Lunar Infrastructure via Microscale Regolith Assembly

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Multiscale Granular Stacking (MSGS) is a technology for assembling planetary-surface infrastructure from unprocessed regolith. The unprocessed grains serve directly as additive manufacturing feedstock in a process that exploits their natural variation in size and shape. With precise, single-grain scanning, computation, and packing, MSGS minimizes and potentially eliminates the need for adhesives, fluids, and other binders, saving the associated mass and energy. Preliminary calculations suggest that MSGS requires less mass transport and energy for construction than traditional terrestrial building methods, drastically reducing the reliance on earth resources for sustaining a deep-space human presence and long-term exploration goals. Constructing a desired structure may require stacking millions of grains which demands extensive computation. Packing solutions with many objects exist in the literature, e.g. some versions of the knapsack problem. However, micro- to macro-scale particle dry stacking itself has never been investigated, let alone in the context of space additive manufacturing. Modeling these fabrication process dynamics as a discrete-step linear system allows for tuning of parameters such as build speed, surface finish, and contour smoothing while providing the opportunity to leverage controls theory for determining system convergence, steady-state error, and overshoot of desired build height. This paper details attempts to bring multivariable control theory to bear on additive manufacturing by using feedback on overall build geometry, a technique proven to yield more accurate results than using feedback at the process level in traditional additive manufacturing.

I. Introduction

A. Overview of MSGS

Landing pads, habitats, and communications towers will be key in the development of lunar infrastructure - a goal of NASA, other government agencies, and commercial entities. In a future where we explore our solar system with an eye toward permanent settlement, we will have to live off the land and effectively use its resources [1]. Various proposals focusing on in-situ resource utilization (ISRU) stem from this restriction. For example, Contour Crafting creates paste made from available lunar water, sulfur, and regolith and extrudes it in a layered fashion to produce the desired structure [2]. Solar 3D printing uses concentrated sunlight to sinter lunar soil layer by layer [3], and microwave processing allows for the melting of lunar soil for building and binding purposes [4]. In contrast, what if we could create infrastructure with minimal energy devoted to materials pre-processing, saving time and energy during construction? This study considers multiscale granular stacking (MSGS) as an answer.

MSGS is a technology for assembling planetary-surface infrastructure from unprocessed regolith particles. MSGS exploits resources from the local environment, in-situ regolith particles, to minimize materials, energy, and construction time. Today, structures are created only using binder material, sintering, and other technologies with high cost in mass and energy. In cases where binding capabilities are necessary for structural integrity, MSGS optimally uses adhesive and regolith in a way that exploits the in-situ particle distribution for long-term exploration objectives, especially in missions with limited resources. Compared to current approaches that use binder and other materials, this technology has the capability of building larger and a greater number of structures with lower energy and minimal mass sent from Earth.

A long-term lunar presence, and certainly permanent settlement, requires dedicated, large-scale infrastructure to support surface operations, including transportation, buildings, resource management, and other elements of scientific and commercial activities. MSGS addresses three issues that fundamentally limit the size of extraterrestrial structures in such a future:

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1) It uses minimal processing of in-situ material and thus maximizes the amount of structure that can be built with limited time and energy.
2) It minimizes the binding consumables, which are energetically expensive to fabricate or to transport.
3) It has a small manufacturing footprint; the required equipment can build structures that efficiently leverage the effort of transporting the equipment.

The grain-by-grain assembly of large structures, exploiting the shape, size, and chemistry of the regolith as it occurs in the environment makes these solutions possible.

The surface of the Moon is covered by a fine regolith, so that small particles are readily available. About 10% of the regolith is 1 mm or larger and would be suitable for reproducing detailed surfaces [5]. Larger, “hand-sized” regolith is seen scattered on the surface in available images. These rocks are likely the result of impact formation from micro-meteorites [6], and it is expected that, especially around larger craters, large particles should be readily available for MSGS construction. Ingenious basalt deposits are also available in the mare regions [5]. This suggests that appropriate regolith distributions exist for successful MSGS technology.

The process is similar to macroscopic (heatless) sintering, which currently produces some of the most sophisticated engineering materials. Sintering uses heat to bond powdered particles without completely melting them as in casting processes. As a result, many of the bulk properties of the constituent powders are retained, and specialized new materials are made by mixing high-performance constituent powders. As individual grains do not have to fully melt during the forming process, this process uses comparatively little energy. MSGS aims to replace the statistical forces that rearrange and attach individual particles during sintering [7] with deliberate planning and manipulation, and (where necessary) replaces heating-based bonding with the generic use of minimal adhesive. In contrast to Earth-bound sintering which pushes the envelope in terms of material performance, MSGS pushes the envelope of material efficiency in terms of energy, consumable resources, and support machinery to produce large-scale infrastructure projects.

