Regolith Advanced Surface Systems Operations Robot (RASSOR)

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Abstract—**Regolith is abundant on extra-terrestrial surfaces and is the source of many resources such as oxygen, hydrogen, titanium, aluminum, iron, silica and other valuable materials, which can be used to make rocket propellant, consumables for life support, radiation protection barrier shields, landing pads, blast protection berms, roads, habitats and other structures and devices. Recent data from the Moon also indicates that there are substantial deposits of water ice in permanently shadowed crater regions and possibly under an over burden of regolith. The key to being able to use this regolith and acquire the resources, is being able to manipulate it with robotic excavation and hauling machinery that can survive and operate in these very extreme extra-terrestrial surface environments.**

In addition, the reduced gravity on the Moon, Mars, comets and asteroids poses a significant challenge in that the necessary reaction force for digging cannot be provided by the robot's weight as is typically done on Earth. Space transportation is expensive and limited in capacity, so small, lightweight payloads are desirable, which means large traditional excavation machines are not a viable option.

A novel, compact and lightweight excavation robot prototype for manipulating, excavating, acquiring, hauling and dumping regolith on extra-terrestrial surfaces has been developed and tested. Lessons learned and test results will be presented including digging in a variety of lunar regolith simulant conditions including frozen regolith mixed with water ice

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1. INTRODUCTION

Space resource utilization promises to revolutionize the human condition [1], but the first step in this activity is acquiring the space resources to be used as feedstock. In this case the space resource under consideration is extra-terrestrial regolith, with emphasis on lunar regolith, since it is well characterized from previous missions such as NASA's Apollo program. The lunar regolith consists of approximately 42% oxygen by mass, [2] which can be extracted using chemical engineering methods and then used in space for rocket engine propellant, life support air, water production and usage as a consumable gas [3]. In addition, there are other volatiles present in the lunar regolith such as water, hydrogen, helium, carbon monoxide and helium 3 which are all potentially valuable in a space resource utilization system [4]. Other byproducts of extracting these volatiles are useful metals such as aluminum, iron and titanium.

2. REGOLITH EXCAVATION NEEDS

Since typically more than 90% of the mass required for chemical rocket propulsion systems (such as hydrogen-oxygen combustion engines) is propellant [5], the highest priority in space resource utilization is to make and use propellants in-situ. Large mission mass savings will result since the deep gravity well of the Earth, which accounts for 9.3 -10 km/s of delta-velocity to reach low Earth orbit from Kennedy Space Center at an orbital inclination of 28 degrees, can be avoided. The logistics train can also be simplified, and the robustness of a mission can be improved as the crew becomes more self-reliant, without regular critical supply shipments from Earth.

If two NASA Constellation class lunar lander missions are assumed per year, then the oxygen propellant required for a chemical propulsion system is approximately 4 tonnes for a four crew, human class vehicle, resulting in 8 tonnes of oxygen required per year. In addition, 2 tons of oxygen would be required per year for life support and fuel cell consumables. Therefore, the regolith required would be proportional to these needs, since the oxygen would be extracted from the regolith. The exact quantities are discussed below and vary based on the chemical process used (1%-28% efficiencies) and the possible presence of water ice (5%-10%) at the lunar poles [4]

The Regolith Advanced Surface Systems Operations Robot (RASSOR) project assumed that the near-term missions would be robotic precursor landers with limited total payload masses of fewer than 500 kg. These robotic precursors will prove that regolith excavation and utilization is possible as a technology demonstration. Subsequently, multiple micro-excavators operating in a swarm can be delivered on small landers and meet total mission requirements in a scalable and affordable fashion.

In this paper a prototype robotic micro-excavator is presented that can meet the requirement of excavating enough regolith feedstock to supply 2.5 tonnes of oxygen per year. To achieve the 10 tonnes of oxygen, four RASSOR micro-excavators would be deployed and operated simultaneously.

3. RASSOR Concept of Operations

The nominal mission of RASSOR is a five-year long mining operation to deliver lunar regolith to an oxygen production plant. (The plant itself is outside the scope of this project.) An estimated 255,500 kg of regolith needs to be delivered in order for a plant of approximately 1% efficiency to produce 2,555 kg of oxygen in that period of time.

