Advantageous bucket-wheel configuration for lightweight planetary excavators

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Abstract

Robotic regolith excavation on the Moon and Mars enables outposts, fuel depots, and sustained space exploration. In any space mission, mass is always at a premium because it is the main driver behind launch costs. Low mass and reduced gravity (1/6 of Earth gravity on the Moon, 1/3 on Mars) results in machines with limited weight available to produce traction or plunge tools into regolith. Bucket-wheel excavators have been shown to produce low resistance forces that enable lightweight operation, but in the past have had difficulty transferring regolith from bucket-wheel to collection bin. Exposed conveyors and chains fare poorly in harsh lunar regolith and vacuum. A novel excavator configuration, with bucket-wheel mounted centrally and transverse to driving direction, achieves direct transfer into a collection bin. Experiments with a bucket-wheel digging in lunar simulant show that transverse bucket-wheel orientation does not increase resistance significantly. Excavation resistance is shown to depend mostly on the ratio of bucket-wheel rotation rate to forward advance rate.

Keywords: Excavation, planetary rovers, bucket-wheel

1 Lightweight Planetary Excavators

Lightweight robotic excavators enable compelling exploration and regolith operations on the Moon and Mars. An excavator can feed regolith to precursor In Situ Resource Utilization (ISRU) processing plants, or remove overburden to study and to mine ice found near the lunar poles. The capability to excavate and manipulate regolith makes future lunar outposts, fuel depots, and even sustained human exploration possible.

Like exploration of the Martian surface, extraterrestrial excavation will first be performed by robots. Missions to collect and process native regolith into oxygen, water, and fuel will begin before human astronauts set out for Mars or return to the Moon.

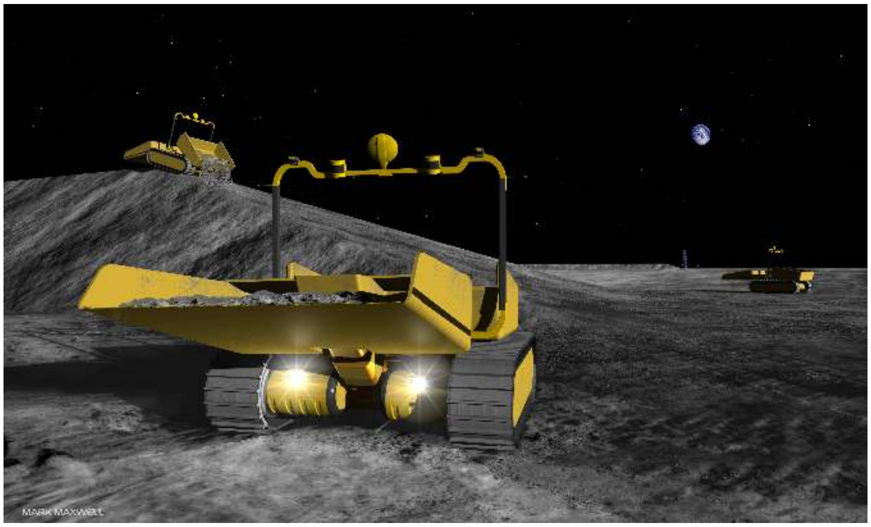

Fig. 1: *Conceptual excavation robots building outpost infrastructure on the Moon*

In any space mission, mass is always at a premium because it is the main driver behind launch costs. Small excavators that can achieve mission goals are preferable to larger ones. Low mass machines can also reduce risks for more advanced regolith operations by providing measured performance in actual lunar or planetary conditions before larger and more expensive launches are required. Low mass and reduced gravity (1/6 of Earth gravity on the Moon, 1/3 on Mars) results in machines with limited weight available to produce traction or plunge tools into the regolith. Engineering challenges associated with lightweight excavation necessitate a rethink of excavation configurations, possibly beyond the dozers, loaders, and excavators typical in terrestrial applications [1].

In recent years, several robot prototypes have been developed specifically for lunar excavation and In Situ Resource Utilization (ISRU). These have varied widely in weight class and in tooling configuration.

