Dust-Off 2005 a.k.a. 'Dunes Bury' USA

(O.R. Walton)[rev2] Oct 5, 2005 PROJECT DUST – An eclectic group of researchers spent the past weekend at the Great Sand Dunes National Park in southern Colorado, getting a first hand look at the wide range of behavior exhibited by a relatively simple granular material (sand) and testing techniques that robotic rover vehicles might use to deal with that behavior. Our group of nine individuals included physicists, engineers, graduate students, educators, CEO's of small businesses, numerical modelers, model rover developers, computer visualization experts, university professors, and a science news reporter, with some individuals fitting more than one of these descriptors. The majority had never been to these dunes before. Much of the weekend was spent observing and learning about the behavior of near-surface sand and the dunes. We also tested out various hypotheses for traversing dunes and getting vehicles unstuck. We brought along five model rovers, with a variety of capabilities. Figure 1 shows one model rover carrying a 'payload' equal to 25% of its weight speeding to the crest of a relatively steep dune. Table 1 lists the clear set of winners and losers we identified for traversal over steep dune faces. Additional explanation for the various table entries is included in the section on Rovers later in this report.

Figure 1. A fast rover, dubbed the Green Machine, speeding toward the crest of a dune loaded with a sandbag weighing 25% of the weight of the unloaded rover, including its batteries.

Table 1.
Winners and losers for Rover traversal tests on steep dunes

Winners	**Losers**
Rockin' & Rollin'	Jacking
Slow & Steady Avalanche Ladders	Rapid Spinning
High Speed Frontal Assault	Angle Traversals
Bantam weight	Overloads
[independent drive for each wheel]	Ordinary differential

The Dunes

During the two clear autumn days we were at the Dunes, only the top layer of sand, ranging from a few millimeters up to 10's of centimeters, was dry and free-flowing. The depth of the dry layer varied spatially, with time of day, and with the prevailing wind conditions. In some areas the wind constantly scoured the driest surface grains in saltating-flows up to a dune crest, whereupon the sand was deposited on the trailing face of the dune and formed a surface with a nearly constant angle-of-repose (~34°). Each day the dune surfaces would become covered with foot-prints and sand-slide trails from the scores of visitors who explored and played on the lowest dunes, closest to the parking lot. On each of the two mornings we came to the dunes, most of the evidence of the previous day's human activity was erased or substantially eroded away by the action of the wind over-night. In the windiest areas only features that had been 10 to 20*cm* or larger were still visible the next day. We saw first-hand how various transport mechanisms, including *saltation*, *avalanches* and *size-segregation* resulted in a dynamic surface that had dramatic spatial variations at all length scales. Figure 2 shows an overview of the entire 26 square mile dune-field from the Project Dust campsite at dawn.

Figure 2. Dunes at dawn from approximately 4 miles south of the main dune-field

Sometimes the variation was a nearly-regular set of ripples a few centimeters high with 10 to 20 *cm* spacing, with fines (~0.1*mm* size grains that were dark grey in color and attracted to permanent magnets) on the windward faces, and larger quartz grains (~1*mm*) on the leeward face of each ripple (see Figure 3). Behind the wake of any obstacle (plants, pebbles, or any object) a small dune of fine sand would form (often being many times longer than the object causing the sand deposition).

Figure 3. Small ripples with grey fines on the windward sides

The larger dunes in the dune-field ranged from three to over one-hundred meters high, and appeared to be relatively stable (*i.e.*, stationary). These large dunes often had meandering cross-wind ridge lines that were from 10's to 100's of meters long, as shown in the photograph in Figure 4, taken looking north from the top of 'High Dune.'


Figure 4. Ridge-lines on large dunes (note people in the center foreground).

Many of the dunes exhibited a double-ridge line with a shelf-like second ridge line a half-meter or so lower than the sharpest crest of the dune, as shown in Figure 5.


Figure 5. Example of a double-ridge line.

The Sand

Near the stream bed at the edge of the dunes there were a substantial number of small dunes and ripples (< 1*m* high) with substantial quantities of coarse material (grains exceeding 2*mm* across); however, once we were over the first 5 to 10 meter high set of dunes, most of the sand ranged in size from 0.1*mm* to 1*mm* across (optically estimated using a 7X magnifier with a 0.1*mm* per division scale). Most of the grains were light colored and translucent (quartz); however, a small percentage of the material was comprised of fine (0.1*mm* < diameter < 0.2*mm*) dark grey material, much of which we found would stick to a permanent magnet (See Figure 6).