RASSOR will arrive on a lander comparable in size to the Mars Phoenix Lander and deploy itself from an approximately 1-meter-high deck by simply driving off the edge, which sidesteps the need for ramps or other offloading systems. RASSOR is designed to withstand the impact of the fall, land on any side and right itself if necessary. The excavator will need to drive more quickly than previous space exploration robots in order to meet its mining requirements, so it will be free of hazard avoidance software, which would slow it down. Instead, the landing site will be selected in an area that is as flat as possible, and RASSOR will perform "acrobatics" (the process of using the arms to assume various positions) to handle the obstructions and loose soil it will encounter. It will drive over small rocks and either drive around rocks or use acrobatics to pull itself over larger rocks, furrows or ridgelines. In the event of traction loss, RASSOR can somersault to become unstuck or rise up on its arms and roll on the bucket drums, then lower itself and resume normal driving.

RASSOR will drive at least 100 meters away from the lander to avoid kicking dust up onto the lander's solar panels during mining operations and to provide ample surface regolith. The round trip takes 17 minutes, with RASSOR driving at a speed of at least 20 cm/s. In comparison, the Mars Science Lab rover has a top speed of 4 cm/s. It will collect 20 kg of regolith each trip, making a total of 12,775 trips per year to meet regolith mining requirements. This amounts to 35 trips per day (24-hour period). If the mobility portion takes 17 minutes and the mining takes 10 minutes, then a 30 minute mining cycle will suffice, and the RASSOR can operate for 16 hours per day to achieve its goal of 255,500 kg of regolith mined. It can mine the upper surface layer, or it can trench to access water ice that may be located a meter or more below the surface. The capability of digging in areas with higher concentrations of ice is being tested and will also possibly have a higher yield of 5.5% water. This will require that RASSOR take very small scoops – more of a shaving action – and would be a much longer operation than digging in drier surface regolith. However, much depends on the characteristics and properties of the icy regolith, which are unknown at this time.

At the end of each mining trip, RASSOR returns to the oxygen production plant near the lander, where it raises itself into a vertical dumping position and reverses rotation of its bucket drums to dump the regolith into a receiving hopper that can be up to a meter high off the ground [6]. RASSOR is powered by batteries that will be recharged at the lander in between mining treks as required. The concept of operations has factored in 8 hours per Earth day for recharging operations.

4. RASSOR Generation I Requirements

After the needs and concept of operations had been identified the more detailed requirements were written. Some of these requirements are specific about how they shall be met, although, a number of the requirements are meant to bound the problem without forcing a specific design. This is to allow the team to be more creative while still meeting requirements to achieve to overall mission. These bounding requirements fit within the Technology readiness level (TRL) 3: "Analytical and experimental critical function and/or characteristic proof of concept." [7]

- RASSOR shall successfully deploy itself from the lander.
- RASSOR shall drive 100 m, excavate, and return to the lander.
- RASSOR shall have a maximum mass of 50kg, with a preferred mass of 20kg or less.
- RASSOR shall mine the top 5 cm of surface regolith for nominal regolith mining operations
- RASSOR shall be capable of mining 1 meter deep using a slot dozing trench method, for icy regolith mining and science observations

- RASSOR shall successfully mine 700 kg of regolith within 24 hours.
- RASSOR shall be equipped with one or more cameras.
- RASSOR shall recharge its battery at the lander using a dust tolerant connector.
- RASSOR shall have a minimum lifespan of 5 years.
- RASSOR shall have the ability to self-right itself.
- RASSOR shall be tele-operated while it will still offer the option to later add redundancy and autonomy for the driving system.

5. RASSOR Generation I: Design Solution

RASSOR uses two bucket drum excavators to accomplish its primary function of collecting and transporting regolith. A bucket drum excavator is a novel device that excavates, stores and dumps regolith. Lockheed Martin Space Systems, Denver (under a contract from NASA) developed the first bucket drum for use on a small robotic excavator [8]. The Granular Mechanics & Regolith Operations (GMRO) Lab at NASA Kennedy Space Center has developed a novel application of the bucket drum concept by employing two counter rotating bucket drums in a robotic platform that has advanced positioning and posing capabilities.

