Configuring Innovative Regolith Moving Techniques for Lunar Outposts

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Abstract—The NASA exploration vision calls for extended human presence at lunar outposts within the coming decades. Any permanent outpost requires a significant amount of infrastructure and a cost-effective way of preparing this infrastructure is to utilize native materials such as regolith and rocks inherently present. This work investigates techniques for excavating, transporting, and building up regolith in the context of berm building, surface stabilization, and other critical tasks using small (100 kg to 300 kg) robots. Terrestrial excavation techniques and machines are reviewed. REMOTE (the Regolith Excavation MObility & Tooling Environment), a simulated task model that accounts for the special requirements of excavating in the harsh lunar environment, is presented. The model is used to quantitatively compare excavation systems according to key metrics including production ratio. It is shown that the teleoperated lunar berm construction robots achieve a production ratio less than 1/10th that of commercial equipment employed in terrestrial construction. A preliminary sensitivity analysis shows that these results are affected by the operating velocity as well as excavation blade design. A prototype of a rock rake for soil stabilization is also demonstrated. The goal of this work is to arrive at innovative robotic approaches that are best suited for excavation and infrastructure preparation tasks on the moon. [1 2]

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1. INTRODUCTION

The fundamentals of earth working have been applied in practice extensively, and are well studied in literature. What is needed for the Moon is to scale, synthesize and specialize machines and site work for the lunar environment. This initiative analyzes and configures robots for lunar site development. The top-level objectives include devising an array of lunar-relevant machine types, and modeling the best mix to accomplish the surveying and site-prep work of the 2010s while also considering the full range of robotic regolith work required to support human operations in the 2020s. Over these two decades, robotic devices will establish and maintain sites for habitation and enterprise by creating roads, hab-pads, radiation caps over habs, level landing zones, berms around landing zones, and trenches for buried utilities. Machines are needed for surveying, ripping, scarifying, dozing, excavating, grading, drilling, compaction, haulage, trenching, maintenance, dust-cleaning, etc.

Lunar development campaigns are similar to terrestrial site work in some ways, with standard constructs such as soil-tool interaction, temporal-spatial planning and operator control. However, lunar site work will be distinct from terrestrial work in important ways:

- Dust plays a dominating (and profoundly challenging) role in terms of containment, suppression, stabilization and removal.
- There are unique considerations for electrical prime power and actuation, low specific power, and the vacuum environment.
- Profound constraints flow from self-contained operations without the broad terrestrial advantages of resupply, wash down, and shirt-sleeve service environments.
- Machine configurations, kinetics and energetics (including light-and-power cycling) dictate novel fleet design, site operations and site development scheduling.
- Lunar gravity imparts greatly reduced stabilizing inertial forces, imposing challenging machine dynamics on locomotion, hauling, and bulldozing.

While an abstraction of the dynamics of excavating lunar regolith might not be exact, maximal constraints imposed by the dynamic properties of the robot and the lunar environment can be determined. The excavating robot can then be designed using this empirical knowledge to

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optimize its function. Using this methodology, configurations are being developed that are suitably low in mass, sufficiently strong, and efficient in terms of moving and manipulating regolith as necessary for actualizing and supporting lunar outposts.

In order to determine the feasibility of these machines, parameterics are explored via modeling and simulation. Based on previous work comparing terrestrial machines, trends can be observed relating vehicle size, mass, efficiency, etc. Using parameters for various excavation methods in conjunction with environmental conditions and previous regolith excavation research [2, 3], variables such as energy and time requirements can be estimated for certain excavator-task combinations (i.e. berm construction with a simple plow versus a windrower). The results of such a simulation give a conclusive understanding of the tasks at hand and a starting point for development of the excavators themselves.

2. Terrestrial Excavation Equipment

Terrestrial excavation machines have become specialized according to the tasks for which they are designed, as well as their weight class. Caterpillar Inc. has maintained an empirical heritage of their equipment [4], making analysis of trends in terrestrial machines possible.

Over the years bulldozers, excavators, loaders, and other earth-moving machines have grown in size. With increasing machine size and weight, production rates also increase, as can be seen in Figure 1. Operating on Earth, equipment mass is not a significant constraint and larger machines have the advantage of achieving higher production per operator.

In space applications such as lunar excavation, earth-launch mass is a critical measure of merit as it is a good indicator of cost [5]. Scaling production and other key metrics by machine weight identifies trends that may be important when adapting terrestrial designs to space. Figure 2 shows the same production data as Figure 1, but scaled by vehicle weight. Highest production per unit of weight is achieved at lower weights, which means that multiple small vehicles may be able to match or exceed a single large vehicle's production for less overall mass.

Drawbar pull, the amount of horizontal force available for work, is another key metric for excavation vehicles. Scaling of drawbar pull by weight for bulldozers is shown in Figure 3. The maximum pull to weight ratio is at a weight of approximately 250 kN, with the ratio dropping off as vehicle size is either increased or decreased. The falling pull to weight ratio with decreasing vehicle size can potentially be attributed to smaller fractions of the vehicle weight being devoted to producing the forces required for excavation and mobility. The weight of some critical terrestrial subsystems, such as combustion engines, scale poorly or not at all.