Figure 1 shows a concept in which a robot assembles regolith particles of widely varying size. Because of careful placement, and thanks to a computational strategy that exploits multiple scales, the gaps are so small that adhesives can exhibit high tensile strength compared to familiar mortars without innovative chemistry. Simple salt solutions may suffice for the mechanical moduli sought here.

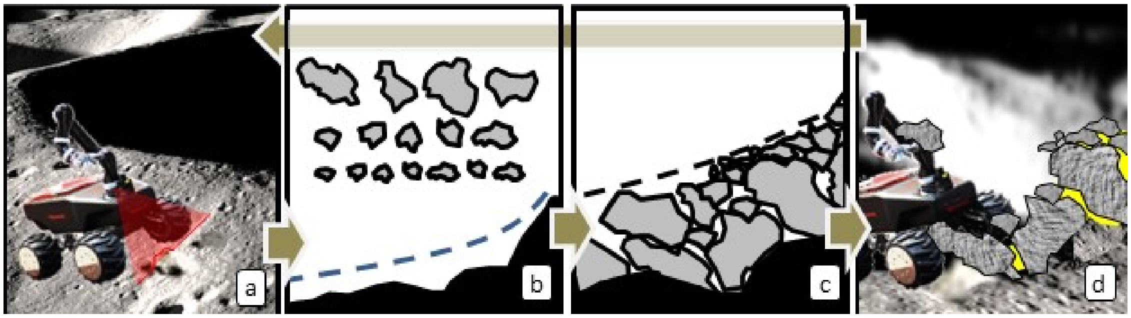

Fig. 1 Robotic assembly through Multiscale Granular Stacking. a) A mobile robot or other device scans the regolith particles available in the environment. b) A dynamic library stores digital representations of particles as part of a software-driven approach to achieving the objective structure (dashed line) given the current natural or build environment (dark surface). c) Digital representations are used to generate a short-term assembly plan that minimizes the need for additional binder, where possible, by using multi-scale dry stacking. d) A robotic system - some combination of rovers and a gantry - executes the assembly plan (binder application not shown) and repeats: it continues to update the particle library and measure the as-built structure as it approaches the desired shape. The result is a closed-loop fabrication process.

B. MSGS and Traditional Additive Manufacturing

MSGS is a complex, multidisciplinary research problem. Innovation in in-situ assembly and manufacturing (ISAM) is the goal, and additive manufacturing (AM) is the focus of the present study. Some novelties in the hardware realm require attention, but this study focuses on the synthesis of a controls approach. MSGS is, strictly speaking, an additive process. However, it does not fit within the defined seven families of AM. MSGS structure and operations most closely resemble the material jetting process, with some significant differences:

1) MSGS does not require a print bed. Using scanning technology, it can create a desired surface from an uneven base.
2) MSGS does not use support structures.
3) MSGS does not know available build material before construction (MSGS is adaptable and can seek out the next object for placement).
4) MSGS "print head" is a pick-and-place robot.
5) MSGS exploits pre-existing material features rather than depending on melting and other pre-processing measures.
6) Unlike material jetting, the MSGS objects are always solid when placed.

Thus, a by-product of MSGS research is that it has the potential to define a new family of additive manufacturing.

Traditional AM processes use feedback on low-level system variables such as machine temperature and material deposition rate to indirectly monitor builds. A study by Cohen and Lipson of a material jetting AM process shows that monitoring whole-part geometry through measuring locations near the most recent material deposition and building on the column with greatest difference to desired build height produces a more accurate build than typical AM procedures can achieve [8]. MSGS combines this same algorithmic approach with a linear time-invariant dynamic model of the fabrication process, enabling the straightforward tuning and determination of system performance through a robust and theoretical controls approach that is foreign in the AM realm. Since the contents of the MSGS "feedstock" are likely not known prior to construction, determining how to choose an object for the control input is of great importance.

