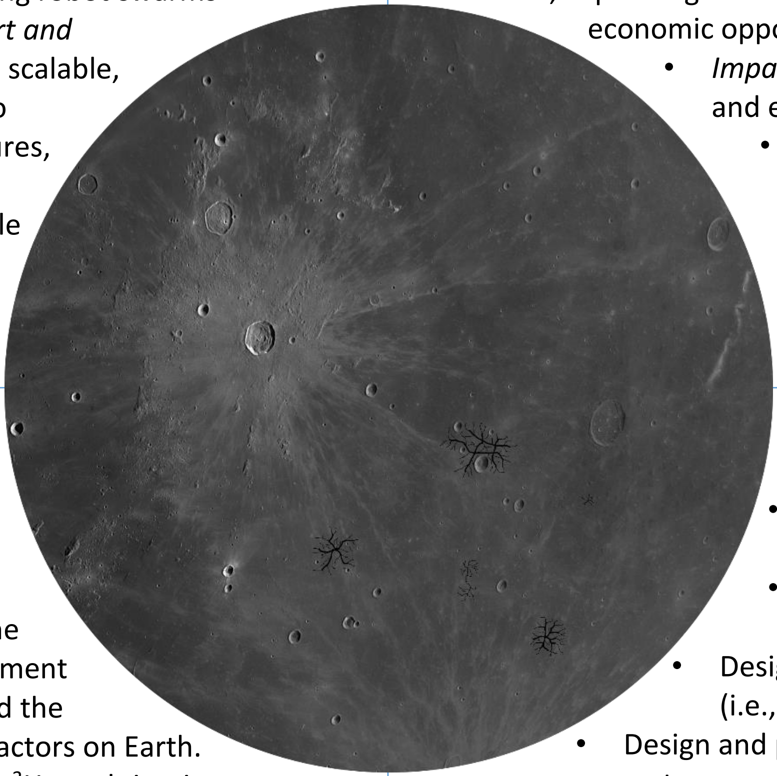
RootBots: Sprawling Robot Networks for Lunar Resource Extraction



Innovation

- *Concept*: km-scale robotic roots for resource extraction.
- *Novel technology*: scalable self-constructing mobile systems built by two interacting robot swarms
- *Compared with state of the art and alternative approaches*: more scalable, fully autonomous, adaptive to environment, resilient to failures, in-situ resource utilization, logistically simpler, less volatile loss during mining; less environmental impact.

Impact

- *Contribution to the aerospace community*: support the development of a potentially profitable industry on the Moon, expanding human presence in space, creating economic opportunities.
- *Impact to Earth*: addressing the energy and environmental challenges
- *Other benefits*: advance research on modular, scalable, and self-assembling robot systems; capture public interest and imagination (potentially visible from Earth).

Mission

- *Mission context*: Helium-3 (^{3}He) mining on the lunar surface.
- *Starting time*: second half of the 21st century after the establishment of basic lunar industry base and the commercialization of fusion reactors on Earth.
- *Location*: lunar maria with high ^{3}He and titanium contents (e.g., Oceanus Procellarum).
- *Target productivity*: one ton of ^{3}He annually per rootbot, meeting 1/40th of U.S. electric power needs.

Approach

- Mission concept refinement and economic analysis.
- Comparison studies with other potential concepts.
- Design of modular robot components (i.e., cells and transporters).
- Design and prototype a sub-scale hardware system.
- Algorithm development for decentralized problem solving.
- Simulation with >10,000 agents.

RootBots: Sprawling Robot Networks for Lunar Resource Extraction

Yu Gu, West Virginia University

1. Motivation

Lunar Helium-3 (^{3}He) mining has the potential of addressing the energy and environmental challenges on Earth. As an essential fuel of future nuclear fusion reactors, ^{3}He is extremely rare on Earth, with currently less than 2 kg/year production in the US [1], but is much more abundant on the lunar surface, with an estimated reserve of over one million tons [2-4]. Just 40 tons of ^{3}He, combined with deuterium, a resource available on Earth, could meet the current annual energy need of the U.S [5-6].