The main advantages of a bucket drum are that the excavation scoops are small and staggered so that at any given time only one or two are engaged in the regolith, thereby keeping the excavation forces low, and the regolith collected becomes trapped inside the drum due to a set of baffles until the direction of rotation is reversed. This approach completely eliminates the need to have a separate regolith storage and dump bin. The bucket drums used on RASSOR each consist of 5 segments with 3 scoops per segment (see figure 1). Each bucket drum is designed to collect and hold 10 kg of regolith when 60% full. They have scoop openings that can accommodate rocks up to 5 cm in diameter. These rocks may be excluded through a grating or other system in the future.

Aluminum sheet metal was used to construct the scoops and baffles which were placed around plates that divide the segments. Five aluminum rods with tapped ends run the length of the bucket drum and attach to the end-caps, compressing the segments together. The scoops on the bucket drums also have stainless steel removable cutting edges that are riveted on. The sheet metal approach kept the mass of the bucket drums to about 7 kg each.

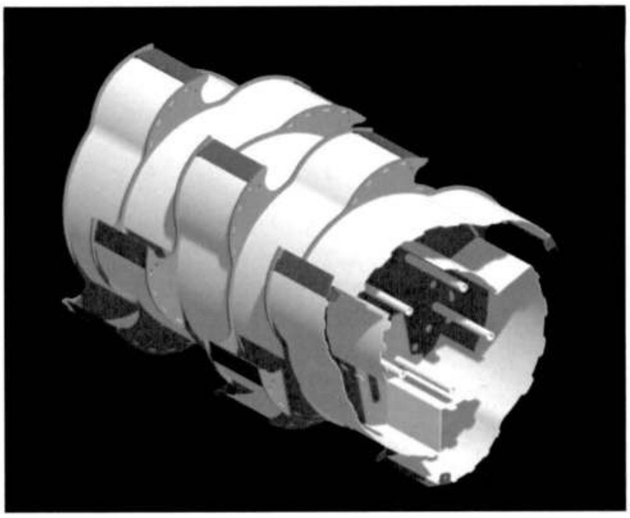

Figure 1 - Bucket drum without end cap to show baffles.

RASSOR's solution to the issue of excavation with low vehicle mass and traction (especially in an extra-terrestrial environment) is to excavate with both bucket drums at the same time while rotating them in opposite directions. This technique counters the horizontal excavation loads of one bucket drum with the other.

The height of the bucket drums with respect to the ground plane needs to be actuated in order to engage the soil and control the cutting depth of the scoops. RASSOR accomplishes this by placing the bucket drums on the ends of single degree-of-freedom arms (see figure 2). Each arm is driven at a rotational joint on the RASSOR chassis and houses the motor and gearbox for the bucket drum rotation. The bucket drum rotation motor and gearbox are mounted inside the structure of the arm, and a drive shaft transfers the torque from the gearbox output to a bevel gear pair, which in turn drives the bucket drum (see figure 3). Inside the RASSOR chassis, a motor, planetary gearbox, and worm gear system is used to drive the arm rotation.

Figure 2 – RASSOR field test in October 2012.

The arms also were designed to perform acrobatics as a useful mobility feature. Using the dual arm configuration, the vehicle is able to right itself if flipped over, climb over obstacles much taller than the tread height, dump regolith at heights taller than one arm length, and stand the chassis up to clean out debris from the tracks (see figure 4).

The mobility system on RASSOR was also designed to be very simple as the primary goal of this version is to prove the concept of low reaction force dual bucket drum excavation. To that end, the mobility system is a tank tread design that was initially modeled from similarly-sized commercially available drive trains. During testing, however, it was observed that the fine particles would get caught between the treads and the drive pulleys, causing the treads to jam up or track off the pulleys. To fix this, new drive pulleys were designed that have large openings between the teeth so that the soil can clear out from treads.

