Autonomous System Operations for Lunar Safe Haven Establishment and Sustainment

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To enable a sustainable, permanent human lunar presence, NASA must provide a safe haven shelter to protect astronauts and equipment from radiation, thermal extremes, and micro-meteoroids (MM). Planning and development for a robust Safe Haven includes an examination of NASA activities in site preparation, excavation, regolith transfer, surface operations, autonomous monitoring and maintenance, advanced manufacturing, and in-situ resource utilization (ISRU) for identifying the best approaches when implementing a safe haven shelter. These NASA activities were reviewed as a part of a trade study conducted at NASA Langley to assess technological needs and estimated technology readiness levels (TRL). This paper presents a thorough review of the role and level of autonomy in the establishment and sustainment operations of a Lunar Safe Haven.

I. Introduction

Returning to the moon under the Artemis program, NASA is increasing efforts to utilize state-of-the-art technologies and develop means to protect astronauts and equipment. The Lunar Safe Haven (LSH) seedling trade study was a one-year effort funded by the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program to perform comprehensive investigations of shelter designs, operations, and advanced technologies establishing and sustaining a protective shelter for crew and equipment [1]. Consistent with NASA's "Artemis Plan" [2] the study defined high-level requirements, ground rules, assumptions, and parameters to guide and assess conceptual shelter designs and operations. Key technological requirements and objectives include but are not limited to:

- Shield crew, electronics (such as computers providing command and control of autonomous systems), and other exploration and habitation systems that require radiation shielding for at least ten years
- Protect crew, electronics and other systems from the hazards of the lunar environment, including but not limited to micro-meteoroid impacts, thermal loads, seismic activity, electrical charging, dust, vacuum, sun, and other LSH external assets that could cause collisions or ejecta for at least ten years
- Minimize crew involvement during establishment and sustained operations
- Minimize negative impacts to crew performance, habitability, and safety requirements
- Maximize the utilization of in-situ resources, including both natural and repurposed resources
- Identify and define necessary surface equipment concepts to emplace, assemble, and/or construct the shelter
- Technologies shall be ready to be deployed and operational on the lunar surface by 2026
- Maximize evolvability and Mars extensibility of the conceptual operations and systems
- Balance resiliency and robustness of LSH systems
- Ensure compatibility with NASA's lunar lander systems
- Minimize investment costs

The study identified sixteen concept alternatives for the LSH shelter establishment and sustainment systems. Concept alternatives were evaluated using decision attributes selecting the Baseline Concept 1.1A shown in Fig. 1. The structure is designed with a metallic frame delivered from Earth, assembled on the lunar surface, and covered in three to seven meters of bulk regolith. Establishment and sustainment systems for the shelter include various mid to high TRL autonomous systems. The baseline concept uses semi-autonomous agents where operators give mission-level commands

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Fig. 1 Lunar Safe Haven Baseline Concept 1.1A cutaway view. Structure shown is notional and for illustration purposes.

and the agents autonomously navigate, path plan, and monitor work progress. The study concluded by suggesting that autonomy technologies and software be allowed to evolve through continuous improvement practices, development, strict software management processes, and on-line learning algorithms.

Through technical innovation autonomous systems have the potential to enable safer lunar operations, require less crew involvement, and address high latency control of distant systems. This paper focuses on autonomous systems and operations to establish and sustain the Lunar Safe Haven shelter. Section II details a general lunar autonomous framework to provide structure for one or more complex autonomous systems. Mobile agents must also be capable of navigation, communication, and information sharing. Concluding this section is a review of health management, different levels of autonomy and an outline of autonomous systems for establishment and sustainment. Establishment of conceptual operations for transportation, site surveying, excavation, and assembly/construction are explained in Section III. Section IV describes sustainment operations and new health strategy considerations for the shelter including maintenance and repair. Finally, a brief review, additional details, and future work are provided in Section V.

II. General Lunar Autonomy Architecture

Efficiency, crew safety, and crew involvement are priorities for system autonomy of the shelter and functions. A general autonomy framework applicable to both single and multi-agent systems is presented in Fig. 2 with reference to the 2020 NASA Technology Taxonomy [3].

A. Autonomy Framework

At the highest tier, a multi-agent task planning system allocates tasks to each agent within the system. Tasks are represented in terms of a coordinates, precedence constraints, and agent constraints. The coordinates the physical location an agent must be in to complete the task. Precedence constraints indicate which other tasks must be completed before the task can be performed. Agent constraints specify characteristics or capabilities an agent must have to perform the task. Examples of agent constraints include specification of end-effector tools or the type of sensors available. Using a global objective function, task allocation is a multi-parameter optimization process that minimizes or maximizes total build time, total energy usage, agent performance, and other high-level considerations. The multi-agent task planning system communicates a motion planning goal state to each agent. A motion planning system uses the goal state to compute a collision free, feasible trajectory from the agent's current state to the goal state. Each agent may have its own motion planning system. The trajectory generation process results in either end-effector or joint commands for the agent as a function of time. These commands are tracked via low-level robot control.

