A Bootstrap Lunar Industry with Semi Self-Replication

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Space Machines Corporation (www.space-machines.com) is a small consultancy which has kinetic sculpture as its normal focus, but which has also become involved with the subject of space exploration as exemplified by a white paper (http://www.space-machines.com/publications/SMC_Response_100YSS_RFI.pdf) submitted in response to DARPA's 100 Year Starship RFI, and which paper also takes advantage of an appropriate opportunity to document the company's not insignificant technological track record. The current paper is the culmination of a multi-year effort to bring a 3D design sensibility to bear on the question of establishing an autonomous manufacturing capability on the lunar surface.

Abstract

In accordance with a possible line of inquiry outlined in the historic NASA study *Advanced Automation for Space Missions* (1982), this paper describes a seed lunar industry which, in the interest of achieving autonomous operation, in-situ resource utilization, and some degree of self-replication, has as its focus a manufacturing technology of low to intermediate precision. That technology, in the present instance, is *solar furnace casting*, albeit with some unique adaptations to the lunar environment — and with a possible evolutionary path toward large-scale additive manufacturing/3D printing. However — inasmuch as no quantitative analyses whatsoever of the proposed system are included herein — this paper must be regarded as purely conceptual.

Introduction

A brief glance at the history of early seventeenth century English migration to the American colonies will shed some light on the transport capabilities requisite for the establishment of a viable space colonization effort.

During the first period of sustained migration, 1630 to 1640, we can make a quick estimate that some 5,000 souls per year made the leap, i.e., an average of one ship per week with 100 passengers [1].

Given that England had approximately 5 million inhabitants at the time [2], the logistics were therefore in place to provide passage to a mere 0.1% of the population per year, and which movement history regards as the first trickle of what would become a much larger migration.

Extrapolating to a 2014 US population of 314 million, that same trickle equates to space cabin accommodations for 314,000 individuals per year — and the possibility of providing which capacity must be seen as a threshold for generating some real enthusiasm among tax-paying Americans for space colonization.

On the one hand, this would seem to be an impossible challenge; yet as has been clear to students of space travel for some time, there is available to humankind an ideal platform for its leap into the cosmos: one having a vast and largely uniform surface rich in pulverized ores, a highly stable incidence of intense solar energy, and low gravity and lack of atmosphere such that whatever is manufactured there can become space-borne with relatively little effort. Indeed, so ideal is this platform as a manufactory for the components of a space fleet — these to receive final assembly in cislunar space — that an earth launch capability can be dedicated to the ferrying of passengers and provisions to the completed vessels.

The platform to which we refer is, of course, the moon; and as has also been clear to students of space travel for some time, its effective utilization must depend upon autonomous, self-replicating manufacturing systems.

Hence the daring 1982 NASA study *Advanced Automation for Space Missions*, which has as its focus a self-replicating industry with across-the-board, state-of-the-art capabilities, and with said industry to be initiated via the delivery of a 100-ton "seed" factory to the lunar surface.

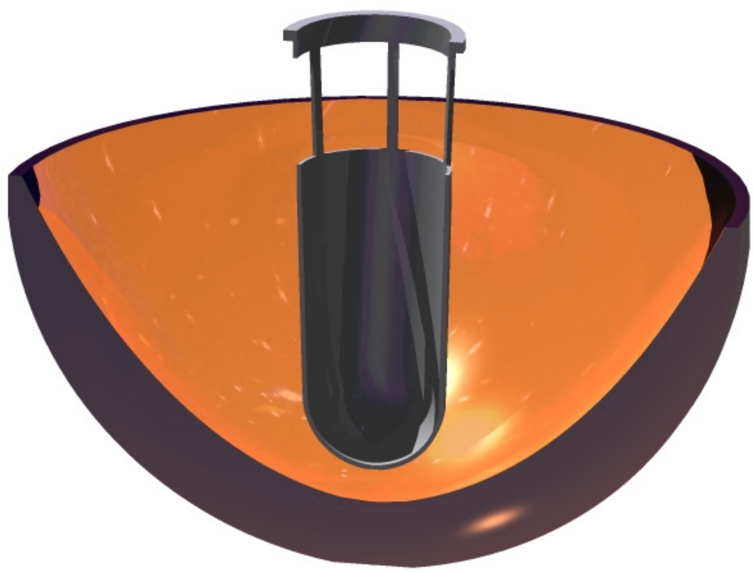
This same document, however, also includes an appendix entitled " Issues and Concepts for Further Consideration", and which appendix suggests one of the two principles to be explored herein, namely, that 1) a manufacturing technology of lower precision and higher modularity might better lend itself to the initial stages of attempts to achieve self-replication [3].