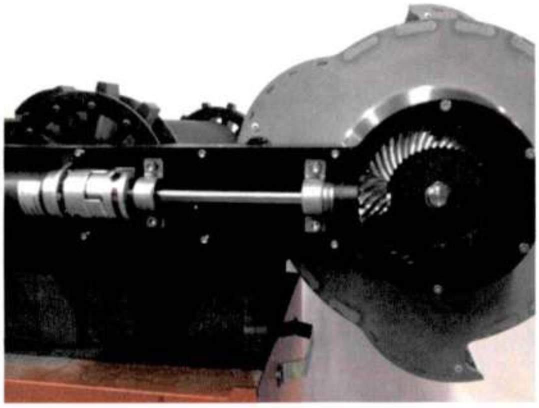

Figure 3 – A motor, gearbox, and bevel gear drive system turns each bucket drum.

The loose and compacted properties of lunar regolith provide unique mobility challenges due to the loss of traction experienced once the regolith is sheared. The choice of tracks versus wheels is being actively studied and traded against the RASSOR requirements. Each approach has distinct advantages, and this RASSOR prototype has revealed that tracks are much more complex than wheels in the finely powdered lunar regolith simulant.

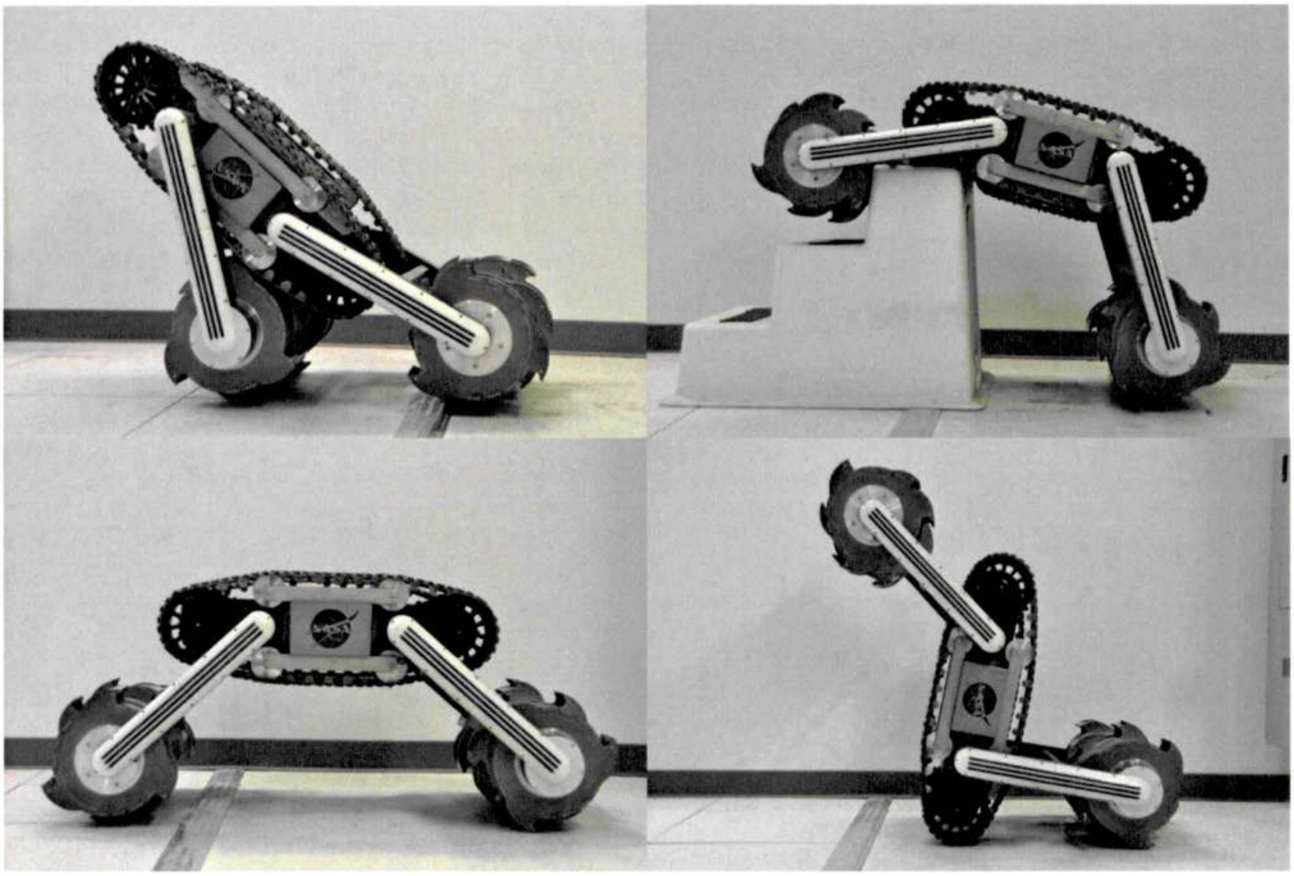

Figure 4 – Clockwise from top left: RASSOR self-righting (shown just before tumbling over its left drum); climbing over an obstacle much taller than its tracks; positioning to dump its left bucket drum, also called the "Z" position; and raising its chassis (iron cross position) to spin the tracks and free them of debris.

RASSOR is controlled via remote driver station software on a laptop. The driver station shows the display from the cameras and reads inputs from a gamepad controller. High level control commands are then sent to the vehicle via a wireless radio. An Ethernet to CAN converter onboard the vehicle then decodes the Ethernet commands and sends the appropriate CANopen commands to the motor controllers. All of the actuators on RASSOR are controlled using Elmo Motion Control motor controllers. Each motor is equipped with an incremental encoder for closed loop velocity control. An axis video encoder converts analog video from two cameras and streams them back on the wireless Ethernet network. Two 12V 19AH lithium iron phosphate batteries are wired in series to power the vehicle.

