Manipulation Challenges of Robotic Lunar Construction With Regolith-Filled Sandbags

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***Abstract*—One proposed approach for lunar habitat development is the assembly of structures by stacking regolith-filled sandbags, for radiation shielding and structural support. This paper presents an overview of the key robotic manipulation challenges associated with the autonomous sandbag handling. A representative "Lunar Sandbox" experimental testbed is introduced to investigate these challenges. The study focuses on three principal areas: perception, manipulation, and planning. Perception challenges arise from extreme illumination conditions, high light-shadow contrast, and texture blending between ground and sandbag. Manipulation difficulties stem from the deformable nature of sandbags and the shifting distribution of granular material, leading to uncertainties in grasp stability and dynamic behaviour. Planning challenges include environment-aware placement, task sequencing dictated by structural architecture, and localisation and mapping as the habitat evolves. This work establishes foundational requirements for autonomous robotic systems capable of constructing sandbag-based lunar habitats and outlines directions for future research toward higher technology readiness.**

***Index Terms*—component, formatting, style, styling, insert**

I. INTRODUCTION

The success of Artemis I and II missions has reinvigorated humanity's efforts to establish a lunar base. There exist multiple architectures proposed for constructing the lunar base [1], with some examples including using inflatable compartments, 3D-printed processed regolith, and existing lunar caves. One notable approach is the assembly of a habitat made of regolith-filled sandbags [2] [3]. In this concept, the habitat is either made completely out of sandbags, or the sandbags provide an external layer of sheltering. Constructing a habitat on the lunar surface is a difficult task for astronauts, and so assembling the first habitats is a task more suitable for robots. This makes the need for developing all the relevant robotics and automation capabilities for building the sandbag-based habitat necessary. The aim of this paper is to provide an overview of some of these capabilities that a robot would need to develop for handling regolith-filled sandbags, and describe the relevant challenges. It should be noted that the list is not exhaustive, and the paper does not aim to describe hardware or engineering challenges related to the sandbag manufacturing and qualification for lunar surface, or the hardware engineering challenges of the handling robotic system [4]. The engineering challenges of filling the sandbags with regolith are also out of the paper's scope, with existing work providing solutions for this [5] [6]. Instead, the paper focuses on describing the robotic handling, visual estimation, and robotic planning challenges that a robot would face under the assumption that it is presented with regolith-filled sandbags to stack as a structure. The paper also describes our existing setup for current research on tackling these fundamental challenges.

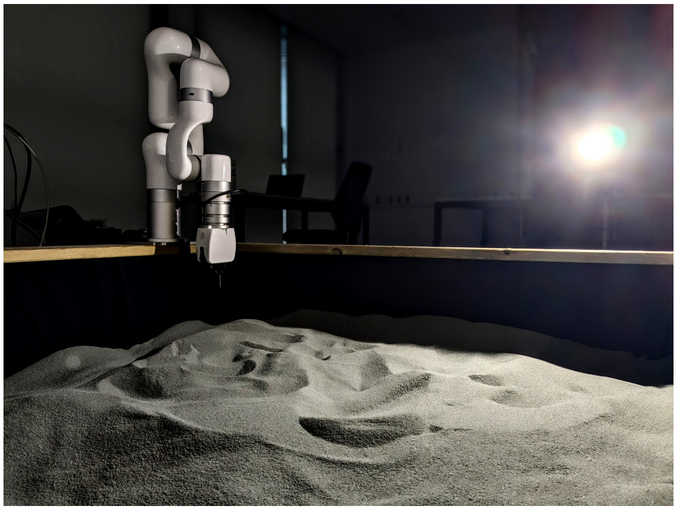

Fig. 1: The Lunar Sandbox used for the experiments of sandbag-based construction, consisting of a 6-DOF robotic arm, 120 kg of grey sand, and spotlight.