A class of these excavator prototypes with mass less than 100 kg includes a bucket-wheel excavator [2], a Bucket-Drum Excavator with a novel regolith collection/containment system [3], NASA's Cratos scraper [4], and several designs entered into NASA's Regolith Excavation Challenge and subsequent Lunabotics mining competitions. Winners of these contests have all employed bucket-ladder excavators. A team from Carnegie Mellon University participated in two of these competitions with Lysander, a scraper excavator.

Juno rovers [5], equipped with front-loading load-haul-dump scoops, have mass well over 200 kg and thus are in a somewhat different class of excavator prototype. NASA's Chariot (equipped with LANCE bulldozer blade) and Centaur II (with front-loader bucket) both have mass over 1000 kg and can hardly be classified as lightweight excavators, but were nonetheless envisioned as lunar/planetary excavators.

Aside from weight, another way to classify various lunar/planetary excavator prototypes is by their configuration type. One distinction is between continuous and discrete excavator configurations. Continuous excavators (such as bucket-wheels or bucket-ladders) achieve productive digging by taking cuts of soil with multiple small buckets in quick succession. Discrete excavators (such as front-loaders or scrapers) fill one larger, wider bucket with a single cut.

Fig. 2: *Lysander, a lightweight scraper excavator, transporting lunar regolith simulant*

This work argues that continuous excavators are more suitable for lightweight operation than discrete wide bucket excavators. A configuration is proposed that makes using a bucket-wheel particularly advantageous and lunar-relevant.

2 Theory predicts high productivity for wide bucket excavators

Classical excavation models incorrectly suggest that wide bucket excavators cutting regolith at low depth are the most productive. This section explores the theoretical underpinnings of this prediction, and the next section describes the reasons why it fails in practice.

The maximum horizontal excavation resistance an excavator can sustain without losing traction, denoted F_{max}, is limited by its drawbar pull, which on level ground can be assumed to be a constant bound. An excavator's productivity is its rate of soil collection when digging at max resistance, and both productivity and resistance depend on bucket geometry.

Classical models commonly put forward as candidates for simulating lunar and planetary excavation [6, 7] include Luth & Wismer, Balovnev, McKyes, Swick & Perumpral, and Gill & VandenBerg. Subsequent subsections describe these models and show how they steer toward wide bucket configurations.

2.1 Applying Luth & Wismer excavation model

Luth and Wismer [8, 9] developed separate excavation models for sand and clay. These models use non-dimensional ratios of relevant parameters, with coefficients and exponents empirically fit. Although developed separately for purely frictional sand and purely cohesive clay, the two models are sometimes used additively for soils that exhibit both frictional and cohesive strength [2, 6, 10]. A bucket is estimated as an inclined plate, with no side walls modeled.

Horizontal excavation resistances modeled by Luth and Wismer for sand and clay are:

$$F_{H,sand} = \gamma g w l^{1.5} \beta^{1.73} \sqrt{d} \left(\frac{d}{l \sin \beta} \right)^{0.77} \times \left[1.05 \left(\frac{d}{w} \right)^{1.1} + 1.26 \frac{v^2}{gl} + 3.91 \right] \tag{1}$$

$$\begin{aligned} F_{H,clay} &= \gamma g w l^{1.5} \beta^{1.15} \sqrt{d} \left(\frac{d}{l \sin \beta} \right)^{1.21} \\ &\times \left[\left(\frac{11.5c}{\gamma g d} \right)^{1.21} \left(\frac{2v}{3w} \right)^{0.121} \left(0.055 \left(\frac{d}{w} \right)^{0.78} + 0.065 \right) + 0.64 \frac{v^2}{gl} \right] \end{aligned} \tag{2}$$

Bucket width is denoted w, cut depth is d, cut velocity is v, and soil density is γ. Other parameters are defined in the notation section.

Excavation production (in kg/s) can be estimated by the product $wdv\gamma$. Production for various bucket shapes is calculated by holding cut velocity and soil density constant. Depth is treated as an independent variable, and the bucket width that results in F_{max} (also constant) is solved for numerically.

Predicted production rises monotonically as a function of bucket width aspect ratio (w/d), as shown in Figure 3. The Luth & Wismer excavation model predicts highest productivity for very wide buckets cutting very shallowly.