6. TEST RESULTS

RASSOR was tested in sand, KSC crawler-way fines (crushed river rocks), and lunar regolith simulant Black Point -1 (BP-1). Fine sand is a readily abundant but low-fidelity simulant, which was suitable for early testing such as demonstrating RASSOR's ability to drive, dig and assume acrobatics positions (see figure 5).

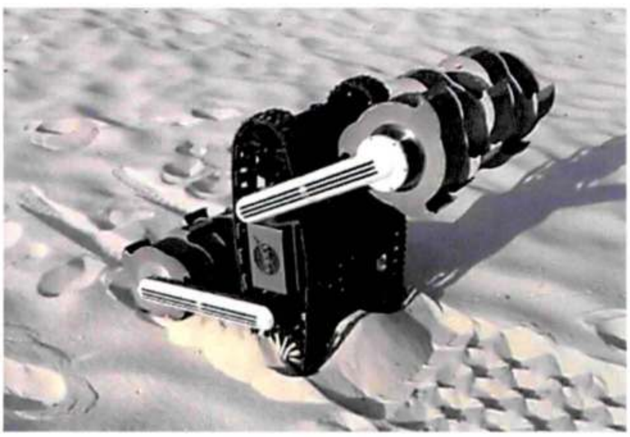

Figure 5 – RASSOR in the "Z" position demonstrating its ability to dump sand.

The crawler-way fines compacted well, which provided a way to test RASSOR's ability to overcome higher excavation forces. RASSOR was able to dig successfully, as long as the digging depth was very shallow (less than a centimeter), which meant it took much longer to fill the bucket drums. The crawler-way fines also contained a lot of rocks and gravel, which tended to get caught between the wheels and the tracks and caused much trouble during testing, especially during counter-steering. (See figure 12 in the Lessons Learned section). RASSOR also demonstrated that it was able to climb a 20 degree slope, turn, and drive laterally. While it failed to climb straight up a steeper 30 degree slope, this was because the crawler fines were in a loosely piled mound that sheared and avalanched under RASSOR's weight and caused it to slide backwards. It is expected that RASSOR would have succeeded if the hill was more compact, and further testing will be performed to resolve this. In addition, the bucket drum scoops may be used as a "climbing piton" device used for controlled ascending and descending, and this hypothesis will also be tested in the future.

Figure 6 – Driving up a 20 degree slope of loose crawler-way fines.