II. SETUP

Our setup consistsof a 1.5 x 1.5 meter wooden sandbox, filled with 120 kg of grey sand, to visually resemble lunar regolith. The sand has a grain size of 0.1-0.3 mm, similar to table salt. We are using a uFactory xarm6 with a 2-finger gripper for grasping, mounted on the sandbox. The sandbox is illuminated by an LED spotlight at 6000K, to simulate sunlight on the lunar surface. We have 2 types of sandbag "bricks": the first consists of resealable 70 x 100 mm poly bags, which weigh around 0.25 kg when filled. The second type is 70 x 350 mm poly bags, weighing around 0.9 kg when filled. The smaller sandbags were selected to fit within the 85mm opening length of the gripper, and to

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enable stacking of various architectures, useful in vision and planning experiments. The larger sandbags were selected to offer increased payload (about 18% of the maximum robot payload) and larger deformations while grasped, which creates the conditions for dynamic handling experiments. Fig. 1 shows the sandbox with arm.

III. CHALLENGES

A. Perception

Perception challenges in lunar robotics are related to the high contrast between illuminated and shaded areas, variable illumination angles from sunrise to sunset, and lack of texture due to the uniformity of lunar regolith.

1) Variable contrast: Depending on the sunlight angle, different parts of the sandbag may be illuminated or shaded, which affects the perception of the sandbag shape. Fig 2 shows how shadows affect the perceived sandbags over a low illumination angle with the sun behind the camera (Fig. 2a), high illumination angle (Fig. 2b), and low illumination angle with the sun in front of the camera (Fig. 2c). The harsh shadowing introduced by the variable illumination angle can lead to perception errors in the volume, shape and texture of the sandbags by the vision subsystem.

2) Texture blend: Visual texture blend can manifest as bag-to-bag, or ground-to-bag. Bag-to-bag blend refers to the uniform texture of a sandbag throughout its length interconnecting with the texture of another sandbag. This can make segmentation of sandbags in a stack difficult, and is exacerbated by the lighting conditions. An example is shown in Fig. 3 where the scene is passed through the Meta Segment Anything model [7]. While the sandbags on the top seem to be segmented accurately, there are texture-blend segmentation errors towards the bottom and sides of the stack.

Ground-to-bag texture blend refers to the difficulty in segmenting the bag from the lunar surface. This is an issue if the bag is of similar colour to the lunar surface, or during the lunar night when ground and bag would appear indistinguishably dark. The bag texture and colour should be selected to avoid texture blend, with visual markers highlighting the end of the sandbag.

Dealing with these challenges would be suitable for AI-based segmentation, reconstruction and pose estimation algorithms. As a first step, we plan to extract a dataset of images of stacked sandbags under variable light intensity and light angles, to test the robustness of segmentation algorithms.

B. Manipulation

Challenges in sandbag manipulation are related to the grasping of the soft bag, the variable dynamics of the bag while handled, and the robot arm control.

1) Sandbag grasping: Grasping the sandbag is crucial, as choosing a suitable grasping point affects not only the motion dynamics, but also the planning for structure building [8].

One of the most important challenges of grasping a filled sandbag, is that contact of the end-effector with the bag shifts the sand inside. In our testbed, this is amplified due to trapped air in the poly bags, but this manifests in space due to the bag material elasticity. This sand shifting would alter both the initial finger-bag contact point, and the contact force vector and magnitude. In the absence of slippage and force control, these effects could result in loss of contact.

The grasping process would vary according to the choice of end-effector and subsequently the grasp configuration. A multi-contact end effector, like a robotic hand or clamp, would require the generation of multiple contact points on the sandbag surface. A single-contact end effector can be realised with the existence of a docking point on the sandbag, like a magnetic tag. A supporting or engulfing grasp (as with the use of a spade or claw) would provide more secure grip with no bag deformation, however this may result in end-effector contact with the underlying stack during the unloading process.

It is evident that the grasp generation algorithm needs to take these issues into account when synthesising contact points, along with any planning constraints arising from the positioning of the sandbag.

2) Manipulator control: The manipulation challenges come from the variable dynamics of the sandbag due to its soft object nature.

The sandbag is a soft object filled with granular material. While the total mass is constant, the mass distribution can constantly shift because of the bag sagging under gravity when lifted up. This is shown in Fig. 4, where the bag is sagging from a straight rectangle by an angle of $\Delta\theta$. This sag is difficult to estimate and predict. The robot would need to manipulate an unknown payload, which can induce vibrations and affect positioning accuracy, especially in cases of a low robot-mass-to-payload ratio. This effect would be mitigated with the implementation of adaptive control during transportation [9], or by using an augmented dynamics model with uncertainties [10] [11].

