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# Push–pull locomotion for vehicle extrication

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**Abstract**

For applications in which unmanned vehicles must traverse unfamiliar terrain, there often exists the risk of vehicle entrapment. Typically, this risk can be reduced by using feedback from on-board sensors that assess the terrain. This work addressed the situations where a vehicle has already become immobilized or the desired route cannot be traversed using conventional rolling. Specifically, the focus was on using push–pull locomotion in high sinkage granular material. Push–pull locomotion is an alternative mode of travel that generates thrust through articulated motion, using vehicle components as anchors to push or pull against. It has been revealed through previous research that push–pull locomotion has the capacity for generating higher net traction forces than rolling, and a unique optical flow technique indicated that this is the result of a more efficient soil shearing method. It has now been found that push–pull locomotion results in less sinkage, lower travel reduction, and better power efficiency in high sinkage material as compared to rolling. Even when starting from an "entrapped" condition, push–pull locomotion was able to extricate the test vehicle. It is the authors' recommendation that push–pull locomotion be considered as a reliable back-up mode of travel for applications where terrain entrapment is a possibility.
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*Keywords:* Mobility; Articulation; Extrication; Sinkage; Entrapment; Locomotion; Thrust; Wheel slip

## 1. Introduction

One of the most difficult challenges faced when driving unmanned vehicles through unfamiliar terrain is preventing immobilization. Manned vehicle operations have the benefit of using the driver's observations to survey the terrain conditions; whereas autonomous or remotely operated vehicles rely on either sensor feedback or previous knowledge of the terrain to determine whether an area is safe to traverse. Situations where a vehicle could potentially become entrapped can be difficult to assess, especially in extraterrestrial locations.

Robotic vehicles with on-board sensors can be a useful method for determining the traversability of an area. However, it may not become apparent that the terrain is too difficult or unsafe to drive through until the vehicle has already become immobilized, such as in the case of robotic exploration. For example, in 2009 the Mars Exploration Rover, Spirit, became embedded in a soft sandy material on Mars, a terrain condition that was not anticipated and could not have been predicted (NASA Jet Propulsion

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Laboratory, 2013). Typically the drivers for the Spirit rover would assess its wheel slip by taking photos of its tracks and observing how often certain tread patterns appeared in the terrain. However, this assessment could only be conducted after the commanded movements were completed and the photos were sent back to Earth. This challenge, coupled with a broken drive motor on one of the wheels, resulted in a case where the rover had become entrapped in a high sinkage material before the drivers on Earth were aware of the situation. Alternative modes of locomotion could provide a greater likelihood of extrication in extreme situations such as this.

This paper addresses the challenge of traversing terrain that generally results in high sinkage and high wheel slip under normal all-wheel drive modes. The authors demonstrate how adding additional degrees of freedom to a robot significantly helps not only traverse difficult terrain, but extricate the robot from an immobile state. Though there are other alternative modes of locomotion that can be used to improve a robot's extrication abilities, the focus of this paper is on one specific mode, referred to here as "push–pull locomotion".

## 2. Push–pull locomotion

The term push–pull locomotion is used to describe a general mode of generating thrust. Unlike conventional rolling where thrust is produced by a rotating implement, the thrust force for push–pull locomotion is generated by keeping a portion of the vehicle stationary relative to the ground and re-positioning another portion of the vehicle to a different location by active articulation (Creager et al., 2012). The stationary portion is then re-positioned while the previously moved portion remains planted to the terrain. This alternating process continues resulting in a translation of the entire vehicle. During this cycle, the stationary implements in contact with the terrain are essentially "pushing" or "pulling" the vehicle while gripping the ground. Walking, which the NASA ATHLETE robot is capable of (Wilcox et al., 2007), is a familiar form of push–pull locomotion; however systems that implement walking are typically complex and inefficient due to the requirement of many active degrees of freedom.

### *2.1. Scarab and "inch-worming"*

The specific variation of push–pull locomotion that is the focus of this research is often called "inching" (or "inch-worming"). It is visually similar to the method an inch-worm uses to propel itself forward and uses a combination of rolling wheels and vehicle articulation. The Scarab roving vehicle (Wettergreen et al., 2010), developed at Carnegie Mellon University, is a four wheel drive robotic vehicle with the ability to move by conventional rolling or by inching (Fig. 1). On each side, each wheel is attached to the end of an arm that extends out from the center of the chassis at a shoulder joint. An actuator controls the angle between these arms, thus creating the ability to vary the wheel base (distance between the front and rear wheels). When inching, the rear wheels are first held in place relative to the ground while the wheel base is increased and the front wheels are driven forward. Once the front wheels are in place, the back wheels are driven forward while the wheel base is reduced. Fig. 1 shows Scarab undergoing the inching process starting with the largest wheel base. During this cycle, two wheels (either front or rear) are always stationary, relative to the ground acting as anchors from which the rest of the vehicle can push or pull itself into position.

### *2.2. Previous research using this technique*

The concept of inching is not unique and has been investigated in the past. At the Army Land Locomotion Laboratory (Czako et al., 1963) the concept of a segmented vehicle with the ability to inch was introduced. It was determined through theoretical analysis that by keeping one axle stationary and propelling the other forward, the thrust generated by the stationary wheels would be transferred to the rolling wheels allowing them to better overcome the resistance on the moving axle. The stationary wheels would not encounter rolling resistance, thus the net resistance on the vehicle as a whole decreased while the thrust remained the same. In theory this would allow an inching vehicle to generate more net tractive force than a pure rolling vehicle, but only by an amount equal to the rolling resistance on one axle.