The BP-1 simulant had the highest lunar simulant fidelity but was only available in one small outdoor test bin. RASSOR was able to successfully drive, perform acrobatics, dig loose surface regolith, and trench. Measurements were taken that confirmed the bucket drums were able to collect not only 10 kg of regolith each, as designed, but upwards of 14.5 kg. Current draw was measured and recorded for different activities (see fig. 8.). RASSOR pulled 3 to 5 amps while driving; 8 to 10 amps while raising its chassis into the iron cross position; 3 to 4 amps while lowering the chassis back down; and 2 amps during shallow mining. Temperature was also measured and exceeded 150 degrees F after less than two hours of outdoors testing (see fig. 9). This was of concern because the motor controllers have a rated maximum operating temperature of 180 degrees F, so temperature will continue to be monitored, particularly when testing outdoors in the heat. Future versions of RASSOR will include provisions for cooling and will provide traceability to lunar conditions with a suitably sized radiator on the top surface.

RASSOR was also tested in BP-1 using a setup that off-loaded 5/6th of its weight to simulate lunar gravity. One bucket drum was lowered into the simulant to mine, and the excavation reaction forces were greater than the traction, which translated the vehicle without excavating soil. When the second drum was lowered, RASSOR stopped sliding and both drums began to collect soil, thereby demonstrating the efficacy of dual counter-rotating bucket drum system. It also appeared that vertical reaction forces were low enough not to influence RASSOR's digging, and there are future test plans to quantify them.

RASSOR was tested again with the gravity off-loader, this time in icy regolith, which was a mixture of BP-1 with 10% water by weight, that was compacted and cryogenically frozen to 83K using liquid nitrogen. RASSOR demonstrated it was able to mine, with the advantage that frozen BP-1 was very brittle and able to be broken up. A shortcoming of the test, however, was that it was performed outside in the summer, where the air temperature exceeded 90 degrees F and continually warmed the test bed. Prior lab tests showed the BP-1 stayed frozen at the core for an hour. But during testing it appeared that the outer layer was easier for RASSOR to scrape off until it hit a harder, more frozen layer, which then subsequently warmed. For future tests, it would be desirable to have liquid nitrogen keeping the regolith frozen during testing, which would involve a more complex test setup but have higher fidelity.

Figure 7 – RASSOR testing using gravity off-loader and icy BP-1

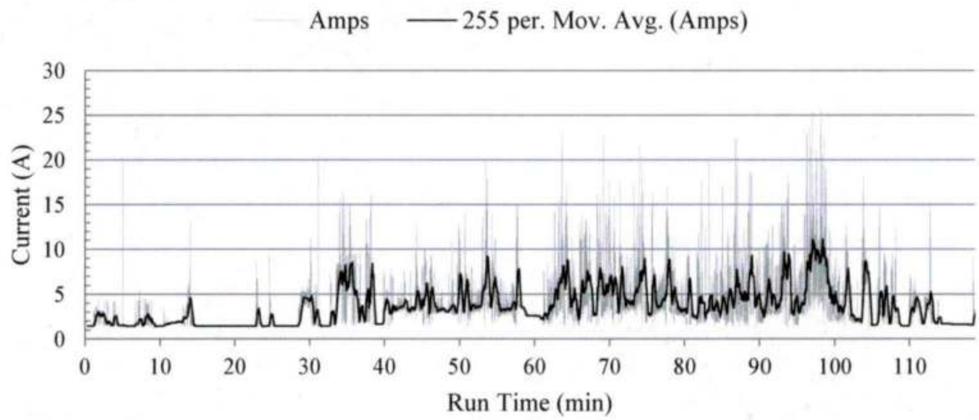

Fig. 8 – Current draw during two hours of testing RASSOR's driving, mining, and acrobatics capabilities. Lower current draw (i.e. 0 to 15 mins) corresponds with driving or light mining; higher current draw (i.e. 85 to 100 mins) corresponds with multiple operations run simultaneously, such as driving and trenching.