It is important to note that all the analysis in this section is based on terrestrial systems, and that there is no guarantee that the trends observed will translate directly to systems designed for lunar operation. Still, the scaling of production, as well as drawbar pull and other digging forces, by vehicle weight exhibit results that merit further attention when designing excavation systems for lunar and planetary exploration.

3. Lunar Excavation Tasks

Beginning several years before the first human explorers arrive and a base is constructed, robotic precursors will be sent to a lunar landing site to prepare the area for human habitation and to support exploration initaitves. Robotic site preparation would effectively develop the terrain and create an early infrastructure; rock fields need cleared, landing sites must be leveled, and the location will be surveyed in detail far surpassing the mapping capabilities of an orbiter.

The current NASA exploration architecture for a lunar base defines explicit zones allocated for specific purposes including landing zones, habitation zones, and power production zones. A permanent lunar outpost would likely require a variety of regolith moving tasks, including but not limited to:

- Trench digging
- Berm construction
- Ground leveling
- Obstacle clearing
- Radiation shielding
- Surface stabilization
- Dust suppression

These tasks could be explored and developed by robotic pioneers. A rover utilizing plowing and rock-clearing capabilities coupled with a mechanism to unload rocks would be able to construct a landing pad rivaling terrestrial analogues. Capabilities of such an excavator would include clearing a landing area of obstacles, reinforcing blast areas affected by exhaust plumes from landers, and constructing a berm to block plume-accelerated regolith from reaching the habitation zones. A rover with digging capabilities could prepare cable trenches from the power production zones to the habitation zones, or begin work for underground equipment and facilites to be shielded by regolith. Even a small excavator sent sufficiently ahead of time would save future explorers man-hours that would be taxing on the astronauts themselves and their equipment.

This work focuses on surface stabilization and berm construction, which would be critical components of the construction of a landing pad.

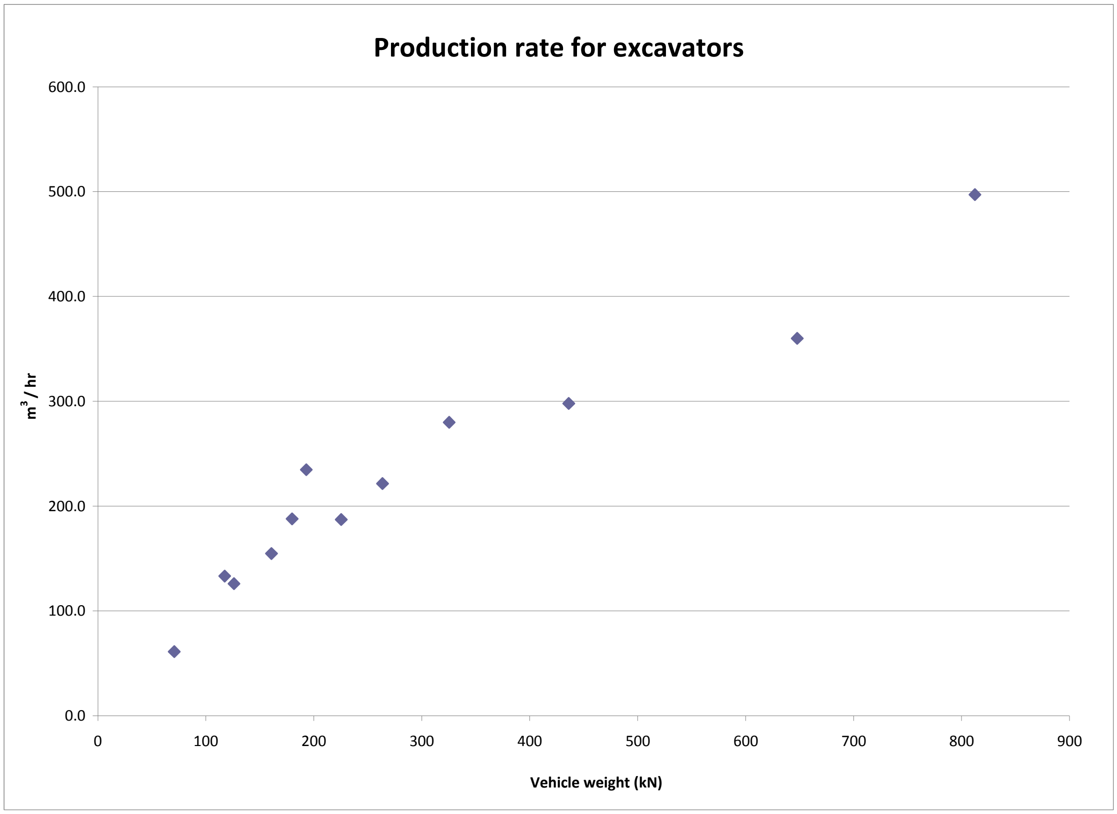

Figure 1 - Production rates of excavators increase with increasing excavator size/weight