#### *2.2.1. Drawbar pull testing*

More recently, a series of drawbar pull tests were conducted at the NASA Glenn Research Center (GRC) that quantitatively compared the net tractive forces of inching to rolling (Creager et al., 2012). It should be noted that the terms "rolling" or "conventional rolling" in this paper refer to the case where all four wheels are being driven at the same rotational speed.

For these tests, the Scarab rover was driven through a simulated lunar terrain consisting of a granular material called GRC-1 (Oravec et al., 2010) while a drawbar pull test apparatus applied a controlled pull force to the vehicle in the direction opposite of travel. For both modes of travel, rigid and compliant tires were tested over multiple levels of pull force. A relationship between pull force and the reduction in forward speed was developed. It was found that inching was able to generate approximately 37% of the vehicle's weight in drawbar pull force with the pneumatic tires, compared to only 27% when rolling. For rigid tires, the maximum pull forces were approximately 33% for inching and 25% for rolling.

The drawbar pull force, or net tractive force, is equal to the thrust generated by the wheels minus any rolling resistance in the system. Therefore, if inching requires less rolling resistance as theorized by Czako et al. (1963), this could account for a higher maximum drawbar pull force as

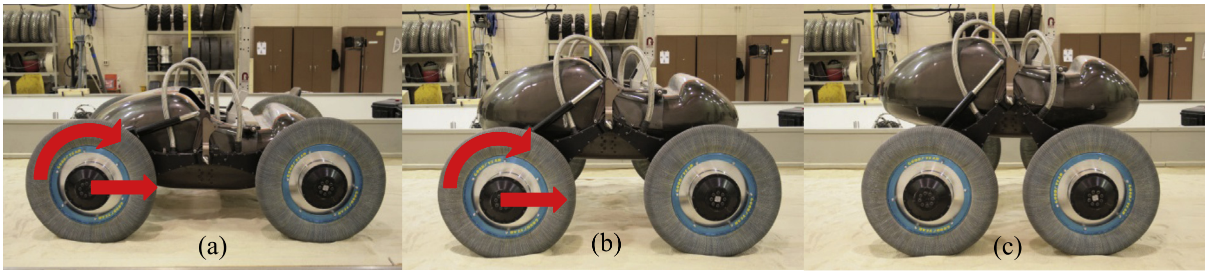


Fig. 1. Scarab going through inching procedure: (a) at its greatest wheel base, (b) mid position, and (c) smallest wheel base.

shown in the results above. To estimate how much effect rolling resistance typically has on a vehicle in this terrain, a cart with four rigid wheels mounted on bearings was towed in GRC-1. The wheels were roughly the same dimensions as the ones used in the drawbar pull tests, but the tire loads were approximately one third that of Scarab's (this was because the cart could only handle certain loads). The maximum pulling force measured, which represents the total rolling resistance, was about 5% of the vehicle weight. For Scarab's greater tire loads, this percentage could be slightly higher but likely not much. Also, it can be assumed that each axle only accounted for half of that resistance, approximately 2.5% of the vehicle weight. Because the increase in drawbar pull force from rolling to inching was significantly more than this, it indicates that inching must have produced more thrust in addition to a lower rolling resistance.

### 2.2.2. Soil response beneath wheels

In order to understand why push–pull locomotion has a higher capacity for generating thrust than conventional rolling, an experiment was run that produced a visualization of soil motion beneath a wheel (Moreland et al., 2011). This novel method, termed "Soil Optical Flow Technique" (SOFT), was developed at Carnegie Mellon University through collaboration with NASA GRC (Skonieczny et al., 2014). The technique involved positioning a wheel in a soil tank up against a clear glass wall so that the soil directly beneath the wheel can be viewed externally (Fig. 2). The soil bin in this case had been filled with GRC-1 and prepared to a repeatable condition through a process of loosening, leveling, and compaction. For this experiment, a rigid wheel with a diameter 1/3 that of the wheels used on Scarab was placed against the glass. In order to simulate soil directly underneath the center of the wheel, the width of the wheel was made to be only 1/6 that of the full size one (instead of 1/3); in other words the glass wall was placed virtually through the center of the wheel in the width direction. By assuming the soil response to be symmetric about the center of the wheel in the width direction, the glass wall was determined to have a negligible effect on the soil response as long as friction forces between the glass and soil were minimal (Wong and Reece, 1967). It is believed that any effect of the glass