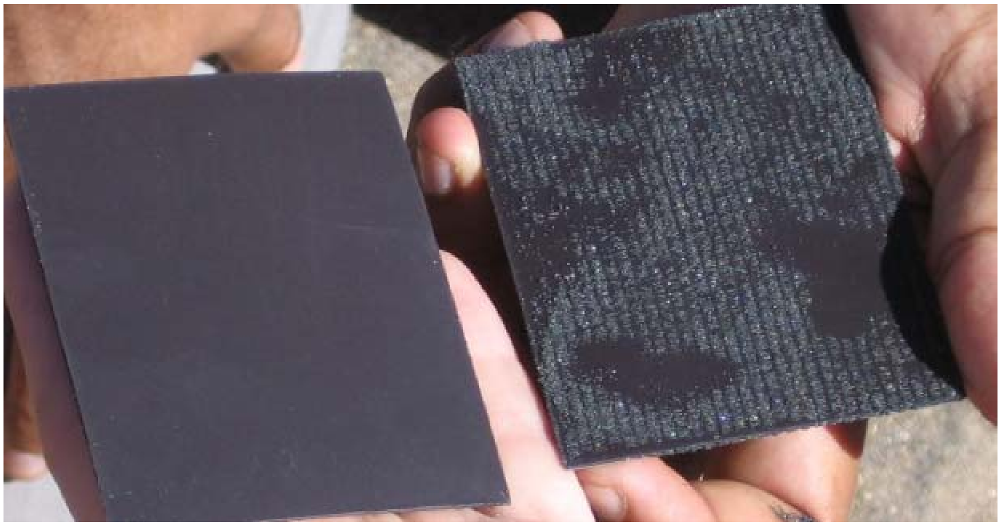

Figure 6. Left – clean magnet surface; Right – magnet after putting sand on it and tapping it off, leaving the fine, grey material stuck to the magnet surface.

<u>Angle of Repose</u>

We measured the angle-of-repose of the sand on the trailing edge of a couple of dunes and found it to be approximately 34°. A small sample of sand taken from a location that was a few hundred meters away from the measured dunes was tested in a drained-angle-of-repose apparatus, and it, also exhibited a slope of ~34° as shown in Figure 7.

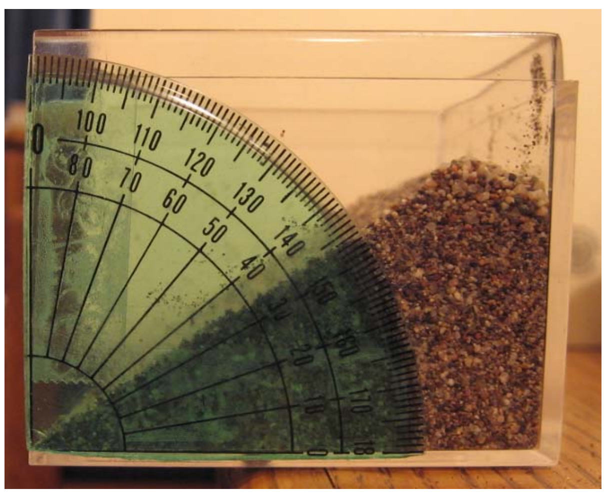

Figure 7. Drained-angle-of-repose test of sand from one of the larger dunes.

<u>Avalanches</u>

Quickly stepping on the trailing edge of a dune (or deliberately 'digging' a hole by scooping some of the material down the slope a short distance) could cause two small avalanches to form, one traveling down from the disturbance, depositing some of its material as it flowed like a viscous fluid (resembling a lava flow). Another small avalanche could travel slowly up from the disturbance, as the dry free-flowing layer of sand above, cascaded into the depression that was steeper than the angle-of-repose. Depending on the depth of the dry sand, the slope and the amount of sand scooped out, shallow avalanches could occasionally be made to slowly travel 5 or 10 meters up or down the trailing face of a dune. The velocity of propagation of the shallow (< 2*cm* deep flowing layer) downward-flowing avalanches was usually at or below 0.5*m/s*; while the propagation velocity of the upward flowing avalanches could sometimes be much slower. The surface velocity of the sand itself, within one of the small avalanches, was considerably greater than the avalanche propagation velocity. We did not measure the surface particle velocity; however, eyeball estimates would put the surface particle velocity of the flowing sand a somewhere around 1 *m/s* or perhaps a little higher, depending on the size of the avalanche. Figure 8 shows one of the researchers watching an avalanche propagate down the trailing face of a dune.

