A Design Concept for a Robotic Lunar Regolith Harvesting System*

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Abstract—In order to meet NASA’s call to “live off the land” and use lunar resources for future bases, a design concept for a robotic lunar regolith harvesting system is discussed. Topics include the motivation for regolith harvesting, lunar environmental design factors, and robotic system tasks and constraints. Details are presented for the proposed semi-autonomous, modular system concept.

I. INTRODUCTION

The Stanford Space Systems Development Laboratory (SSDL) is developing a concept for a robotic system to harvest lunar regolith and support a lunar base. The system will consist of modular, low mass, low power equipment that excavates, handles, and transports lunar regolith for site preparation, construction activities and in-situ resource utilization (ISRU).

II. MOTIVATION FOR ROBOTIC REGOLITH HARVESTING

A. Establishing a permanent moon base

A robotic regolith harvesting system can be an invaluable piece of a future permanent moon base. It offers a safe, efficient approach to performing menial tasks required during exploration missions, such as site preparation and regolith collection for ISRU. Robotic systems launched ahead of crewed missions can prepare the site and assure working on-site systems prior to crew arrival.

Lunar regolith is the primary material subject to robotic harvesting. Regolith is a valuable resource that can provide oxygen for life support and propulsion [1]–[3], protect crews from radiation [4], and be converted to manufacturing and construction materials [5], [6]. The harvesting system will support extraction of oxygen and other regolith-based resources with a flexible capability to excavate, transport, and deliver material as required for a given project. It will also support building structures for future manned missions, and assist in on-site evaluation of granular physics and dust mitigation. In addition, development of a reliable lunar harvesting system will assist NASA with ISRU on Mars, asteroids, and other solar system bodies beyond the moon.

B. Reduction of cost and risk

An artificial distinction is often drawn between robotic and manned space exploration, when in fact the two are complementary. There is no machinery capable of the subtle and wide ranging observational capabilities of the human sensor suite. However, wherever we go in space, we need infrastructure to sustain us, and we need not deliver that infrastructure in person. In fact, it is less expensive and less risky to have robotic missions take the first steps in delivering and assembling the infrastructure needed to support life on the moon.

Robotic infrastructure development has the potential to save cost in at least three ways. First, robotic flights do not require life support systems. This allows them to instead deliver greater payloads in a vehicle which has lower development costs. NASA is following the same logic by separating cargo and crew vehicles in the Ares launch system being developed to replace the shuttle [7].

Second, unmanned missions do not require the margins of safety required to protect human life. This can further reduce both launch and equipment costs by moving toward commercial off-the-shelf (COTS) supplies. In contrast, man-rated missions require far more expensive parts due to safety tolerances.

Finally, robotic missions can save costs by delivering, initiating, and maintaining equipment from which following human explorers can “live off the land” [8]. For example, prior to human arrival at the surface, robotic precursor missions can confirm that adequate oxygen for human needs (including propulsion for the return flight) has been processed from the lunar soil, and safely stored for future use. The savings here, which come from a reduction in the need to launch and deliver supplies such as oxygen, are accentu-
ated as mission times are extended or evolve into a permanent human presence.

Robotic systems will also reduce the risk associated with space exploration. Accidents are inevitable. They will happen from meteorite impact, human error, system complexities that cannot be completely simulated, or other unforeseeable causes. The tragedies in space exploration, in addition to the loss of human life, have led to programmatic time delays and costs due to the necessarily severe investigations, reanalysis, and redesign.

Robotic precursor missions can test transportation vehicles before regular manned use, and help develop the actual “live fire” experience needed for long-term missions to other planets. As a testbed, loss of robotic flights do not cost human lives, so infrastructure can be built without the risk of multi-year setbacks from accidents. Additionally, pre-confirmation of in-situ supplies lowers the risk that an accident leading to critical supply loss during transportation (e.g. Apollo 13) could strand astronauts on the moon.

Beyond the risk reduction related to flight systems, robotic precursor missions reduce risk to the health of astronauts at a moon base. A well-established robotic infrastructure at the base reduces the number of EVAs that the astronauts must make, and can create a safer station by burying it under regolith, all reducing radiation exposure to the astronauts.

III. LUNAR ENVIRONMENTAL DESIGN FACTORS

A. Radiation

The Moon’s surface is exposed to hazardous ionizing radiation, including solar wind, solar flares, and cosmic rays. The solar wind is a relatively constant flux of charged particles, mainly electrons and protons, plus ions of various elements. It travels at an average velocity of 400 km/s. In cislunar space, it has an average density of about ten particles per cubic centimeter [9]. A solar flare is similar, but possesses higher energies.

Galactic cosmic rays are produced outside the solar system. They are made up of very high energy particles consisting mostly of protons and electrons, plus positrons, gamma rays, and some heavy nuclei such as iron.

