REALIZING A SELF-REPRODUCING SPACE FACTORY WITH ENGINEERED AND PROGRAMMED BIOLOGY.
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NASA studied the technological feasibility of a self-replicating lunar factory nearly four decades ago [1] to mitigate the severe cost of multiple shipments to the moon. The idea was to harness local resources to manufacture desirable products on site. This factory would also grow outwards to slowly increase its capacity from an initial seed (Figure 1) by producing copies of its constituent elements. These elements included autonomous task-specific robots; some would procure raw materials, others would transform these materials into structural and sustenance (e.g., power) outputs, and yet more would store final products for future use.

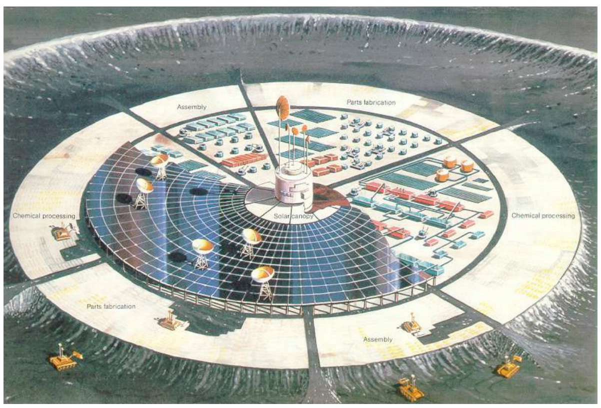

Figure 1 [1]: A 1980 self-replicating lunar factory concept that used autonomous robots in outwardly-growing sectors devoted to chemical processing, parts fabrication, and assembly.

Attempts were made towards realizing this concept in the following years [2], and we examined associated questions such as determining the optimal seed for such factories [3] and ensuring that a self-reproducing collective would be resilient to disturbances like solar flares or meteoroid strikes [4], [5]. But a fundamental trade-off exists with robot self-reproduction [6]: either the self-reproduction process is "simple" because the environment is complex, in that ready-made parts exist to be assembled, or the self-reproduction process is "complex" because the environment is simple (i.e., disordered and unstructured), and thus requisite parts must be synthesized and connected. The latter challenge is applicable to the extraterrestrial environments of self-replicating space factories.

Of course, biology can already self-reproduce, and this complex process has a potential use in "simple" off-Earth environs. In fact, recent studies [7-10] have advocated deploying existing biology for space manufacturing, and we calculated in [9] that such deployment can substantially minimize payloads over abiotic approaches, even before any engineering occurs. These calculations suggested that 26-85% mass reductions are possible depending on the application. Biological technologies can also lower power demand and launch volume, for instance by innately harnessing solar energy and by growing only upon activation using available destination resources, respectively. In [11], we articulated grand challenges facing the resultant nascent field of space synthetic biology. This field was included in NASA's 2015 technology roadmaps [12], where biological technologies were described as having "promising potential" that "deserve some attention."

Our recently-awarded Center for the Utilization of Biological Engineering in Space (CUBES) will leverage partnerships between NASA, other federal agencies, industry, and academia to support biomanufacturing for deep space exploration [13]. CUBES involves five universities: the University of California, Berkeley; the University of California, Davis; the University of Florida; Utah State University; and Stanford University. CUBES will advance the practicality of an integrated, multi-function, multi-organism biomanufacturing system on a Mars mission, and showcase a continuous and semiautonomous biomanufacturing of fuel, materials, pharmaceuticals, and food in Mars-like conditions. Akin to an abiotic, robotic space factory, task-specific organisms will convert raw materials (e.g., Mars atmospheric and regolith resources) for downstream biological use as media and feedstock, and will manufacture structural and sustenance mission products like propellants, building materials (biopolymers that can be 3D-printed), food, and pharmaceuticals. It is envisioned that this biomanufacturing system will be initialized from some seed set.

The biology in this system will not be the only thing that reproduces; CUBES will also study self-reproduction and growth from the factory seed. For instance, for the case of agricultural cultivation receptacles, open questions include how much biopolymer will be required to produce a receptacle of a certain size that will still be manufacturable by a 3D-printer and that will then exponentially increase yield if that bioreactor is used by more biopolymer-producing microbes or is used to grow plants, and how much media will then be required for that biopolymer amount.

Beyond CUBES, there will be a need to program the utilized biology. In general, CUBES harnesses a fundamental trade-off of space synthetic biology: mass savings at a cost of longer process times. Accordingly, any self-reproducing space biofactory deployment will be in advance of astronaut arrival, or on a large scale where some operations are remote from astronaut oversight. Hence, electromechanical or cell-based controllers must ensure satisfactory (quick, and autonomous or telerobotic) space biomanufacturing.

Consequently, the notion of a self-reproducing space factory has come full circle from the original concept, and will be realizable in the near future through engineered and programmed biology. With a deep space gateway, there is an opportunity to test proof-of-concept versions of this biofactory that can self-reproduce from a seed set and that can operate autonomously at this gateway. These tests will be foundational for evaluating a possible vital support technology in future manned space missions.

A first test can start small, such as converting available exhaled carbon dioxide into a fuel or into a biopolymer. Follow-on tests will then scale up both bioprocessing function and autonomy, eventually realizing a near-complete biofactory from a seed. These tests will yield valuable operational and autonomy information. Potential operational insights include corroborating prior studies on minimizing mass, power, volume, and cost over abiotic approaches. Potential autonomy insights include determining the minimum crew interaction required for biofactory operation, and confirming flawless growth from the seed set.

Test needs that will have to be met by the deep space gateway include emulating prospective mission conditions where the biofactory seed would be deployed. CUBES includes a space and complex systems engineering component to analyze, guide, test, improve, and integrate the internal processes of a space biofactory, and will provide the necessary data, metrics, and operating condition information upon center conclusion to inform future space tests and activities.

In sum, there is an opportunity to test a data-driven, technologically-backed space biomanufacturing platform at the deep space gateway that realizes a highly-valued concept, a self-reproducing space factory. This opportunity lies at the intersection of space biology and telerobotics-enabled science.

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