2.2 Applying Balovnev excavation model

Balovnev [11] developed a theoretical excavation model that incorporates bucket side walls and cutting edge thickness. The horizontal component of excavation resistance is given by:

$$\begin{aligned} F_H &= wd(1 + \cot \beta \tan \delta) A_1 \left[\frac{dg\gamma}{2} + c \cot \phi + gq + B * (d - l \sin \beta) \left(g\gamma \frac{1 - \sin \phi}{1 + \sin \phi} \right) \right] \\ &+ w e_b (1 + tan\delta \cot \alpha_b) A_2 \left[\frac{e_b g \gamma}{2} + c \cot \phi + gq + dg\gamma \left(\frac{1 - \sin \phi}{1 + \sin \phi} \right) \right] \\ &+ 2sdA_3 \left[\frac{dg\gamma}{2} + c \cot \phi + gq + B * (d - l_s \sin \beta) \left(g\gamma \frac{1 - \sin \phi}{1 + \sin \phi} \right) \right] \\ &+ 4 \tan \delta A_4 l_s d \left[\frac{dg\gamma}{2} + c \cot \phi + gq + B * (d - l_s \sin \beta) \left(g\gamma \frac{1 - \sin \phi}{1 + \sin \phi} \right) \right] \end{aligned} \tag{3}$$

Bucket width is denoted w, cut depth is d, cut velocity is v, and soil density is γ. Other parameters are defined in the notation section. As with the Luth & Wismer model, v, γ, and F_{max} are kept constant, d is treated as an independent variable, and w is solved for numerically to calculate excavation production. Figure 3 shows maximum production predicted for a bucket approximately 100 times wider than cut depth, which corresponds to a very wide bucket cutting very shallowly.

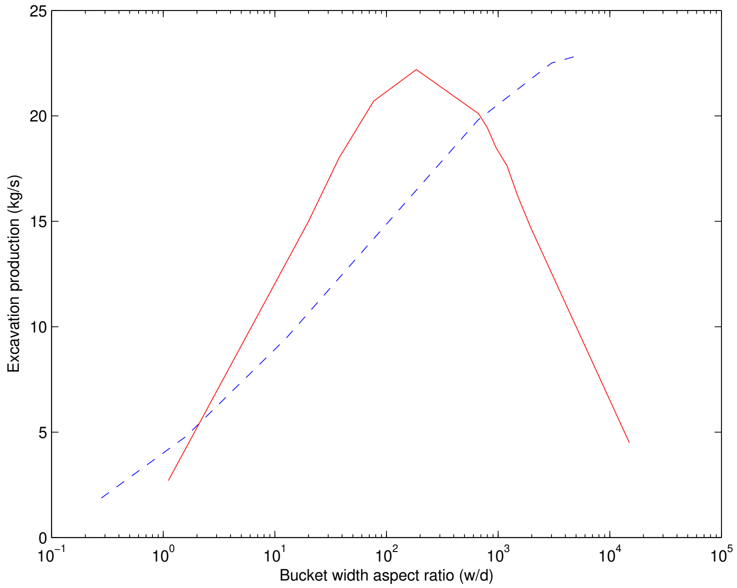

Fig. 3: *Luth & Wismer (dashed blue) and Balovnev (solid red) excavation models predict maximum production at very high ratios of bucket width to cut depth*

2.3 Applying McKyes and other excavation models

The theoretical excavation models developed by McKyes, Swick & Perumpral, and Gill & VandenBerg share a common form, and differ primarily in types of terms that are included or omitted, and in some coefficients. All three models are of the form:

$$F_H = wd[\Gamma_1 d + \Gamma_2] \tag{4}$$

Bucket (assumed a flat plate) width is denoted w, cut depth is d, and Γ_i denote coefficients that do not depend on w or d. Assuming a contant F_{max} as before, w can be expressed directly in terms of d:

$$w = \frac{F_{max}}{d[\Gamma_1 d + \Gamma_2]} \tag{5}$$

Excavation production, driven by the product wd, then follows the form:

$$\frac{C}{\Gamma_1 d + \Gamma_2} \tag{6}$$

which is maximized as d approaches 0 or, in other words, an infinite bucket width aspect ratio is approached. This is the theoretical limit of a very wide bucket cutting very shallowly.