II. Methods

A. MSGS Framework

Adapting prior work on 2D [9] and 3D [10] stacking allows the incorporation of heuristic methods from masonry instructional manuals [11] into simulation based, next-best assembly planning [7]. This approach achieves a 20% improvement in mechanical performance over the state-of-the-art in building self-stable structures [10]. MSGS provides a transition from this work to assembly planning of scanned regolith particles. One result is that, even though a final structure can be made up of millions or billions of particles, large-scale structures in final stages of construction with surface-finish requirements and the construction of small-scale structures can proceed with a small pool of next possible assembly objects. After each step, the new structure is rescanned and the pool is replenished. So, it is feasible to scan and maintain a library of available regolith particles during construction, drastically simplifying the memory and computational requirements of selecting the next assembly step. This approach also limits the need for long-range pose prediction using simulation, which is unlikely to yield satisfactory results as it depends on unknown, microscopic, regolith surface features. By adding a small amount of binder to fill voids, the strength of these already stable structures can be vastly improved. A key insight is that a generic dry-stacking method can be run at different scales so that the use of macroscopic stones or bricks (a familiar approach) can provide the bulk of the structure, and “stacking” microscale particles can provide better surface quality and fill in gaps (reducing binder material usage). This approach has the potential to minimize the amount of glue and produces a spectrum of mission options: if more glue can fill in gaps, the planning is simpler at the cost of consuming more glue-like material per unit volume.

Not all desired structures are small in scale or in need of high quality surface-finish, in which case large grains and rocks would be ideal for construction. Thus, object selection from sources other than the pool of possible assembly objects must be possible since it is impractical to transport such large objects. This case of object selection is closely related to a form of the NP-hard knapsack problem. The classical knapsack problem involves a set of n items with each j item assigned a (usually integer) profit p_j and a (usually integer) weight w_j. All parameters are known a priori. The problem seeks the subset of items with maximum profit that does not exceed the specified weight limit of the knapsack [12]. An extension of this classical knapsack problem is the dynamic and stochastic knapsack problem (DSKP) which encompasses the essence of MSGS assembly object selection. The DSKP involves Poisson process item arrival with the profit and weight unknown prior to arrival. A knapsack with known weight capacity is to be filled with maximum profit, not exceeding the weight capacity. As items arrive, they may be accepted or rejected - accepted items provide profit, rejected items incur penalty. Lastly, a deadline is set such that once reached, items will no longer be accepted [13].

MSGS object selection is similar to the DSKP in that the desired structure with dimensional constraints is analogous to the knapsack with weight constraints. In the case where large objects are needed that are not housed in the pool of available assembly objects, information about object parameters is unknown until object arrival. Thus, a decision must be made upon arrival if the object is accepted or rejected. An accepted object contributes to construction, while a rejected object incurs a time penalty - another assembly object must be found and considered. MSGS is unique in that it has millions of potential objects for building. Therefore, consideration of all objects is impractical. In fact, an optimal build plan is virtually impossible to determine and of little value. The DSKP reveals that a solution that meets requirements can be obtained. However, this analysis does not consider the necessary object configuration requirements of MSGS. Instead, classical feedback control using error metrics specific to the continuously updated structure allows a single particle or a small number of particles, to be placed at each step, obviating the need for an optimal plan.

B. MSGS Modeling Approach

MSGS will operate in space environments with very low process control. The lunar surface is rocky and uneven, providing virtually no locations where building can occur on a naturally flat surface. Thus, MSGS must be able to build a desired structure from an uneven surface. Furthermore, the lunar surface consists of orders of magnitudes of non-uniformly distributed grains from dust to boulders, all uniquely shaped. Measuring these intricate objects inevitably introduces sensor noise, and stacking these grains must result in unpredictable internal movement and settlement due to the minimization of materials pre-processing measures and binding capabilities. Lastly, there is inevitable breakage and crumbling of the grains after being packed in the structure, which alters the overall build in an unknowable magnitude. For all of these reasons, MSGS departs from purely combinatorial solutions and, instead, exploits feedback.

As described previously, monitoring whole-part geometry in a material jetting process by measuring error in defined columns or other forms of shape classification throughout the build produces a more accurate build than typical AM procedures can achieve [8]. MSGS will ultimately combine this method of monitoring whole-part geometry through tracking build performance with algorithmic approaches such as that described in the DSKP. Thus, system convergence, build time, overall error, and other parameters of interest can be calculated through studying the dynamic model stability, damping and overshoot, rise time, and steady-state error - a feat for a system with such low process control. Furthermore, modeling the build process as a dynamical system allows for easy tuning of surface finish, build contour smoothing, and other desired qualities.