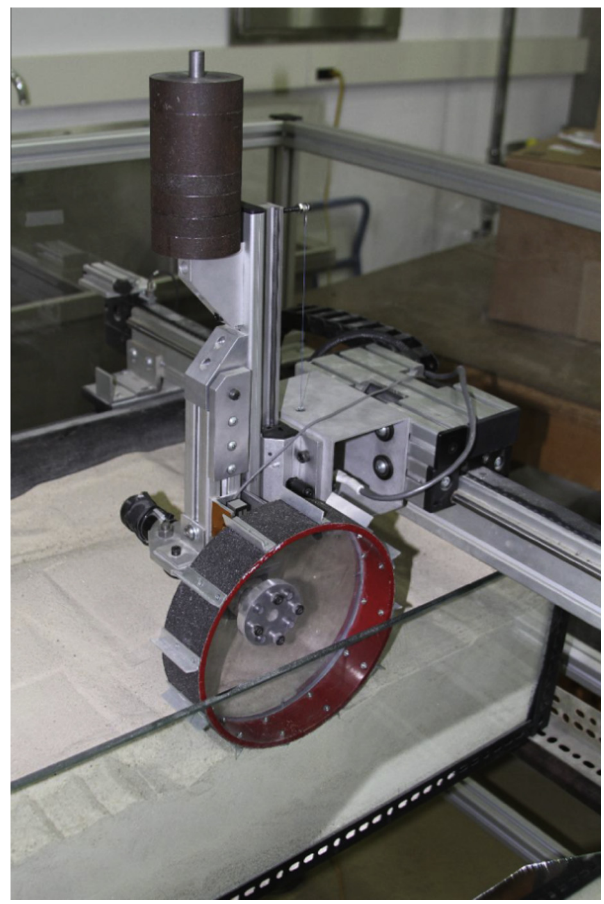

Fig. 2. Wheel test rig used with Soil Optical Flow Technique.

on soil movement was not significant enough to impact the soil flow patterns beneath the wheel.

The wheels were mounted in such a way that they could either be driven, free-rolling, or braked but have free motion in the vertical direction. The carriage on which the wheel and drive unit were mounted was also speed controlled in the horizontal direction parallel to the glass wall, and was used to simulate the vehicle speed. By controlling both the carriage velocity and rotational speed of the wheel, wheel slip was induced. A camera mounted outside of the bin took high resolution images of the soil beneath the surface at a constant rate. The SOFT computer software then read in these images and tracked the soil particle motion between frames creating velocity vector fields of the soil particles at each interval of time.

Two specific cases were studied to better understand the increase in net traction observed from push–pull locomotion over conventional driving in GRC-1. In the first case, the wheel and the carriage were driven at rates that produced a significant amount of slippage at the wheel-terrain interface. This served to simulate a condition where conventional driving would generate close to the maximum amount of drawbar pull force possible for a given wheel and weight. As seen in the top halves of Figs. 3 and 4, the soil particles moved at a fairly even rate along the profile of the wheel. From the directional analysis in Fig. 4, the soil appeared to follow the edges of the wheel, moving with a downwards component at the leading edge and with an upwards component at the trailing edge. This type of soil response was defined by Bekker as “grip failure” (Bekker, 1960) and is typically how a driving wheel generates thrust.

In the second case, the wheel was braked to prevent rotation while the carriage was driven at a slow but constant rate. This essentially mimicked the maximum drawbar pull force condition of an “anchored wheel” using push–pull locomotion. The bottom halves of Figs. 3 and 4 show the velocity and directional response, respectively, of the soil for this case. From these results, it is obvious that the soil responded differently for the two modes of driving. When the wheel was pushed or towed (braked), a larger mass of soil was relocated than when rolling. Of even more significance is that the direction of motion for the particles was more uniform; instead of following the edge of the wheel, the soil mass was pushed opposite the direction of travel. Since only the component of forces in the transverse direction is useful when driving, it appeared as though less energy was lost compared to conventional driving where the soil underwent more vertical displacement. Bekker described this response as “ground failure” or “general shear failure” (Bekker, 1960). Also in the case of the towed wheel, most of the soil displacement occurred in front of or behind the wheel, whereas with the rolling wheel case, more soil was engaged below the wheel. This displacement of soil beneath the wheel could be a contributing factor to sinkage. These findings support the notion that push–pull locomotion has a higher capacity for generating thrust due to the more efficient terrain response.

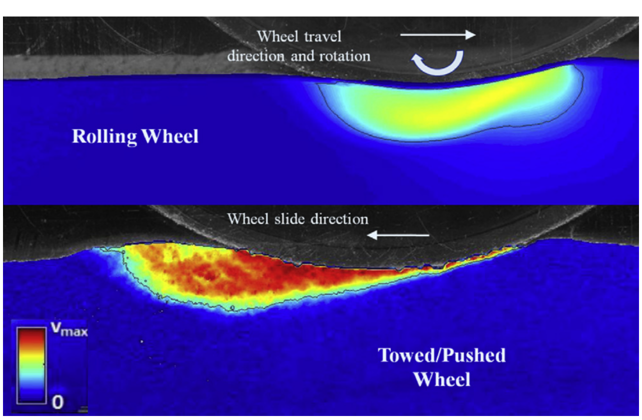


Fig. 3. Soil velocity response to rolling wheel vs. pushed wheel; color indicates relative magnitude of soil particle velocity (Moreland et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

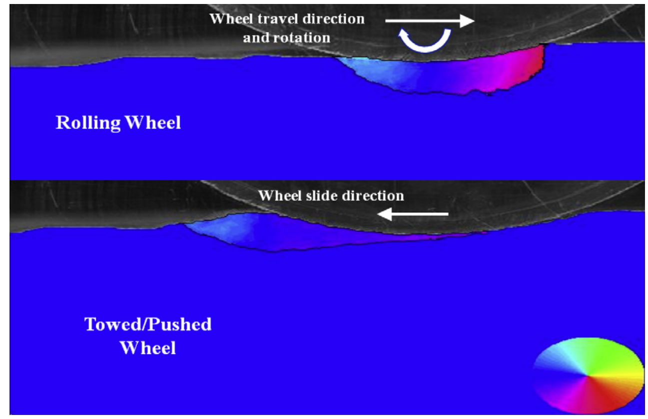


Fig. 4. Soil directional response to rolling wheel vs. pushed wheel; color indicates direction of soil particle velocity (Moreland et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 3. Extrication testing in the NASA GRC Sink Tank