3 Soil accumulation reduces wide bucket productivity in practice

Theory developed in the previous section suggests using a wide bucket excavator to maximize productivity when weight, and thus drawbar pull, are limited. Typical wide bucket excavators include scrapers and front-end loaders. Classical excavation models assume, though, that excavation resistance depends only on initial bucket setup and remains constant throughout the full traverse of a cut.

Excavation resistance in fact varies significantly during a cut as soil accumulates in the bucket, and classical models fail to incorporate this effect sufficiently.

Agui [12] shows that horizontal excavation resistance rises approximately linearly with cut distance, as soil accumulates in a wide aspect ratio bucket. King [7] demonstrates significant rises in horizontal forces on a bulldozer blade (another earthmoving configuration with a wide cutting tool) as surcharge increases with cut distance.

Classical excavation models described in previous subsections do not directly accomodate rise in excavation resistance due to soil accumulation. Some of the models have a surcharge term to account for an evenly distributed load acting on the soil being cut. Soil accumulation near the leading edge of a bucket could also be partially captured as an increase in cut depth. Agui showed that the shape and location of a soil pile accumulating in a bucket is nontrivially dependent upon time as well as cut depth, cut angle, and possibly other parameters. Modeling soil accumulation in a bucket by continuously changing surcharge distribution and cut depth is therefore difficult because it requires additional modeling of how the soil flows as it enters the bucket.

Weight-limited scrapers, front-end loaders, and bulldozers lose productivity because they are discrete excavators, not directly because they have wide buckets. It is the soil accumulation in a discrete bucket that increases resistance, not the aspect ratio of the bucket itself. Incorporating wide buckets in a continuous excavator, as some bucket-ladder excavators do, maintains productivity advantages of wide aspect buckets without the drawbacks due to soil accumulation.

4 Bucket-wheels and bucket-ladders

Bucket-wheel excavators have been shown to produce low resistance forces suitable for lightweight operation [13]. Bucket-wheels, and any other continuous excavators such as bucket-ladders, also do not suffer from increasing resistance from soil accumulation described in the previous section. Prototype bucket-wheel excavators have had difficulty transferring regolith from bucket-wheel to collection bin in the past, and as a result bucket-ladders have gained favor [14].

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. However, bucket-ladder chains are exposed directly to the soil surface and these would degrade very quickly in harsh lunar regolith and vacuum. Exposed bucket-ladder chains are thus not 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 dump-bed. The bucket-wheel is a single moving part, with no need for chains or conveyors. This reduces complexity and risk from regolith