III. Results

A. MSGS Dynamic Modeling

The MSGS process is modeled as a discrete-step problem, where each step corresponds to a new object placement. Typically a discrete-time system assumes uniform stepping in time. Here, time is not of direct interest. Instead, these discrete steps represent discrete placements of additive material. Likely, the simplest example is that of a single column in one dimension, where column width is irrelevant. This model gives rise to single degree-of-freedom feedback-control architecture where overall part geometry consists of a single scalar, the column's height. Ideally, the column will reach the desired height without overshoot using blocks of a height selected by the feedback control input. An error state, x_n, is used to represent the difference between the current height and the desired height. The dynamics are modeled with state equation

$$x_{n+1} = Ax_n + Bu_n \tag{1}$$

and output equation

$$y_n = Cx_n \tag{2}$$

with

$$A = B = C = 1. \tag{3}$$

A = 1 guarantees stable geometry, B = 1 demonstrates a strictly additive input with stable building elements, and C = 1 reveals the surface geometry is observable. The control input is

$$u_n = -Kx_n. \tag{4}$$

Control synthesis with a linear quadratic regulator provides the proportional gain $K = 0.6559$ with fast convergence rates weighted more heavily than aggressive input: a 5:4 ratio. A performance goal is to eliminate overshoot, which would result in multiple cycles of adding and subtracting material: wasteful and time consuming, but also difficult to implement if binder is used. The closed loop dynamics matrix

$$A_{closed} = A - BK \tag{5}$$

is used to find the closed loop eigenvalue $\lambda = 0.3441$. Given that this value lies within the unit circle, asymptotic stability is guaranteed. The pole-zero map shown in Figure 2 reveals that the system has critical damping and therefore no overshoot, meeting specified requirements. The root locus in Figure 3 reveals that a gain of up to 2.05 results in a stable system, but this range does not necessarily meet damping and overshoot requirements.

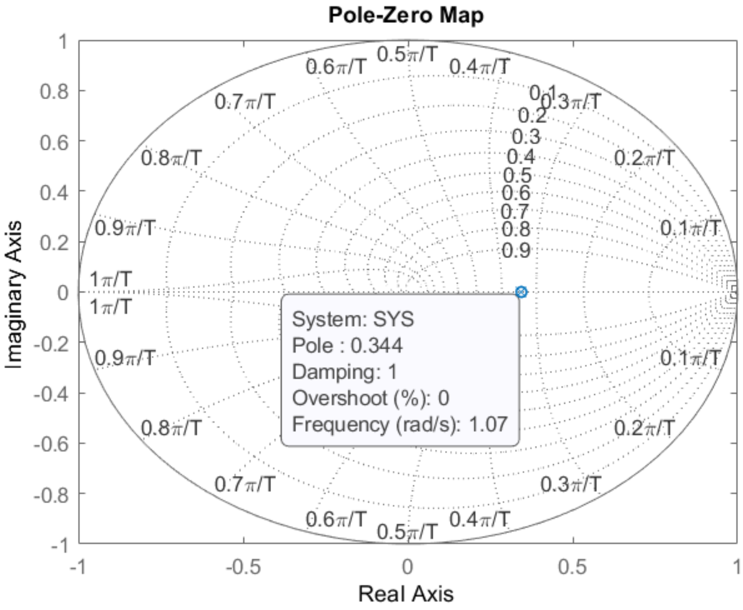

Fig. 2 **Pole-zero map for single column build process shows asymptotically stable system with critical damping.**

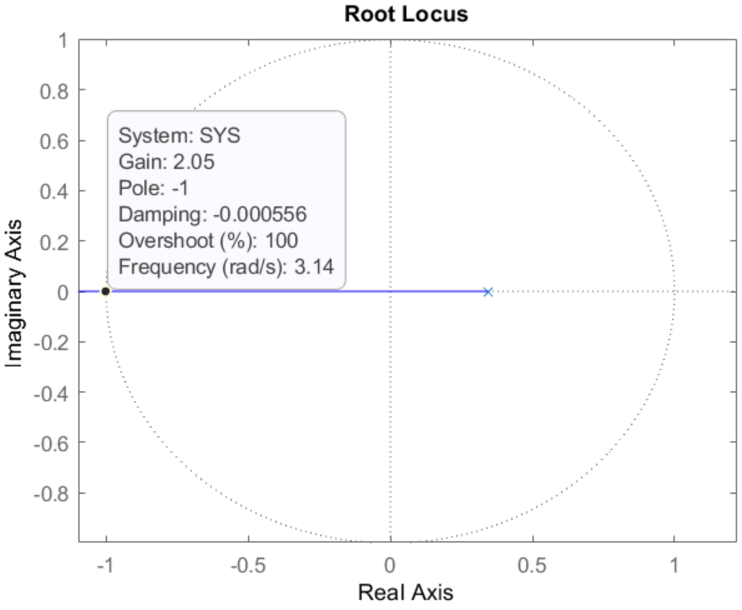

Fig. 3 **Root Locus for single column build process.**

The system is stable and thus the steady-state error, E_{ss}, in response to a step input, $R(z)$, can be calculated.