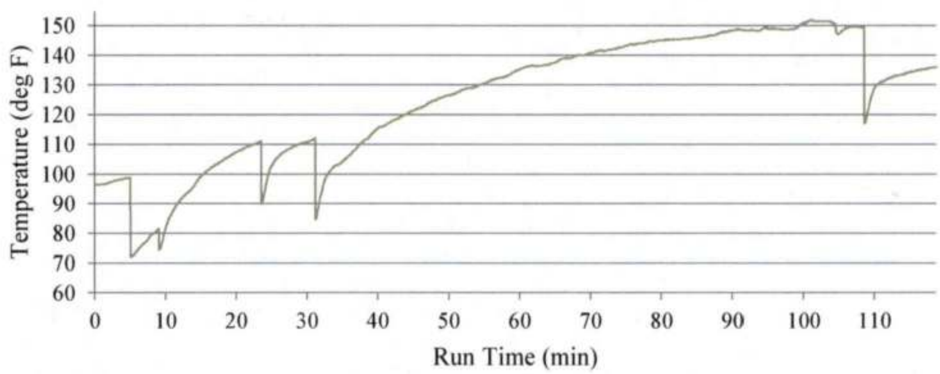

Figure 9 – RASSOR internal temperature during two hours of testing. Sharp drops in temperature correspond to shutting RASSOR off for periods of time, during which data was not recorded.

7. Lessons Learned and Good Practices

Improvements to the design of RASSOR were found during fabrication, assembly, and testing. The three sections below summarize the lessons learned during these stages.

Fabrication

One improvement learned from the fabrication process is to design for minimized part count rather than ease of fabrication. In many cases, it may actually be quicker to machine a complicated part on a multi-axis CNC rather than machine and assemble several parts on a simpler machine, such as a water-jet cutter. This would also avoid problems later on during assembly, as those multiple parts may need to be aligned very closely to function properly. A single piece part avoids stacked tolerances.

Assembly

With a tight requirement on size and weight, it was beneficial to pack hardware into the chassis as tightly as possible. This resulted in limiting the accessibility of many components during both assembly and maintenance. As more components of the system were tested, it was necessary to remove some of them to fix or adjust certain aspects. If the whole robot had to be disassembled to get to the drive wheel motor, for example, it became very time consuming and impractical. Another problem with taking components apart and putting them back together many times is that some may actually wear out in ways that wouldn't happen during normal robot operations.

Another point is to ensure that wiring has been well-accounted for. Designers will often create CAD models that neglect the wires connecting all the motors, controllers, cameras, etc., which makes it hard to envision the final setup. Wires may run very close to open gears and shafts and could get caught as the rover moves over rough terrain. Additionally, wires may block access to components that need to be adjusted in place, such as the tensioner for a chain or belt. In the case of RASSOR, these problems were mitigated after final assembly of the robot, but in the future, including them in the model would provide better results.

Testing

With a complex design, the testing phase will typically reveal the most areas in need of improvement. This was certainly the case with RASSOR.

The first subsystem that required many adjustments were the tracks. It turned out to be very challenging to design a track drive system that could work in a variety of soils analogous to lunar regolith. Initial tests in sand exposed the clogging problem, where regolith particles accumulated between the wheels and the tracks, causing the track to lose tooth engagement and slip off the wheel. This was remedied by redesigning open wheels that allowed the dirt to flow out towards the hub as the wheels turned. This solved the clogging issue for most types of soft and hard soil, except for those like the crawlerway fines with larger size rocks that could still get wedged in the wheel (fig 12).

Figure 12 – Crawler-way gravel lodged in the track, which pushed up against the arm crossbar and locked up the drive system.

Another improvement was to exchange an all-rubber belt material with one that encompassed stainless steel wire ropes running continuously through it. This corrected a belt stretch issue that had been contributing to the belt coming off the wheels when clogged. That issue was exaggerated at elevated temperatures due to the rubber softening. It should be pointed out the on the moon the opposite issue would occur where the rubber would lose its flexibility. However, rubber would not be used on the moon; but as a terrestrial analog it was acceptable in this prototype.