In addition, vacuum and lunar gravity would affect the soft-body dynamics of the sandbag compared to terrestrial dynamics when lifted and transported. This effect can be approximated on Earth by offloading some of the sandbag weight when using an active response hanging system.

In addition to position and adaptive control, the robot should have force or compliance control capabilities to ensure soft contact with the ground or other bags. The robot would require levels of autonomy that enable it to switch between control modes seamlessly.

C. Planning

The planning challenges are mostly dependent on the architecture of the built structure, the task sequence for building the structure, and the autonomy and decision making related to the placement location of the bags.

1) Environment planning: While the habitat location would have been selected prior to the robot arrival, the robot would still need to plan for local features while it lays the sandbags. Fig. 5a from the Apollo 12 mission shows a mixture of large, sharper rocks with finer regolith. Larger protruding rocks could risk a puncture on the sandbags. Placement of heavy bags on


(a) (b) (c)

Fig. 2: Changes in the shaded and illuminated areas under variable sunlight angle. (a) Low sunlight angle, behind the camera (b) High sunlight angle, on top of the structure (c) Low sunlight angle, in front of the camera


Fig. 3: Visual segmentation of individual sandbags while stacked on the structure. Texture blend can lead to incorrect segmentation, as shown on the bottom left side of the structure.

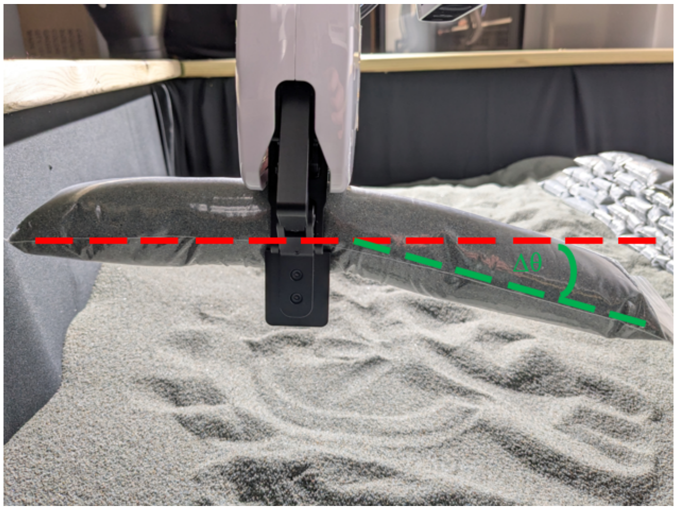

Fig. 4: Distortion caused by soft bag material and gravity. This distortion can vary the mass distribution and dynamics of the bag, leading to placement errors and inaccurate motion.

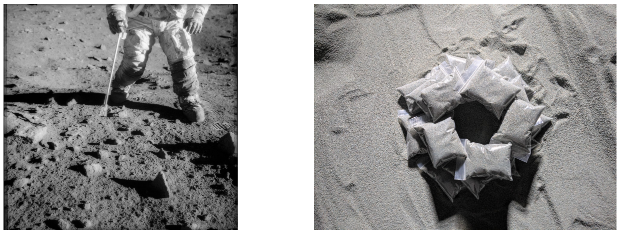
(a) (b)

Fig. 5: (a) Lunar ground as photographed by the Apollo 12 crew. Distinctive ground features should be avoided when laying the sandbags. Image by NASA. (b) A dome-shaped structure. The habitat architecture influences manipulation planning.

loose regolith should also be performed with care, to avoid dust generation.

2) Task sequence planning: The architecture of the habitat would influence the overall manipulation planning. Fig. 5b shows a dome-type structure under construction. Larger sandbags would be placed as foundation, with the structure becoming lighter as it progresses higher. Heavier sandbags require more crude handling, while lighter sandbags would require precise manipulation and softer contacts. To accurately place the bags next to and on top of each other without gaps, the robot would need increased autonomy, planning, and error correction capabilities. Structural and strength analysis of the ground and bag-contact could enable the robot plan for this [12] [13].