Figure 8. Jared Reece watching a small avalanche propagate, from a 'footprint,' down the trailing face of a dune.

Sand-sounds

Many reports of booming or quaking dunes appear in the literature. As we explored the dune-field we listened for booming-dune sounds, and, at certain locations in the dunes (usually on the trailing face of a dune) we found that, if we stepped quickly on the dune face, or sat and slid down the steeply sloping dune, it could emit a relatively low-pitched audible sound with a superimposed amplitude modulation at a sub-audible frequency of something like 5 or 10 Hz. One researcher commented that he would not describe the sound so much as booming-dunes, but perhaps something more like flatulent dunes. Locations where we could generate sounds by disturbing the sand were relatively rare, and in any one area, it might take several minutes of exploration and trial to locate a several square meter patch where the sand was in an appropriate in-situ state for sound generation.

Dry-quicksand

Literature on sand dunes often mentions a dry-quick-sand condition where ordinary objects (and vehicles) can partially sink into the sand. Such under-consolidated conditions were difficult to locate in the Dunes; however, while returning from a hike to the top of High Dune (~200m elevation above the base of the dune-field) we came across a small patch of a few square meters of almost flat very-soft sand, several centimeters deep, that did not look any different from the firmer sand surrounding it. Figure 9 shows one of the Project Dust participants standing ankle-deep in this patch of very-compressible, under-consolidated sand. Notice that the sand surrounding his feet is depressed (*i.e.*, densified) compared to undisturbed sand further away.

Propagating disturbances

In several other areas we came across patches of nearly flat, horizontal sand which, when we stepped on it would sink under our shoes but would raise-up in distinct ripple-like waves in the surrounding surface. Sometimes the displaced and elevated patch would extend only 20cm or so around the shoe with the weight on it, other times it would slowly propagate, in discrete steps, out distances as far as a meter or more.

Figure 9. Gary "Rod" Rodriguez standing ankle-deep in a patch of very-soft, under-consolidated sand. Note the depressions in the sand around his legs, where he is standing (dry-quicksand?).

Rovers

Traction in sand or soft soils is a subject of much research for the off-road vehicle industry. The *Journal of Terramechanics* is devoted to this subject. During the 1930's, physicist Ralph Bagnold conducted extensive studies of the sand dunes of the Sahara desert, and in the process developed practical methods to solve many of the transportation problems he encountered. His best method of getting across a large dune with a fully loaded truck was to 1) get a high-speed-run-at-it, 2) go-straight-up-the-face, and 3) maintain-full-throttle-to-the-top. Using that technique, along with reduced air pressure in the tires, and carrying special steel channels to assist in getting 'unstuck,' he was able to drive to almost any part of the Sahara he wanted. While the high-speed-run-at-it method is not a viable option for use in robotic exploration for lunar or planetary rovers, we decided to do a few tests with a 4WD high-speed model vehicle, to corroborate Bagnold's findings on a smaller scale. The Rover we dubbed the Green Machine (shown in Figure 1) was a commercially available radio controlled model truck, with an advertised top speed of nearly 35mph on dry pavement. We selected it as our candidate for testing Bagnold's high-speed dune traversal method. This fast vehicle could not achieve speeds in the sand that were close to its advertised capabilities on pavement, however, we measured its top speed traveling in dry sand up a 2° to 3° slope at around 5.6m/s (~12.5 mph).