Initial testing of the arms revealed that the chain connecting two gearboxes in series worked as designed in one direction, but skipped teeth under load in the other direction. This was due to the entrance angle of the chain onto the drive sprocket not being equal in both directions. The issue was solved by tightening the chain, which had to be done repeatedly, as the chain stretches. With this improvement in place, the next issue that occurred was too much friction between gears on a custom gearbox housing using off-the-shelf gears. The root of this problem was a misalignment between the gears caused by tolerance stacking among the multiple parts comprising the gearbox housing.

A general improvement to be made during the testing phase is to test subsystems that appear multiple times on a single unit prior to integration. This will allow adjustments to be made to the single assembly rather than all copies at once. This was most apparent on the arm mechanism, which utilized four identical gear trains that underwent several iterations. The speed at which iterations were made would have increased if updates had been made to a single unit only.

A set of encoders was linked to the output of the motor through a set of spur gears. The backlash of the spur gears coupled with some wobble in the associated ball bearings was enough to confuse the motor controllers and cause the motors to stop intermittently. The last set of encoders was attached directly to the output shaft of the motor, which was optimal. However, even this setup needed one improvement primarily because of the way the encoder wheel was designed. The plastic encoder wheel was intended to simply press-fit onto a shaft, which in RASSOR's case was smooth and had high accelerations and decelerations. This resulted in the encoder coming loose. Knurling the surface of the shaft and using an adhesive solved this negative. It is highly recommended to use encoders with positive locking encoder wheels directly on the motor output to avoid this issue.

The remaining lessons learned do not suggest hardware changes, but rather refinements and proper implementation of the operations concept. The original concept of the counter-rotating bucket drums was to make shallow skim cuts off the soil surface and drive while digging to fill up the scoops. In practice, this turned out to be difficult due to the purely manual control that required constant driver input. If there was any initial unevenness in the soil surface, those bumps would make the rover move off level as it drove forward, which meant one drum would be raised off the ground while the other would be driven deeper into the soil. This created more unevenness for the next time the rover would make another pass. Another unintended side effect of the deep cut is that under some soil conditions the scoops could get clogged with compacted regolith, and therefore become ineffective. On the moon, low gravity, electrostatic forces, Van der Waal forces, and high friction forces between the particles could create a similar situation whereby cohesion of the granular material is increased, causing similar bridging and clogging. This will be addressed in future designs by opening the size of the scoop opening to prevent bridging or by vibrating the drum to free the particles.

Figure 13 – Scoop clogged with damp sand.

The digging depth problems could be mitigated by automating (with scripting) the skim cut operations so that the driver would not need to try to adjust the arms constantly to keep them level even as the rover chassis bounced. Driving very slowly while digging would allow the arms to keep up with the moving chassis in order to take even, shallow cuts. The same scripting approach should be taken for the acrobatics moves in order to smooth out the loads during those maneuvers.

Lastly, testing in icy regolith required some changes in the digging approach. It seems to be more effective to first break up the hard, icy soil and then scoop up what has been broken loose. A faster drum rotation will help the breaking up step, while the slower drum rotation will then be used to pick up the soil. Improvements in the cutting edge of each scoop, such as serrations or sharp pick ahead of the cutting edge will also help the rover perform better while digging icy regolith.

8. SUMMARY

A novel, compact and lightweight excavation robot prototype for manipulating, excavating, acquiring, hauling and dumping regolith on extra-terrestrial surfaces has been developed and tested at NASA, Kennedy Space Center. Lessons learned and test results have been presented in this paper, including results from digging in a variety of lunar regolith simulant conditions as well as frozen regolith mixed with water ice.

This prototyping effort has shown promising results and proven the concept of using counter rotating bucket drums as an effective method of manipulating regolith in a load, haul and dump scenario, to produce a micro-excavator system that can be delivered to the moon and other extra-terrestrial bodies on small robotic landers. This method successfully mitigates the problem of only having low digging reaction forces available in low gravity environments, which is a major challenge when using traditional excavation methods, such as those used on Earth.

The lessons learned have been valuable and the testing has also revealed opportunities for improving the design and operations. A second generation RASSOR will be designed, fabricated and tested to take advantage of these opportunities. Eventually, it is hoped that a swarm of RASSOR's will operate on the moon and other extra-terrestrial bodies to enable regolith mining for space resource utilization.

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Biographies

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