Considering the Effects of Gravity when Developing and Field Testing Planetary Excavator Robots

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Abstract One of the challenges of field testing planetary rovers on Earth is the difference in gravity between the test and the intended operating conditions. This not only changes the weight exerted by the robot on the surface but also affects the behaviour of the granular surface itself, and unfortunatly no field test can fully address this shortcoming. This research introduces novel experimentation that for the first time subjects planetary excavator robots to gravity offload (a cable pulls up on the robot with 5/6 its weight, to simulate lunar gravity) while they dig. Excavating with gravity offload underestimates the detrimental effects of gravity on traction, but overestimates the detrimental effects on excavation resistance; though not ideal, this is a more balanced test than excavating in Earth gravity, which underestimates detrimental effects on both traction and resistance. Experiments demonstrate that continuous excavation (e.g. bucket-wheel) fares better than discrete excavation (e.g. front-loader) when subjected to gravity offload, and is better suited for planetary excavation. This key result is incorporated into the development of a novel planetary excavator prototype. Lessons learned from the prototype development also address ways to mitigate suspension lift-off for lightweight skid-steer robots, a problem encountered during mobility field testing.

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1 Introduction

Excavating on the Moon and Mars enables in situ resource utilization (ISRU) and extraterrestrial contruction. However, planetary excavators face unique and extreme engineering constraints relative to terrestrial counterparts. In space missions mass is always at a premium because it is the main driver behind launch costs. Lightweight planetary operation, due to low mass and reduced gravity, hinders excavation and mobility by reducing the forces a robot can effect on its environment.

This work considers lightweight excavation from the point of view of excavator configuration. It shows that continuous excavators (bucket-wheels, bucket chains, etc.) are more suitable than discrete excavators (loaders, scrapers, etc.). Figure 1 shows an example of a continuous and discrete excavator.

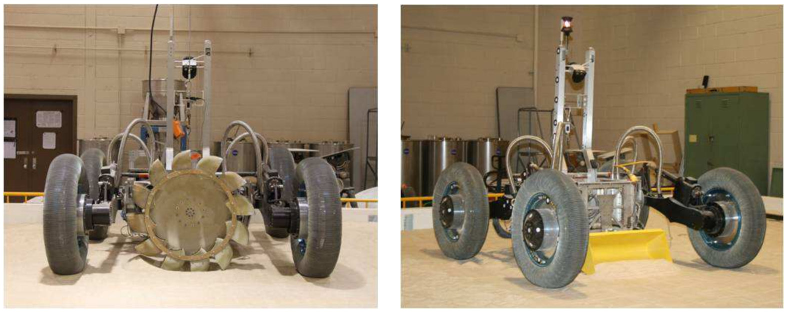

Fig. 1 A robotic excavator configured for continuous (left) and discrete excavation (right).

A wide assortment of planetary excavator prototypes have been developed in recent years, of both the continuous and discrete variety, specifically for excavation and ISRU. Muff et al. proposed a bucket-wheel excavator [15]. A Bucket-Drum Excavator, which is an adaptation of a bucket wheel [6], excavates regolith directly into a rotating drum. NASA's Regolith Advanced Surface Systems Operations Robot (RASSOR) has counter-rotating front and rear bucket drums, enabling it to balance horizontal excavation forces [13].

Examples of discrete excavator prototypes include NASA's Cratos [5], a scraper with a central bucket between its tracks. Other examples include NASA's Centaur II with front-loader bucket and Chariot with LANCE bulldozer blade [11]. The Canadian Space Agency's Juno rovers [20] can be equipped with front-end load-haul-dump scoops. The wide variability in prototypes and approaches highlights the need for a far-reaching framework to analyze, test, and classify planetary excavators.

Testing of planetary excavation has been done almost exclusively in Earth gravity with full-weight excavators. Only a single set of experiments has been published characterizing excavation with a scoop in reduced gravity [3]. A discussion of these experimental results, as well as other results pertaining to traction in reduced gravity, in Section 2 shows why testing in Earth gravity can substantially overestimate planetary excavator performance, thus highlighting the need for a new testing methodology; a test method for gravity-offloaded excavation experiments is then presented. Section 3 predicts analytically why continuous excavators should be expected to perform better in reduced gravity than discrete excavators, and Section 4 uses the newly developed test methodology to provide experimental evidence supporting this result. Section 5 outlines the development of a novel prototype excavator based on the results of this research campaign, and also describes practical issues that were encountered during mobility field testing. Finally, Section 6 presents conclusions, lessons learned, and future work.