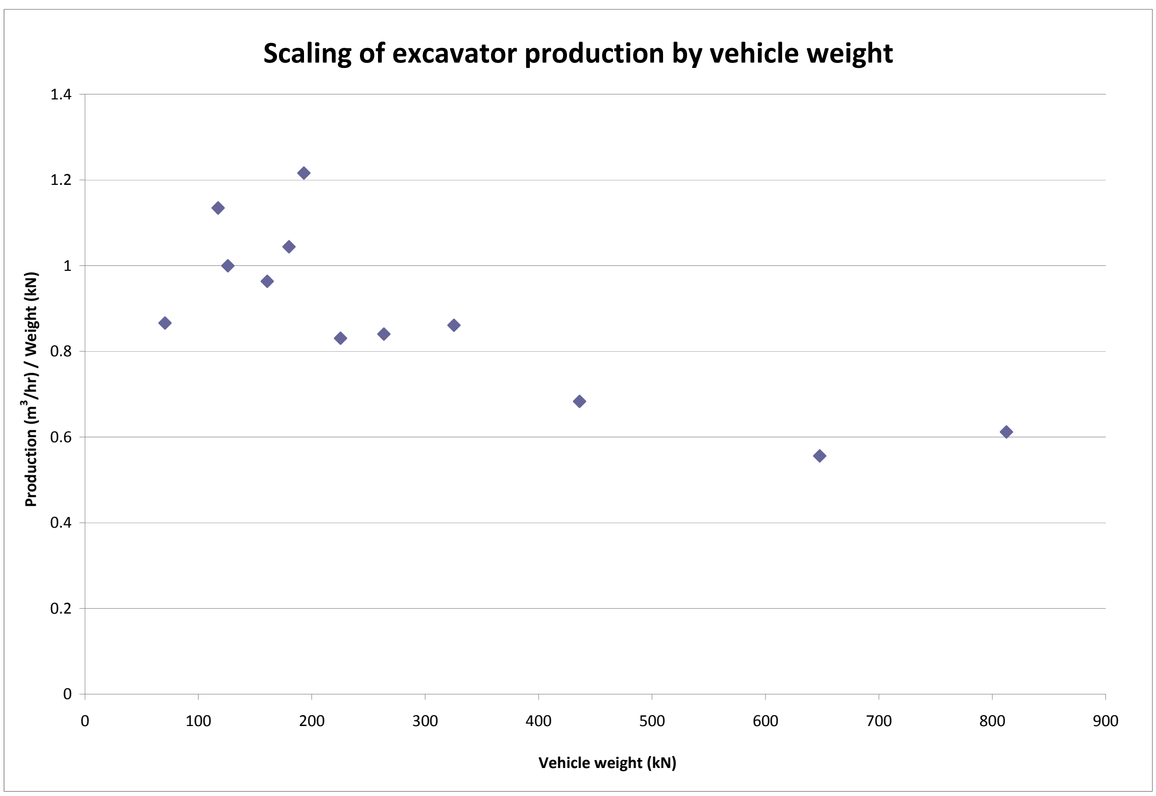

Figure 2 - Production rates of excavators scaled by vehicle weight show that large vehicles may not be the most productive in space applications

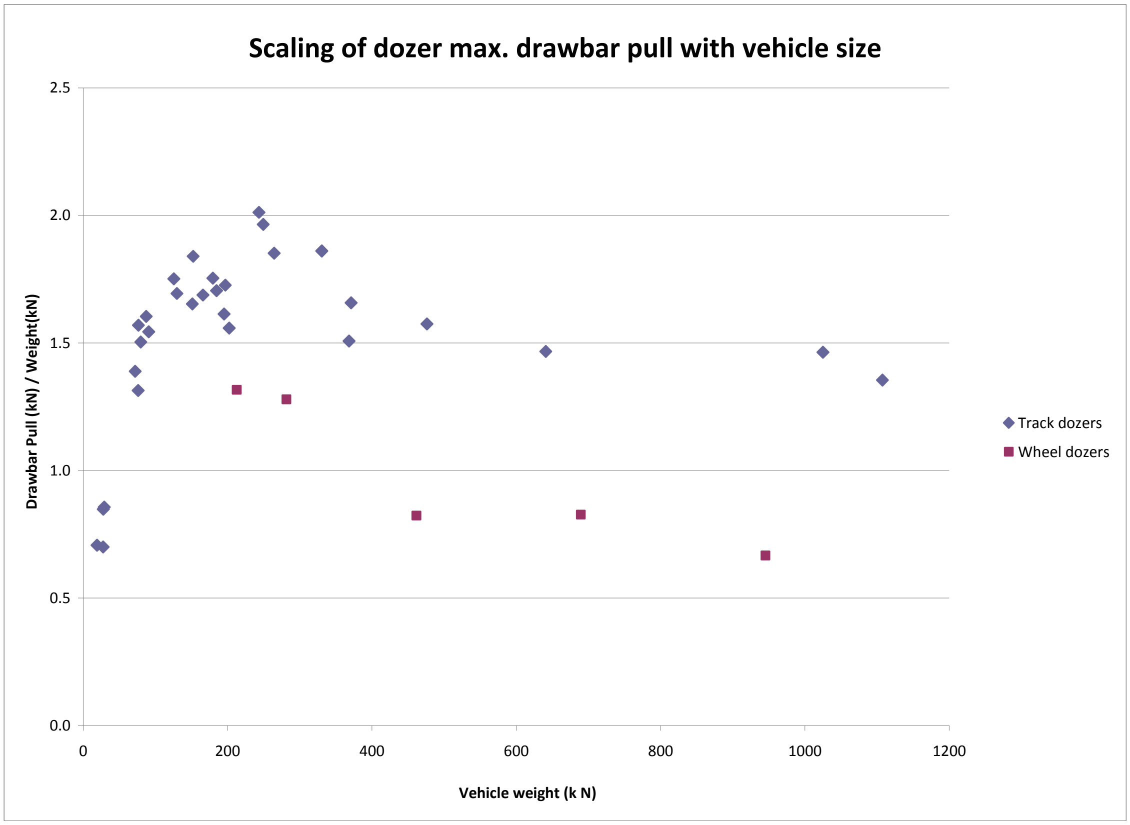

Figure 3 - Drawbar pull of bulldozers scaled by vehicle weight show that highest pull to weight ratios are achieved at neither the lowest nor highest vehicle weights

