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A Basic Robotic Excavator (the "Glenn Digger"): Description, Design, and Initial Operation

Steve Bauman
Glenn Research Center, Cleveland, Ohio

Paul Newman
Vantage Partners, LLC, Brook Park, Ohio

Alain Izadnegahdar
Science Applications International Corporation, Brook Park, Ohio

Kyle Johnson and Phillip Abel
Glenn Research Center, Cleveland, Ohio

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National Aeronautics and
Space Administration

Glenn Research Center
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Brook Park, Ohio 44142

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National Aeronautics and Space Administration
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Cleveland, Ohio 44135

Abstract

This paper describes the design, commercial part selections, fabrication, assembly, installation, and initial operation of a two degree of freedom robotic excavator. Colloquially referred to as "the NASA Glenn Digger," it was designed specifically to be mounted onto, and to operate with, the then newly developed Centaur 2 robotic mobility base. The excavator, when mounted to Centaur 2, is designed to scoop loose regolith from the terrain, raise its loaded bucket up and dump the load into a hopper of at least a 1-m-height. The hopper represents the input to a machine that would process the raw material, such as to produce oxygen from lunar regolith as would be required for long-term lunar habitation.

This equipment debuted at the annual Research and Technology Studies ("Desert RATS", Ref. 1) event held north of Flagstaff, Arizona, in September of 2010, when the Digger was successfully joined to Centaur 2 and the shoveling articulation was demonstrated. During 2011, the hardware was modified for added strength, strain gauges were added to measure loads, and the controls were improved in preparation for the 2011 Desert RATS event, where additional "field operations" experience was gained.

Introduction and System Overview

The Moon has been suggested as a useful "jumping off point" for exploration further into the solar system. Fundamental to that version of exploration expansion would be the use of lunar resources, such as polar water or oxygen extracted from lunar minerals (see "NASA and the Moon" in the Appendix). The need to collect mostly-loose lunar regolith from the surface and deliver it to a processing machine led to the drafting of specific design requirements for the robotic excavator. This same implement may also perform other soil moving tasks, like excavating or flattening areas for lunar bases, landing sites, or machinery platforms (Figure 1). Human-tended bases may need to be buried under lunar regolith as a long-term means of attenuating harmful radiation. Building berms around landing or launch sites may be required to deflect rocket blast debris. All of these same functions would also be required for repeated crewed landings on Mars.

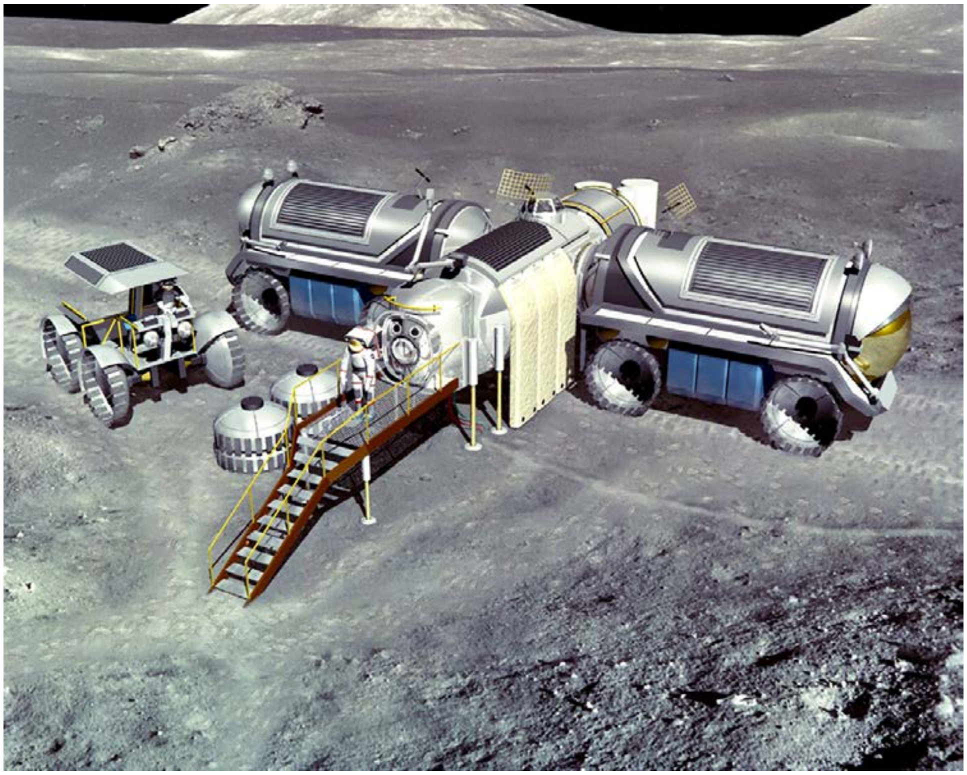

Figure 1.—Lunar habitat (Ref. 2).

The carrier vehicle selected to mount this implement to and act as the “tractor” is the rover prototype Centaur 2 (or “C2”, also see “Centaur 2” in the Appendix and Ref. 3). Developed by the NASA Johnson Space Center (JSC, in Houston, TX), this vehicle is about the size of a golf cart (as clearly seen in Figure 2, Figure 3, and others). The Digger was modeled after what is commonly known as a front-end loader. It has only two degrees of freedom; a “shoulder” pivot for the arms located near the C2 mounting point, and continuous bucket rotation (Figure 2). The shoulder rotation allows for positioning the bucket on the ground such that when C2 is moved, the bucket will scoop the loose regolith. The shoulder is then rotated to raise the bucket for the dumping operation. The bucket rotation allows for proper angular positioning of the bucket for scooping, for maintaining a no-spill angle while being raised, and for dumping (Figure 3).

Most terrestrial front-end loaders use hydraulic linear actuators. For the vacuum and extreme temperatures of lunar applications, the use of hydraulics is widely considered to be unacceptable given its dependence on fluids and linear seals. There is also concern about the use of any linear actuator, such as electric (ball-screw type) actuators, because the fine, abrasive moon dust may foul the bearings and seals. (See “Lunar Considerations” in the Appendix) Therefore, this design exposes only rotary seals to the environment.