### *3.1. Description of terrain*

The extrication research discussed here was conducted in the NASA GRC Sink Tank, a bin 12 m long by 3 m wide by 0.5 m deep filled with a high sinkage material. The purpose of the Sink Tank was to produce conditions under which most vehicles would become immobilized using conventional driving techniques. Though GRC-1 is a difficult material to traverse, it was never able to immobilize the Scarab rover, even when the vehicle was buried up to the wheel hubs. Several granular materials were investigated to determine the appropriate medium for the Sink Tank. The material had to have low bearing capacity and shear strength so that the vehicle would sink as the tires attempted forward motion. Its mechanical properties, such as particle size, shape, and cohesion, must be in the same realm as granular materials found during roving missions so that the research could have practical value.

After considering many options, a material called Fillite (Tolsa USA Incorporated, 2013) was chosen as the high sinkage material. Fillite consists of hollow alumina–silica microspheres with a particle size distribution that is poorly graded (see Fig. 5). Because of its low specific gravity, it is primarily used to reduce the weight of liquid and solid compounds such as cement or plastics. However, the shape and uniformity of the particles provide low shear strength when in bulk quantities because the microspheres move so freely. Typically when well graded granular materials

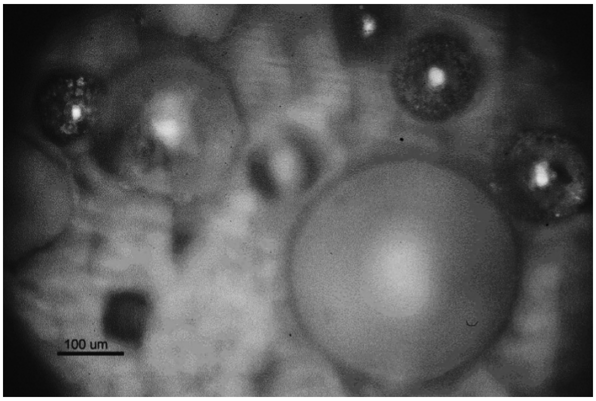


Fig. 5. View of Fillite microspheres under microscope (100× magnification).

Fig. 6. Pneumatic rubber tires buried in Fillite.

get disturbed, the smaller particles fill in the voids left by the larger particles creating a denser and stronger bulk unit. However, because the Fillite microspheres are fairly homogeneous in size, the voids do not get filled in easily and the bulk density does not change significantly. Instead, particles flow past one another with relatively low shear resistance. This leads to low bearing strength and high sinkage.

Some basic geotechnical properties of Fillite (Edwards et al., 2014) are listed in Table 1, along with properties for other granular materials, JSC-1a (Zeng et al., 2010) and GRC-1 (Oravec et al., 2010), that have been widely used by NASA for terramechanics research. JSC-1a consists of angular basaltic particles made to simulate the lunar soil driven on by Apollo astronauts. GRC-1 is a lunar strength simulant that consists of silica sand and was made to be slightly more challenging in terms of generating traction, as compared to JSC-1a. Though the other materials listed here were created to simulate specific lunar terrain properties, Fillite was chosen for its high sinkage properties to create a general mobility challenge.

It should be noted that the low bulk density of the material gives it the unique ability to represent low gravity terrain response due to the hollow nature of the particles. When performing traction studies with extraterrestrial simulants on Earth, the weight of the soil particles is usually assumed to be of minimal importance. However for extrication studies, the weight of the soil does factor in because the tires are typically embedded in the terrain under a significant amount of soil which adds resistance. Fig. 6 shows Scarab with rubber tires in Fillite after significant sinkage.

Typically when conducting traction tests in a granular material, the bulk density of the material is affected by the weight of the vehicle and the shearing that takes place beneath the tires resulting in a different terrain condition. For these cases, it is important to reset the terrain to its natural loosened state before each test and then compact the terrain if desired. However, Fillite has a narrow range of bulk densities and remains in a loose state even after being traversed or sheared; typically the only way to significantly increase the bulk density of the material is through excessive vibration and normal loading. The preparation instead consisted of leveling the terrain to a specific uniform height before each test run so that the vehicle was always driving on flat ground and sinkage measurements could be consistently taken with respect to the surface.