The robot control systems interface directly with the robot hardware. As a trajectory is carried out, raw sensor data from the hardware is fed into a sensor fusion system as well as a fault detection, isolation, and recovery (FDIR)

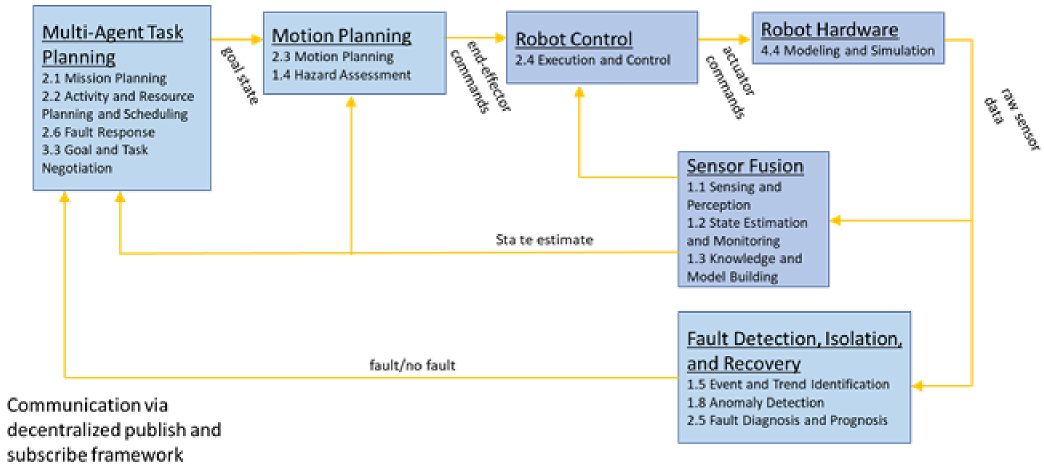


Fig. 2 General Autonomy Architecture.

system. The sensor fusion system uses the raw data to compute state estimates to be used as feedback signals for each level of control. Sensor fusion can have multiple instantiations both onboard the agents to estimate their own local states and off-board to collect information from all agents to create global estimate of the worksite state. Together these autonomy architectural components outline the core processes of an autonomous system that underpin high level navigation, communication, shared information, and health management.

B. Navigation, Communication, and Shared Information

Mobile autonomous agents that navigate and localize within the lunar operational environment must navigate using redundant systems to ensure robust, efficient, and reliable long-running autonomous system operations. A lunar location determination reference system (LDRS), Fig. 3, could consist of passive fiducials, active short/long range beacons, navigation towers, satellites, data collected a-priori, sensor fusion, and information shared between agents. A task planning system determines optimal beacon locations, minimizes blind spots, and maximizes the number of LDRS systems available using topographical data collected from initial surveys, satellites, mobile autonomous systems, and manned missions. Localization using triangulation requires mobile agents to have line-of-sight of at least three beacons at all times, so the beacons should be placed at high points around the site to minimize obstruction from geographic features and future construction. Satellites without GPS provide additional pose estimation of individual agents by using the reverse-ephemeris technique. Reverse-ephemeris is a method to calculate position of an object using a detection and ranging system coupled to the object to transmit a signal to satellites having a known ephemeris or location. Pose is estimated by taking the range of the object from the satellite using a time delay between transmission of the signal and receipt of the reflected signal and the range-rate using a Doppler frequency shift between the transmission of the signal and the receipt of the reflected signal makes it possible to calculate a position fix of the platform using the determined range, the determined range-rate, an altitude of the platform, and the known ephemeris of the satellites [4]. A robust and redundant navigation solution employs one or more methods including visual-inertial odometry, triangulation using towers, star-tracker maps, terrain-relative navigation, simultaneous localization and mapping (SLAM), and robust communications between towers and mobile assets.

Communication networks will be dependent on available resources, optimal placement of antennas, and communications equipment installed on each agent. Resources may include amount of on-board compute, allowable bandwidth, and network infrastructure such as relays, switches, and load balancers. Missing information or uncertainty in measurements affecting navigation can also be addressed by sensor fusion techniques and information sharing between stationary and mobile assets. A distributed network of autonomous systems benefits from compute agents or servers to alleviate local high-processing and storage needs. Information provided by agents or from stored data could include agent status, environment measurements, global/local maps and terrain information that together also provides autonomous systems and human operators with extensive situational awareness and knowledge of the entire system. This same knowledge and information is a primary input for health management systems.