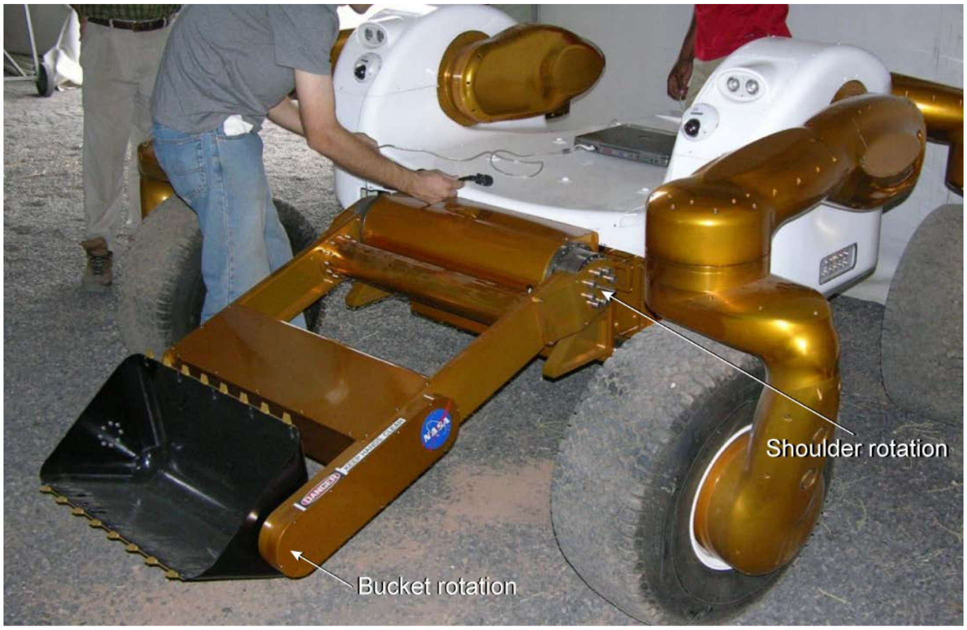

Figure 2.—Early at Desert RATS 2010, Centaur 2 with GRC Digger mounted, preparing to test.


Figure 3.—Arm is raised, bucket is dumping.

Design Requirements

The system design requirements developed for the Digger were:

1. The bucket shall elevate a full load of regolith, and dump it into a hopper with an edge height of 1 m. (This requirement came from the KSC Roxgyen Project.)
2. The bucket shall elevate to the 1 m dumping height in 10 sec or less.
3. The bucket shall collect, hold and lift at least 32.6 kg of lunar simulant.
4. Shall be capable of digging in both the forward and reverse vehicle directions.

5. Shall rigidly hold the bucket at a set digging depth and rake angle during vehicle motion.
6. The mass limit for the whole implement with the maximum bucket load is 150 kg or less.
7. Do not use hydraulics. Use electric/magnetic devices only.
8. All working components such as the motors, gears, sprockets, chains, brakes, and torque limiters, etc., shall be enclosed.
9. Attach to, and work in concert with, C2. This includes matching the C2 frame bolt pattern, operating using 300 V DC, and matching controller inputs. Also, it shall not interfere with the C2 wheel steering or suspension motion when mounted on either end.

Post-project notes: All the above requirements were met. The empty weight of the final hardware was 94 kg, which left 56 kg for maximum regolith loading before reaching the whole-implement limit. While 32.6 kg was the nominal bucket capacity, 56 kg was deemed possible.

Goals and Objectives

The following requirements were derived engineering objectives. They were levied as part of the design process by the GRC project team, but were not required. Post-project notes are in *italics,* most of which are better explained later in this paper.

1. Do not use linear actuators in the design, only rotary. Due to the extremely fine and abrasive lunar dust, there is grave concern about the effectiveness and wear-life of linear seals given their more difficult surface-wiping function when compared to rotary seals. *Accomplished by using Harmonic Drives.*
2. Provide articulation such that dumping onto a C2 chassis mounted hopper would be possible. *The arms can rotate back 20° beyond vertical toward the chassis (and the bucket rotates 360°). Whether this would be enough to actually dump onto the chassis has not been demonstrated.*
3. Minimize mass as much as possible to reduce rotary joint torque demands. *A single minimally-sized bucket drive was used, and the profile of one arm was narrowed near its end to minimize the shoulder torque demand. Detailed Finite Element Analysis was not used to optimize the final design, nor more elaborate materials.*
4. Select motors and drives from product lines used commonly by JSC. *Motors were supplied by JSC and the harmonic drives, planetary drives, and brakes were all from vendors recommended by JSC.*
5. Protect the rotary joint drives by using torque limiters. *The harmonic drives were deemed adequately robust to prevent the need for torque limiters. Plus, arm stops prevent the arms from extending lower than –40° below horizontal to prevent over-torque in this position – although these were later deemed unnecessary and were removed due to the small likelihood of the implement being operated at this extreme position.*
6. Provide rotary positional encoders at each rotary joint. *A rotary encoder type recommended by JSC was to be mounted outside of each boom arm; however, for Desert Rats 2010, only limit switches were used. For Desert Rats 2011, an encoder was mounted on only one arm. For the bucket, an encoder is sprocket-engaged with the bucket chain. Also, each motor has its own integral encoder which was used for control.*
7. The bucket will remain in raised position when the power is off. *Brakes were added to each shoulder actuator motor to prevent the arms from dropping when power was turned off.*

8. Provide interchangeable leading edges for the bucket. *One toothed and one smooth set of leading edges were made, however, only the toothed leading-edge pair was used in practice.*
9. Design curved corners into the bucket where the sides join the main length panels. This helps assure evacuation of the bucket, and makes the structure stronger. *Accomplished.*
10. Integrate bucket reactionary force sensor instrumentation. *Post Desert Rats 2010, strain gages were applied directly to the arms and calibrated with weights.*
11. For aesthetic purposes, the end product should appear sturdy, and have polished and anodized features. *The end product did appear sturdy, and proved to be so. The surfaces were polished and gold anodized using the same vendors used for the C2, so they were an exact match.*

Configuration

The Digger configuration was comprised of the following assemblies (1) base plate to attach to C2, (2) shoulder drives, (3) arms and connecting frame, (4) bucket drive, and (5) bucket (Figure 4). The parts were modeled and assembled in Pro-E (Figure 5). Pro-E was also the tool used to do limited finite element stress analysis, and create the detailed drawings. These are described in the following paragraphs.