To verify the consistency of this terrain preparation method, six identical rolling tests were run with pneumatic

Table 1
Geotechnical properties of Fillite compared to simulants used for traction testing.

| Soil type | Fillite microspheres[a] | JSC-1A[b] | GRC-1[c] |
|---|---|---|---|
| Description | Cement/plastic filler | Lunar soil simulant | Lunar terrain strength analog |
| Particle shape | Spherical | Angular | Sub-angular |
| Material | Alumina–silica | Sand/silt | Sand |
| $D_{10}$ (mm) | 0.13 | 0.017 | 0.094 |
| $D_{60}$ (mm) | 0.21 | 0.110 | 0.390 |
| Specific gravity | 0.67 | 2.875 | 2.583 |
| Min bulk density (g/cc) | 0.415 | 1.57 | 1.60 |
| Max bulk density (g/cc) | 0.476 | 2.03 | 1.89 |
| Friction angle (deg) | 32.2 (20% rel. density) | 41.9 (25% rel. density) | 33.4 (20% rel. density) |
| Cohesion (kPa) | ~0 (20% rel. density) | ~0 (25% rel. density) | ~0 (20% rel. density) |

[a] Fillite information based on Tolsa USA Incorporated (2013) and Edwards et al. (2014).
[b] JSC-1A information based on Zeng et al. (2010).
[c] GRC-1 information based on Oravec et al. (2010).

tires on Scarab. For each of these, three measurements were taken every 2 s (the methods of measurement are described in the following sections): front wheel sinkage, rear wheel sinkage, and total forward distance traveled. The only noticeable variation occurred during the first couple of seconds when the vehicle was accelerating. The wheels continued to sink throughout each test. After driving for 80 s, the average front wheel sinkage was 17.6 cm, the average rear wheel sinkage was 24.6 cm, and the average distance traveled was 1.02 m. Aside from the initial acceleration period, a standard deviation was calculated at each sample time for the three metrics. The maximum standard deviations were: 1.01 cm for front wheel sinkage, 1.22 cm for rear wheel sinkage, and 3.3 cm for distance traveled. In addition, there appeared to be no pattern of change from test to test indicating that the terrain was not being compacted by the vehicle. It was determined that the preparation method was sufficient to produce consistent and reliable results.

### 3.2. Test setup and procedures

#### 3.2.1. Start condition

The extrication research discussed here was broken up into two cases defined by their different starting conditions. The first case, which involved starting Scarab on virgin terrain, served to investigate how push–pull locomotion could be used to avoid becoming immobilized, and will be referred to here as the "free" condition. This was achieved by leveling the terrain, then lowering Scarab to the surface with a crane so that only sinkage due to the vehicle's weight occurred. This resulted in sinkage less than 15% of the tire radius, as seen in Fig. 7a. Both rolling and inching tests were conducted using this starting condition. From this starting position, the vehicle was either rolled or inched until either it became entrapped or successfully traversed the terrain.

The second case, referred to here as the "entrapped" condition, explored how push–pull locomotion could help extricate a vehicle after it has already become entrapped or immobilized. This was achieved by driving Scarab using conventional rolling until it reached a condition where forward velocity was near zero and the rear wheels had sunk to where the wheel motor hubs were almost touching the surface of the Fillite (see Figs. 6 and 7b). From this position, the inching mode was initiated.

For both the free and entrapped cases, two different tires of identical dimensions (71 cm diameter and 18 cm width) but varying stiffness were used. Rubber pneumatic tires with very low tread were inflated to a pressure of 2 psi (Fig. 6). This created a highly compliant tire with a large footprint. Rigid tires of identical dimensions (Fig. 7) were also used that resulted in a smaller footprint and higher ground pressure. This contrast in footprint size and ground pressure was used to investigate the benefits of push–pull locomotion over a range of applications. The mass of the Scarab vehicle for these tests was 400 kg which, if taking gravity into account, would have similar tire loads to a 1052 kg vehicle driving on Mars.

Each test run consisted of driving the Scarab rover through the Sink Tank, starting from either a free or entrapped condition, until either the vehicle was making negligible forward progress or reached the end of the leveled terrain. For the rolling tests, a constant wheel rotational speed was commanded. The inching maneuver involved a combination of varying wheel speeds and wheel base in an attempt to achieve constant forward chassis velocity. However the chassis velocity did fluctuate throughout the cycle due to varying wheel slippage and transient controller errors. The rate of inching was limited by the maximum rotational speed of the wheel motors (approximately 0.14 rad/s or 1.3 RPM) which have been geared for low speed and high torque.

#### 3.2.2. Photogrammetry technique for tracking vehicle motion

In order to measure the forward travel and sinkage of each wheel, a novel photogrammetry method was implemented which allowed for the tracking of numerous points on the vehicle in three dimensions. A series of two dimensional targets (in this case white circles) were placed strategically on the vehicle including the chassis and front and rear wheels. Coded targets were also placed next to the bin to create a reference plane. A pair of cameras was rigidly mounted next to the Sink Tank so that the near side of the vehicle could be viewed at all times during a test. Then while the vehicle was driving, the cameras were triggered synchronously at a rate of one image pair every 2 s.

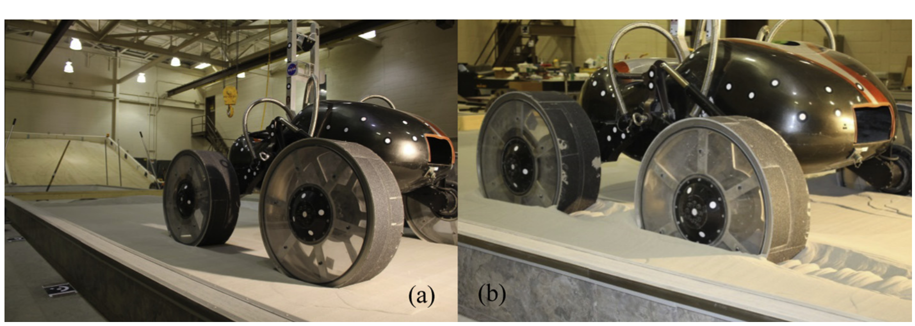


Fig. 7. The Scarab rover with rigid tires (a) before beginning driving and (b) while driving in the Fillite.