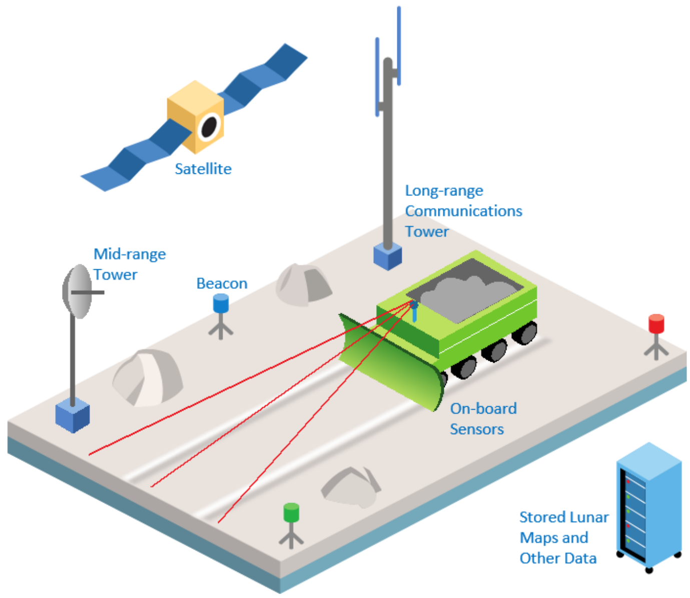


Fig. 3 Navigation Concept.

C. Health Management Strategy

Health refers to the estimated performance of a component or system [5]. Managing the health of an asset involves strategic and proactive diagnostics and prognostics to sufficiently detect and predict degradation, faults, and failures. A multi-agent health management strategy illustrated in Fig. 4 outlines three hierarchical tiers as mission, multi-agent, and single agent. The hierarchical nature is due to the level of governance, encapsulation of scope, and the dependency, readiness, and maturity of lower tiers. Each tier includes tailored health monitoring guidelines and general considerations such as hardware and software, determined by a selected implementation. An overall effective strategy shares knowledge and relevant health information between tiers and the multi-agent task planning system. With this information, the task planner can avoid or allocate tasks to compromised agents to maintain optimal performance of the entire system in the presence of degradation, faults, and failures.

Mission health monitoring refers to the collective performance, progress, or status undertaken by one or more autonomous agents. Clear objectives with associated success criteria must be identified to qualitatively or quantitatively assess milestones, events, or outcomes. This tier is the most application-specific and depends on the healthy operation of agents associated with missions.

Multi-agent health management involves the control, coordination, collaboration, communication, and behavior of agents. Requirements detail the robustness and capability that communication buses and networks must achieve for successful operation and execution. Multi-agent systems also present new health considerations such as swarm formations, fleet operations, and collaborative actions. Additionally, high-level health management tasks take advantage of multi-agent systems to design new behaviors for alternative health assessments and techniques of other agents, components, operations, or assets.

The single-agent tier illustrates the monitoring strategy of an individual agent and its sub-systems through online and offline monitoring methods. Health monitoring of typical robotic systems minimally includes hardware, software, sensors and actuators. Computational hardware, as with single-board computers, may include monitoring memory usage, temperatures, available disc space, and central processing unit (CPU) performance. Sensors must also have established processes to verify calibration and function in accordance with specifications [6]. The health management strategy and system requirements will specify the quality and quantity of different sensor types and use. For example a motor actuator would need at a minimum a single encoder, current sensor, and voltage sensor for health monitoring. Techniques such as sensor fusion, state and parameter estimation, external sensing, and pose estimation contribute valuable information for health monitoring [7].

Managing health performance through monitoring and diagnostics involves introducing new competing priorities for the task management system to optimize. Tasks could be modified, terminated, or new allocated tasks and assigned based on the analysis and nature of the impacted system. The following list describes possible outcomes as a result.

1) Assess health of another agent through pose estimations
2) Reassign agents for a given Task
3) Assign an agent to receive maintenance
4) Modify task characteristics such as expediting or delaying expected completion time