Over an 11 year solar cycle, solar flare particles with energies greater than 30 MeV can deliver 1000 rem. The cosmic ray dosage at the lunar surface is about 30 rem per year [4]. As a comparison, NASA’s 30-day exposure limit is 25 rem, the terrestrial occupational limit for radiation workers is 5 rem per year, and the median lethal dose is 450 rem [10]. A shielding layer of compacted regolith over inhabited lunar base modules would maintain a resident’s radiation exposure to 5 rem per year [4].

Anomalously large flare events with much higher radiation levels are also possible. In August 1972, a flare delivered unshielded radiation doses of 45 rem per hour, and lasted for over 15 hours. Storms with such lethal particle fluxes are expected to appear only once every ten years [10].

B. Regolith characteristics

Lunar regolith is generated from meteor bombardment. It consists of many metal oxides, as outlined in Table 1. Table 2 describes the gradation of lunar regolith, which is very fine compared to terrestrial material. Without any atmospheric weathering, the particles remain extremely abrasive. During the Apollo missions, the regolith scratched gauge dials on equipment and sun shades on EVA suits. On Apollo 17, the gloves worn while operating a core drill lasted only two EVAs before wearing through. EVA suit fittings developed leaks resulting in a higher pressure decay than expected.

In addition to its abrasive nature, lunar regolith is extremely cohesive at low pressures. This resulted in clogging and jamming mechanisms on Apollo mission equipment. Radiator surfaces were also coated, reducing their effectiveness and causing excess heating.

Gene Cernan and John Young, two Apollo astronauts, have both stated that lunar dust is the primary obstacle in returning to, and living on, the moon [13].

IV. ROBOTIC SYSTEM TASKS

The lunar regolith harvesting system will perform a variety of tasks supporting the establishment and maintenance of a permanent lunar base. These can be categorized into construction and harvesting tasks.

A. Construction

Initially the robotic system will assist with assembling the

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>AVERAGE COMPOSITION OF APOLLO SAMPLES BY PERCENT [11]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-11</td>
</tr>
<tr>
<td>SiO₂</td>
<td>42.47</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>13.78</td>
</tr>
<tr>
<td>TiO₂</td>
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<tr>
<td>Cr₂O₃</td>
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</tr>
<tr>
<td>FeO</td>
<td>15.76</td>
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<td>MnO</td>
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<tr>
<td>MgO</td>
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<tr>
<td>CaO</td>
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<tr>
<td>Na₂O</td>
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<tr>
<td>K₂O</td>
<td>0.15</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.12</td>
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<tr>
<td>S</td>
<td>0.12</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>LUNAR REGOLITH PARTICLE SIZE DISTRIBUTION [12]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Size (mm)</td>
<td>% Weight</td>
</tr>
<tr>
<td>10 - 4</td>
<td>1.67</td>
</tr>
<tr>
<td>4 - 2</td>
<td>2.39</td>
</tr>
<tr>
<td>2 - 1</td>
<td>3.20</td>
</tr>
<tr>
<td>1 - 0.5</td>
<td>4.01</td>
</tr>
<tr>
<td>0.5 - 0.25</td>
<td>7.72</td>
</tr>
<tr>
<td>0.25 - 0.15</td>
<td>8.23</td>
</tr>
<tr>
<td>0.15 - 0.090</td>
<td>11.51</td>
</tr>
<tr>
<td>0.090 - 0.075</td>
<td>4.01</td>
</tr>
<tr>
<td>0.075 - 0.045</td>
<td>12.40</td>
</tr>
<tr>
<td>0.045 - 0.020</td>
<td>18.02</td>
</tr>
<tr>
<td>less then 0.020</td>
<td>26.85</td>
</tr>
</tbody>
</table>
structure of the lunar base. The base will eventually be buried under regolith in order to have adequate radiation shielding. Excavators will be required to dig trenches to accommodate the inhabited base modules as well as to pile regolith over them once they are placed.

Once the base is established, the harvesting system will transition to a maintenance role. The region around the lunar base will require constant cleaning, especially around egress ports, at landing and take-off sites, and at solar power stations. The rovers may utilize a variety of cleaning methods such as electrostatic, ultrasonic, and physical sweepers as well as cleaning fluids [14].

B. Harvesting Regolith

In addition to the construction tasks, the robotic system will also harvest regolith for ISRU and manufacturing applications. Initially, oxygen can be extracted from the metal oxides in regolith for life support and propulsion. Regolith also has cementitious properties and might be used as a construction material [5], [6] for expansion of the lunar base. In the more distant future, regolith can also be used in processes to extract Helium-3 [15] and in the production of solar panels [16], computer chips [17], and fiberglass [15]. In order to supply ISRU processors with a supply of regolith, the harvesting system can draw significantly upon the regolith collected while cleaning the lunar base, since this is the most easily harvested regolith. To increase the supply of regolith, the robotic system will have to dig out the more densely packed regolith and transport it to where it will be used.