A separate NASA-funded document, the *Lunar Sourcebook* — and here we must pause in tribute to the visionary faith of the authors of these two volumes — has articulated the second principle upon which the current exploration is based, namely, that 2) the apparently alien lunar environment can, if properly apprehended, have some unique advantages for manufacturing [4].

Solar Furnace Casting as a Bootstrap Lunar Industry

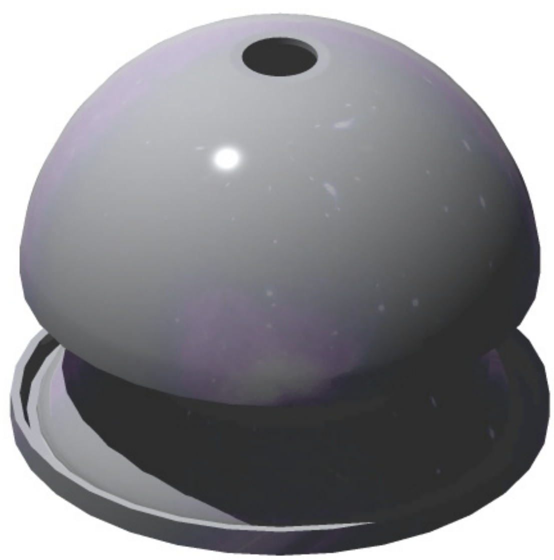
As illustrated in Fig. 1, the core element of the present exploration is a solar furnace mirror with a) an aperture of, say,1 meter; b) a hemi-spherical outer profile; and c) a parabolic inner profile whose focal point is at the center of the hemi-spherical lower portion of the crucible shown — and said mirror to be cast from the material of the lunar regolith. The previously-referenced *Advanced Automation for Space Missions* notes that there are terrestrial precedents for the use of basalt as such a casting material; however — inasmuch as a) semi-pure glass beads constitute a significant portion of the regolith; b) a relatively simple *mechanical* means might be devised for their separation, if such does not already exist; c) glass as a material is highly amenable to casting; d) the low gravity of the moon and the "weightlessness" of the space environment largely offset the relatively low tensile strength of glass and likewise make possible the use of relatively thick sections; and e) in the anhydrous environments of the moon and space in general, glass is in fact likely to have much higher tensile strength than it typically does on earth [5] — it is this material which has been selected for the current inquiry. Moreover, the capability of bringing glass to the molten state provides a possible path to the production of a composite material in which glass is the matrix [6], and which material in turn might serve as a feedstock for additive manufacturing/3D printing.

Fig. 1. Conceptual cross section of lunar-originated solar furnace mirror with earth-originated crucible. (Mirror shown without its vacuum-deposited aluminum coating to better illustrate glass composition.)