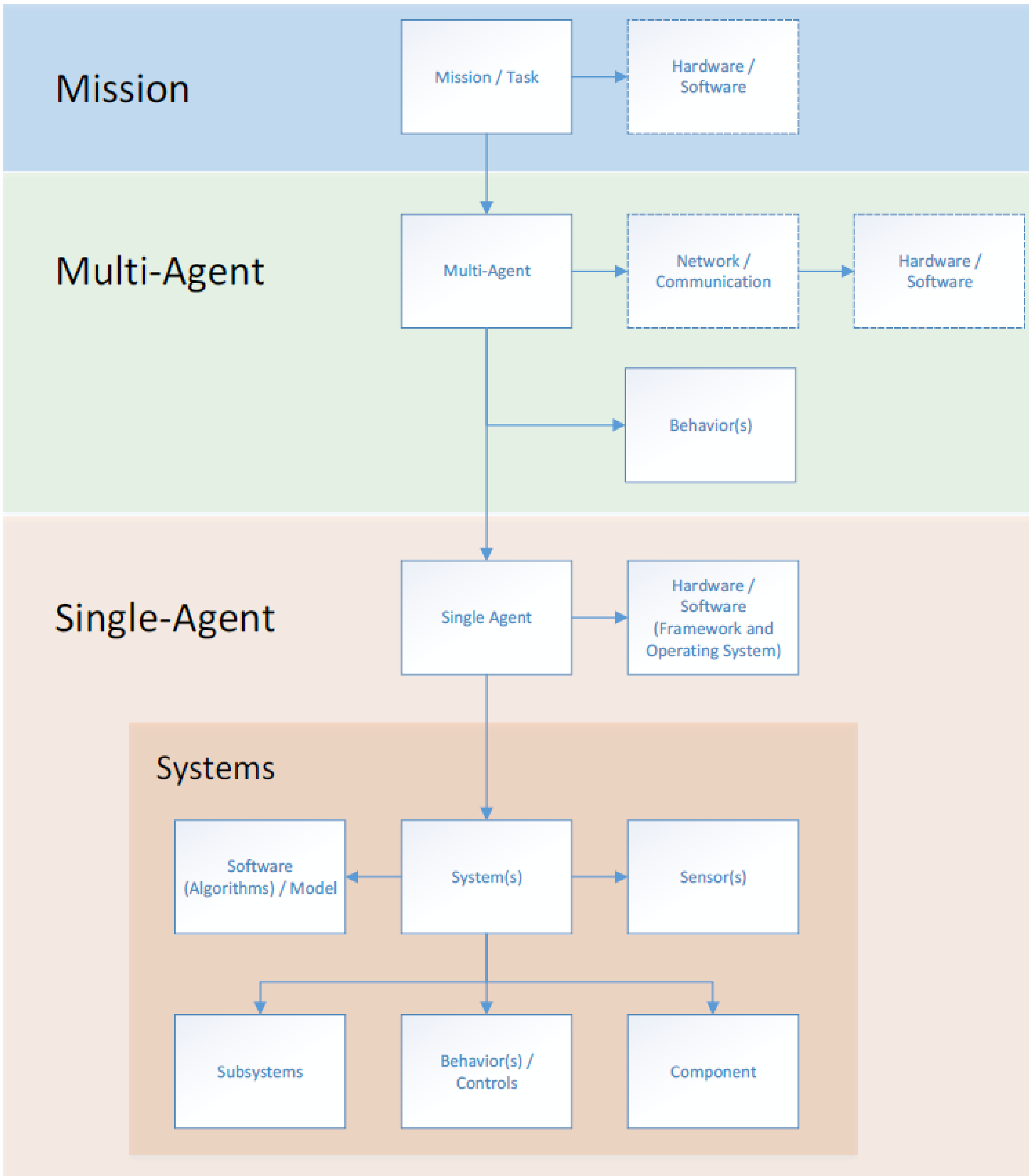


Fig. 4 Health Management Strategy for Autonomous Multi-Agent Systems [5].

D. Levels of Autonomy

The LSH team designated three categories or levels of autonomy as fully-autonomous, semi-autonomous, and manual. These categories describe the complexity of autonomous systems and estimated level of control, involvement, and collected information for operators in the specific context of the LSH.

Fully-Autonomous A fully-autonomous system implements one or more of the systems described in the autonomy framework outlined in Section II.A. Operators would only need to give few, high-level commands such as "begin preparing build site here," "assemble the truss structure here," or "add bulk regolith to the regolith shield." Intelligent and organized information provide operators with the most situational awareness from the various systems, sensors, cameras, and sensor fusion algorithms. From these high-level commands, the system coordinates work efforts between each of the mobile agents. Executing tasks requires each mobile agent to be equipped with a complex sensor package typically including multiple LiDAR sensors, cameras, IMUs, and radar. Optimally placed beacons determined by the high-level task planning limit blind spots caused by terrain reducing potential LDRS issues. Additionally, fully autonomous systems would demonstrate and validate autonomy capabilities for future Mars missions, where increased latency means autonomy is the only feasible option for establishing infrastructure for crewed missions.

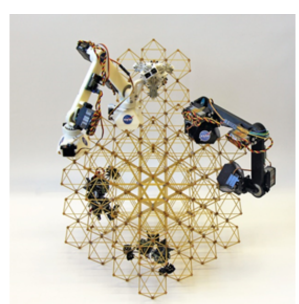
Semi-Autonomous System operators of semi-autonomous systems input mid-level commands such as “move to this way-point," "clear loose regolith from this region," or "pile X tons of regolith at this location." The mobile agents then autonomously perform the necessary lower-level tasks, like navigation, path planning, and determining the status of the current task. In some situations, human operators may step in to provide manual tele-operation, but this should only happen in unexpected circumstances like loss of LDRS. This level of autonomy balances operator effort, amount of situational awareness, and autonomous capabilities between fully autonomous and manual processes.