2 Gravity Offload Experimentation

This work presents novel experiments that for the first time subject excavators to gravity offload (a cable pulls up on the robot with 5/6 its weight, to simulate lunar gravity) while they dig. Although not fully representative of excavation on planetary surfaces (where the regolith is also subject to reduced gravity), these experiments are more representative of planetary excavation performance than testing in full Earth gravity. Testing in Earth gravity is an inadequate evaluation of planetary excavators, as it over-predicts excavator performance relative to reduced gravity. The following subsections discuss the effects of gravity on traction and excavation resistance, and explain why gravity offload testing is a more balanced approach than testing in Earth gravity. Details of the testing methodology are then described.

2.1 Effects of reduced gravity on traction

A vehicle's drawbar pull is its net traction: DP = T - R (i.e. Thrust - Resistance). Note that both Thrust and Resistance depend on wheel slip. Drawbar pull at 20% slip is a good measure of tractive performance, as pull begins to plateau around 20% slip for many wheels (or tracks) while negative effects such as sinkage increase [21]. A non-dimensional quantity, P_{20}/W (Drawbar pull at 20% slip, normalized by weight), has been used as a benchmark metric for lunar wheel performance from the times of Apollo [7] to today [25, 22].

The most representative test environment for planetary rovers is a reduced gravity flight, where rover and regolith are both subject to reduced g [3, 12]. Another class of tests reduces the weight of the robot, but not the regolith. NASA JPL runs mobility tests for the Curiosity rover using a full geometric scale $3/8^{th}$ mass 'SCARECROW' rover [23]. SCARECROW's $3/8^{th}$ mass loads the wheels with an equivalent weight to the full mass Curiosity rover in Mars gravity. Another way to achieve equivalent results is to use a full mass robot, but to 'offload gravity' by offloading a portion of the robot's weight; this is the approach used in this work.

Testing with reduced robot weight in Earth gravity does not exhibit the same mobility performance as planetary driving (or reduced-g flights), where the regolith is also subject to reduced gravity [24]. It seems to in fact over-predict traction for scenarios governed by P_{20}/W, such as pulling and slope climbing. P_{20}/W is approximately constant with changing load (i.e. changing W but keeping scale and gravity constant, as with SCARECROW or gravity offload), as has been observed experimentally [7]. This is because both thrust, T, and resistance R, are reduced under lower loads; the former due to reduced frictional shearing, the latter due to reduced sinkage. On the other hand, changing W *by* reducing gravity *reduces* P_{20}/W. Kobayashi's reduced-gravity parabolic flight experiments showed that wheel sinkage is *not* reduced when driving in low gravity [12], though thrust still is.

These results suggest that gravity offload testing underestimates detrimental effects on rover tractive performance, by maintaining constant rather than diminished P_{20}/W at conditions meant to represent lower gravity environments. However, the next subsection explains that for excavators this fact is balanced by an overestimate of the detrimental effects on excavation resistance.

2.2 Effect of reduced gravity of excavation resistance forces

Reduced gravity increases the ratio of excavation resistance to weight in cohesive lunar regolith. Boles et al. compared excavation resistance forces measured in Earth gravity to resistance forces measured during reduced-gravity parabolic flights (for otherwise identical experiments), and showed that excavation resistance in 1/6 g could be anywhere between 1/6 and 1 of the resistance experienced in full Earth gravity ($F_{ex/E}$) [3]. This result is consistent with a theoretical analysis of excavation forces. Consider the two dominant terms of Reece's fundamental equation of earthmoving mechanics [9], based on the principles of passive earth pressure: $F_{ex} = N_\gamma \gamma g w d^2 + N_c c w d$ Gravitational acceleration is denoted g, γ is soil density, c is cohesion, d is cut depth, w is blade width, and the N_i are non-dimensional coefficients pertaining to different sources of resistance. The frictional part of F_{ex} is proportional to g, whereas the cohesive part is independent of g. This suggests that for a purely frictional soil F_{ex} in 1/6 g should be 1/6 of the $F_{ex/E}$, for a purely cohesive soil F_{ex} in 1/6 g should be 100% of $F_{ex/E}$, and for typical combination soils the result should be somewhere in between. Sample data from Boles et al. shows examples of F_{ex} in 1/6 g that average 1/3 of $F_{ex/E}$.