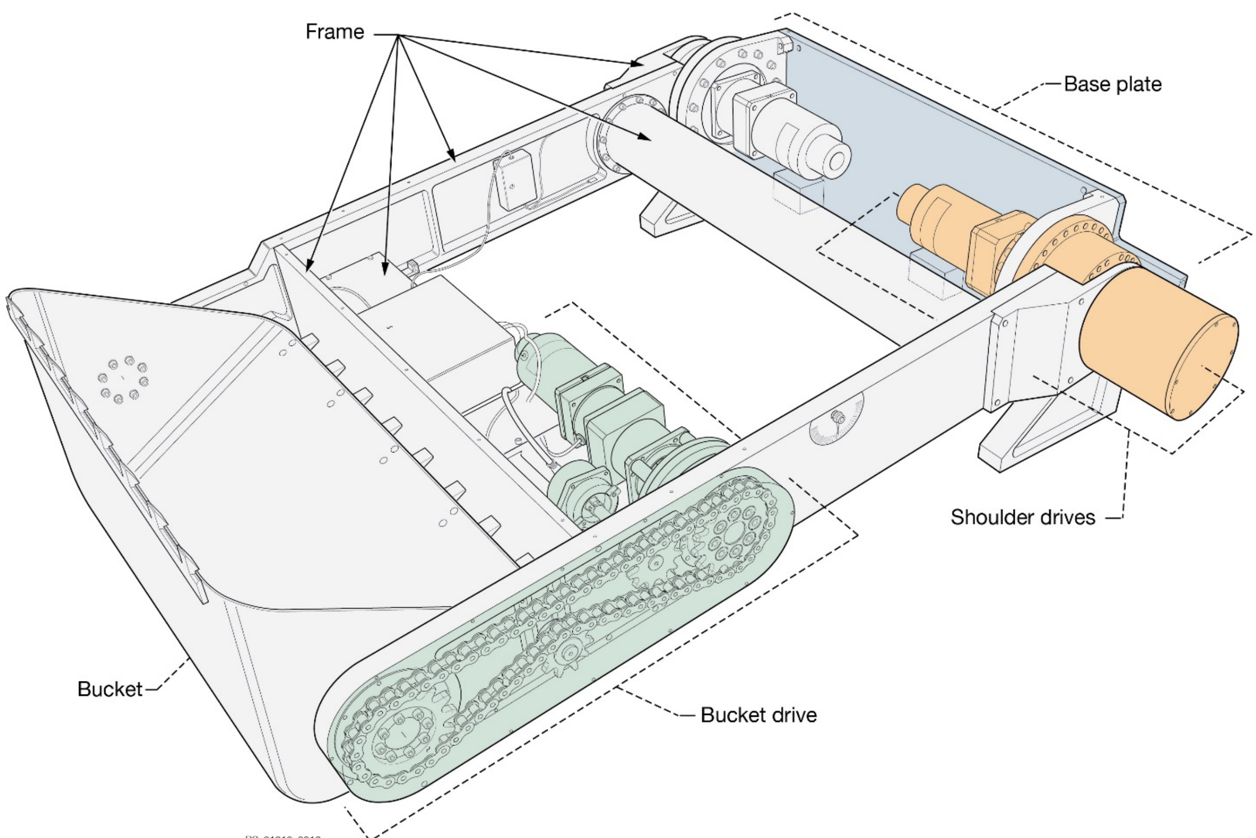

Figure 4.—Digger.

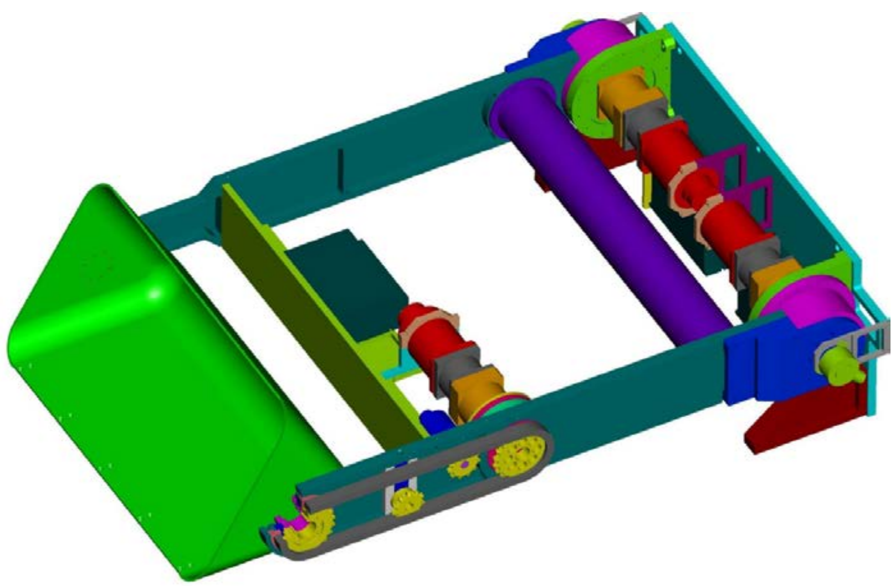

Figure 5.—Pro-E Solid Model.