Manual The lowest level of autonomy refers to manual or tele-operation of mobile agents without support from autonomous systems. Tele-operated systems send low-level commands analogous to "move-forward with specified velocity," "turn right with specified angular velocity," or "lift blade to a specified angle." Minimal information would be provided to operators in the form of camera feeds or raw data streams from sensors, limiting situational awareness and increasing effort and training for operators. Such low-level control impacts Mars extensibility, especially where tele-operation becomes infeasible with the several minute delay. The Lunar Safe Haven provides valuable opportunity to develop and test autonomous systems, a necessary precursor for planned missions on Mars. Choosing to save the resources on developing this technology for the moon would waste this opportunity.

E. Autonomous Systems

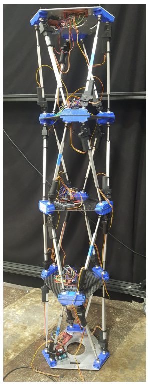
The LSH seedling study considered Several autonomous systems in illustrated in Fig. 5 and Table 1. This section is not a comprehensive review of potential lunar autonomous systems and does not prohibit consideration of other systems, tools, end-effectors, equipment, or technologies. The reviewed systems are intended to reflect a diverse set of heterogeneous autonomous systems capable of establishing and sustaining a LSH shelter by 2026.

(a) A-PUFFER [8].

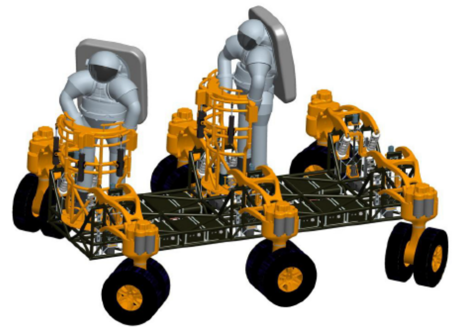


(b) Automated Re-configurable Mission Adaptive Digital Assembly Systems (ARMADAS) [9].

Fig. 5 General Establishment and Sustainment Autonomous Systems.



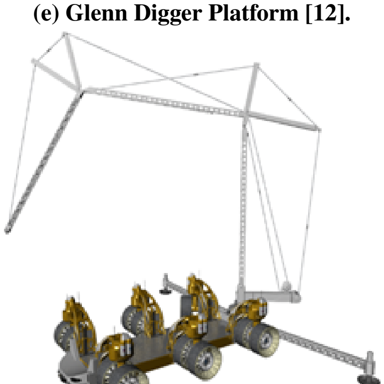
(c) Assemblers Stacked Stewart Platform Manipulator System.[10].



(d) General Purpose Chariot Concept [11].

(e) Glenn Digger Platform [12].

(f) LANCE: Chariot with blade attachment [13].



(g) LSMS mounted on Chariot [14].

(h) Lunar All-Terrain Vehicle [15].

(i) RASSOR for Excavation [16].

Fig. 5 General Establishment and Sustainment Autonomous Systems (cont.).

Table 1 Autonomous Systems

Agent	Description
A-PUFFER	Small, collapsible two-wheeled robot designed to collaboratively scout and investigate regions of the moon [17].
ARMADAS	Autonomously assemble materials to make a variety of functional structures such as habitat structures, large antennae arrays, and even a spaceport [9].
Assemblers	A manipulator composed of multiple stacked Stewart platforms, capable of being dynamically reconfigured for different construction tasks. [10]. Mounting an Assemblers manipulator on a mobile platform like the LTV is an alternative configuration.
Chariot	Robust and versatile vehicle chassis designed to provide a base for next-generation lunar vehicles [11].
Glenn Digger	Front-loader style mobile autonomous vehicle [12].
LANCE + Chariot	LANCE blade is a lightweight implement in combination with the Chariot platform to perform lunar site preparation activities such as area clearing of rocks, leveling, dozing, grading, and berm construction [13]. A compactor drum is another alternative implement for the Chariot.
LSMS + Chariot	Tension-based robotic manipulator designed dual function as a serial or crane type manipulator [18].
LTV	An unenclosed intelligent rover that astronauts can drive on the Moon while wearing their spacesuits [15].
RASSOR	Excavation autonomous vehicle designed to collect regolith in drums that extend from the front and rear [19].

III. Establishment

The LSH establishment systems are responsible for transportation, site surveying, excavation, and assembly/construction operations. Table 2, provided in the Appendix, maps several establishment operations to different types of autonomous systems. Some systems that perform similar functions as other agents, such as the Glenn Differ developed by NASA Glenn Research Center (GRC), will not be identified in conceptual operations for simplicity but remains as a viable alternative. The task management system is responsible for determining optimal tasks for agents based on availability, alternative systems, capability, health status, other critical tasks, and task requirements.