The photo pairs were then uploaded to software called "Pontos", developed by Gom (Gom Optical Measuring Techniques, 2013). Through a calibration procedure, the software is able to recognize the location and position of each camera relative to one another, and therefore used the pixel location of the targets on the vehicle to determine their actual three dimensional coordinates. When grouped together, these individual sets of coordinates were used to compute six degree of freedom motion for specific components on the vehicle, such as for one wheel. By knowing the deformed radius of the tires under load as well as the vertical distance between the terrain surface and the reference plane outside of the bin, true sinkage was measured.

## 4. Discussion of experimental results

### 4.1. Metrics used for evaluation

For this discussion, the metrics used to evaluate the performance of inching vs. rolling were broken up into three categories: wheel sinkage, forward travel, and power efficiency. Wheel sinkage was measured for both the front and rear axles. Though forward travel is also represented here in terms of distance or speed as a function of time (both measured at the chassis), the metric travel reduction (TR) was used to normalize the results. Travel reduction quantifies the reduction in forward velocity of the vehicle ($v_{actual}$) relative to a specific reference velocity ($v_{ref}$), and is defined in Eq. (1).

$$TR = \frac{v_{ref} - v_{actual}}{v_{ref}} \times 100\% \tag{1}$$

The metric is designed to allow for different reference conditions to be used. For this study, the reference condition was chosen to be the self-propelled case (no external forces acting on the vehicle) on hard ground with the same tire load and wheel rotational speed used in the Sink Tank. It is repeatable and independent of terrain. This was chosen because it represents the fastest and most efficient driving condition for this load/tire configuration.

It is important to note that this reference velocity was used when calculating travel reduction for both rolling and inching. Though inching on hard ground is significantly slower than rolling on hard ground, it was believed that the rolling case should still be used as a reference. This was so that the performance of Scarab inching could be related to the best case condition, and so that rolling and inching results could be compared directly in terms of speed.

Power number (PN) was used to evaluate the power usage for both modes of operation. It is equal to the power ($P$) being used by the vehicle normalized to the vehicle weight ($W$) and forward velocity ($v_{actual}$), as defined in Eq. (2).

$$PN = \frac{P}{W * v_{actual}} \tag{2}$$

Power number can also be defined in terms of energy ($E$) as shown in Eq. (3), which is useful when determining the amount of total energy needed to traverse a specific distance ($d_{actual}$).

$$PN = \frac{E}{W * d_{actual}} \tag{3}$$

The power being used was recorded on the vehicle so that all vehicle actuation was taken into account, not just from the wheel motors. This means that hotel loads (i.e. computing, sensing, etc.) were also included in the final power results. Low power number values indicate the vehicle is making an adequate rate of progress for the amount of power being used. As the forward velocity approaches zero, PN approaches infinity, and if the vehicle travels backwards, PN becomes negative. Because the inching mechanism does not produce constant vehicle motion (there are instances during the process where the chassis pauses or shifts backwards for a second), power number was averaged over 6 s intervals to eliminate any negative values which do not give true representation. This was done as a moving average using power data centered around the time stamp, so each time stamp with velocity data has a PN value associated with it.

### 4.2. "Free" starting condition

The results for the "free" starting condition tests are displayed in Figs. 8–12, each displayed with respect to time. The data in Figs. 8 and 9 indicate a significant decrease in sinkage for inching as compared to rolling (negative values represent the distance of the bottom of the tire below the terrain surface). The fluctuations in the inching data correspond to the inching cycles. Vehicle pitch is indicated by the difference in sinkage between the front and rear wheels, which is also more severe for rolling than inching. It is important to note that the vehicle appears to reach a steady state condition in terms of sinkage, implying that the sinkage of the vehicle will not get worse over time as it might with rolling.

The most important takeaway from the forward travel data (Figs. 10 and 11) is the trend over time. For the first

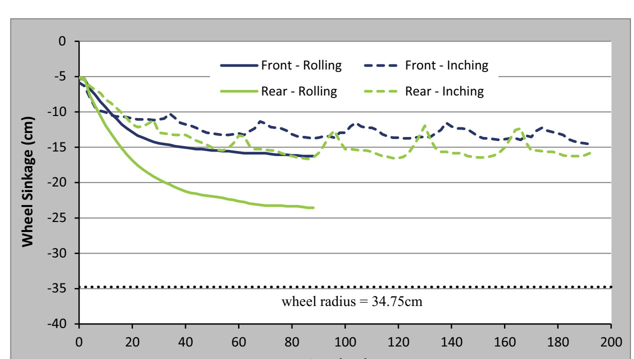


Fig. 8. Pneumatic tire sinkage (more negative represents deeper sinkage).

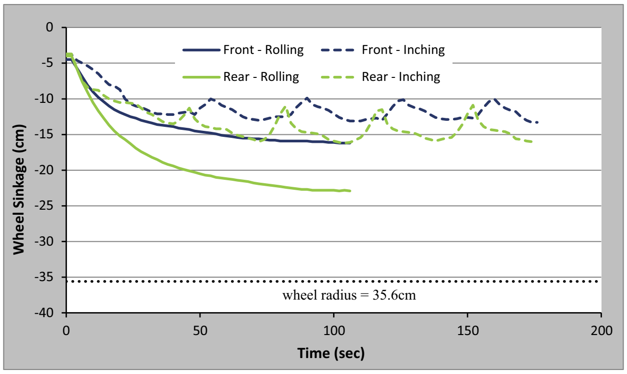


Fig. 9. Rigid tire sinkage (more negative represents deeper sinkage).

