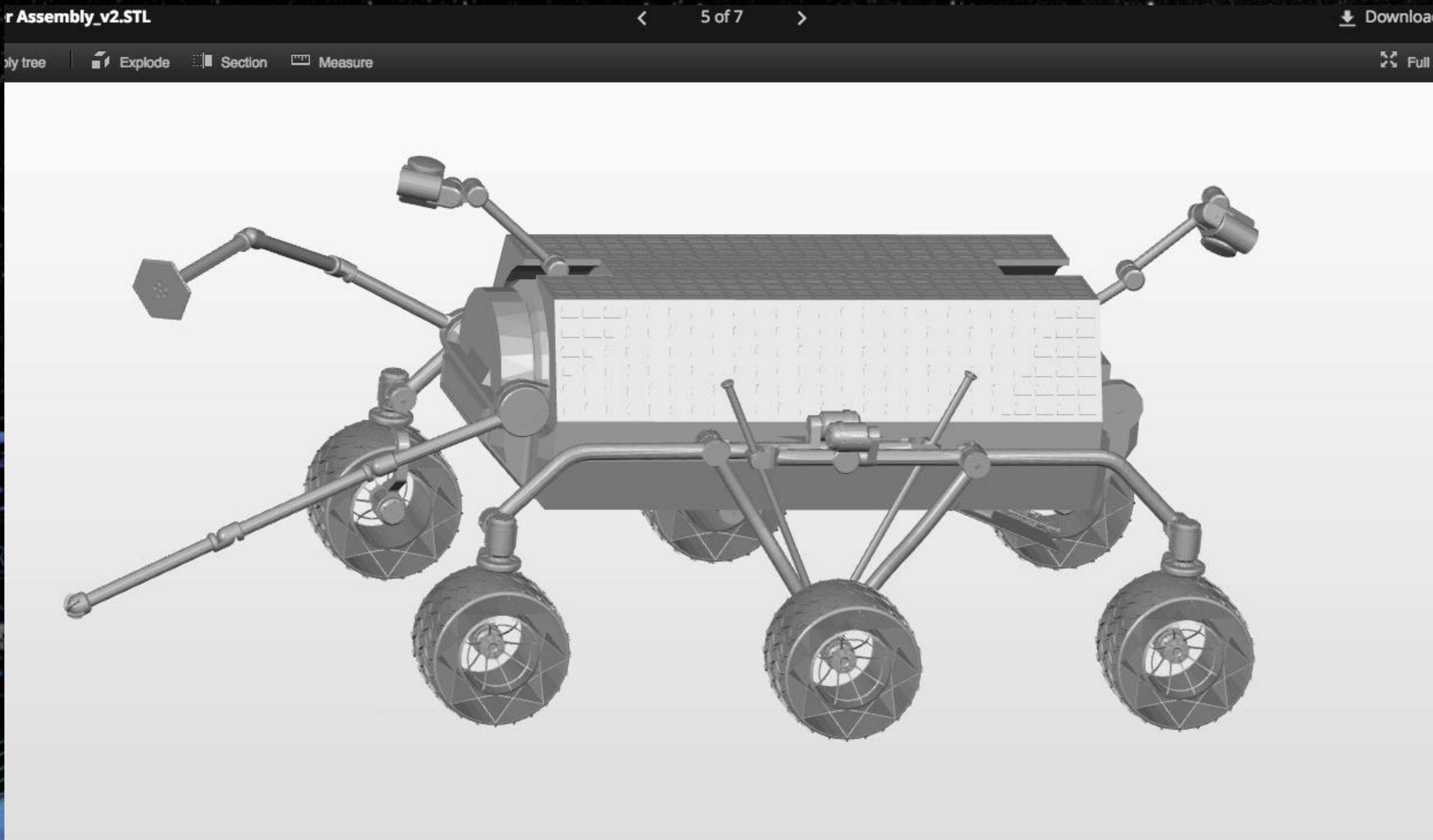
- **The goal is to establish what a reasonable design might look like.**
- **For example, one of the primary issues is going to be power (and the associated issue of dealing with the low temperatures).**
  - Batteries are not very efficient
  - Can we use a fuel cell to store energy?
  - If so what are the packaging issues?
- **The goal is to explore the areas in the solution space that need to be addressed**
- **Ideally we'd develop a technology roadmap hy the end of the project**
- **This informs our evolutionary approach**