A. Transportation

Transportation builds from the autonomous capabilities from Section II.A to enable the moving of crew, payloads, or in-situ resources such as regolith or ice. Material or payload from a lunar lander intended for the LSH shelter could initially be offloaded by a LSMS or scaled version of the LSMS depending on physical payload characteristics [20]. The Chariot, LTV, or similar capable transportation system then transports the payload to its destination for off-loading. Payload identification and related perception topics are considerations for future studies.

B. Site Survey and Excavation

Before beginning establishment of any surface systems, preliminary surveying must be completed, and accomplished using a combination of satellite observation for coarse surveying and surface agents for finer details. An example of detected boulders by satellites shown in Figure 6 were labeled by hand. Future studies using commercial off the shelf (COTS) autonomous image processing, decision support tools, and machine learning can assist with sorting through large image volumes and other data to improve identification of suitable work-sites. Once permanent assets are available on the moon, further resource and construction site mapping could be accomplished by a fleet of small, lightweight agents such as A-PUFFERs equipped with cameras, Light Detection and Ranging (LiDAR), and ground-penetrating radar. These rovers function either fully or semi-autonomously, conducting detailed sweeps of regions of interest identified by or coordinated by human operators. Larger vehicles such as the Chariot or LTV would be considered for surveys over further distances or longer durations. Upon site selection, autonomous systems must then deploy and install LDRS for navigation and site preparation. The next task is the removal of at least twenty cm of loose regolith and small rocks to reveal stabilized building surfaces using LANCE. The displaced regolith is utilized in berm-like structures or removed by the RASSOR excavation system. Rocks too large for LANCE or RASSOR will be handled by a LSMS mounted on a Chariot. A Chariot agent using a separate compactor attachment will provide a firm, stable foundation for the shelter.

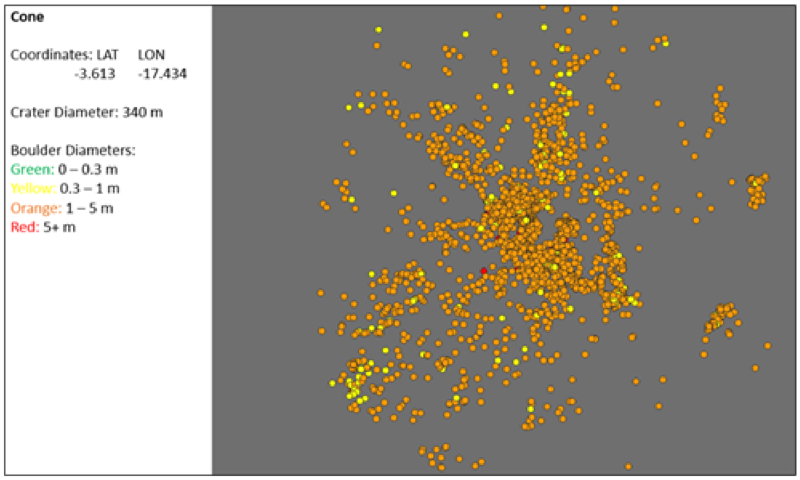


Fig. 6 Data from Lunar Reconnaissance Orbiter (LRO) Survey showing Boulder Locations [21].

C. Construction and Assembly

Once site preparation is complete, the same systems move on to deployment, construction, and/or assembly functions for the shelter. The Baseline structure consists of an inner metallic truss structure covered in seven meters of loose regolith. The following systems are considerations for assembling the shelter or components:

1) LSMS on Chariot: Manipulation of heavy equipment, lift truss segments into place, remove large rocks and debris
2) ARMADAS: Attaching truss segments together and inspect progress in real-time
3) Assemblers: Dexterously manipulate truss components or perform fastening operations

After assembling the inner structure, the next function is to excavate, transport, and deposit the regolith shielding material. For this task, RASSOR and LANCE would be reused from the site preparation functions to move regolith onto the shelter. However, these systems alone are not be able to maneuver regolith as high as is needed. Therefore, the LSMS equipped with a bucket attachment is required to scoop regolith to the necessary height.

IV. Sustainment

After establishment is completed, routine sustainment is needed as a part of the health management strategy to involve proactive and reactive diagnostics, prognostics, and maintenance elements for the shelter and its mobile assets. The following list identifies some expected types of health issues to manage through the different health tiers.