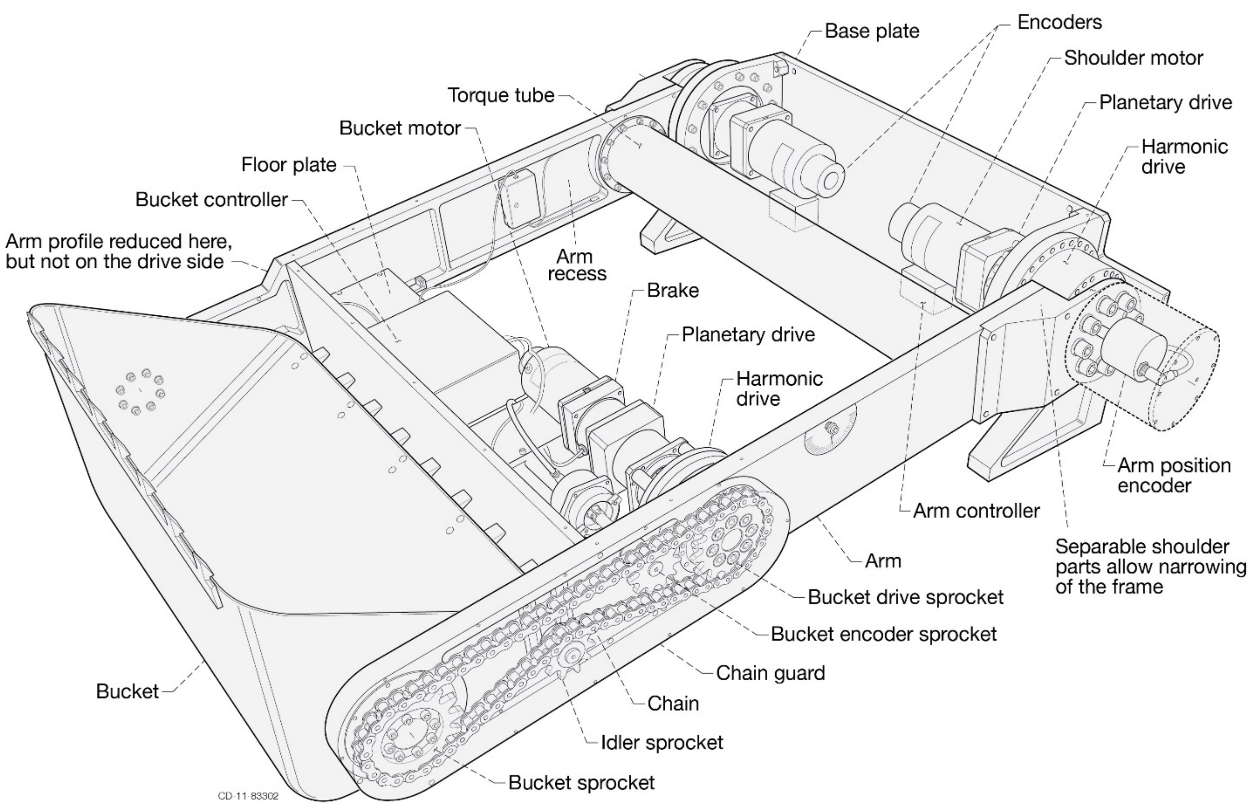

Figure 6.—Labeled illustration of the Digger.

Base Plate

The Base Plate is what fastens to the hole pattern provided on the C2 frame. Six 1/2-in.-diam. bolts, four near the four corners and two more mid-span, pass through holes in the base plate into threaded holes in the C2 frame. The Base Plate has mounting ears (90° brackets) that are mounted to the plate where the shoulder drives are fastened (Figure 6).

Mounted directly below the shoulder motors and drives are their controllers.[1] Between these controllers, and above the motors, additional circuit boards are mounted.

All of these components are enclosed with Shoulder Shields. The three separate shield parts include, from the bottom up; a half-box-like shield that covers both motor-controllers, a curved bridge shield that covers the bottom portion of the motors/drives, and a curved top shield that covers the top portion of the motors/drives. All of these shields are screwed into place along their edges. Gold Kapton tape was used to seal between the bridge and top shields. This tape also frequently served as a hinge for when the top plate screws were removed to allow for limited service access to the motor, drives, and top-mounted circuits.

Shoulder Actuation

To provide shoulder rotation, harmonic drives (HDs) were selected for several reasons:

- They provide a very high reduction ratio and high torque in a relatively small package. This proved invaluable given the limited real-estate available in the envisioned framework that would fit, and still meet all the requirements.
- They are a proven commodity on the Moon. The Apollo Lunar Rover Vehicles of Apollo 15, 16, and 17 used them to drive each of the four wheels.
- JSC robotics engineers have much experience using them.
- According to the experience of JSC engineers, HDs continue to work even after being overloaded. When overloaded, the flexspline gear-like teeth slip relative to the circular spline inner-diameter teeth, but incapacitating damage does not typically occur. Instead, there is a mild loss of torque capability.

Therefore, HD's were selected as the final shoulder drive component (Figure 6).

HD's can be selected in many different sizes and reduction ratios. The size determines the torque output capability. It is difficult to decide which model will safely provide the torque that is required without selecting one that is too large, heavy, or expensive.

HD Inc., the only full-service commercial provider of HD's at the time, offered 15 different frame sizes ranging in designation from 8 to 100 (Ref. 4). Among most of these, the speed reduction ratios offered are 50, 80, 100, 120, or 160. Four different torque ratings were provided for each frame size and each speed reduction (see "Harmonic Drive Torque Ratings" in the Appendix). Considering all the models and the rating, the shoulder drive HD's were selected.[2]

Many different ways of powering these HD's were considered. This included powering both with one motor drive and carrying the torque across to both in several different ways. Right-angle drives were also considered as a way to more compactly fit one or two large motors and drives between the shoulders areas to drive both shoulders. With careful planning, it was decided that each HD could be driven by its own in-line motor-drive, positioned in between the shoulders, mirror-images of one another, and without making a 90° turn. Pre-loaded spring assistance was considered to help relieve the shoulder lifting torque requirements—but it was decided that this would be too difficult, heavy, and awkward to implement.