3) Localisation and mapping: As the structure grows bigger, the robot would need to keep track of both the structure progress and its positioning within it. The lunar robot would need to create and update a map of the structure, and keep track of its position within the structure. This would require planning capabilities similar to mobile robots that perform SLAM in unknown environments.

IV. CONCLUSION

The paper describes some of the robotic manipulation challenges of constructing a habitat from regolith-filled sandbags on the Moon. The main challenges are related to perception, handling dynamics, and task sequence planning. Our current research will provide solutions to these identified challenges initially. Future work would attempt to deal with the engineering challenges of inserting the regolith to the sandbags, qualifying the sandbags, and raising the TRL of the whole approach through representative experiments and tests.

REFERENCES

[1] H. Benaroya, “Lunar habitats: A brief overview of issues and concepts,” *Reach*, vol. 7, pp. 14–33, 2017.

[2] C. S. Dickinson, F. N. Shi, K. Vasudeva, R. M. Mukherjee, J. Blanchard, S. Dubrule, J. Empey, J. Kugler, P. Maghoul, A. J. Ryan, *et al.*, “A pathfinder lunar construction mission concept using regolith filled bags,” *Aerospace*, vol. 13, no. 3, p. 223, 2026.

[3] K. Vasudeva and M. R. Emami, “Lunar robotic construction system using raw regolith: Design conceptualization,” *Aerospace*, vol. 12, no. 11, p. 947, 2025.

[4] A. Thirupathi Raj, J. Qiu, V. Vilvanathan, Y. Xu, E. Asphaug, and J. Thangavelautham, “Systems engineering of using sandbags for site preparation and shelter design for a modular lunar base,” in *Earth and Space 2022*, pp. 904–919, 2022.

[5] A. Antonic, S. Muniysamy, A. Dinkel, C. Dickinson, R. Mukherjee, and J. Thangavelautham, “Smart regolith containment units (rcus) for lunar pioneer development,” in *AIAA AVIATION FORUM AND ASCEND 2024*, p. 4866, 2024.

[6] G. A. Smithers, M. K. Nehls, M. A. Hovater, S. W. Evans, J. S. Miller, R. M. Broughton Jr, D. Beale, and F. Kilinc-Balci, “A one-piece lunar regolith bag garage prototype,” tech. rep., 2007.

[7] A. Kirillov, E. Mintun, N. Ravi, H. Mao, C. Rolland, L. Gustafson, T. Xiao, S. Whitehead, A. C. Berg, W.-Y. Lo, *et al.*, “Segment anything,” in *Proceedings of the IEEE/CVF international conference on computer vision*, pp. 4015–4026, 2023.

[8] O. O. Kadiri, M. Annis, I. R. Higgon, and K. A. McIsaac, “Synbag: Synthetic training data for autonomous grasping of regolith bags in the lunar environment,” *Aerospace*, vol. 13, no. 2, p. 204, 2026.

[9] P. Zhou, J. Qi, H. Wu, C. Wang, Y. Chen, and Z. Zhang, “Bagit! an adaptive dual-arm manipulation of fabric bags for object bagging,” *IEEE Robotics and Automation Letters*, 2025.

[10] O. Khatib, “Augmented object and reduced effective inertia in robot systems,” in *1988 American Control Conference*, pp. 2140–2147, IEEE, 1988.

[11] N. Mavrakis, R. Stolkin, L. Baronti, M. Kopicki, M. Castellani, *et al.*, “Analysis of the inertia and dynamics of grasped objects, for choosing optimal grasps to enable torque-efficient post-grasp manipulations,” in *2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids)*, pp. 171–178, IEEE, 2016.

[12] Y. Xu, S. Muniyasamy, C. Doe, and J. Thangavelautham, “Structural analysis of sandbag topology for lunar environment utilization,” in *Earth and Space 2024: Engineering for Extreme Environments*, pp. 463–473, 2024.

[13] M. Singh, *Construction Technique and Strength of Connected Regolith Bag Structures*. PhD thesis, 2007.