Mining ^{3}He on the Moon would be quite different than traditional mining process on Earth. Over the time, ^{3}He, along with other volatiles, were implanted into the lunar regolith by the solar wind [7]. This means that surface mining operations would need to cover vast areas at shallow depths. Agitation to the regolith will lead to a significant release of the volatiles [8], which presents both a challenge and an opportunity. Other challenges associated with large-scale space industrialization, such as the limited human presence and the high reliability/autonomy requirements, meaning radically different mining concepts need to be developed.

2. Inspiration

Vascular plants use roots to anchor themselves, to explore and extract resources from earth, to store nutrients, and to compete with others [9]. The roots grow by producing new cells, which are regulated by both extrinsic and intrinsic stimuli [10]. Sensing of extrinsic factors, such as gravity, barriers, light, air, water, and nutrients, directs roots to grow toward favorable directions [11]. Hormones (i.e., intrinsic stimuli) such as Cytokinins and Auxin (with often opposite effects) [12], as a part of both local and long-distance signaling, also help coordinate the root development. The plant roots are time and real-world tested designs for functionality, intelligence, and resilience.

3. Vision

We envision *rootbots*, sprawling networks of robot organisms (Fig. 1), for performing planetary resource extraction tasks at an unprecedented scale. A rootbot will be made of modular and interlocking smart components called the *cells*. Each cell interacts with the environment and makes its own decisions, influenced by local stimuli and decisions of nearby cells. One important decision to be made is whether for a cell to stay in place or relocate. If a cell decides to move, it will wait for a mobile agent, called a *transporter*, to come by and pick it up. Traveling only on top of the existing “root” network of cells, the transporters carry cells and deploy them in places where they desire. With two decentralized and interacting robot swarms (i.e., the cells and the transporters), a rootbot can grow like a plant root for exploring and exploiting favorable conditions.

The rootbot concept offers several potential benefits. First, like a plant root, rootbot allows spatial-temporally extensive coverage of a surface area, supporting applications such as construction and mining. Moreover, it naturally adapts to a complex terrain (e.g., with slopes, craters, and boulders) and moves toward resource rich regions. The modular design and decentralized decisions offer system redundancy and robustness, thus supporting long-term autonomous missions. Additionally, the rootbot expands through paving its own road network, avoiding mobility challenges on planetary surfaces. Finally, the use of only two agent types, which share the same footprint, makes it easier for the components to be made and handled locally, benefiting from the economies of scale.

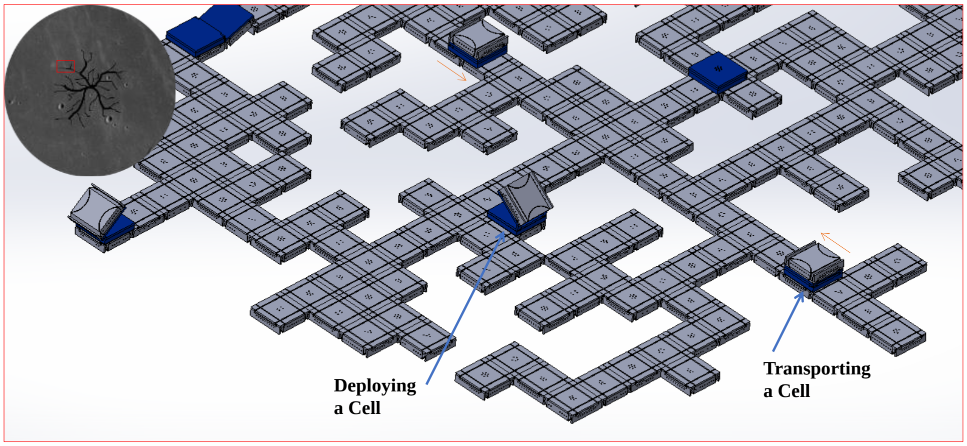


Fig.1. An illustration of the proposed rootbot concept.

4. Preliminary Mission Concept Design

4.1. Cell and Transporter Designs

We baseline the mission design around a rootbot that can produce 1 ton of ^{3}He annually. The ^{3}He may be used as fuel for interplanetary travel [13]. When transported to Earth, 1 ton of ^{3}He is equivalent to 100 million barrels of crude oil and worth $11 billon (at $110/barrel) [8]. It can power a 10GW power plant for a year, satisfying roughly 1/40th of U.S. electric power needs [2, 5] with no carbon emission and radioactive wastes [14]. The byproducts of the mining process, such as N_2, H_2O, CO_2, and H_2 [15], are also valuable resources for the lunar habitats and industry.