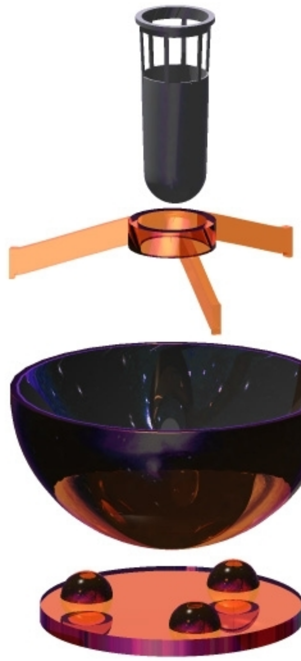
Thus the basic premise of the current study: a solar furnace mirror which can bring to a molten state the material from which its duplicate is to be cast — this a not inconsiderable feat. Given, however, that the goal of the current study is not to describe some system of theoretically perfect self-replication, but rather one capable of actual implementation in the near future, this study envisions extensive use of earth-originated components, tooling, and equipment, as shall be considered in detail later. In reference to Fig. 1, this proviso first makes itself felt in that, although the initial complement of crucibles for the project are earth-originated, their low weight and stackable "paper cup" design make it possible to equip the mission with n-hundred such crucibles; and second, the mirrors themselves, while cast on the moon with self-generated energy, are produced with an earth-originated, two-part mold as per Fig. 2 following:

Fig. 2. Conceptual illustration of earth-originated, two-part mold for casting initial set of solar furnace mirrors. (Shown in exploded position.)



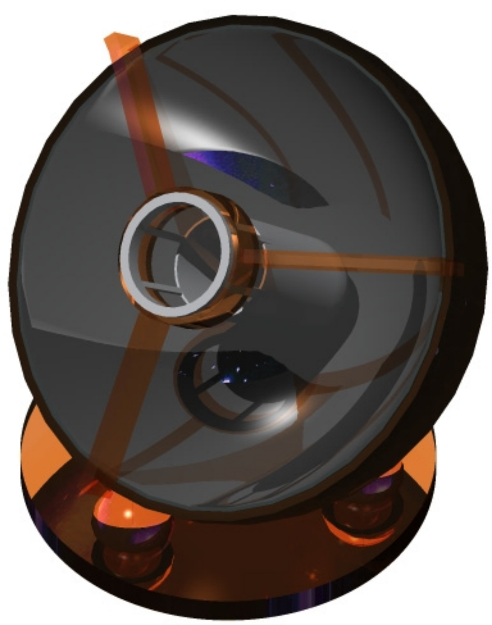
Indeed, two additional such earth-originated molds are anticipated — one for casting the glass mirror base plates, upon the hemispherical bosses of which the mirrors can be tilted for maximum solar energy collection, and a second for casting the thick-sectioned glass tripods which hold the crucibles in place [7]. A complete solar furnace casting station thus appears as shown in Fig. 3, albeit a) in vertically exploded form, and b) with the inner parabolic surface of the mirror now aluminized — a process which, in the native and near-perfect vacuum of the lunar surface, becomes almost trivial.

Fig. 3. Conceptual illustration of complete solar casting station in vertically exploded form. (Ribbed section of crucible wall inhibits migration of heat to its neck, thus preventing softening of glass tripod.)



Reference has already been made to the possibility of tilting the mirrors for maximum incident solar energy collection, and Fig. 4 following shows a solar casting station in such a configuration:

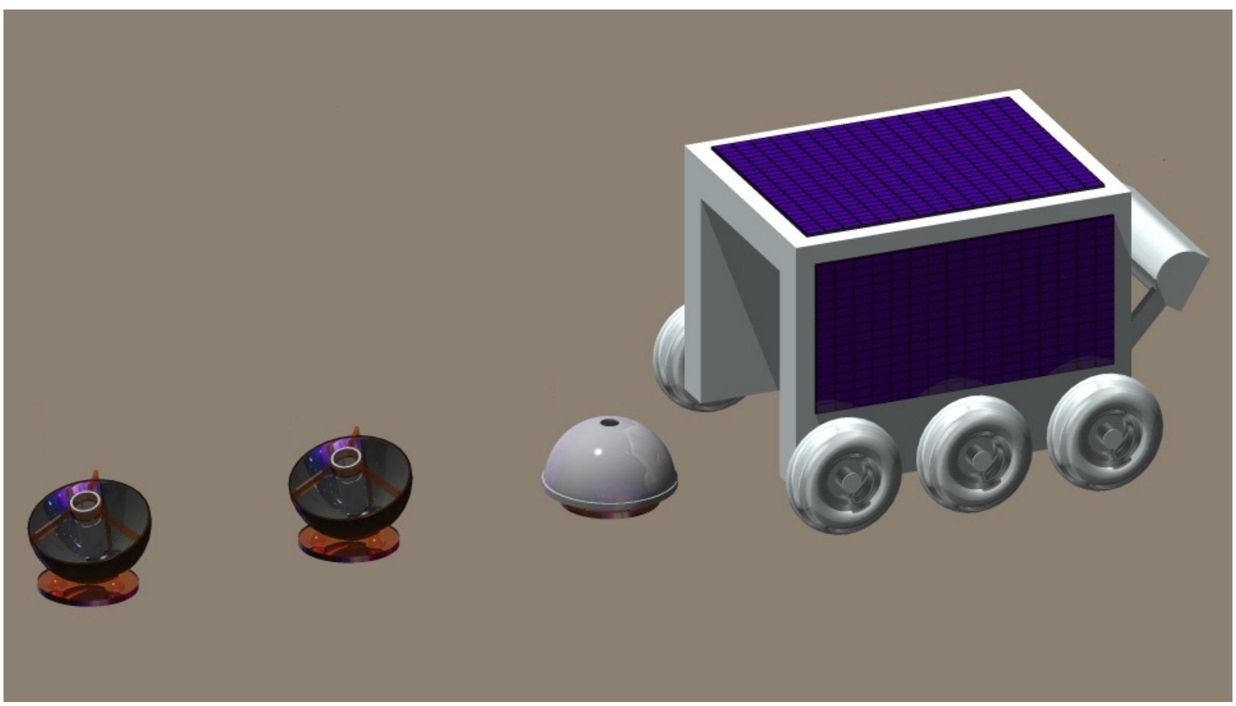
Figure 4. Conceptual illustration of solar furnace casting station tilted at 45° from vertical; crucible is of sufficient depth that molten contents are retained.



In respect to said tilting — and here yet another example of the seemingly alien but actually beneficial aspects of the lunar environment — the salient point is that the sun, as is well known, moves across the lunar sky with much lower apparent speed than it moves across the terrestrial sky, with the result that an array of such mirrors would not need complicated internal sun-tracking hardware, but could be kept in near-optimal alignment by the periodic intervention of some external entity.

As shown in Fig. 5, that entity as envisioned in the present study is in fact an earth-originated "Multi-Function Service Vehicle", and with the periodic tilt adjustment of the solar mirrors only one of its many responsibilities, the others to include: a) providing storage within its internal 2 x 1.5 x 3 m envelope for the three molds, the initial complement of crucibles, and one additional item — a pre-fabricated, aluminum-shelled mirror assembly as the initial "seed" furnace; b) periodic excursions across the lunar regolith to collect the glass bead feedstock; c) placement of molds and sequencing of molding operations; d) the placing of a cover over each semi-completed mirror and the vaporization of an aluminum foil wick pulled from an integrated dispenser to achieve its interior aluminization ; and e) manipulation and placement of molded elements to complete a given solar furnace casting station.

Figure 5. Conceptual illustration of line of solar furnace casting stations as attended by Multi-Function Service Vehicle. As shown here, a mirror — albeit in inverted position — is about to be cast atop a previously cast base plate. Also as shown here, the service vehicle is powered by solar cells; were it to be RTG powered, the glass bead collection and re-charging of the crucibles could be undertaken throughout the long lunar night, and with the long lunar day dedicated to the actual casting.