$$\frac{E(z)}{R(z)} = \frac{1}{1+\frac{K}{z-1}}$$

$$R(z) = \frac{1}{1-z^{-1}}$$

$$E_{ss} = \lim_{z \to 1} (1-z^{-1})E(z)$$

$$E_{ss} = \lim_{z \to 1} (1-z^{-1}) \frac{1}{1+\frac{K}{z-1}} \frac{1}{1-z^{-1}} = 0 \tag{6}$$

The calculated asymptotic stability, critical damping, and zero steady-state error reveal that the column fills up with objects decreasing in size with each step and zero overshoot. Simulation, shown in Figure 4, confirms. Here, the initial height was set to ten units below the desired final value.

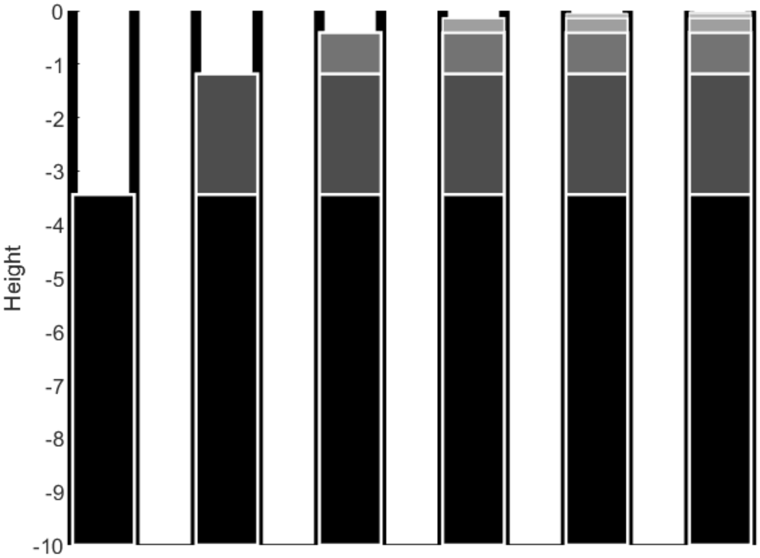

Fig. 4 Build progression of one-dimensional column modeled as dynamic system. Left to right, columns represent current height after input.

With the ability to select the exact object height for placement, it may seem unnecessary to incorporate feedback into the system when the desired height of the column can be matched with one object. However, when process noise and part uncertainty are included in a scenario more closely resembling MSGS conditions, it is immediately apparent that feedback is necessary. Figure 5 shows that all of the closed-loop results are acceptable while the majority of the open loop results are unacceptable.

This one-dimensional problem can be extended to a multiple degree-of-freedom (MDOF) model, one comprising three columns. In addition to specifying the height of each column, we create another control objective: a level surface for building throughout the fabrication process, which provides greater range for object placement and helps address a situation where the columns begin at uneven heights or a situation where they increment at different rates. In any case, this additional measurement helps illustrate the synthesis of an MDOF controls approach. The deviation of each column from the average is combined into a single scalar and used as a measurement in the feedback control. An error state, $\vec{x}_n$, is used to represent the difference between the current height and the desired height. The dynamics are modeled with state equation