Characterizing planetary excavators performance based on tests in Earth gravity is equivalent to assuming that excavation resistance scales down proportionally to a reduction in gravity, which Boles' experiments show is not generally, or even typically, the case. Making such an assumption would thus underestimate the detrimental effects of reduced gravity on excavation resistance.

Reducing robot weight but not regolith weight makes excavation more difficult than is to be expected in reduced gravity. Longitudinal soil-tool interactions are not directly affected by reduced robot weight, so excavation resistance force, F_{ex}, remains unchanged. Reducing weight to 1/6 thus directly increases F_{ex}/W sixfold. For planetary excavation, this corresponds to the worst possible case of purely cohesive regolith. As neither lunar nor Martian regolith is purely cohesive, excavation resistance on these planetary surfaces in not expected to scale quite so poorly.

Excavating with gravity offload thus underestimates the detrimental effects of gravity on traction, but overestimates the detrimental effects on excavation resistance. This is a more balanced and conservative test than excavating in full Earth gravity, which underestimates detrimental effects on both traction and resistance.

2.3 Experimental Setup

Gravity offloaded excavation experiments were set up at NASA Glenn Research Center's (GRC) Simulated Lunar OPErations (SLOPE) lab. The facility contains a large soil bin with GRC-1 [16] lunar simulant. This research developed an experimental apparatus for achieving gravity offload in the SLOPE lab. The main aspects of the apparatus are shown in Figure 2. A cable pulls up on the robot, tensioned by weights acting through a 2:1 lever arm. The weights and lever assembly hang from a hoist that is pulled along a passive rail by a separate winch-driven cable. All tests are conducted in a straight line below the hoist rail. The winch speed is controlled so that the hoist is pulled along at the same speed as the robot is driving, keeping the cable vertical. For tests where excavator speed remains constant, winch speed is set open loop. For tests where the excavator enters into high slip, winch speed has to be manually reduced to match the robot's decreasing speed.

Fig. 2 Gravity offload testing with bucket-wheel (left) and front-loader bucket (right) on the Scarab robot. A cable pulls up on the robot, tensioned by weights acting through a 2:1 lever arm. The offload assembly hangs from a hoist that is pulled along a rail by a separate winch-driven cable.

Continuous bucket-wheel and discrete bucket excavation was performed using the Scarab robot (for a detailed description of the robot, see ([2],[22]). With Scarab's shell removed, excavation tools were mounted to the robot's structural chassis. For continuous excavation, a bucket-wheel was mounted with its axis of rotation aligned with Scarab's driving direction. The bucket wheel is 80 cm diameter with 12 buckets, and each bucket has a width of 15 cm. The bucket used for discrete excavation is 66 cm wide, and was mounted behind Scarab's front wheels at a cutting angle of 15 degrees down from horizontal. Figure 1 shows Scarab configured both as a continuous and as a discrete excavator.

Scarab has a mass of 312 kg (weight of 3060 N in Earth gravity) in the configuration used for these experiments. The connection point for the gravity offload cable was adjusted to preserve the robot's weight distribution (54% on the rear wheels). This was confirmed by weighing Scarab on 4 scales (one under each wheel) before and after being connected to the gravity offload apparatus. The offloading cable was equipped with a 2-axis inclinometer and a single-axis load cell to measure cable angle and tension, respectively.

Continuous and discrete excavation experiments were conducted at equivalent nominal production rates of approximately 0.5 kg/s, and at equal speeds of 2.7 cm/s. To account for the differing geometry of the excavation tools, the rectangular discrete bucket cut at a depth of 2 cm, and the circular bucket-wheel cut at a central depth of 5 cm. Depth was set using Scarab's active suspension, which raises and lowers the central chassis. Regolith picked up by the bucket-wheel was manually collected in 5-gallon buckets not connected to the robot, and weighed. The discrete bucket collected regolith directly, and after a test that regolith was transferred into 5-gallon buckets and weighed. To capture mobility data, the excavator's position was tracked using a laser total station at a data rate of 1 Hz during all experiments.

Between each test run, soil conditions were reset using a technique developed at NASA GRC. First, the GRC-1 simulant is fully loosened by plunging a shovel approximately 30 cm deep and then levering the shovel to fluff the regolith to the surface; this is repeated every 15-20 cm in overlapping rows. Next, the regolith is leveled with a sand rake (first with tines, then the flat back edge). The regolith is then compacted by dropping a 10 kg tamper from a height of approximately 15 cm; each spot of soil is tamped 3 times. Finally, the regolith is lightly leveled again for a smooth flat finish. A cone penetrometer was used to verify that the soil preparation consistently achieved bulk density between 1700 kg/m^3 and 1740 kg/m^3.