Discussion

Three related questions immediately present themselves for discussion: 1) Even though this study has declared itself to be merely "conceptual", how creditable is the attribution of most of the complicated operations of the proposed system to a black box "service vehicle"? 2) Given that the crucibles, the molds, and, above all, said "service vehicle" are earth-originated, can this system be said to represent some significant degree of self-replication? 3) Do the facilities thereby generated readily lend themselves to the "bootstrapping" of ever greater and more varied facilities; i.e., can this system be said to represent some real foot-hold in respect to autonomous manufacturing on the lunar surface?

In regard to question 1 — the dependence on a black box "service vehicle" — it be could be argued that one of the precise strengths of the current proposal is the segregating of all of its real complexities within a single, earth-originated vehicle rather than their being distributed throughout a complex "factory". This is a type of vehicle, moreover, which we have become quite expert at building (with the possible exception of the glass bead separation function) — now deployed, however, not for the sake of gaining additional intelligence about our solar system, but rather for the sake of putting that intelligence to good use. (Which is not to say that each and every aspect of this mission will not require detailed scrutiny, and, in particular, the design of molds which can be re-used multiple hundreds of times on the dust-laden lunar surface.)

In regard to question 2 — the level of self-replication represented — the point has already been made that the goal of this paper to present a system which might inspire us with the possibility of its near-term implementation; and this being the case, it has seemed acceptable to embrace a design which falls considerably short of complete self-replication. Even so, the fact remains that at the end of its growth phase — i.e., when the last earth-originated crucible has been placed into service — this system can be expected to have created an array of some n-hundred solar furnace casting stations, and these vastly exceeding in total mass and volume the initial delivery package. Nor will these be flimsy "solar cooker" type affairs, but rather solar furnaces of quite robust construction, and again with the recognition that because of the moon's low gravity, the use of thick sections does not necessarily imply a lack of engineering elegance. *What is "clunky" on earth is not necessarily "clunky" on the lunar surface, nor in cislunar space — especially when some earth-like solidity, or shielding from solar radiation, is a desirable quality.*

In regard to question 3 — the extent to which this system can feed into and give rise to a next level of autonomous, self-replicating lunar manufacturing — an obvious general principle is that a source of concentrated heat is the basic requirement for many industrial and chemical processes.

One example, if not to say variant, of this principle deserves particular mention inasmuch as it represents a striking extension of the original system: were a second service vehicle to be dispatched with a complement of thermocouples for installation in place of some of the crucibles — and with the wiring to connect them — the array of mirrors could also generate electricity. (In this case, the preferred configuration for the array of mirrors would perhaps be a set of lines radiating out from a central plaza.)

One might also imagine yet another dramatic extension to the basic system: the possibility that some non-vitreous fraction of the regolith — perhaps after roasting and/or grinding — could serve as an aggregate, and could thus be [re]processed with virgin glass beads to produce a composite material [6] of perhaps sufficient tensile strength for the production of structural elements and fluid containment vessels. Given the high viscosity of such a melt, the crucibles, as per Fig. 6, would likely need to evolve in the direction of becoming something like screw press-evacuated cartridges within a larger additive manufacturing/3D printing system — yet still heated within the original solar furnaces.

Figure 6. Conceptual illustration of second generation crucible/cartridge.

Such extensions to the basic system, however, pale in potential importance in comparison with an adjustment to its original profile.

As per the earliest mammals, evolution has shown us that "small is beautiful" in terms of gaining a foothold in a given environment; and it may be that a quantitative analysis of the proposed system — especially in respect to the solar energy flux at the lunar surface, and therefore the minimum practical aperture of a solar furnace mirror — will demonstrate that the system can be reduced to, say, Mars Pathfinder scale.

All of these are exciting possibilities — but we must conclude this discussion section with a procedural caution. The brainstorming in which we have been engaged here is valuable and inevitable; but this must be conducted with an awareness of the fact that, by drawing out the planning process, the very fertility of self-replicating systems may tend to inhibit their implementation.