Opening the project for community input

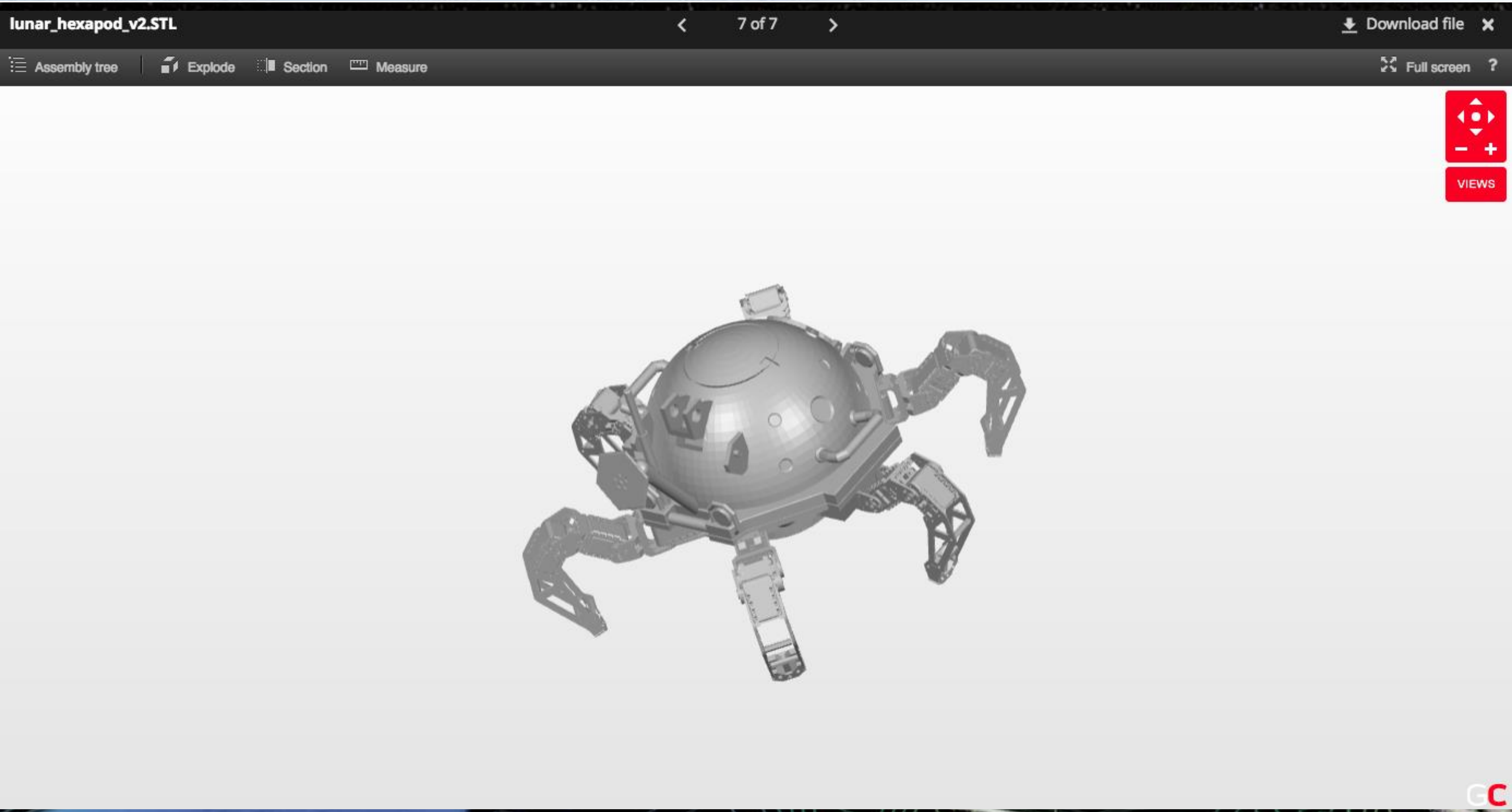
- https://grabcad.com/library/lunar-robotics-1