1) Structural degradation, due to settling, thermal cycles, seismic activity, or micro-meteoroid impacts
2) Regolith shield degradation or damage
3) Unexpected radiation inside the shelter
4) Unexpected temperature extremes inside the shelter
5) Degradation, fault, or failure of external mobile assets

A. Shelter Health Management Strategy

Building from the health management strategy in Section II.C the mission level consists of maintaining a fully operational shelter and its mobile assets for the LSH system. Monitoring the health of the shelter can be accomplished by a combination of inspections and strategically placed embedded sensors in the structure. For example strain gauges could be placed in regions of high stress suggested by simulation and modeling. Other sensors may include:

- Strain gauges – detection of displacement and vibrations from micro-meteoroid impacts, other external damage or structure setting issues
- Cameras/LIDAR – Visual inspection, pose estimation, general awareness inside/outside of structure, and micro-meteoroid impact detection
- Thermocouple – thermal monitoring to ensure crew and equipment safety
- Geiger – measure the amount of radiation inside the shelter
- Capacitive – detection of doors or other rigid bodies in relative proximity to other rigid bodies
- Radar – penetrative sensing to determine density of objects or ground penetrating radar (GPR) to assess material under structure, detection of voids, and general stability assessments

B. Micro-meteoroid Impacts

Typical cratering was on the order of 1mm in depth in regolith at lunar gravity occurring at the rate of 3 impacts/m2/yr resulting in less than 1000 cm3 of regolith loss over a 10-year period [22]. This loss is insignificant, and no maintenance schedule would be required to replenish the regolith after initial construction. The definition of catastrophic damage will be dependent on the final design, including materials selection, thickness, and energy absorbing properties, in addition to the elements inside the shelter, since the elements affect the risk assessment. Autonomous systems and crew using shelter cameras or specialized sensors periodically inspect the regolith shield. Mobile inspection systems include LTVs, A-PUFFERs, and satellites. Establishment systems are also responsible for repair of the regolith shield. If structural damage occurs, then the damaged parts of the shelter would be disassembled and repaired prior to shield repair.

C. Agent Repair

Maintenance and repair of mobile autonomous agents requires dexterous manipulator agents to perform the various repair tasks as shown in Fig. 7. A miniature scaled LSMS installed inside the shelter would be able to lift and hold tools and parts. The Assemblers manipulator then provides precise tool articulation for more detailed actions such as removing or installed vehicle components.

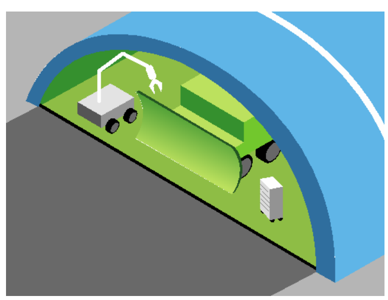


Fig. 7 Agent Repair in Shelter Concept.

Due to extreme cold, lack of light for visibility, and other environmental hazards, most outdoor tasks would be scheduled during the day, and agents would park inside the shelter during the night. Therefore, repairs and regular maintenance would be scheduled during this downtime. Each agent would continuously monitor its status, and keep track of faults and degredations. Maintenance and repair tasks would be scheduled based on priority and available time and resources.

V. Final Remarks

The LSH shelter concept and system operations are designed to protect crew and equipment from radiation, thermal extremes, and micro-meteoroid impacts. This provides a unique opportunity to develop robust, reliable, safe, and continuously evolvable autonomous systems. An expansion on the seedling trade study would see continued investigation of other shelter operations such as thermal management, waste disposal, dust mitigation, power systems, tower installation, and trench digging. Further studies would benefit from comprehensive simulation environments focused on simulating system of systems, integration of autonomous agents/systems, and environmental effects including lunar nights, meteor showers, and the effect of lunar dust. Advancing the shelter health strategy could be pursued in the analysis of relationships between individual systems contributing to mission, multi-agent, and single agent tiers. Emergent health behaviors as part of monitoring and maintenance are avenues for developing holistic and reliable autonomous systems that enhance crew safety, performance, and reduces operational costs.

Appendix

Table 2 System Functional Responsibilities for the Baseline Concept's Establishment Systems.

Operations	LSMS+Chariot	Truss Assembly Robot	RASSOR	LANCE + Chariot	Compactor + Chariot	Surveyor	Command + Monitoring
Site Preparation							
Survey site						X	
Deploy/Place Location Determination Reference Systems	X					X	
Remove rocks and grade/level the construction site	X		X	X			
Rough compact site and stabilize surface					X		
Transfer construction materials (e.g., bulk regolith)			X	X			
Shelter Establishment							
Transfer construction equipment and pieces of structure	X						
Assemble pieces of inner structure	X	X					
Construct shelter protective shield: bulldoze/lift bulk regolith on top of shelter	X		X	X			
Verify compaction, grading, and construction operations complete						X	
Communicate and provide command and data with other systems							X

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References

[1] Grande, M., Moses, R., Cosgrove, P., Mueller, R., Prater, T., and Blanchard, A., "Protecting Crew and Surface Systems with a Long-Duration Lunar Safe Haven," AIAA, 2021.

[2] NASA, "Artemis Plan: NASA's Lunar Exploration Program Overview," , September 2020. URL https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.