Conclusion

The author of this study is well aware that it is a mix of largely familiar ingredients, and, further, that it is but one of a thousand or more proposals as to how humankind might best use our lunar companion as a stepping-stone into the cosmos. It represents, nonetheless, the patient thought of a designer long accustomed to the humiliations of mass, gravity, propagation delay, material science, systems engineering, and entrepreneurship [8] [9] [10], and, as such, may incorporate the type of subtle but also crucial refinements which led from the ill-fated Langley Aerodrome to the not-so-different — yet triumphant — Wright Flyer.

References

[1] The Wikipedia article "Puritan migration to New England (1620 - 1640)" reports that "from 1630 through 1640 approximately 20,000 colonists came to New England", i.e., some 1,800 individuals per year, and from which we might estimate a total migration of 5,000 per year to the full set of English North American colonies. http://en.wikipedia.org/wiki/Puritan_migration_to_New_England.

[2] http://homepage.ntlworld.com/hitch/gendocs/pop.html

[3] "Can SRS [self-replicating systems] be designed to have few or no precision parts? Can milling and turning operations be eliminated? What substitutes might be found for the usual precision components such as ball bearings, tool bits, metering instruments, micron-feature computer chips, etc.? It is possible to imagine Stirling engines, solar mirrors, electromagnets, and mechanical gear trains using only native lunar basalt, iron, and gases with no chemical processing - but are complete (but simple) SRS possible using just two or three non-chemically recovered elements/minerals? Could SRS be patterned after terrestrial biological protein synthesis, in which the factory is made up of perhaps two dozen fundamental 'building blocks' (similar in function to amino acids) assembled in virtually limitless combinations?" From Appendix 5K, "Issues and Concepts for Further Consideration", in Freitas, Robert A., Jr. and William P. Gilbreath, eds., *Advanced Automation for Space Missions*, NASA, 1982, pg. 333. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19830007077.pdf

[4] "The Moon is indeed an alien environment. While these differences may appear to be of only academic interest, as a measure of the Moon's 'abnormality,' it is important to keep in mind that some of the differences also provide unique opportunities for using the lunar environment and its resources in future space exploration." From "The Lunar Environment" in French, Bevan M., Grant H. Heiken, and David T. Vaniman, eds., *Lunar Sourcebook*, Cambridge University Press, 1991, pg. 27. http://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter03.pdf

[5] Blacic, James D., "Mechanical Properties of Lunar Materials Under Anhydrous, Hard Vacuum Conditions: Applications of Lunar Glass Structural Components", *Lunar Sourcebook*, Cambridge University Press, 1991.
http://www.lpi.usra.edu/publications/books/lunar_bases/LSBchapter07.pdf#pagemode=bookmarks&page=53

[6] "Instead of water-set lime-based cement, we can use glass to cement particulate material together." From Spudis, Paul, "Regolith, The 'Other' Lunar Resource", *Air & Space Magazine*, Jan. 5, 2011. http://www.airspacemag.com/daily-planet/regolith-the-other-lunar-resource-156943194/

[7] The casting process is perhaps a microcosm of the potential negatives and positives of manufacturing on the lunar surface. On the negative side, a concern might be that the low lunar gravity would render impossible the casting of a viscous melt — but the fact is that thoroughly melted glass has nearly the fluidity of water. On the positive side, that same low gravity will *reduce* the tendency of the pour to split open its mold. Also on the positive side, it might be supposed that the absence of a lunar atmosphere will contribute to the quality of a piece which is the result of multiple pours, as is clearly a necessity with the components of the current system.

[8] Smith, G. W., "Response to Request for Information (RFI): DARPA 100 Year Starship™ Study". http://www.space-machines.com/publications/SMC_Response_100YSS_RFI.pdf

[9] "BLAST (Protocol)", *Wikipedia*. http://en.wikipedia.org/wiki/BLAST_(protocol)

[10] Smith, G. W., *Aesthetic Wilderness: A Brief Personal History of the Meeting Between Art and the Machine*. New Orleans: Birds-of-the-Air Press, 2011.