Determining the total required shoulder drive reduction ratio was based on the required arm raising speed and the speed rating of the motors. Selected were compact motors that JSC had experience with and which met the full power requirement.[3] All three HD's (both of the shoulder drives, and the bucket drive) were driven by these same motors.

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[1] Shoulder Controllers; Advanced Motion Controls (AMC), model: DPRANIE-030A400.

[2] Selected for the Shoulder Drives; HD Inc., model: CSG-50-160-2UH. Also note the CSG style was selected which is an increased torque variant over the more conventional CSF. See Reference 4.

[3] Shoulder and Bucket Drive Motors; Magmotors Technologies, Inc., model: B34-I-200HFE.

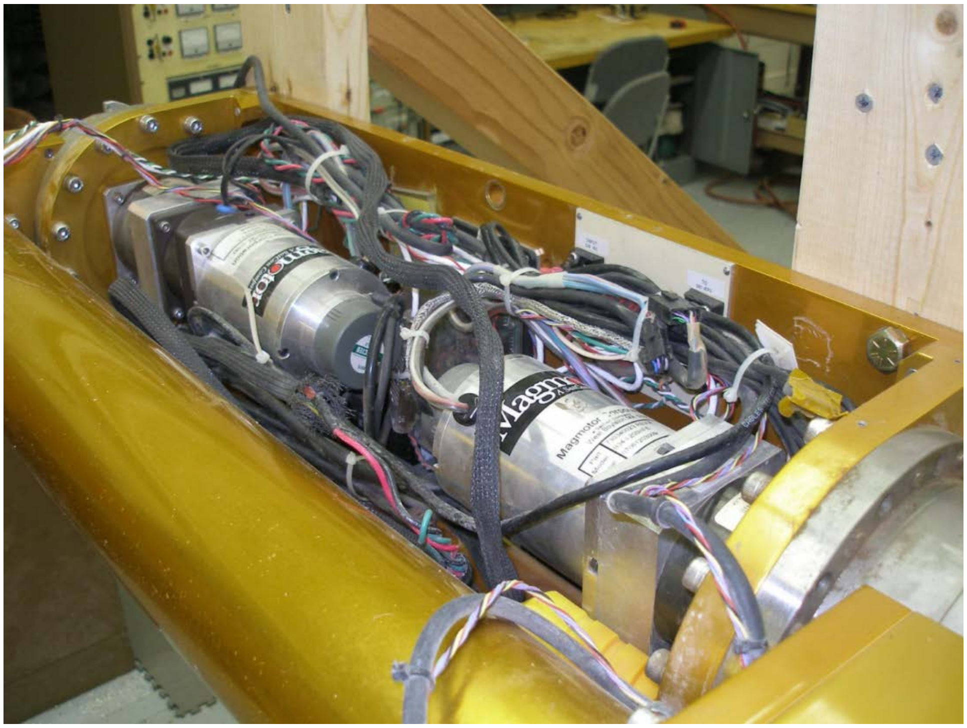

Figure 7.—Shoulder Drive Area (post Desert Rats 2011).

The HD reduction ratio alone was not enough for the shoulder drive, so additional reduction was necessary, and yet space between the shoulders was tight (Figure 7). A single-stage planetary drive (PD) designed to fit the motor would fit, but a double-stage PD would not. The largest ratio single-stage PD available was 10:1,[4] which when combined with the largest HD reduction of 160:1, provided the torque that was needed while still providing more than enough output speed.

Brakes were also required for all the motor drives. The main reason for them was to stop all motion when the Digger power was turned off (Requirement 5). It was demonstrated that without the brakes installed or functioning, the loaded bucket would fall, back-driving the gear reduction stack. The brakes fit in the stack between the motor and the planetary gears, where the torque levels were lowest. The brakes are normally engaged when power is off. When power is applied and a motor is to run, the brakes are disengaged. Several brake suppliers proved viable.[5]

Arms and Frame

The shoulder actuation design, the two sets of motors with brakes and encoders, and stacked PD's and HD's located back-to-back, dictated the minimum distance between the shoulder hubs. These hubs are spaced too far apart to allow straight and parallel arms to extend from them out to the bucket, because this width would interfere with the 360° steerable front wheels of C2. In order to narrow the frame, separate Shoulder parts were designed that allowed the Arms (frame sides) to be closer-spaced than the HD driven shoulders (Figure 6). These separate Shoulders had the added advantage of allowing the arms to be removed and reattached without disassembling the Shoulder Hub, which improved field serviceability.

[4] Shoulder Planetary Drives; Applied Motion Products, Part No. 34VL004.

[5] Shoulder Drive Brakes were: (a) Motion Control Group, Inc., model MCG-B5 (recommended by JSC). (b) Due to order delays, from Servo2Go, Inertia Dynamics, model 8934-2661 MPC 34, and (c) from Drive Systems Group, Inc., model DY-PO222AAA.

The arms extending to the Bucket are straight, but the profile height of the non-bucket-driven-side arm is reduced at the bucket bearing (Figure 6). The reduction in the profile height reflects the cantilever-nature of the stress distribution on the arms. Conversely, the profile height of the bucket-drive-side arm does not reduce so that it may accommodate the bucket drive chain and sprockets, and the full enclosure that is required. The cross-section of the arms features a middle recess that forms a C-channel shape to reduce weight while maintaining the necessary strength. This recess also provides convenient space for wiring, load-cells, and circuitry.

Near the shoulder end, a "torque tube" crosses between the two arms and ties them torsionally together. It was established by analysis that the potential twisting force between the two arms would be very substantial if only one shoulder is driven to lift a substantial bucket load with no contribution from the other. A tube has the best torsional inertia-per-area shape. In practice, this proved to be an important feature while getting the two shoulder actuators to act together.