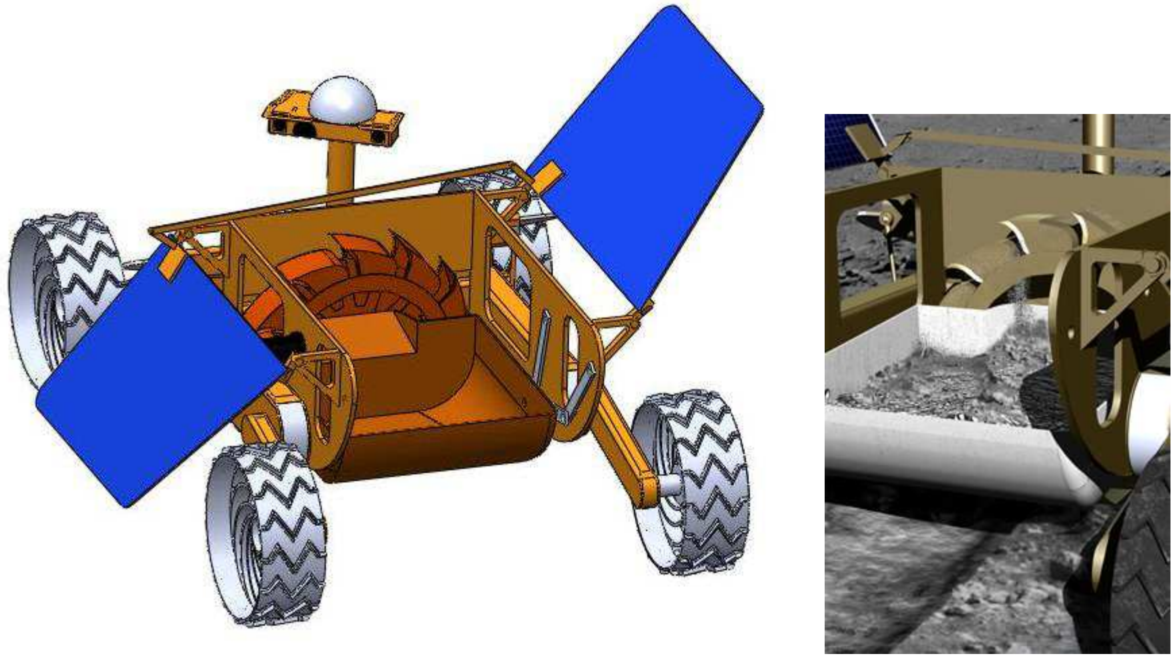

Fig. 4: *Left: Robotic excavator configuration with transverse bucket-wheel and large dump-bed*
Right: Close-up of regolith transfer into dump-bed

and dust. Once regolith has been carried to the top of the wheel in an individual bucket, it drops down a chute into a dump bed. This configuration offers a simple solution to the transfer problem for bucket-wheels identified in past literature [14].

A large dump-bed achieves a high payload ratio (mass of regolith that can be carried by the excavator, normalized by excavator mass). High payload ratio has been shown to be a key feature that governs productivity for lightweight robotic excavators [3]. The proposed configuration is thus highly productive even though it operates lightweight.

5 Testing a transverse bucket-wheel

The novel bucket-wheel excavator configuration simplifies regolith transfer into a dump-bed, but it is important to establish if that does not come at a cost, such as higher excavation resistance. A transverse bucket-wheel configuration must not lose the low resistance that makes bucket-wheels desirable in the first place.

Excavation forces and production rates of bucket-wheels digging in lunar simulant are measured experimentally. Experiments compare resistance forces encountered by bucket wheels advancing through GRC-1 lunar simulant in a transverse configuration (axis of rotation along direction of travel) and in a forward configuration (axis of rotation lateral to direction of travel).

An experimental apparatus pushes a bucket-wheel along a direction of travel while rotating it; the bucket-wheel orientation can be set either transverse or forward. A load cell measures the horizontal force opposing travel.

Excavation resistance for a transverse bucket-wheel is shown to depend strongly on rotation speed (as a ratio to forward advance rate). Once a sufficiently high rotation speed is achieved,