[3] Terrier, D., "2020 NASA Technology Taxonomy," 2020. URL https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf.

[4] Reed, P. L., "Reverse-ephemeris method for determining position, attitude, and time," , U.S. Patent 10254392, Apr. 2019. URL https://patents.justia.com/patent/10254392.

[5] Waltz, W., "An Intelligent Framework for Proactive Health Analysis and Monitoring of Autonomous Mobile Robots," 2019.

[6] Cheng, S., Pecht, M., and Azarian, M., "Sensor Systems for Prognostics and Health Management," Vol. 10, 2010, p. 5774–5797.

[7] Qiao, G., and Weiss, B., "Monitoring, Diagnostic, and Prognostics for Robot Tool Center Accuracy Degradation," *Proceedings 2018 ASME International Manufacturing Science and Engineering Conference*, 2018.

[8] NASA, "Autonomous Pop-Up Flat Folding Explorer Robot (A-PUFFER)," , 2020. URL https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/A-PUFFER.

[9] NASA, "Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS)," , 2020. URL https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/armadas.

[10] Cooper, J., Neilan, J., Mahlin, M., and White, L., "Assemblers: A Modular, Reconfigurable Manipulator for Autonomous in-Space Assembly," AIAA ASCEND, 2020.

[11] Harrison, D. A., Ambrose, R., Bluethmann, B., and Junkin, L., "Next generation rover for lunar exploration," *2008 IEEE aerospace conference*, IEEE, 2008, pp. 1–14.

[12] Bauman, S., Newman, P., Izadnegahdar, A., Johnson, K., and Abel, P., "A Basic Robotic Excavator (the "Glenn Digger): Description, Design, and Initial Operation," , 2016. NASA/TM—2016-218961.

[13] Mueller, R., Wilkinson, R., Gallo, C., Nick, A., Schuler, J., and King, R., "Lightweight Bulldozer Attachment for Construction and Excavation on the Lunar Surface," *AIAA SPACE 2009 Conference and Exposition*, AIAA, Pasadena, California, 2009. URL https://arc.aiaa.org/doi/pdf/10.2514/6.2009-6466.

[14] Jefferies, S., Doggett, W., , Chrone, J., Angster, S., Dorsey, J., Jones, T., Haddad, M., Helton, D., and Caldwell, D., "Lunar Lander Offloading Operations Using a Heavy-Lift Lunar Surface Manipulator System," AIAA SPACE 2010, 2010.

[15] NASA, "NASA Prompts Companies for Artemis Lunar Terrain Vehicle Solutions," , August 2021. URL https://www.nasa.gov/feature/nasa-prompts-companies-for-artemis-lunar-terrain-vehicle-solutions, accessed 27 Nov 2021.

[16] Mueller, R., Smith, J., Schuler, J., Nick, A., Gelino, N., Leucht, K., Townsend, I., and Dokos, A., "Design of an Excavation Robot: Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0," *15th Biennial ASCE Conference on Engineering, Science, Construction, and Operations in Challenging Environments, ASCE*, 2016. URL https://ntrs.nasa.gov/api/citations/20210011366/downloads/ASCE%202016%20RASSOR%202%20Final%20%206_8_2016.pdf.

[17] NASA, "Autonomous Pop-Up Flat Folding Explorer Robot (A-PUFFER)," , April 2020. URL https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/A-PUFFER, accessed: 2021-11-24.

[18] Doggett, W., Dorsey, J., Collins, T., King, B., and Mikulas, M., "A Versatile Lifting Device for Lunar Surface Payload Handling, Inspection and Regolith Transport Operations," American Institute of Physics, 2008.

[19] Mueller, R. P., Cox, R. E., Ebert, T., Smith, J. D., Schuler, J. M., and Nick, A. J., "Regolith advanced surface systems operations robot (RASSOR)," *2013 IEEE Aerospace Conference*, IEEE, 2013, pp. 1–12.

[20] Cline, J., Vaughan, M., Waltz, W., and Wong, I., "LANDO: Developing Autonomous Surface Operations for Planetary Surfaces," AIAA, 2022.

[21] Watkins, R., Jolliff, B., Mistick, K., Fogerty, C., Lawrence, S., Singer, K., and Ghent, R., "Boulder distributions around young, small lunar impact craters and implications for regolith production rates and landing site safety," *Journal of Geophysical Research: Planets*, Vol. 124, 2019, p. 2754– 2771. https://doi.org/10.1029/2019JE005963, URL https://agupubs.onlinelibrary.wiley.com/action/showCitFormats?doi=10.1029%2F2019JE005963.

[22] Wong, I., Siochi, E., Grande, M., Moses, R., Waltz, W., Silbernagel, S., Hayward, E., and Barkhurst, M., "Design Analysis for Lunar Safe Haven Concepts," AIAA Scitech, 2022.