Berm Construction

Lunar regolith was observed to be lifted off the surface and blown out radially below the Apollo landers. As a permanent base would require multiple landings within close proximity, methods for mitigating this ballistic projectile hazard,akin to sandblasting, are needed. One way to protect existing structures and equipment is to separate the landing area from the rest of the base with a berm.

Requirements on the size of the berm are based on an estimated plume ejecta angle of 3^{o} [3]. The side slopes of such berms could range between 45^{o} and 60^{o} for dumped regolith, or approximately 70^{o} for regolith compacted with a stability factor of safety of 1.5 [1]. Thus different excavated volumes could be required depending on whether the berm building equipment has the ability to shape and compact the regolith or not. Another important consideration determining the side slopes is safety of the construction machine itself. If a small machine is used, required to drive and operate on the berm itself, steep slopes may not be desirable due to the possibility of tip-over.

An analytical model of the berm construction task is described in section 4. The time and power required to complete the task are estimated for various system designs. The current NASA architecture assumes that a new landing pad and berm would be required every 180 days.

Surface Stabilization

Another way to mitigate the risk of ballistic regolith particles is to limit the amount of regolith lifted off the surface in the first place. Larger particles require more energy to be lifted and blown, meaning that a landing surface could potentially be stabilized by covering it with gravel- to rock-sized particles. The collection and redistribution of rocks could also be a critical component of obstacle clearing and ground leveling tasks.

During the Apollo missions, astronauts used a rock rake as part of their sample collection toolkit. Figure 4 shows a photo of a rake used during the Apollo 16 mission. Similar passive rakes are often employed in agriculture to clear fields of rocks. They may be attached to the front of a tractor or towed behind. Actuated rock pickers and windrowing machines use rotary motion in addition to being passively dragged, to either collect rocks or translate them to the edge of a track, respectively.

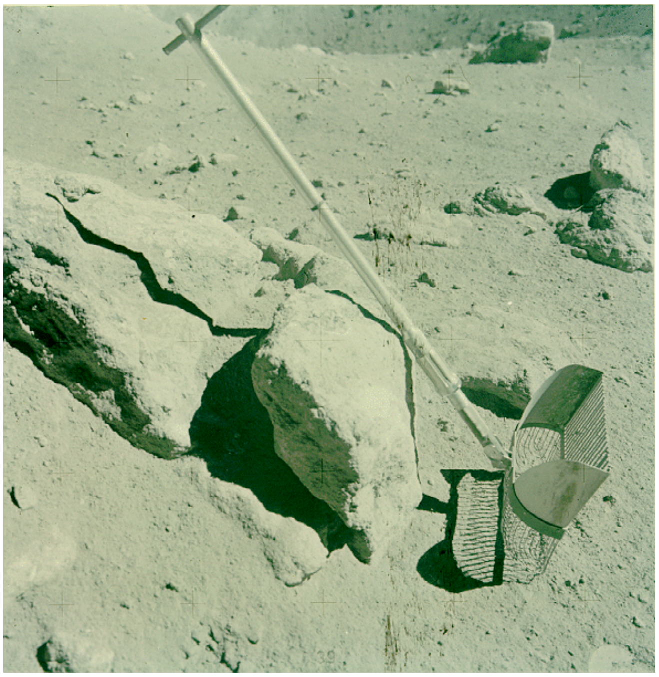

Figure 4 - Rock rake used for sample collection on Apollo 16

The use of rock rakes, rock pickers, and windrowers could be adapted to the particular tasks required for lunar outpost preparation. With regards to surface stabilization, a passive rake could be used to move buried rocks to the regolith surface. This concept is shown schematically in Figure 5.

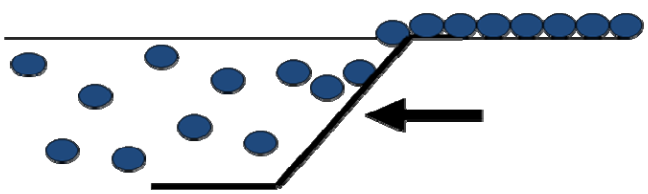

Figure 5 - Schematic of a modified rock rake used for surface stabilization

A prototype of a surface stabilization rake was developed and successfully demonstrated. A photograph of the prototype is included in Figure 6. Video of the prototype moving buried rocks to the surface has also been produced.