3 Predicted Excavation Performance

Considering that gravity offloaded excavation experiments are, on balance, more representative of planetary operating conditions, there is value in investigating cases where offloaded test results may diverge from tests in full Earth gravity; one such case is the comparison of continuous and discrete excavation. Estimates of excavation performance predict that continuous and discrete excavation should both be successful in 1 g, but that a continuous excavator achieves this with a higher performance margin. These differences in performance margin become apparent at conditions offloaded to 1/6 g, where discrete excavation is predicted to fail.

Predicted excavator performance is based on a comparison of traction and excavation forces. Excavator failure is defined as a degradation of mobility (i.e. significant increase in slip and/or sinkage), which is caused by excavation resistance forces exceeding the traction forces that the robot can sustainably produce.

The achievable traction is directly comparable for continuous and discrete excavation experiments, because in both cases Scarab is equipped with the same ’spring tire’ wheels. These wheels can sustainably produce a DP/W ratio of 0.25, as measured by drawbar pull - slip experiments. Achievable traction is thus approximately equal at the start of continuous and discrete experiments, when weight is approximately equal. In the course of a discrete excavation experiment, weight and thus traction increases as regolith is collected. In continuous experiments, on the other hand, traction remains approximately constant as regolith is collected into buckets not connected to the rover. Thus in 1 g, the maximum sustainable drawbar pull for continuous excavation is 765 N, while for discrete excavation it is 765 N plus 0.25 N for every 1 N of regolith collected. Similarly in offloaded 1/6 g, the maximum sustainable drawbar pull for continuous excavation is 128 N, while for discrete excavation it is 128 N plus 0.25 N for every 1 N of regolith collected (note that collected regolith is not offloaded).

Force measurements from preliminary tests show that continuous excavation forces are bounded [18], and are in the range of 6 N to 12 N in the case of the bucket-wheel being tested. Discrete excavation forces, on the other hand, rise approximately linearly with payload collected [1] [18], at a rate of 1.2 N to 1.5 N per 1 N or regolith collected for a similar discrete bucket [1]. This rise in force for discrete excavation is attributable to accumulation of surcharge at the cutting edge, resisting entry of further regolith into the bucket.

Comparing continuous excavation force to achievable traction predicts consistent margins of at least 98% to 99% in 1 g, and at least 90% to 95% in 1/6 g. For discrete excavation, on the other hand, initially high margins are predicted to decrease to zero once 600 N to 800 N of regolith is collected in 1 g, or once 100 N to 140 N of regolith is collected in offloaded 1/6 g. The maximum capacity of the discrete excavation bucket is approximately 450 N of GRC-1, so in 1 g it is predicted to be filled to capacity with leftover performance margin, but in 1/6 g the zero margin condition is predicted to be reached before the discrete bucket is filled.

Analyses of these preliminary force measurements also suggest that continuous excavation is somewhat more energy efficient than discrete excavation. By integrating over a 2.5 m excavation distance, and taking into account the 1.2 N to 1.5 N increase in excavation force per 1 N of regolith collected, 0.5 kg/s production and 2.6 cm/s forward speed, discrete excavation of 45 kg in 1 g requires 700-900 J. On the other hand, accounting for lateral and longitudinal bucket-wheel forces and displacements as well as vertical lifting of excavated soil, continuous excavation of 45 kg in 1 g requires 500-600 J; in lower g continuous excavation would be even more efficient because much of the energy goes into lifting the soil against gravity.

Despite the additional actuator to turn the bucket-wheel, energy is saved due to lack of energy-sapping resistive soil accumulation.

4 Experimental Results

Experimental data support the predictions made in the previous section, highlighting the importance of including gravity offloaded experiments into testing campaigns for proposed planetary excavators. Experiments show that in 1 g continuous and discrete excavation both achieve successful performance. On the other hand, in gravity offloaded 1/6 g, discrete excavation fails from degraded mobility, while continuous excavation does not.

Three or four runs were conducted at each of the test conditions, including baseline runs of driving without digging. Total station data were analyzed to calculate excavator speed during each test, as shown in Figure 3. The excavator maintains constant forward progress in all cases except discrete excavation with gravity offload. Average speed (as well as standard deviation) for the various test cases, is summarized in Table 1.