Near the bucket, a horizontal floor-plate crosses between the arms and creates a mounting location for the bucket motor-drive. Another cross plate, oriented vertically and just clear of the bucket rotation zone, creates a hard barrier between the bucket and the bucket drive components. Both of these components also provide cross-structure that is needed between the arms. Added to this is a single thin-metal shroud that fully encloses the bucket motor-drive and controller. Similar to the Shoulder Shields, it is screwed to the structure along its edges. After Desert RATS 2010, this shroud was redesigned.

Aluminum 6061 was the material selected for all of the frame parts. It was selected for its light weight compared to any steel, for its machinability, and its commonality with most of the C2 machine, as well as with other GRC and JSC robotics. Advanced alloys, or venturing into composites materials, was considered too expensive and unnecessary for the scope of this demonstration project.

Bucket Drive

The Digger is designed to scoop up regolith using a single bucket in either the forward or reverse directions (Requirement 6). The bucket itself is designed symmetrically with both of its long edges usable for ground-scraping. The bucket can face forward to scoop as C2 travels forward, or the bucket can be rotated about 120° to be rearward facing so that it will scoop when C2 travels in reverse.

The Digger was also designed to dump bucket loads into a C2 chassis-mounted hopper, which would require a reverse bucket-dumping action. Given this and the desire for forward and reverse scooping directions, the bucket was designed to rotate a continuous full 360°.

The bucket is chain and sprocket driven from one side. The bucket itself was judged to be rigid enough that driving from only one side would be adequate; a simpler mechanism with fewer parts. Most trials demonstrated that this was true, though in some of the more demanding situations, the bucket could be seen to twist a few degrees. However, no damage occurred, and negligible functionality was lost.

The two sprockets were selected to be the same size because all the necessary speed reduction is accomplished by the HD, PD and motor stack assembly. Also, the two large sprockets allow for the mounting of a sprocket inside the chain path to drive an encoder. An idler sprocket is mounted outside the chain path so that the chain is easily tensioned. It deflects the lower chain path substantially to minimize the size of the chain cover.

The HD selected was one frame size smaller than the shoulder HD's since the torque requirements were less.[6] The smaller drive was also selected to minimize weight, and therefore the required shoulder torque, since it is far out from the shoulder hub. In practice, the torque produced appeared to be more than

[6] Selected for the Bucket Drive; HD Inc., model: CSG-32-160-2UH. For the future, for a faster dumping bucket, suggested is CSG-32-100-2UH. See Reference 4.

adequate; however, the bucket rotation speed was exactly the same as the shoulder and was deemed too slow, particularly when it was desired to dump the bucket after it was elevated. It is suggested that changing the HD to a smaller reduction ratio would exchange torque capability for speed and would be a preferred configuration.

Bucket

The dual-edged shoveling bucket was modeled after hardware in use at the Simulated Lunar OPErations (SLOPE) lab, and similar to commercially-produced buckets. The bucket is 27-in.-long, has a 15 in. opening and is 11-in.-deep. The geometry is kept simple, and it is kept symmetrical so that both edges can be the scraping surfaces for both the forward or reverse digging functions described above. Like many commercial buckets, a separate leading edge part fastens to both bucket edges. Both toothed and sharp-knife cutting edges 23-in.-long were designed and fabricated to fasten to the bucket edges.

To reduce weight, the bucket was fabricated in 6061 aluminum alloy. In the terrestrial excavation industry, this is never done due to the greater expense, the greater difficulty of welding, and the poorer durability of aluminum as compared to steel alloy. However, keeping the bucket light was the more important consideration, as it would be when the design evolves into a Moon-bound implement. The reduced durability of this aluminum bucket made having the separate tougher and interchangeable leading edges described above even more important. While a composite bucket might reduce weight even further, the added expense and other uncertainties about this approach placed it beyond the scope of this project.

During testing with similar bucket designs, it was noticed that when dumped, the regolith simulant (GRC-1, a lunar simulant that is a blend of commercial sands) sometimes clung in the extreme back corners of the bucket, where the curved backside meets the sidewalls at a square angle. This makes sense given the larger ratio of surface area to regolith bulk mass in these zones. Ideally, the bucket should instead have rounded corners. This would be more difficult to fabricate because these rounded corners meet the rounded back wall creating compound curves which are somewhat spherically shaped. The rounded-corner bucket was not prohibitively more expensive, was purchased, and in practice did seem to improve the thorough evacuation of the bucket during dumping.

Fabrication and Assembly

Detailed part and assembly drawings were completed by April 2010. After first test assembling all the parts, Mound Manufacturing delivered them by the end of June. This included having the parts gold anodized by Turn-key Coatings in Houston, Texas, a commonly used coating source of JSC. In August 2010, a mechanical fit check was conducted at JSC on C2, which resulted in minor alterations to the baseplate (Figure 8). Once back at GRC, two mechanical limit switches were positioned on one shoulder so as to prevent shoulder actuation beyond the physical angular limits. After Desert RATS 2010, these switches were replaced by Hall Effect electronic switches which are robust and immune to dirt and dust, and have a very long life expectancy. A long lead time item, motor brakes, were not installed prior to Desert RATS 2010.

Figure 8.—At JSC, C2 with Digger Base Plate mounted, and temporary arms for shoulder actuation coordination testing.

Desert RATS 2010

After the Digger was attached to C2 mechanically and electrically, it failed to power-up (Figure 9). It was determined that the act of turning the Digger on caused an unexpected current spike that blew a power fuse inside C2. An inductor-based soft-start circuit was quickly put together and mounted to the Base Plate, and this solved the power-on problem so that the fuse did not blow again. Since the size of the C2 fuse was judged to be correct for the available auxiliary current, Digger, and all future implements, may need to provide soft-start circuitry.

Remote control of the Digger at Desert RATS 2010 was only achieved through the addition of a laptop computer wireless communication channel dedicated to the control of the excavator. Integration of the remote command communication function into the C2 host vehicle communication channels did not occur until the following year.