<u>Drive slowly up the face approach, and getting 'unstuck'</u>

Before attempting the high-speed runs on steep dune faces, we tested the Green Machine at low speed on a several-meter-long 14°slope below the base of a steep dune face. The model vehicle only managed to travel about 2.4*m* up the 14° slope before digging itself into the sand, up to its axles. Backing up (down hill) worked as a method of getting the rover unstuck, only if it was done soon enough (*i.e.*, before it was dug in too deep). Once the vehicle was dig-in we tried rotating the wheels alternatively backward and forward, attempting to avoid wheel slippage, if at all possible, and were successful in getting it unstuck with this approach 3 out of 3 times, under conditions where backing alone had been unsuccessful. We referred to this method as the *rock 'n' roll* technique, although we are not sure that, as implemented, any inertia or momentum contributed to the getting unstuck, even though the name might imply that dynamics played a key role. We also tried 'jacking' the vehicle up (using a mylar balloon as a jack, see Figure 10) and setting it back down in the same place, before attempting to back up. Because the rover had dug into cohesive wet sand beneath the thin dry sand layer near the top surface, very little sand flowed into the hole beneath the wheels when the vehicle was jacked up. It appeared that, if we had waited long enough, some of the sand on the side walls would have dried out and then cascaded into the wheel holes; however, we only left the vehicle jacked up for 20 to 30*s*, before we attempted to back it out of the hole. The Green Machine had a weight per unit tire width of approximately 149.4 *N/m*, nearly evenly distributed on all four drive wheels when it was on a level surface, with tires that were approximately 14.8*cm* in diameter.

We tested other high-torque, low speed rovers on slopes of 11°, 14°, and 34°. One of these, dubbed Rover #84, was a rear wheel drive vehicle with a weight per unit tire width of 106 *N/m* on the drive wheels (on flat surfaces), with tires that were approximately 12.6*cm* in diameter. Rover #84 could not travel any significant distance (e.g. less than 1*m*) up any of the three slopes before digging in and stopping almost all forward motion. Again, if reverse was attempted soon enough, it could back out, but once a significant pile of material had built up behind the drive wheels, it could not always back out. On the steepest slope (*i.e.*, 34°) we found a new phenomena, that we call an *avalanche-ladder* (described later in this report) which allowed Rover #84 to slowly climb right up the trailing face of a dune (at the 34°angle of repose).

Figure 10. Using a mylar balloon to jack up the ‘Green Machine’ after it was stuck,

<u>Angling up the slope</u>

We attempted to drive some of the 2WD rovers up the slope at an angle in order to lower the effective slope of the climb; however, we found that the combination of lightly loaded front wheels and an ‘ordinary’ rear differential made it quite difficult to maintain a steady angle trajectory across and up the dune face. The 4WD rovers were more successful at this, but even they had difficulty maintaining direction control as the slope got steeper.

Figure 11. Rover #84, slipping diagonally across a dune face as an angled climb up an approximately 14° dune face is attempted.

<u>High-speed-run-at-it method</u>

Bagnold’s high-speed frontal assault technique did prove to be the fastest method to get to the top of a steep dune. We found that the method did require that a significant velocity be maintained all the way to the top. If the speed ever dropped below some threshold the rover would either bog down or turn slightly sideways and sometimes loose the ability to turn back up hill. We did not do sufficient quantitative tests to establish what the threshold, or minimum maintenance speed, was. A couple of anecdotal points can serve as illustration of our qualitative observations. Using a gently sloping region to get-a-run-at-it, the Green Machine was able to nearly make it to the top (stopped a meter, or so, before the crest) of a 5m high dune (e.g. ~10*m* traversal up the slope) when it was traveling at around 2*m/s* as it left the gently sloping (2° to 3° slope) region and headed up the steep face (25° – 34°). On the other hand, when it was traveling ~5.5*m/s* as it left the gently sloping region, it was able to make it all the way to the top. On the second day we continued with a few more-strenuous tests, adding a payload to the Green Machine. With a 25% increase in total mass (loaded to 187 *N/m* tire width) the Rover was able to easily climb and accelerate up 7° to 8° slopes, and once it got up to speed could make it up a steep dune face that was nearly a 10m change in elevation (~20*m* traversal distance). However, with this increased-load there was a relatively high probability that any individual attempt might fail (e.g. it took multiple attempts to make it to the top). Figure 1 at the beginning of this report, and Figure 12, show the Green Machine with the 25% load going up a 15°- 20° (variable) slope dune-face at high speed. When the load was increased to 50% (e.g. 224 *N/m* tire width) the Green Machine could barely make it up a 7° to 8° slope, traveling just 0.06 *m/s* (with wheels spinning much faster) at full throttle. Figure 13 shows a snapshot of the sand thrown up as the heavily loaded rover climbs a 7° slope.

Figure 12. The Green-Machine Rover carrying a 25% load up a 19° slope at high speed

Figure 13. Climbing a 7° slope carrying sand-bags representing a 50% increase in mass (shortly before getting stuck).