Excavation type	'Gravity'	Average v	σ_v
Driving only	$1g$	2.6 cm/s	0.2 cm/s
Continuous	$1g$	2.6 cm/s	0.3 cm/s
Discrete	$1g$	2.6 cm/s	0.4 cm/s
Driving only	$1/6g$	2.7 cm/s	0.3 cm/s
Continuous	$1/6g$	2.7 cm/s	0.3 cm/s
Discrete	$1/6g$	no S/S	n/a

Table 1 Discrete excavation offloaded to $1/6\ g$ is the only test condition that does not maintain constant steady state (S/S) velocity. Note that σ_v represents the mean of the 3 tests' σ values, not the σ of the tests' mean v (which showed negligible variation between tests of any single set)

Tests in 1 g exhibit a slightly slower speed, because the higher weight compresses the compliant 'spring tires' and reduces their radius. Excavation and gravity offload both introduce a small amount of additional variability in speed compared to driving without digging in 1 g. Continuous and discrete excavation in 1 g, as well as continuous excavation in gravity offloaded $1/6\ g$, all collected approximately 45 kg during each 2.5 m test run. Discrete excavation in gravity offloaded $1/6\ g$ collected only 15-20 kg, in contrast.

Gravity offload was controlled with sufficient precision to avoid pulling the excavator forward or backward. During continuous excavation, cable angle was unbiased about vertical, with a mean absolute value of just 0.1 degrees; with a cable tension of 2600 N, this corresponds to 4.5 N, or less than 1% of offloaded excavator weight. In contrast, inducing 20% slip in the spring tires used in the experiments would require sustained horizontal forces of 25% of offloaded excavator weight. Transient

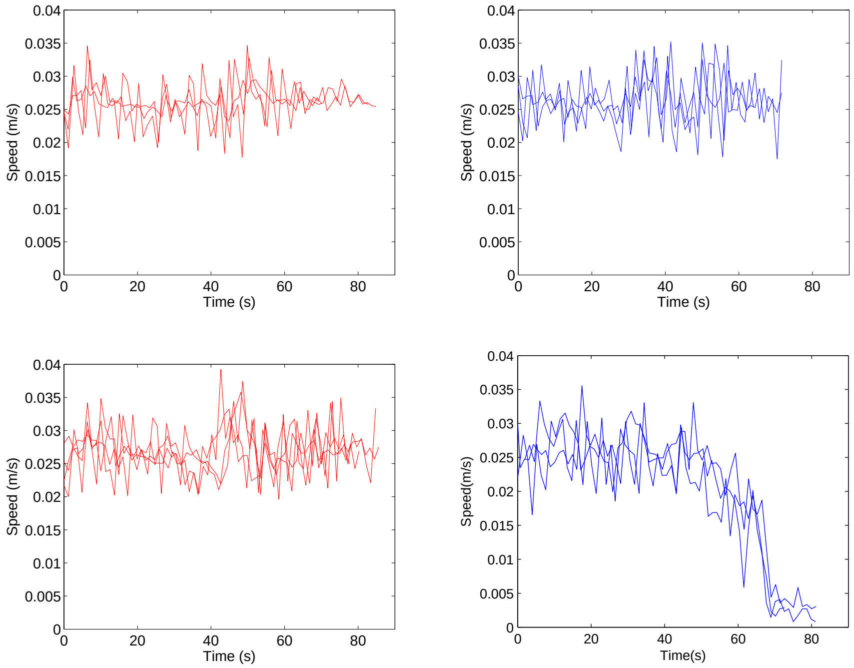

Fig. 3 Excavator forward driving speed during continuous excavation in 1 *g* (top left), discrete excavation in 1 *g* (top right), continuous excavation in gravity offloaded 1/6 *g* (bottom left), and discrete excavation in gravity offloaded 1/6 *g* (bottom right; time axes aligned at stall point). The excavator maintains constant progress in all cases except discrete excavation with gravity offload.

motions of the cable did not exceed 0.8 degrees from vertical for more than a fraction of a second; this corresponds to brief transients of 35 N, or 7% of offloaded excavator weight. Cable tension varies just ±1% which, amplified by the offloading ratio, corresponds to 5% variation in the offloaded excavator weight; this also translates to no more than approximately 1% variation in the ratio of horizontal force to offloaded excavator weight. Figure 4 shows longitudinal cable angle and cable tension for a discrete excavation test, the most challenging test due to the changing speed. Variability in angle and tension were again unbiased and small.