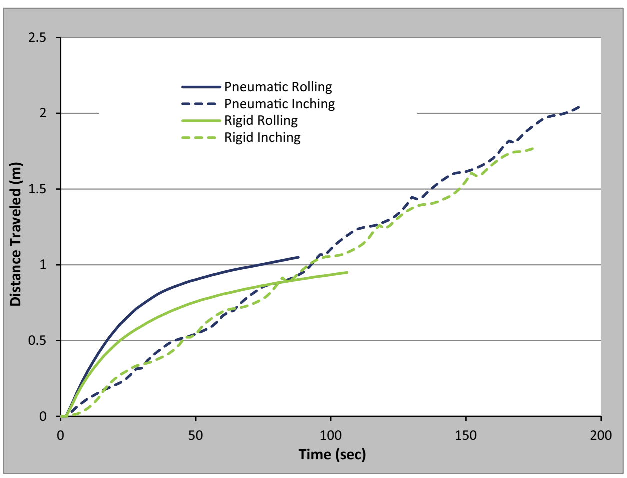


Fig. 10. Total distance traveled as a function of time.

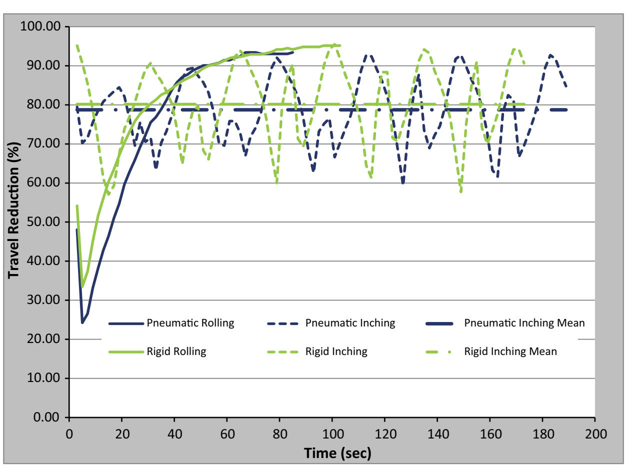


Fig. 11. Vehicle travel reduction as a function of time.

90–100 s of the test, the Scarab rover actually drove further while rolling. However, once the tires began to sink significantly, after approximately 30–40 s, the forward speed of the vehicle dropped considerably. The data in these figures indicates that, after this initial driving period, inching became much faster than rolling. In fact, the average forward velocity while inching remained constant over time, while the rolling case approached zero forward velocity. It should be noted that the rolling tests were run until the wheel hubs bottomed out and contacted the surface, thus the length in time of these tests were much shorter than the inching ones.

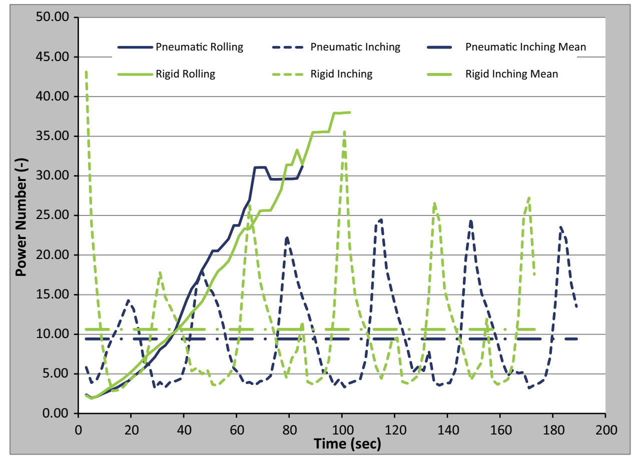


Fig. 12. Power number (total power consumed normalized by vehicle weight and velocity).

As a side note, the initial drop followed by a sudden increase in travel reduction and power number, as seen in Figs. 11 and 12, was due to the initial acceleration of Scarab. Because these tests had to be started from a stand-still position, there is a brief period where the forward velocity was below the commanded velocity, resulting in lower TR and PN values.

Although inching generally consumes power at a higher rate than rolling, the results for power number in Fig. 12 indicate that inching was more power efficient when taking forward velocity into account in high sinkage materials such as Fillite. Again, rolling operated more efficiently in the initial pre-sinkage driving period but became decreasingly efficient over time, as opposed to inching where the power number oscillated around a constant range. This implies that to drive a specific distance beyond this initial driving period, rolling would actually require more total energy than inching. That is also assuming that the rolling vehicle is able to continue without becoming immobilized.