$$\vec{x}_{n+1} = A\vec{x}_n + B\vec{u}_n \tag{7}$$

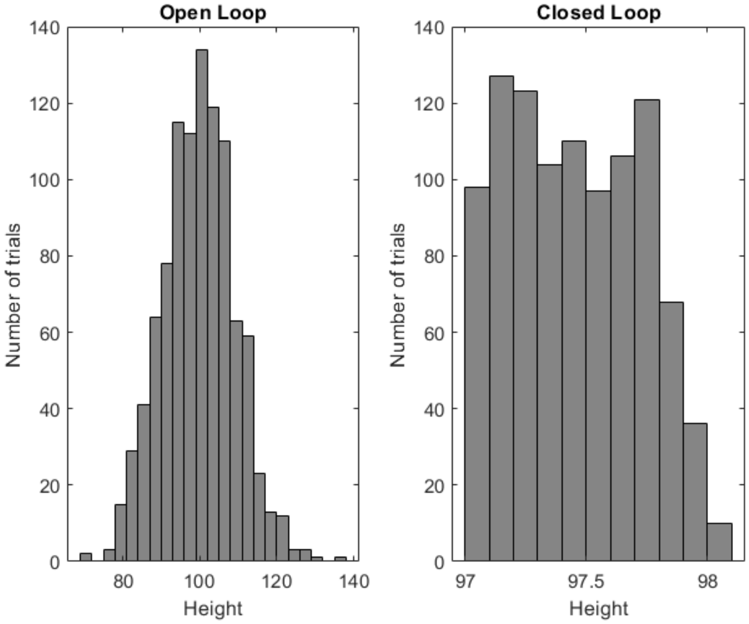

Fig. 5 A column of height 100 is desired with a 97% acceptable accuracy bound on overall height. The open loop system is compared to the system with feedback, both including a multiplicative white noise model of mean $\mu = 1$ and standard deviation $\sigma = 0.1$.

and output equation

$$\vec{y}_n = C\vec{x}_n \tag{8}$$

where

$$A = B = C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{9}$$

The control input is

$$\vec{u}_n = -K\vec{x}_n, \tag{10}$$

and

$$K = K_p \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + K_a \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{-1}{3} & \frac{2}{3} \end{bmatrix}. \tag{11}$$

The proportional gain, K_p, and the average gain, K_a, can be tuned to reflect the relative importance of build speed and creating a smooth build surface throughout the fabrication process. For example, $K_a = 0$ reflects that smoothing is unimportant, and higher magnitudes reflect greater importance of smoothing. The simulation shown here analyzes a case where $K_p = K_a = 0.4$ is chosen to signify that both build speed and build contour smoothing are of similar importance. The eigenvalues of the system, $\lambda_{1,2} = 0.2$ and $\lambda_3 = 0.6$, reveal asymptotic stability. The pole-zero map in Figure 6 shows that all poles provide critical damping and zero overshoot, consistent with system requirements. The simulation in Figure 7 illustrates a comparison of this system to that without an averaging term.

The presented examples are initial steps in the introduction of theoretical controls to the AM realm. The dynamics mimic one-dimensional object placement of selected height in an asymptotically stable fashion towards a desired build height. Critical damping and zero overshoot are desired so that a placed object will never need to be removed - an awkward scenario for MSGS if binding capabilities are included. In the lunar setting, regolith particles have irregular shapes and various sizes, which motivates future work extending these simple case studies. Expanding this controls

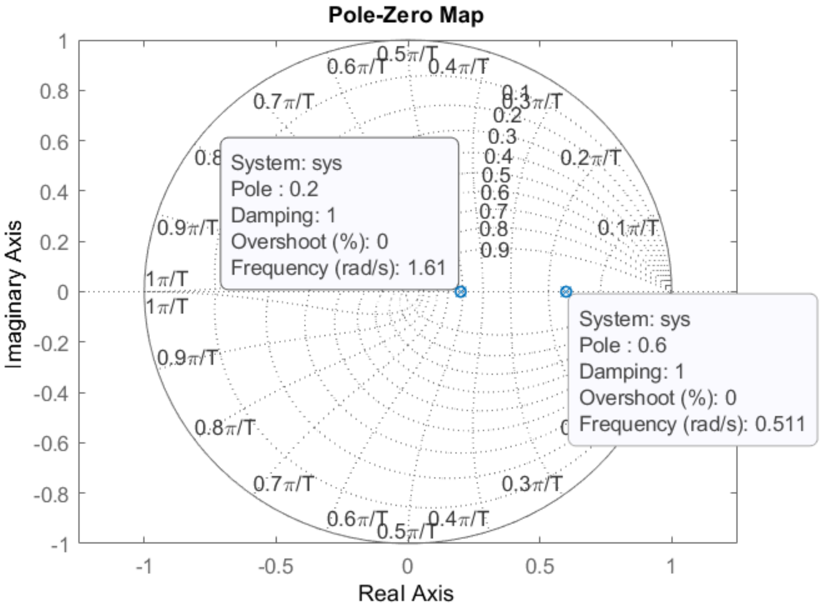

Fig. 6 Pole-zero map for two dimensional build process shows asymptotically stable system with critical damping.