The gravity offload system was implemented primarily to test the hypotheses in this work and is not itself intended for extensive experimentation campaigns. Specialized gravity offload apparatus can be used to achieve even greater repeatability, and to overcome the limitations of the current system that include operating only in a straight line and lacking automatic speed adjustment.

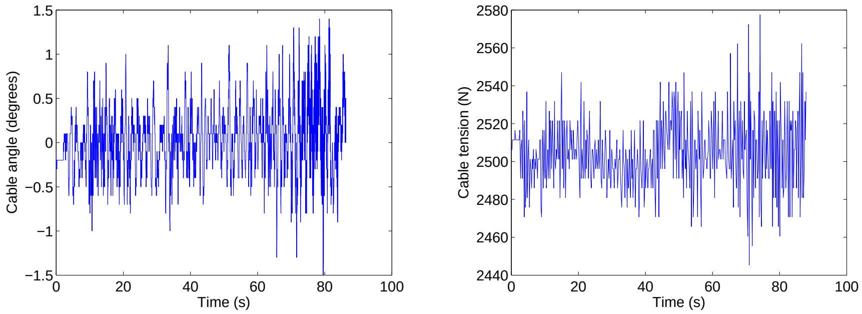

Fig. 4 Longitudinal angle (left) and tension (right) of the gravity offloading cable during a discrete excavation experiment, showing minimal variation.

5 Development of Planetary Excavator Prototype

This section describes a planetary excavator prototype that incorporates the principles established by this research and addresses practical considerations of implementing a continuous excavator for planetary environments. The Polaris excavator, shown in Figure 5, is a continuous bucket-wheel excavator. It is intended for in-situ resource utilization (ISRU), a task requiring substantial productivity. The 200 kg Polaris excavator features a nominal payload capacity of 80 kg for a payload ratio of 40%; prior research by the authors has shown that payload ratio governs productivity [17]. To collect its payload Polaris uses continuous excavation, the benefits of which have been discussed in this paper. The entire bucket-wheel / collection bin subsystem is actuated to engage cutting with the bucket-wheel and to enable dumping at out the back of the bin at a height of 50 cm. Polaris' top driving speed is 40 cm/s.

Fig. 5 Polaris excavator featuring continuous bucket-wheel excavation and high payload ratio.

5.1 Bucket-wheel excavator configuration and performance

Past planetary bucket-wheel excavator prototypes have had difficulty transferring regolith from bucket-wheel to collection bin, and as a result bucket-ladders have gained favor [10]. Bucket-ladders use chains to move buckets along easily shapeable paths, making transfer to a collection bin easy. Winners of the NASA Regolith Excavation Challenge and subsequent Lunabotics mining competitions (which require digging in lunar regolith simulant for 30 minutes) all employed bucket-ladders driven by exposed chains [14]. However, bucket-ladder chains are exposed directly to the soil surface and these could degrade very quickly in harsh lunar regolith and vacuum. The abrasiveness of lunar regolith rapidly degrades exposed sliding contacts or flexible materials [19, 8]. Exposed bucket-ladder chains may thus not be relevant to operation in lunar conditions.

A novel excavator configuration, with bucket-wheel mounted centrally and transverse to driving direction, achieves direct regolith transfer into a collection bin. The bucket-wheel is a single moving part, with no need for chains or conveyors. This reduces complexity and risk from regolith and dust. Once regolith has been carried to the top of the wheel in an individual bucket, it drops down out the back of the bucket and into a collection bin. This configuration offers a solution to the transfer problem for bucket-wheels identified in past literature.

The excavator prototype has demonstrated mining productivity of over 1000 kg/hr. 1040 kg was produced in 58 min, with an average round trip of approximately 14 m, as demonstrated in GRC-1 at NASA Glenn's SLOPE lap. During the hour-long operation, the teleoperated excavator performed 17 dig-dump task cycles, of which approximately 1/3 of the time was spent digging. Average power draw was 470 W, with the wheels causing an average power draw of 142 W, the bucket-wheel 18 W, and lift/dump 310 W. Although this particular test was not conducted with gravity offload, the similarity in continuous excavation results in Table 1 suggests that comparable productivity may perhaps also be possible in 1/6 g. Full-scale excavation task experimentation with gravity offload is suggested for future work.