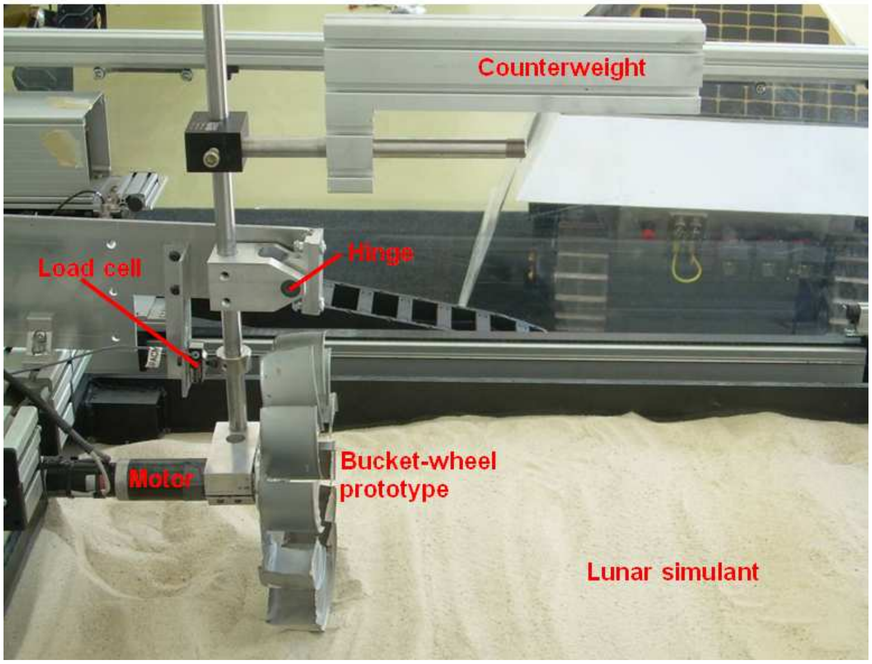

Fig. 5: *Experimental apparatus for bucket-wheel testing*

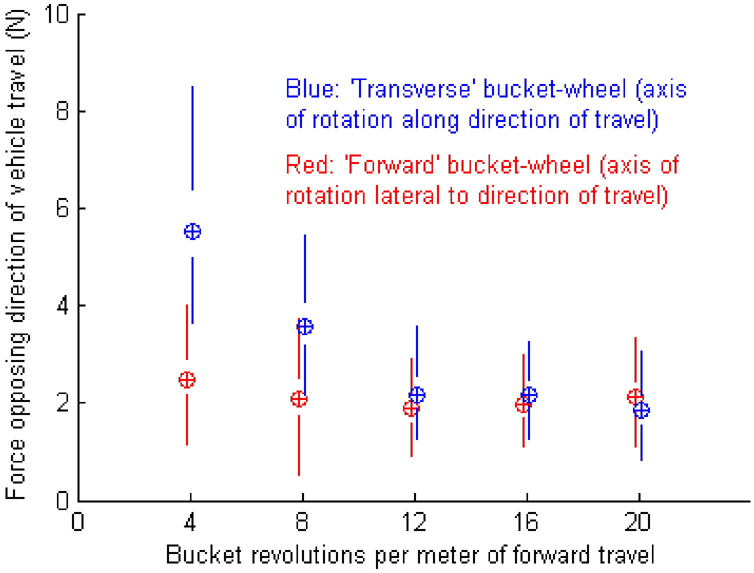

Fig. 6: *Transverse bucket-wheels do not exhibit significantly higher excavation resistance once bucket rotation speed is sufficient*

there is little difference in excavation resistance between transverse and forward bucket-wheel configurations.

Future experiments will measure lateral loads during transverse bucket-wheel tests. Initial observations suggest these are low.

6 Conclusions

Continuous excavator configurations, such as bucket-wheels and bucket-ladders, are preferable to discrete wide bucket excavators, such as scrapers and front-loaders, for lightweight lunar and planetary excavation. Classical excavation theory suggests wide buckets are highly productive, but the theory does not capture the effects of soil accumulation which degrades the productivity of weight-limited systems. Continuous excavators do not suffer from increased resistance from soil accumulation, because a new empty bucket is repeatedly introduced to cut soil.

Bucket-wheel excavators produce low resistance forces that enable lightweight operation, but in the past have had difficulty transferring regolith from bucket-wheel to collection bin or dump-bed. As a result, bucket-ladders have gained favor, but their exposed chains would fare poorly in harsh lunar regolith and vacuum.

A centrally mounted and transverse bucket-wheel configuration achieves simplified transfer of regolith into a dump-bed with no significant increase in excavation resistance. Future work will develop a prototype of this advantageous excavator configuration, for demonstration and further experimentation.

7 Notation

α_b	Blunt edge angle	[rad]
β	Cut angle	[rad]
Γ_i	Analytical coefficients	[]
γ	Soil density	[kg/m^3]
δ	External friction angle	[rad]
ϕ	Internal friction angle	[rad]
A_i	Balovnev model coefficients	[]
B	"Buried bucket" flag	[0,1]
C	Constant	[]
c	Cohesion	[N/m^2]
d	Cut depth	[m]
e_b	Blunt edge thickness	[m]
F_H	Horizontal resistance force	[N]
F_max	Maximum horizontal force	[N]
l	Bucket length	[m]
l_s	Side length	[m]
s	Side thickness	[m]
v	Cut velocity	[m/s]
w	Bucket width	[m]

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