V. ROBOTIC SYSTEM CONSTRAINTS

To utilize regolith, a harvesting system must be capable of operating in the harsh lunar environment. Due to launch costs and limited power on the moon, the system must be lightweight and energy efficient. In addition, it must be durable, and require minimal maintenance and human supervision.

A. Radiation Protection

The robotic systems on the lunar surface will be subject to radiation bombardment, so radiation hardened electronics must be used. Redundancies are needed to ensure that radiation-triggered events do not cause critical failures in the electronic system. Also, robust and simple software must be used so that failures will be easily detected and quickly corrected.

B. Dust Mitigation

There are a number of sources of dust on the lunar surface. Around the lunar base, anthropogenic sources include launches and landings of manned and unmanned supply vehicles, and disturbances caused by construction and regolith harvesting tasks. Natural causes of dust include meteor impacts and ionic charging across the terminator [13].

Due to the abrasiveness of lunar regolith, a methodical approach to dust mitigation is required. This will consist of four levels: minimizing dust generation; containment of generated dust; protection of sensitive components; and using durable equipment.

C. Operational Efficiency

As demonstrated by the myriad of equipment employed for terrestrial excavation, a single lunar vehicle cannot be optimized to perform all of the required tasks. Alternatively, transporting numerous different vehicles to the moon is costly and inefficient, since many of these pieces of equipment use similar drive and power systems. An additional problem is that components will have different rates of wear. For example, on the Mars Exploration Rover Spirit, the Rock Abrasion Tool failed after grinding 15 rock samples approximately 2 mm in depth [18], [19]. An excavator’s digging implement would experience a similar short lifetime compared to the vehicle’s drive train or sensor systems, potentially rendering the entire excavation vehicle useless. Vehicles would also require time to recharge integrated batteries, resulting in downtime. The solution to all of these problems is to have a modular system as discussed in the following section.

VI. THE SYSTEM CONCEPT

The long-term concept is for a fleet of robotic vehicles to work together on the Moon. They would be supervised by one or two operators on Earth or in a regolith-covered lunar control station, and return to a base station for cleaning, battery exchange, module reassignment and routine maintenance.

A. Modularity

The varying tasks of clearing loose regolith from surface areas, deeper excavation of hard-packed areas, trenching, piling regolith in berms or on habitat structures, and delivering regolith to processing facilities lend themselves to a variety of specialized machinery. However, parts such as the core frame, drive system, power system, sensors, computer processor, and communications system can be common to rovers configured for different excavation tasks.

In much the same way that a commercial bucket loader can be outfitted with varying attachments (e.g. scraper, sweeper, trench digger, auger) through its 3-point power take-off (PTO), a robotic multi-functional Core Platform can be outfitted with a suitable attachment to meet the needs of each task. This eliminates overly redundant hardware, thereby decreasing the cost and weight of the overall system. In addition, the harvesting system will allow for easy replacement of worn modular excavating attachments, thereby facilitating repairs and decreasing downtime.

B. The Core Platform

As noted above, the primary design consideration is lunar dust. As such, the geometry of the Core Platform will include steep sides and minimized horizontal surface area in order to prevent dust accumulation. The chassis will be made from aluminum or titanium for weight and durability, with critical
parts contained in an interior closed area for radiation shielding, thermal control, and dust control.

The robotic vehicle will be powered by batteries rather than solar panels to avoid the loss of power resulting from dust coating of panels in excavation work areas. Batteries will be exchanged quickly for recharged batteries at a solar recharging station which is at a distance from the heavily dusted excavation and port areas. The attachment points to the various modules and batteries will be dust-resilient, open-slotted, ball-and-socket joints. These will also serve as the primary power connections and backup communication contact to the attachments. Primary communications will be handled by sealed RF units.

A communications system will be implemented with downlink capability for receiving command scripts and uplink capability for transmitting sensor data. Sensors will allow the operator and base computer to survey the surrounding terrain and script excavation sequences, as well as to monitor the state of the vehicle. The final design of the robotic equipment will require additional trade studies.

### C. The Suite of Modules

Initial modular excavation attachments to be considered include a Blade Actuator Module (BAM), an Integrated Conveyor Module (ICM), a Rotating Wheel Attachment (RWA), an Articulating Digging Module (ADM), an Articulated Loading Module (ALM), and a Regolith Transportation Module (RTM). Other attachments will be developed as the need arises.