Avalanche-ladder

One of the more interesting observations we made was of the progress of Rover #84 as it slowly continued up the steep face of an angle-of-repose surface. We called the mechanism that allowed the rover to continue to climb, an *avalanche-ladder*. In this process the rear wheels would slowly spin transporting sand from in front of the rear tires out to the region behind the tires. The material would pile up behind the rear wheels and allow the rover to advance up the hill as the pile of sand below (behind) it grew. The hole dug by each rotating rear tire created a slight depression in the near angle-of-repose dune face, causing a small avalanche to flow into it from above. Separate small avalanches appeared above each back wheel. The extent of the avalanche gradually encompassed the sand under the front tires. Because Rover #84 had an ordinary rear-differential, we could not independently control the rotation of the individual tires. Thus, occasionally one tire's avalanche would get larger than the other tire's avalanche and the rover would start to turn slowly. Once this direction change started it was irreversible without hand intervention to realign the rover to point it straight up the hill. The front steering provided almost no control. The orientation was determined by whichever avalanche was growing the fastest. If independent drive controls had been available for each rear wheel, then the occasional hand realignment we used could have been accomplished with adjustments to the driving speed of the wheels. This rover was geared for high torque and, at top speed, could travel up a gentle slope (2° – 3°) at 50*mm/s*. While building the avalanche-ladder the speed control was set somewhat below the highest rotation rate to keep the front tires from lifting up off the dune face. We did not measure the actual rear tire rotation rate during this test. The actual rate of travel up the dune (e.g. 4*mm/s*) was 13 times slower than the rover's top speed on relatively flat sand. We estimated that the slip-rate was somewhere between a factor of 5 and 10 (e.g. 10 times as much tire surface travel as distance traveled up the dune face). In Figure 14a and 14b the individual avalanches can be seen. In Figure 14a the left-hand side avalanche has extended beyond the left front tire, while the right-side avalanche has just advanced to the front tire. In Figure 14b the tops of both avalanches have reached the crest of the dune. The large piles of sand behind each rear tire are clearly evident in each of these figures. The rover was able to climb more than 2*m* straight up the near-angle-of-repose face of the dune. This climbing mechanism clearly depends on the free-flowing behavior of the cohesionless dry sand found on the top surfaces of the dunes.

a) b)

Figure 14. Rover #84 climbing up the steep face of a dune at ~4*mm/s* by building an 'avalanche-ladder' (piles of sand behind each slowly spinning rear tire, fed by small avalanches flowing in from well in front of the rear tires). (a) top of the left avalanche is well in front of the left-front tire, while right avalanche lags behind. (b) both avalanches extend to the crest of the dune.

Concluding Remarks, acknowledgments, and credits

Many other phenomena were observed by various Dust-off participants during the weekend. This report focuses on the mechanical behavior of the sand and the traction of rovers in sand. Other participants noted the problems caused by the sand blowing into every opening, tribo-charging, and a variety of other phenomena. This outing provided an opportunity for Project Dust members to observe both the wide range of behavior exhibited by a relatively simple granular material, and to get a feel for some of the difficulties of traversing varied topography and surfaces with different geotechnical properties. All of us learned new things. Although the author of this report describes several phenomena observed during the outing, credit for any 'discoveries' belongs to others. This report is written simply to provide a record of observations made by the participants. The observations of sand behavior were so varied that it is difficult to summarize the findings – mostly we were seeing first-hand phenomena we had read about, or heard about, before venturing into the dunes. Many of the findings we made on dune traversal are embodied in the table of Winner and Losers (see Table 1 at the beginning of this report). Figure 15 shows the Dust-off-2005 participants, including the Rovers we observed/used.

Figure 15. Dust-Off-2005 participants (L to R) Nicole McGee, Gary 'Rod' Rodriguez (standing), Otis Walton, Surajit Sen, Brad Blair, Masami Nakagawa, Trudy Bell, Jared Reece, Bruce Damer.

The mention or use of any commercially available radio-controlled vehicles was not intended as an endorsement or advertisement for any commercial product, nor is it in any way intended to infringe on any intellectual property or Trademark rights of the commercial owners of those rights. Use of the 'body' of a toy truck was primarily as a sand-guard to keep sand out of the mechanical and electrical parts during these tests. This work was supported by NASA through contract NNM05AA88C .

[contact info: walton@grainflow.com Grainflow Dynamics, Inc, 1141 Catalina Drive, PMB #270, Livermore, CA 94550]