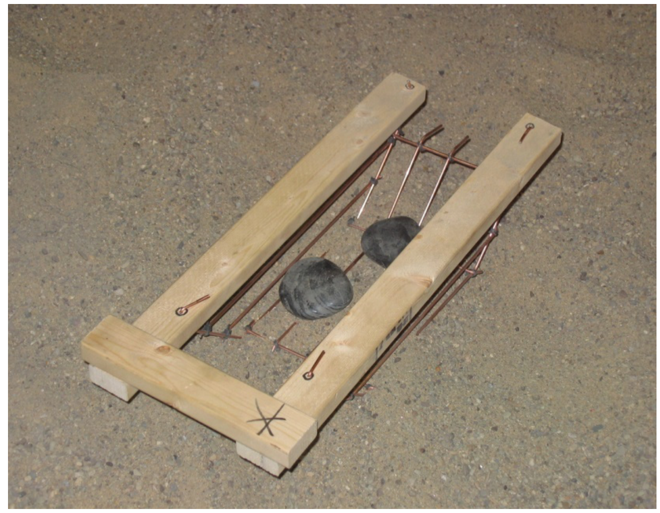

Figure 6 - Prototype surface stabilization rake successfully demonstrated at Carnegie Mellon University

4. REMOTE - EXCAVATION SYSTEM MODELING

In order to permit quantitative analysis of lunar excavation robots, a system model named REMOTE (the Regolith Excavation, MOBility & Tooling Environment) was developed that could be generalized to a large number of different designs based on a few key parameters. The system diagram is included in Figure 7.

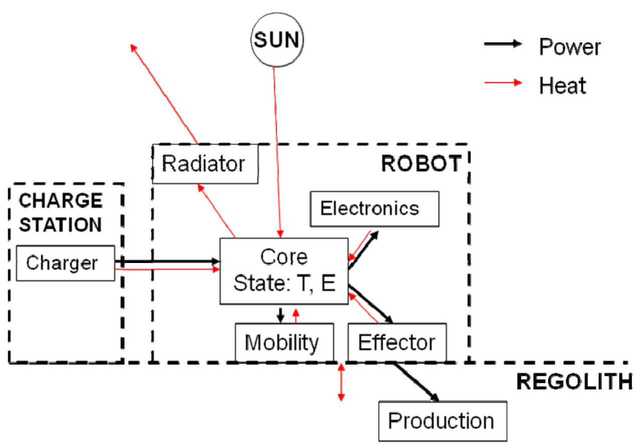

Figure 7 - System diagram of lunar excavation robot (in the diagram, T = temperature, E = energy level)

The core state variables of system temperature and energy level are tracked throughout the completion of a task. Models of the key subsystems and elements of the excavation system are presented in the subsequent sections.

Energy Storage and Charging

An underlying assumption of a central power collection and charging station is included in the system diagram. The requirements of operating in complex and potentially shadowed terrain as well as a very dusty environment make solar power collection on the robot itself impractical, and the relatively high levels of power required for excavation make a radio-isotope source likely inadequate.

In addition to the central power station, it is possible for the excavation robot's power to be augmented by a constant trickle, either from a radio-isotope or from a beamed power source.

The energy storage subsystem on the robot was assumed to comprise 10% of the total mass budget. Lithium Ion batteries with a specific energy density of 150 W·hr/kg were selected. A charge time of 2 hrs was included in the model.

Mobility Subsystem

For rigid wheels in granular terrain, the maximum shear strength of the medium (i.e. regolith) is given by [6]:

$$\tau^{\max} = c + \sigma \tan\varphi \tag{1}$$

where c is the terrain cohesion, σ is the normal stress, and φ is the angle of internal friction. Thus, the maximum tractive force on flat terrain for the robot can be modeled as:

$$T^{\max} = cA_G + mg\tan\varphi \tag{2}$$

where A_G is the ground contact area, m is the system's total mass, and g is the acceleration due to gravity. Values for the cohesion and angle of internal friction of lunar regolith have been measured and estimated in literature [1]. In order to account for the fact that full tractive force may not be available for excavation, lower bounds for c and φ were used in the traction calculation, (2), while upper bounds were used when calculating excavation resistance. An option to model a further reduction to the conversion efficiency of tractive to excavation force was also included in the model, encapsulated in the parameter K_{HfT}.

The power required to drive was estimated by scaling the robot's weight by an empirically derived factor and multipyling by the travelling velocity. The driving power was added to the robot's idling power to determine the total power used while driving.

Excavation / End Effector Subsystem

The excavation tool was modeled as a 2 dimensional blade; a flat plate pulled through the regolith at an angle from the horizontal. A number of models for such an excavation case have been presented in literature [2, 7]. The Lockheed-Martin/Viking model was selected for this work. It was used for the design of the Mars Viking lander robotic excavation arm [2] and provides conservatively high estimates of the forces experienced during excavation.

The horizontal force components of the Viking excavation model, due to friction and cohesion effects, are given below:

$$H_{friction} = \gamma g w l^{1.5} \beta^{1.73} \sqrt{d} \left(\frac{d}{l \sin\beta} \right)^{0.77} \times \left\{ 1.05 \left(\frac{d}{w} \right)^{1.1} + 1.26 \frac{v^2}{gl} + 3.91 \right\}$$

$$H_{cohesion} = \gamma g w l^{1.5} \beta^{1.15} \sqrt{d} \left(\frac{d}{l \sin\beta} \right)^{1.21} \times \left\{ \left(\frac{11.5c}{\gamma g d} \right)^{1.21} \left(\frac{2v}{3w} \right)^{0.121} \left(0.055 \left(\frac{d}{w} \right)^{0.78} + 0.065 \right) + 0.64 \frac{v^2}{gl} \right\} \tag{3}$$

where γ is the soil bulk density, w is the blade width, l is the blade length, β is the blade cutting angle, and v is the cutting velocity.