Assuming 20 wppb (parts-per-billion by weight) average ^{3}He concentration in the lunar regolith [16], 3-meter mining depth, 25 km^2 yearly mined area, and a 50% ^{3}He recovery rate, the baseline rootbot design will have a ground contact area of 1km^2. It will be made of 110,000 “cells” and 1,000 “transporters”, each with a dimension of 3m x 3m x 0.75m, spanning a region approximately 50 km^2 in area. It will likely become a dynamic object visible from Earth through an amateur telescope.

The main functions for the cells are for generating solar power, extracting volatiles from the regolith, separating ^{3}He and useful byproducts, and making intelligent decisions about the next moves. Mechanically, the cells will be interlocking with compliant interfaces (for conforming to the natural terrain), and can exchange power, data, and products between neighboring cells. The top surfaces of the cells will be covered with solar panels and accommodate the mobility system of the transporter. Surface mining will be performed through projecting tendrils under the cell for stirring and locally heating up the regolith [14] to release volatile. Different gas contents are separated through cooling to liquefy. ^{3}He is then separated from ^{4}He through a superleak membrane process [8, 17]. The transporter acts as an “Uber service” for the cells. It has the mechanisms and actuators to pivot a cell, lock-unlock the hinge interface between two cells, and carry a cell to a different location (Fig. 1).

The preliminary designs will be refined during the project. Studies will also be performed to compare the proposed approach to a concept of using conventional equipment for ^{3}He mining on the moon [8]. A prototype system with ten 1/15 scale cells and one transporter will also be developed for proof-of-concept demonstrations.

4.2. Decentralized Coordination and Self-Organization

The global behavior of the rootbot will be shaped by the local interaction rules of the cells and transporters. The cells make the decisions about when and where to go and the transporters decide how to effectively serve the cells. Like in a plant root, the "bottom-up" decisions made by the cells will be based on extrinsic stimuli, such as gravity (e.g., slope angle), solar input, and resource abundance, along with intrinsic factors, such as opinions by the nearby cells. The mechanism for utilizing intrinsic stimuli is mostly through stigmergy [18], leading to emergent higher-level behaviors; e.g., the root grows thicker in more congested areas. For scarce resources, local Vickre auctions [19] will be conducted to coordinate the agent-interactions where agents compete for transportation services, right of way, and favorable cell locations. Large-scale simulation studies, with over 10,000 agents, will be performed during the project to demonstrate decentralized rootbot problem-solving abilities.

4.3. Manufacturing, Deployment, Operations, and Logistics

We envision the initial phase of the rootbot mission starting in the 2nd half of the 21st century, after the establishment of a lunar industry base for Titanium and solar panel production. High ^{3}He concentration lunar maria are also rich in Titanium [16, 20], which will provide the rootbot main structure material (estimated 1,500 kg per cell with 8mm wall thickness, similar mass as a car). Combining locally sourced parts (e.g., titanium frames and solar panels) and components transported from Earth (e.g., microprocessors, sensors, seals), the building of the modular cells and transporters will be done in automated factories on the Moon. With the mobility of rootbots, the delivery of new cells and transporters from the factories can be arranged as smaller rootbots marching toward and eventually merging with the target rootbot. During the extended mining operations, cells and transporters lost key functionality will be simply left alone as the rest of the rootbot move on to other places. Eventually, they will be retrieved by conventional rovers for repair. When a mission ends, the rootbots can march back to factories/warehouses for storage or recycling. Detailed economic analysis and trade studies will be conducted during the project to determine the sources of components, overall design layout, and resource transportation requirements.

5. Impact

If successful, the rootbot concept will support the development of a commercially profitable industry on the moon, expanding human presence in space, creating economic opportunities, and addressing energy and climate challenges on Earth (supporting NASA's Strategic Goals 2.1, 2.2 and 3.1, [21]). The technology developed for rootbot may form the "roots" for future modular, scalable, and self-assembling systems designed for space applications.