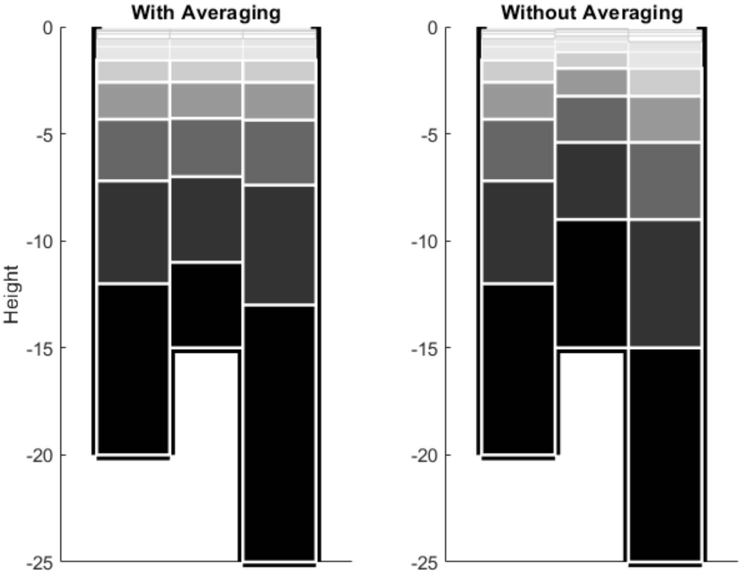

Fig. 7 Three columns are started at different heights below the desired height (zero) to represent a build starting on an uneven surface. Left: system with $K_p = K_a = 0.4$, an approximately smooth surface spanning all three columns is achieved after the third input. Right: system with $K_p = 0.4$ and $K_a = 0$, a smooth surface is not achieved until final input. Both cases result in desired height with no overshoot.

problem to achieve the goal of MDOF-MSGS for arbitrary shapes includes object placement that spans multiple columns, object choice restricted to a finite amount of irregularly shaped objects, and sensor noise. Also necessary are minimizing steady-state error, achieving zero overshoot, allowing for various tuning parameters, and as builds get more complex, establishing an appropriate rise-time. Thus, the ability to apply controls theory by modeling the dynamics of these more complex systems gives rise to a new capability: specifying AM build parameters with mathematical guarantees.

B. MSGS Capabilities

A human mission to implement a kilometer-scale optical system on the Moon requires a large primary optic and standoffs to support a secondary. An immediate benefit of MSGS is that it provides insight into the tradeoff between surface quality and construction effort for such systems. If approximate structures are acceptable, multiscale granular stacking can be combined with such components at longer scales. Such "utility structures" could frame large-scale infrastructure such as standoffs and optimally exploit existing grains of regolith, from dust to boulders.

As an example, consider a long lunar runway fabricated by MSGS. While other examples — a paraboloid radio telescope on the dark side or a habitat foundation—may be equally compelling, the runway plays a unique, transformative role in sustained human exploration. The reason is that it all but eliminates the propellant that a lunar lander typically consumes to land on the lunar surface in Apollo Lunar Module style: the equivalent of roughly 2000 m/s in delta-V. Airbags and crushables can reduce this propellant mass by a small fraction, but consider instead deceleration through a simple, mechanical braking system reminiscent of aircraft. Landing at low-lunar orbit rate (approximately 1640 m/s), a 20-metric ton vehicle must dissipate 26.7 GJ of kinetic energy through this sort of mechanical braking. With a coefficient of friction μ=1, stopping such a vehicle in lunar gravity requires a roughly 800 km runway and 16 minutes of deceleration at a constant 0.17 g_c (where g_c is Earth gravity). The average thermal power dissipated through the brakes during landing is about 27 MW, which is less than required by the Concorde's braking system. This technology brought the 188 MT Concorde aircraft to a stop by dissipating roughly 40 MW through brakes that heated up to 500°C and required several hours of cooling afterward. So, this specific architecture is within familiar technological limits.

MSGS could fabricate such a runway as a straight line, extending across a significant portion of one of the lunar mare, or as a banked spiral of similar length [14]. Considered here is a conservative 800 km long runway (50 m wide and 0.3 m thick runway, as for a typical commercial airstrip). The total mass of such a runway is about 18 million MT. If MSGS can achieve a target of 100 kJ/kg energy investment, 100 robotic MSGS devices could assemble such a runway in 18 years. Each of these robots would be powered by a 100 kW solar array (with 31.8 kW available, on average, during the lunar day), which is only about double the beginning-of-life capability of $10M solar arrays on today's commercial geosynchronous spacecraft. While such an architecture is certainly a reach at present, this sort of infrastructure will become commonplace in a future of sustained human presence on the moon if a suitable fabrication approach, like MSGS, is available.