Once everything was working, the GRC team witnessed and photographed the Digger in action operating in conjunction with C2, and the operator learning curve was rapid. Digger was soon able to scoop up a full bucket of loose dirt, and lift and deposit the dirt to where ever it was directed. The Digger also demonstrated that it had sufficient torque in the shoulder actuation mechanism to, with the bucket on the ground, lift the front wheels of C2 (Figure 10).

Through the ensuing weeks of the event, coordination of the operation continued to improve, and more varied tasks were attempted. For example, while climbing one particularly steep hill with the Digger at the trailing end, it was discovered that by lightly engaging the Digger with the ground, it prevented C2 from tumbling back, thereby allowing it to continue its climb.

Figure 9.—Early at Desert RATS 2010, Centaur 2 with GRC Digger mounted, preparing to test.

Figure 10.—The Digger shoulder actuation is strong enough to lift the front wheels of Centaur 2 off the ground.

Design Revisions of 2010/2011

Once the Digger was returned to the labs at GRC, the following observations were made:

1. The black oxide coating of the aluminum bucket was significantly scratched and gouged (Figure 11).
2. At the bucket edge, there was a tear of the aluminum next to where the steel blade ends (Figure 12).
3. Most of the screws that secure the bucket drive sprocket were loose and partly backed out (Figure 13).
4. The bottom controller shield that protects the two large (AMC) motor controllers on the base plate was significantly dented and gouged (Figure 14).

Figure 11.—During Desert Rats 2010, the black oxide coating of the aluminum bucket got scratched and gouged.

Figure 12.—After Desert Rats 2010, on the bucket edge next to the steel blade, there was a tear of the aluminum.

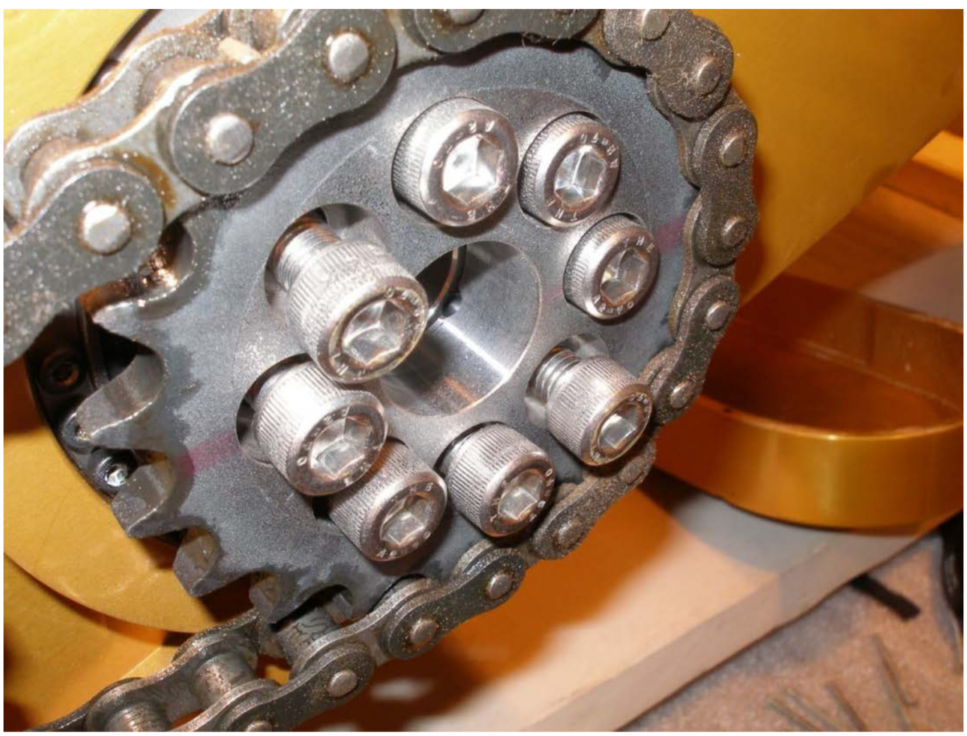
Figure 13.—After Desert Rats 2010, most of the screws securing the bucket drive sprocket were loose and partly backed out.

Figure 14.—After Desert Rats 2010, the bottom controller shield had clearly been challenged.

During the following year between the September 2010 Desert RATS event and the August 2011 Desert RATS event, many physical modifications and controller improvements were made:

1. The bucket was removed, the ripped edge was welded closed, and the bucket was painted black. The bucket could have been polished and then black-oxided again, but this would have weakened the bucket slightly, and not made it any less vulnerable to further scratches.

2. The screws that hold both the bucket drive sprocket and the bucket sprocket were removed and reinstalled with Loctite to prevent the screws from losing their preload.

3. Evident by the damage done, the bottom controller shields were clearly vulnerable to rocks and uneven terrain (Figure 14). These shields were replaced with thicker ones, and made out of stainless steel instead of aluminum. Brackets were added mid-span to better support the new shield. Because this took space where one of the circuit boards had resided, the board was reconfigured and relocated.

4. The arm-angle-limiting stops were replaced with stubs that provided ground-spacing protection (Figure 15). These stubs also served as holders for new short cross-plates between the stubs and the new bottom shield for even more rock protection. At Desert RATS 2011, this proved to be an adequate improvement

5. The C2 platform clearly has a great deal of versatility, especially in its ability to turn within its own footprint at high speeds (Figure 16). Even though it was not a specific problem while there, it was believed that the Digger was vulnerable to a potentially large side-impact load. Therefore, the protective thin-walled single-sheet shroud around the bucket motor-drive and

controller was replaced by two parts. First, a much stronger and stiffer top plate was designed to behave as a structural member to help prevent any arm side-to-side motion (Figure 17). The new top plate is wider and thicker than the shroud it replaces; increasing from 8- to 10.5-in.-wide, and from 0.05- to 0.25-in.-thick. Finite element analysis of this new design revealed a reduction in deflection for the same side load. The second part is a bucket drive shroud that attaches to the top plate, and wraps to the bucket actuator mounting plate to accomplish the same enclosure function as before. This new design adds about 4 lb.