Typical shared content file: Red Rover design



Lunar Hexapod



A simple cricket exploring

- **Initial concept**
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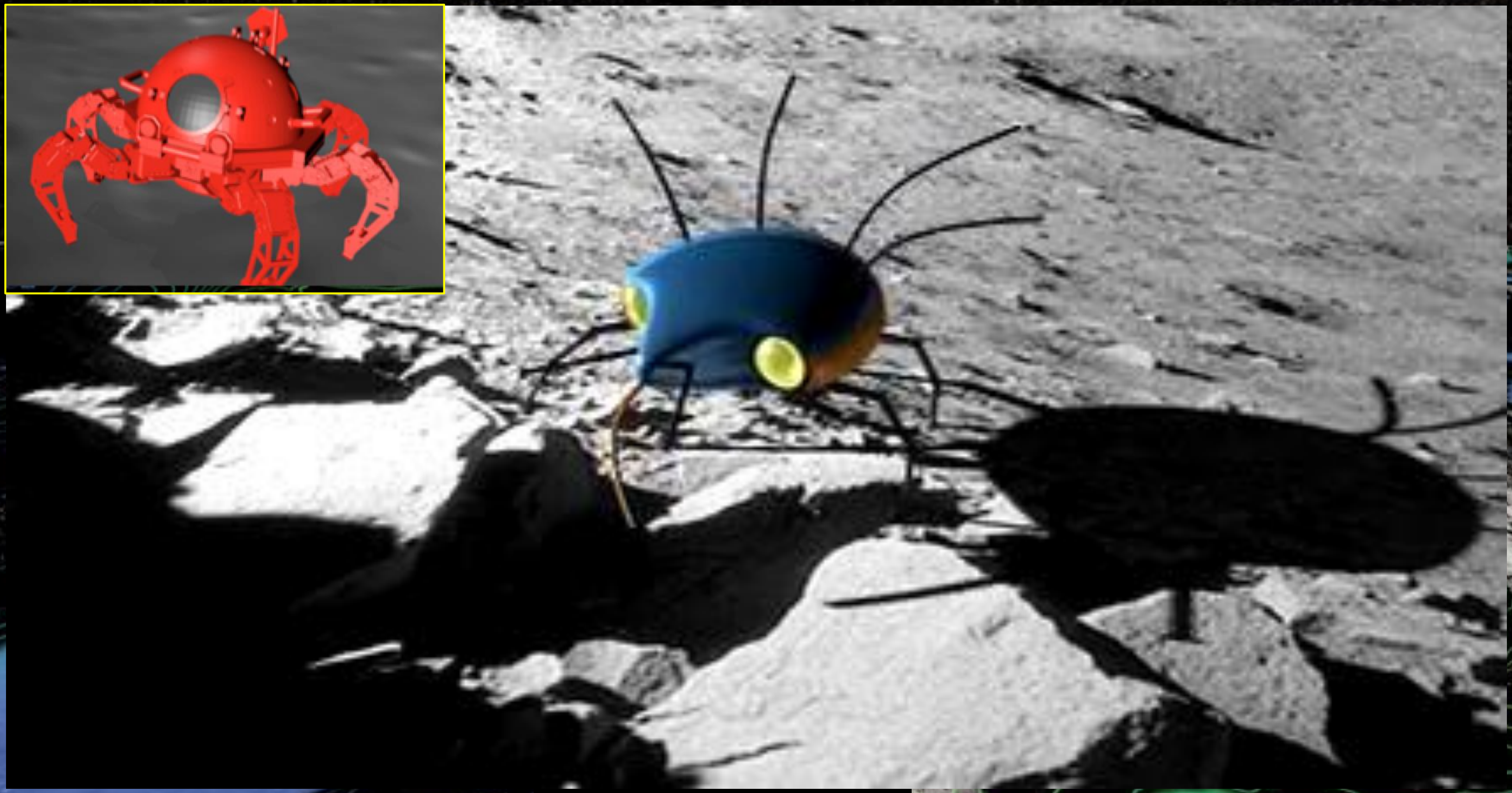

It’s not too late

- A disaggregated system of intelligent biomimetic bots can pave the way for human expansion into the solar system.
- The first step can be the Moon.
- We can demonstrate the technologies for the outward journey there within reasonable cost parameters.