The maximum horizontal tractive force calculated in the mobility subsystem, (2), was equated to the sum of the horizontal excavation forces to solve for admissible blade geometries (w, l, d, and β). The selected blade geometry, in turn, was used to evaluate the volume of regolith production in each excavation pass. A parameter for bucket-filling efficiency was also included in the model.

The power required to excavate was estimated by scaling the total horizontal excavation force and multipyling by the cutting velocity. Total power used while excavating was calculating by summing excavation power, driving power, and idling power.

Thermal Modeling

The thermal model of the system comprised of three major channels of heat flow: heat absorbed from direct and reflected solar energy, heat dissipated internally from electronics and motor inefficiencies, as well as radiative heat emitted to space and the lunar surface.

For thermal purposes, the robot was assumed to be a cube with 6 faces of area A_T each. The bottom face was assumed to interact solely with the lunar surface, the top face solely with deep space, and the 4 side faces were given view factors of ½ for both the surface and space. As this model deals with polar outposts, solar incidence was expected to be at a low angle and thus acting on 1 of the 4 side faces of the cube.

The system was assumed to dissipate 80 W internally (idling power) from its electronics. Motor efficiencies of 50% were assumed. Black paint, with absorbtivity and emissivity values of 0.98 and 0.87, respectively, was selected as the thermal surface material.

5. BERM CONSTRUCTION SIMULATION

The first task selected for simulation was that of berm construction. A berm of height 2.6 m was selected, in a semi-circle around half a landing pad of radius 25 m. A simple wheel loader was modeled for this task. The regolith for the berm is taken from a 40 cm excavation of the landing pad surface. A berm side slope angle of 50^o was selected as a compromise between tip-over stability and limiting regolith volume. A 20^o ramp is assumed to be maintained along the leading edge of the berm as it is built to continually provide access to the robot for dumping and compaction at the top of the berm. Additionally, a flat top of width 60 cm is included on the berm. The total volume of regolith moved for this task is estimated at 780 m^3.

The mass constraints imposed on the problem are that no more than 300 kg of robotic excavation equipment are to be used. This constraint is handled in three different ways in simulation: one robot of 300 kg mass, 2 robots each weighing 150 kg, and a team of three 100 kg robots.

Vehicle velocity was assumed to be 0.15 m/s during shuttling for transport and recharge, and 0.1 m/s during excavation.

With the depth of excavation, d, set to 0.1 m, values of l = 0.3 m and β = 20^o were selected to correspond to analogous scaling used in terrestrial machine designs. The remaining dependent variable defining blade geometry was thus the blade width, w. The filled bucket volume then determined the number of excavation runs the system would need to perform in order to complete the berm construction task.

Combining the time spent performing excavation runs with the time spent charging batteries, the total task completion time was calculated for each of the robotic team system options. The total time was then scaled by environmental and operational efficiencies. The results are presented in Table 1.

Table 1. Berm construction task completion times for various robotic loader team options

Number of robots	Individual mass (kg)	Work time (hr)	Calendar days (with 40% duty cycle)
1	300	3903	387
2	150	4787	475
3	100	5737	569

From the values in Table 1, it is clear that constructing a berm according to the assumptions and parameters described above is a time consuming undertaking. The various robot team options take over 2 to 3 times longer than the desired 180 days.

Production ratio is a useful metric for studying the rate of excavation and construction tasks. Production ratio is defined as the weight of material moved per hour divided by the weight of the vehicle itself (for example, an excavation machine with a production ratio of 10 is able to move 10 times its own weight in one hour). The modeled 300 kg rover, 200 kg rovers, and 100 kg rovers result in production ratios of 1.2, 1.0, and 0.8 hr^{-1}, respectively. Figure 8**Error! Reference source not found.** compares these modeled production ratios to those of Caterpillar wheel loaders measured during terrestrial construction tasks. The modeled production ratios are less than 1/10th of the CAT values. The main differences between the two regimes of data points are the operating speed (0.15 m/s vs. 2 m/s) and the need to recharge (which is not included in the terrestrial data points).

Comparison between various robot team options

Another result that is obvious from Table 1 is that the two 200 kg robots are able to complete the task faster than three 100 kg robots, and a single 300 kg robot is able to complete the task faster than either of these other options. This result is further exhibited by the decreasing production ratio for smaller vehicles, as discussed in the previous section. The 300 kg robots are able to move more regolith, pound for pound, than their smaller counterparts.

The decline in production for smaller robots can be attributed to the assumptions that the amount of available battery power scales with the robot, while the baseline idling power is constant between these vehicles in the same mass class. As a result, the smaller vehicles need to charge more often and thus spend a larger portion of their task time charging (and shuttling to the charge station), and use a smaller percentage of their total energy available for work. The numerical results are shown in Table 2.