C. MSGS Performance

It is apparent that MSGS is possible in principle from terrestrial examples of useful structures such as dry-stacked walls (i.e. built without mortar). Conducted was a preliminary study of automatically creating assembly plans for such structures [15], which significantly advances the state-of-the-art for dry stacking strategies by planning large stable structures instead of a few stable rocks [16]. A result of the exploration was that certain parameters of the regolith shape critically affect the outcome of the built structures, e.g. regular shapes are much easier to assemble into strong structures and also a mix of small "wedge stones" and large ones results in better structures. Thus, it is suspected that minimal processing in addition to dry stacking can result in even better structures, i.e. planning an assembly with unprocessed regolith and then using adhesive or traditional additive manufacturing to make customized wedges to provide good bonds. The result of such a hybrid structure where large-scale planning uses unprocessed materials and local attachment planning uses additive manufacturing is significantly better than either method alone. The material bulk of the structure would not require processing of any sort, and limited resources would be consumed by only a small fraction of the final structure.

This approach suggests that there is a fundamental tradeoff between resource consumption and structure quality. MSGS requires a careful study of this tradeoff in the context of planetary surface regolith. Studies on the size distribution of regolith show that a variety of shapes and sizes are readily available [17] so that a construction plan should depend on the expected types of regolith. For example, building a large paraboloid reflector requires exploiting an existing crater (analogous to the Arecibo radio telescope), using large regolith to build an approximate shape and then using successively smaller scale regolith to assemble increasingly accurate shape representations. By carefully orienting individual particles, a surface resolution below the length scale of regolith particles can be readily achieved, as is common in dry stacked walls.

Preliminary estimates predict at least 50% savings in binder material, around 200% increase in the material moduli, and a reduction in mass sent from Earth by an order of magnitude. The energy cost of MSGS in comparison with traditional sintering (between about 20 and 8000 MJ/kg) is extremely low and is expected to be well below 1 MJ/kg, perhaps 100 kJ/kg [18]. The main reason is that no thermal energy is required to achieve the high mechanical performance, and the use of naturally occurring grain sizes significantly reduces the energy cost of laying down material. These compelling performance numbers come with a downside: the assembly process is slow, for both mechanical and computational reasons (again, by an order of magnitude). However, the speed of fabrication for pre-placement of exploration structures is far less a driver than for familiar, terrestrial manufacturing. Low speed translates to low power, which means less mass required for energy storage and power distribution, lower mass of solar panels or surface nuclear power, etc.

Returning to the lunar runway described previously as an example, 12,000 m^3 of concrete, the amount necessary for construction, is approximately 27,600,000 kg [19]. 100 robotic MSGS devices weighing a maximum of 200 kg each equates to only 20,000 kg, or about 0.073% of the mass of necessary concrete. Furthermore, a pick-and-place robot (PUMA 560 - cyclic path following a 3D cubic spline) was found to operate on a range of 15-33 J/kg per cycle [20] which amounts to significantly less than the 20-8000 MJ/kg sintering requires [18]. Thus, implementing MSGS drastically reduces the transported mass and energy consumption.

IV. Conclusion

In a future where we explore our solar system with an eye toward permanent settlement, we will have to live off the land and effectively use its resources [1]. MSGS aims to minimize materials, energy, and construction time by exploiting the natural shape and variation of in-situ regolith particles and avoiding materials pre-processing measures that are necessary in other lunar infrastructure proposals. For this AM technique to demonstrate the expected versatility and effectiveness, the computational approach must be orders of magnitude more capable than the state-of-the-art. First steps toward modeling the fabrication process as a dynamic system promise to offer a theoretical and robust approach that is absent in traditional AM processes. This robustness arises thanks to decades of theoretical development of feedback control, which we have shown can translate to an AM process in simple, motivating examples. It is hoped that these preliminary results will guide future technological developments to produce maximal impact on the overall MSGS system. In the near term, even a base-level capability in MSGS has the potential to be transformative, as it allows the creation of utility structures in many environments. Advancing the technology readiness will result in higher quality, more versatile structures, enabling a sustainable future for humans as a spacefaring species.

Acknowledgments

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