It is important to note that at high sinkage, boundary effects from the bottom of the bin may have impacted the vehicle's performance. Further analysis would be needed to quantify this effect; however it is the belief of the authors that conducting these tests in a deeper soil bin would only result in a greater disparity in performance between rolling and inching (if there was any change at all). If the depth of the soil bin is shallow enough, the bottom of the bin creates a confining effect where the particles are not able to move freely and the wheels are able to get a firmer grip with the terrain, resulting in higher thrust generation. Because the vehicle underwent twice as much sinkage when rolling as when inching, the rolling modes should have benefitted

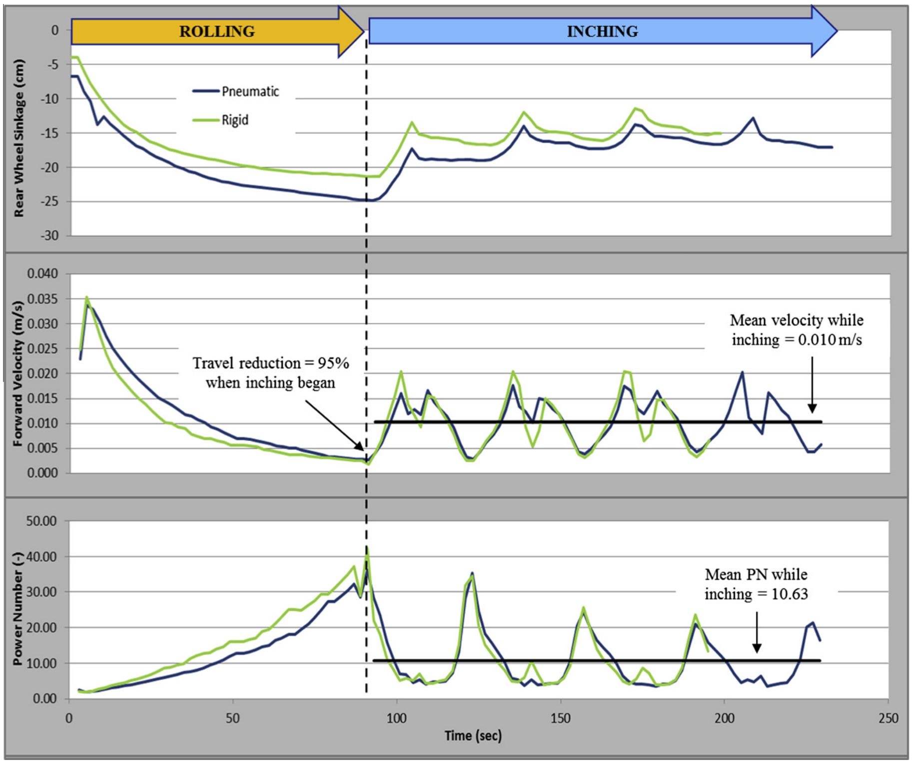


Fig. 13. Results of the Scarab rover driving using conventional rolling for 90 s, then inch-worming.

more from the boundary effects. In a deeper tank, it is assumed that the rolling tests would result in a higher sinkage rate while the inching tests would maintain the same sinkage.

### 4.3. "*Entrapped*" *starting condition*

It is evident from the results above that inching can significantly reduce the likelihood of a vehicle becoming immobilized in a high sinkage terrain similar to that of the GRC Sink Tank. However, a more critical situation would be if a vehicle has already undergone significant sinkage and is approaching or has reached 100% travel reduction (essentially entrapped). Fig. 13 indicates that the inching or push–pull technique still proves to operate in this situation.

The results shown in Fig. 13 were collected by first driving the Scarab rover using the conventional rolling method for 90 s, then engaging the inching mode. Only sinkage for the rear wheel was shown here because it was more pronounced than for the front wheel. Though a complete immobilized condition (no forward progress) was never fully reached during the 90 s of rolling, sinkage continuously increased and the forward velocity approached zero. Once the vehicle began to inch, sinkage immediately decreased and forward velocity increased. After climbing out of the ruts created by rolling, the wheels drove at a fairly constant height, aside from small variations throughout the inching cycle. The average velocity of the vehicle also remained constant at about 0.010 m/s while inching. In addition, the power number continuously increased while rolling, but then fluctuated about a lower average value of 10.63 when inching.

## 5. Conclusions

To summarize this research, the following points were made:

- It has been shown that push–pull locomotion can be very beneficial when high tractive forces are required. By moving soil in a more efficient manner, this mode of locomotion can generate 30–40% more thrust than rolling, while reducing the amount of resistance to overcome.
- In high sinkage material, conventional rolling resulted in continuously increasing sinkage and a forward velocity that continuously decreased and approached zero. By comparison, push–pull locomotion, specifically inch-worming, was able to travel at a constant rate with minimal sinkage.
- Though less efficient on hard ground, inch-worming actually required less energy to travel a given distance in the high sinkage terrain than rolling. This rate of energy expenditure remained constant throughout its traversal as opposed to rolling which saw power usage continuously increase.
- This mode of locomotion was especially useful when a vehicle had already become entrapped in soft soil. For a case where the vehicle was nearly immobilized (wheel sinkage approaching the wheel center and forward

travel nearly at zero), the inch-worming method was able to drive the vehicle out of the ruts and traverse the terrain at a constant speed with a wheel sinkage approximately 50% that of the entrapped condition.

- It is the authors' recommendation that push–pull locomotion be explored as a secondary mode of operation on robotic vehicles. This specific type of movement (inch-worming) only requires two additional actuators and degrees of freedom but gives the vehicle the ability to generate significantly more thrust when needed.
- It is recommended to explore methods of optimizing push–pull locomotion. This mode of travel could be improved by developing a system that does not require the chassis to move vertically, reducing the amount of power needed. More thrust could also be generated by precisely controlling the rotational speed of the wheels relative to the motion of the articulated joint.

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