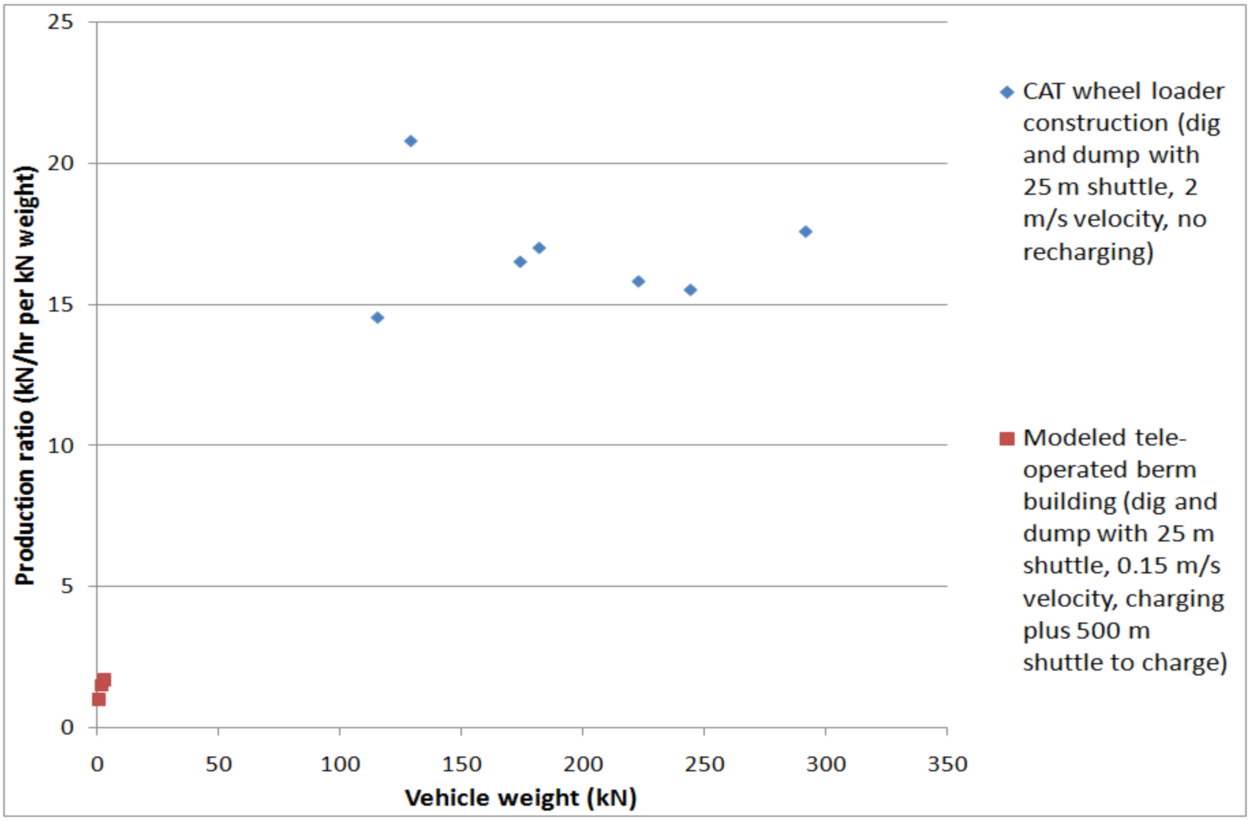

Figure 8 - Production ratios for Caterpillar wheel loaders (from terrestrial data) and the modeled lunar excavator robots performing similar tasks. The main differences include the speed of operation and the need to recharge.

Table 2. Power and Temperature results from lunar loader simulations

Mass (kg)	Total battery energy (W-hr)	Percentage of energy used for work (%)	Percentage of time spent charging (%)
300	4500	91	18
150	2250	87	23
100	1500	84	28

It must be noted that, although the single vehicle achieves a higher production ratio and thus shorter task completion time than multiple smaller robots, the advantage of system redundancy should be kept in mind when designing for overall mission success.

The power and heat transfer modules of the simulation produced the results presented in Table 3. These results show that the excavation tasks modeled do not pose any significant stress on the power budget or thermal equilibrium of the robotic system.

Table 3: Power and temperature values for various robot configurations

Mass (kg)	P Idle (W)	P Mobile (W)	P Excav. (W)	Equil. Temp. (C)
300	80	226	260	16
150	80	153	170	17
100	80	129	140	18

Sensitivity analysis

A preliminary sensitivity analysis was performed on the parameters in the model that are either variables or have associated uncertainty. Each of these parameters was changed from the expected value (quoted, when relevant, in preceding sections) to a maximum and minimum feasible value. The degree of change to the final value of calendar days required to complete the task was then noted.

The parameters that had the highest impact both positively and negatively were the robot's driving speed as well as the excavation blade angle and length. Increasing the driving speed to 0.5 m/s was alone able to reduce the days required for the task to 180. Modifying the blade shape to use a shallower angle but with a longer blade was also able to reduce the timeframe below 180 days. Conversely, decreasing the speed or shaping the blade for deeper but shorter cuts resulted in much longer task completion times.

Values of the maximum regolith cohesion, as well as the conversion efficiency of tractive force into excavation force, also had a significant potential to increase task completion time. The uncertainty regarding regolith cohesion values, expressed by the large range of possible values quoted in the Lunar Sourcebook [1], poses significant risk to the ability to complete the task robotically.

6. CONCLUSIONS AND FUTURE WORK

The suppression of ballistic dust, akin to sandblasting, resulting from lunar lander plumess was addressed in through berm construction and surface stabilization. A prototype modified rock rake was demonstrated collecting buried rocks for dissemination on the surface.