The BAM is a module that performs much like a traditional bulldozer or snowplow. An articulated blade can be raised, lowered, and angled. Its strengths are in moving and dislodging large volumes of moderately sized material by scraping the top surface, clearing flat areas, and pushing material into piles and berms. Drawbacks include dust stirring, no fine digging control, and the inability to lift or load material.

The ICM is a module which will incorporate an excavating implement with a conveyor belt, thus integrating the excavation and loading functions. It has the benefit of simplicity and continuous excavation and loading. Potential drawbacks may include stalling or excessive consumption of power during excavation of more densely packed regolith, and excessive wear on the conveyor system as it interfaces with the regolith being removed. This system is suited for removal of more loosely packed regolith piled by other modules. With a sweeper attachment, it will clear landing, launch, and future building sites.

The RWA is a rotating wheel which will excavate while attached to the ICM. It will resemble the much larger bucket wheel excavators used for large terrestrial excavation projects.

The ADM will be a lightweight, efficient backhoe. For power-limited or difficult digging situations, the ADM will provide the benefit of decoupling the excavation and loading tasks in time. This will allow the full power available to be devoted to excavation, allowing collection of material which would otherwise be inaccessible. Furthermore, the ADM will handle a large variety of rock sizes and regolith densities. The ADM’s maneuverability will enable it to selectively excavate high-yield regions. This capability will allow it to operate in fields strewn with rocks of various sizes without becoming jammed. In addition, the ADM can be used for finely controlled excavation, such as trenching for foundations and underground pipes. Potential drawbacks include the lack of continuous excavation, which may limit yield over time, and prove less energy efficient, as well as a more complex set of control algorithms.

The ALM is effectively a bucket loader. It has a front facing articulated scoop, most efficient for lifting loose regolith onto conveyors, vehicle beds, or berms. It is not optimal for digging or hauling material long distances.

The RTM is a truck bed container with a dumping mechanism. These will transport excavated regolith from the excavation site to the collection site. The RTM can be attached to ICMs for immediate loading of regolith.

### D. Control System

Options for robotic control schemes vary widely from full autonomy to real-time remote control. Operations prior to crew arrival will be controlled via Earth ground stations that will be hindered by several seconds of communication latency. Fully autonomous controls are attractive due to these latencies, but they require large amounts of processing power, and can be complicated, costly and unreliable.

Remote control systems benefit from real-time human decision making power, but require constant attention and rapid feedback methods, such as haptic force-feedback. Thus, they are prone to instability with increased communications latency. They will also be inoperable during communication outages encountered before crew arrival.

The proposed semi-autonomous concept uses a control system which balances autonomy and teleoperation, taking the reliability of remote controls with the efficiency of autonomy. A supervised, semi-autonomous control architecture, where the excavator is intelligent and robust enough to manage the digging task on its own, only requires the human controller to dictate specific pre-programmed, scripted tasks, and to manage occasional situations that the excavator cannot handle. NCMT (Numerical Control for Machine Tools) code can serve as the scripted language to control the actuators and read data from the sensors.

The excavator can be preprogrammed to excavate a certain pattern, and to signal the controller if an obstacle is blocking the excavation path, or if the expected digging force is exceeded by a certain tolerance. The excavator may sense rocks and other obstructions, and plan to dig around those simple, small obstructions. For contingency operations, a semi-autonomous excavator will still be programmed with the ability for a human to take full control of the robot.
Supervised autonomy has several benefits over haptic systems. It increases the efficiency of the system by allowing the human operator to focus on high-level tasks. Trained operators will control multiple excavators simultaneously. Furthermore, supervised autonomy will greatly reduce the power consumed by radio transmission. Supervised autonomy can also reduce the potential for failure due to interruptions in communications.

Supervised autonomy also has benefits over fully autonomous, advanced pattern recognition and artificial intelligence (AI) systems. Supervised autonomy will require less development time and have fewer failure modes than a fully autonomous system. Furthermore, the semi-autonomous system will require fewer sensors and lower power than a fully autonomous system.

E. Supporting Infrastructure

The basic supporting infrastructure includes a port area for extra-lunar vehicles, a regolith processing facility, a repair shop, a solar power station, and a human habitat. Once again, the key driver for supporting infrastructure is the mitigation of dust problems.

Dust problems can be mitigated by geographically locating more dust sensitive components away from dust generating components. Thus, the human habitat and solar station will be furthest from the port and excavation areas, with the regolith processing facility and repair shop in between. Despite the fact that dust will be generated at the port and excavation areas, the dust reaching sensitive areas will be minimized by distance and constantly harvesting any loose dust throughout the lunar base.

VII. Conclusion

The proposed modular, semi-autonomous approach lowers cost, increases power and mass efficiency, increases versatility, and reduces radiation and dust exposure to humans. Maintenance of the lunar base will require constant support of the robotic system to minimize risks to astronauts while simultaneously harvesting in situ resources.

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References