References

[1] Kouzes, R. T. (2009). The 3He supply problem (No. PNNL-18388). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

[2] Stube, K. (2004). Requisites for A Long-Term Lunar Helium-3 Minning Mission. In 55th International Astronautical Congress.

[3] D’Souza, M. R., Otalvaro, D. M., & Singh, D. A. (2006). Harvesting helium-3 from the Moon. Worcester Polytechnic Institute. Worcester Polytechnic Institute. Available: http://www.wpi.edu/Pubs/E-project/Available/E-project-031306-122626/unrestricted/IQP.pdf

[4] Simko, T., & Gray, M. (2014). Lunar Helium-3 fuel for nuclear fusion: technology, economics, and resources. World Future Review, 6(2), 158-171.

[5] Wakefield, J. (2000). Moon's Helium-3 Could Power Earth. Special to SPACE.com. Available: https://fti.neep.wisc.edu/fti.neep.wisc.edu/gallery/pdf/space_com063000.pdf

[6] Independent Statistics Analysis, US Energy Information Administration (2021). Less electricity was generated by coal than nuclear in the United States in 2020. Available: https://www.eia.gov/todayinenergy/detail.php?id=47196

[7] Johnson, J. R., Swindle, T. D., & Lucey, P. G. (1999). Estimated solar wind-implanted helium-3 distribution on the Moon. Geophysical Research Letters, 26(3), 385-388.

[8] Schmitt, H. (2007). Return to the Moon: exploration, enterprise, and energy in the human settlement of space. Springer Science & Business Media.

[9] Ciszak, M., Comparini, D., Mazzolai, B., Baluska, F., Arecchi, F. T., Vicsek, T., & Mancuso, S. (2012). Swarming behavior in plant roots. PLoS One, 7(1), e29759.

[10] Staiger, C. J. (2000). Signaling to the actin cytoskeleton in plants. Annual review of plant biology, 51(1), 257-288.

[11] Cahill Jr, J. F., & McNickle, G. G. (2011). The behavioral ecology of nutrient foraging by plants. Annual Review of ecology, evolution, and systematics, 42, 289-311.

[12] Pernisová, M., Klíma, P., Horák, J., Válková, M., Malbeck, J., Souček, P., ... & Hejátko, J. (2009). Cytokinins modulate auxin-induced organogenesis in plants via regulation of the auxin efflux. Proceedings of the National Academy of Sciences, 106(9), 3609-3614.

[13] Thomas, S. J., Paluszek, M., Cohen, S. A., & Glasser, A. (2018). Nuclear and future flight propulsion-modeling the thrust of the Direct Fusion Drive. In 2018 Joint Propulsion Conference (p. 4769).

[14] D’Souza, M. R., Otalvaro, D. M., & Singh, D. A. (2006). Harvesting helium-3 from the Moon. Worcester Polytechnic Institute. Worcester Polytechnic Institute. Available: http://www.wpi.edu/Pubs/E-project/Available/E-project-031306-122626/unrestricted/IQP.pdf

[15] Gibson Jr, E. K., & Johnson, S. M. (1971). Thermal analysis-inorganic gas release studies of lunar samples. In Lunar and Planetary Science Conference Proceedings (Vol. 2, p. 1351).

[16] Fa, W., & Jin, Y. Q. (2007). Quantitative estimation of helium-3 spatial distribution in the lunar regolith layer. Icarus, 190(1), 15-23.

[17] Wilkes, W. R., & Wittenberg, L. J. (1992). Isotopic separation of He-3/He-4 from solar wind gases evolved from the lunar regolith. Engineering, Construction, and Operations in space-III: Space'92, 1, 547-554.

[18] Theraulaz, G., & Bonabeau, E. (1999). A brief history of stigmergy. Artificial life, 5(2), 97-116.

[19] Ausubel, L. M., & Cramton, P. (2004). Vickrey auctions with reserve pricing. Economic Theory, 23(3), 493-505.

[20] Fegley Jr, B. R. U. C. E., & Swindle, T. D. (1993). Lunar volatiles: implications for lunar resource utilization. Resources of near-Earth space, 367-426.

[21] NASA. (2018). NASA Strategic Plan 2022, Available: https://www.nasa.gov/sites/default/files/atoms/files/fy_22_strategic_plan.pdf