A berm construction task was modeled in REMOTE (the Regolith Excavation, MObility & Tooling Environment) for the specific requirements imposed by the harsh lunar environment. Simulations of robotic loaders were conducted for vehicles with mass of 100, 150, and 300 kg. The berm building task was simulated with teams of 3 robots and 2 robots for the 100 kg and 200 kg designs, respectively, such that the total mass of the excavation machines was constant at 300 kg in each case. It was shown that the berm construction task could be completed by a single 300 kg robot in 387 calendar days, by two 150 kg robots in 475 days, or by three 100 kg robots in 569 days, assuming parameter values to be those described in sections 4 and 5. The completion of a berm within 180 days using a single small robot thus remains a challenging task. The simulated robot tasks result in production ratios less than 1/10th of those obtained from terrestrial construction data. Significant differences in the task that may explain this difference in production ratio include the much slower speeds modeled for lunar tele-operated robots as well as the need to shuttle to a charging station and recharge.

A preliminary sensitivity analysis has identified system driving speed and excavation blade angle and length as design parameters that hold promise for decreasing the task completion time below 180 days. Further investigation of these design parameters is considered for future lunar excavation robot designs.

A single 300 kg robot was able to achieve a higher production ratio than teams of 100 or 150 kg robots. As the smaller robots were able to store less total battery mass but still required the same baseline idling power (for avionics, communication, etc.) they spent more time charging and shuttling to charge and were able to use less of their total energy for task work. These results should be traded off against the advantage of redundancy that teams introduce when designing excavation missions.

Future work

The ultimate goal of this program is to identify innovative techniques that will be best suited for excavation and site preparation on the moon. A secondary result of this analysis is the identification of aspects and parameters which need further study before optimized machines are developed. While modeling and simulation are critical to the design process certain considerations which greatly impact results, such as regolith cohesion, may only be solved with ground-truth measurements. Accurate lunar surface data is key to lowering program costs, accelerating schedules and reducing risk as humankind prepares to return to the Moon. This program will help determine exactly what lunar data is needed with respect to lunar excavation techniques and machine designs.

This paper comprises interim results of a broader analysis. The excavation system model utilized herein is applicable to more tasks than just berm building and to more vehicle types than just loaders. The next step in the investigation includes running simulations with excavators and haulers, bulldozers, and teams of robots performing various tasks. This work will model and characterize combinations of machine systems for overall performance, minimum mass, modularity, energetics, lifecycle, and fulfillment of ISRU needs. Operation of the machines for logical site development will be developed with emphasis on achieving a capability ratio of type of work to type of machine.

The scope of this study is purely technical and does not include higher level considerations such as mission architechture and cost. Future modeling could potentially include mission level metrics such as launch volumes and launch cost per kilogram; launching teams of robots may introduce specific requirements that differ based on the size of the team. Given the extent of an outpost preparation mission, though, such differences may or may not turn out to be mission critical.

An investigation of methods to enhance surface stability to provide proper load support for lunar structures will be completed. Soil compaction techniques and spreading previously collected small rocks are potentially viable methods of enhancing surface structure.

Once a broad variety of systems are simulated using the model described in this work, field testing of the most promising designs will be conducted. Soil tests are currently being performed on samples from a site near Carnegie Mellon University that is likely candidate for these field tests. The goal of the soil tests is to ensure the similarities and differences of the terrain to the lunar environment are properly characterized and accounted for in the analyses.

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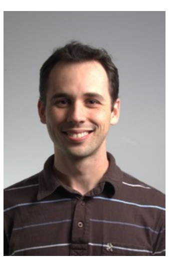
BIOGRAPHY



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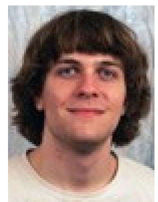

Raymond L. Barsa *is an undergraduate at Carnegie Mellon University, pursuing a degree in mechanical engineering. He spent the past year working on the Astrobotic rover for the Google Lunar X Prize, working on space-relevant design and composite materials. His contributions to the project included CAD design, analysis, and prototype manufacturing for the primary structure and mobility components of the rover.*

Dr. David. S. Wettergreen *is an associate research professor at the Robotics Institute at Carnegie Mellon University. His research focuses on robotic exploration: underwater, on the surface, and in air and space, and in the necessary ingredients of perception, planning, learning and control for robot autonomy. His work spans conceptual and algorithm design through to field experimentation and results in mobile robots that explore the difficult, dangerous, and usually dirty places on Earth, in the service of scientific and technical investigations. Much of this work is relevant to ongoing and future space activities.*

Dr. William L. "Red" Whittaker *is the Fredkin Professor of Robotics, Director of the Field Robotics Center, and founder of the National Robotics Engineering Consortium, all at Carnegie Mellon University. He is Chairman and Chief Technical Officer of Astrobotic Technology Inc. He is also the Chief Scientist of RedZone Robotics. He has an extensive record of successful developments of robots for craft, labor and hazardous duty. Examples include robots in field environments such as mines, work sites and natural terrain. Dr. Whittaker's portfolio includes the development of computer architectures for controlling mobile robots; modeling and planning for non-repetitive tasks; complex problems of objective sensing in random and dynamic environments; and integration of complete field robot system.*