5.2 Suspension Lift-Off for Lightweight Skid Steer Rovers

Prior to integrating the excavation subsystem (consisting of bucket-wheel, dump-bed and raise/lower actuation) into Polaris, field tests were conducted to evaluate the performance of its mobility platform. These field tests revealed an undesireable phenomenon in which a wheel unintentionally lifts off the ground in a wheelie fashion. Field and laboratory testing demonstrating the phenomenon, termed Suspension Lift-Off (SLO), are shown in Figure 6. SLO occurs during skid-steering and results in reduced stability and loss of control authority; it is a problem that can be encountered with any passive differential mobility suspensions, such as rocker bogies.

Fig. 6 Field tests (left) led to the discovery and study of suspension lift-off (right).

An analytical model that relates lateral turning forces to vertical terrain-contact forces was developed, though its full details are omitted here for brevity; these details are presented in [4]. The following parameters are concluded to be root causes of SLO: a tall shoulder height to wheelbase ratio, narrow aspect ratio (i.e. ratio of lateral to longitunal wheel spacing), eccentric weight distribution, and high center of gravity. Operational factors that increase risk are high turning resistance and driving on slopes. Parameter sensitivity analysis suggests that the shoulder height to wheelbase ratio is the single most important factor.

For rovers with two shoulders, like Polaris, the effective wheelbase is the rovers actual wheelbase minus the distance between shoulders. Decreasing the effective wheelbase by separating the shoulders direclty increases the shoulder height to wheelbase ratio and thus the risk of SLO. This overlooked caveat of Polaris' design was the single greatest contribution to the SLO problem encountered in field tests, particularly when the weight distribution on front and rear wheels was highly eccentric prior to integrating the excavation subsystem.

Tests compared the analytical models predictions to experimentally measured values and found good accuracy across thirty-five long duration skid-steer trials that varied suspension geometry and weight [4]. Agreement of empirical evidence with the model suggests that SLO is predictable, and thus preventable if key design criteria are met. The mitigation is to achieve a shoulder height less than one third of the wheelbase, and a center of gravity height less than half the wheelbase. If these design criteria are met, SLO is very unlikely to occur.

The contibution of turning resistance to SLO suggests that operation in reduced gravity may exacerbate the problem. Section 2.1 discussed how sinkage does not diminish in low g for forward driving, decreasing DP/W. If sinkage also does not diminish in low g during skid-steering, this could increase the ratio of lateral resistance force to vertical contact force and lead to greater risk of SLO. Investigation of skid-steering in reduced gravity is thus suggested as a direction for future study.

6 Conclusions, Lessons Learned, and Future Work

Conclusions. The contributions of this work include the first of their kind gravity offload experiments from planetary excavators, and the conclusion that continuous excavation is more suitable for low gravity than discrete excavation. Gravity offload is an important and practical class of field or laboratory test for planetary excavator prototypes. Though not an ideal representation of low gravity operations, as the effects of gravity on regolith are not included, this is a more balanced test than excavating in full Earth gravity, which can misleadingly overpredict performance. Omitting gravity considerations from planetary excavator development misses important distinctions between classes of excavator configuration, such as the advantages of continuous excavation over discrete excavation.

The experiments presented in this work demonstrate that continuous excavation fares better than discrete excavation when subjected to low gravity. They also suggest caution in interpreting low gravity performance predictions based solely on testing in Earth gravity, where both the continuous and discrete configurations, misleadingly, operated successfully.

Lessons learned. The key lesson learned from field testing is the need to consider suspension lift-off (SLO) for lightweight skid-steer robots. The mitigation is to achieve a shoulder height less than one third of the wheelbase, and a center of gravity height less than half the wheelbase. If the need to separate rocker arm shoulders arising in rover design, shoulder spacing should be minimized to avoid reducing the effective SLO wheelbase.

Future work. Future research on lightweight excavation, including skid-steer testing, would benefit from testing in reduced gravity flights or drop towers. Excavation task testing would also benefit from more gravity offload testing in generalized terrain, beyond the flat straight-line tests shown here. Another important direction for future study is deep excavation in the presence of submerged rocks, which pose challenges for lightweight continuous and discrete excavators alike.

Acknowledgements This work was supported by NASA under grants NNX11CB55C and NNX07AE30G. We thank Rob Mueller for his support of this work as NASA COTR. We also thank Colin Creager, whose tireless collaboration and support at SLOPE enabled key aspects of these experiments.

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