6. The controller circuit boards were reconfigured. Space was retained between and under the two shoulder motors to better affix and organize the soft start circuit which had been loosely tied above the motors. Space was retained for the new current-limiting circuit that was still being developed.

7. The shoulder joint motor brakes were added. Room had been reserved for the motor drive stack lengths to become longer as a result of adding these brakes.

8. Strain gauges were added on the inner sides of both arms. Tests were conducted to calibrate these gauges so that the bucket loads in all directions, and in real-time, could be read. Tests were conducted in the GRC TREC Test Rig. This was done to support the objective of automating Digger as described in another publication (Ref . 5)

   Note that during the months before Desert RATS 2011, one of the shoulder drives would randomly lock-up for no obvious reason. It was discovered that removing the motor, brake, and planetary drive, and then reassembling them, would free-up the drive. The cause of the lock-up, or why this remedy worked, has not been definitively resolved.

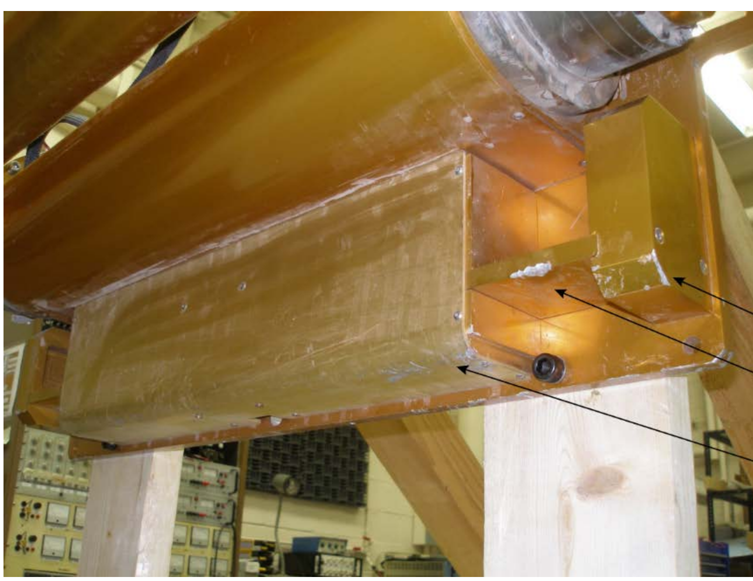

Figure 15.—After Desert Rats 2011, gouges can be seen on the newly designed bottom controller shield, end stubs, and cross plates.

Figure 16.—Because each wheel can be independently steered, Centaur 2 can twist and crab, potentially putting great side loads on the Digger.

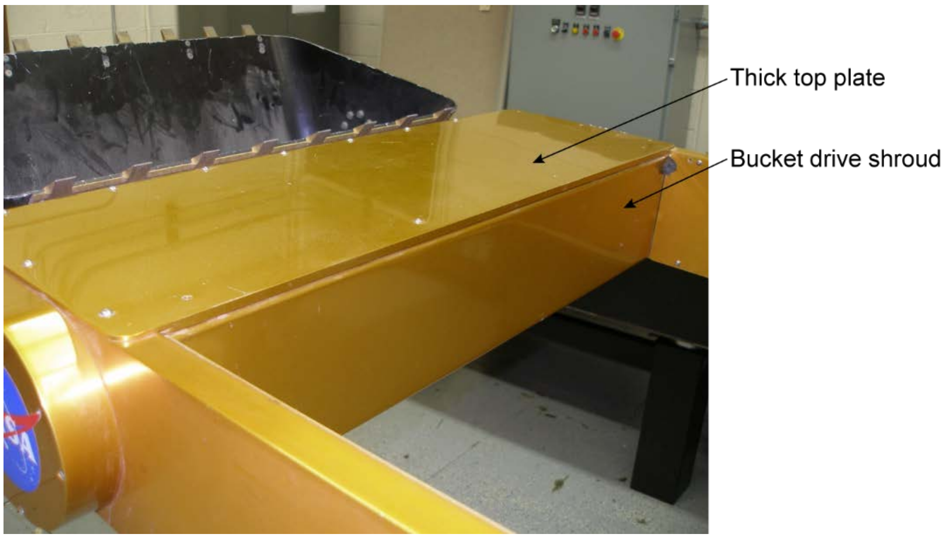

Figure 17.—In preparation for Desert Rats 2011, the new thicker top plate and bucket drive shroud.

Desert RATS 2011

While at Desert RATS 2011, these were the events and observations:

- Remote command communication with the excavator was channeled through the host C2 vehicle, allowing for closer coordination of vehicle motion and bucket operation.
- One of the Shoulder HD's made noises consistent with spline-slip, or "cogging", and this failure was traceable to the previous Desert RATS event, at which the Digger was severely overloaded to the point of spline gear slip. The HD was replaced with a spare and the drive worked for the remainder of the event. (It is ***not*** clear whether this solved the previous shoulder actuator lock-up issues.)
- The bucket and chain guard continued to take significant abuse as it had done during Desert RATS 2010 (Figure 18).
- Rocks would cause interference, often with a crunching noise, between the bucket edges and the frame connecting plate, and between the bucket ends and the frame members. An increase in these clearances is suggested.
- The bucket could be seen to twist when loaded relative to its driven end. An increase in torsional strength of the bucket would reduce this flexure.
- The bucket rotational speed seems inadequate for timely dumping operations to be consistent with the rate at which other operations occur.
- The wiring to a communications connector proved faulty. The connector was eliminated by soldiering the wires directly to the circuit board.
- One of the hall-effect shoulder position sensor wires got loose and needed to be recrimped. These connectors should be strain relieved and of high quality for this application.

Figure 18.—After Desert Rats 2011, the black paint coating of the bucket is scratched, as is the chain guard.

Additional Lessons Learned

The issues experienced with the Harmonic Drives, primarily those for shoulder actuation with the apparent cogging and lock-ups, are of great concern. The team engineers will be very cautious about how they might use HD’s in future robotic designs. The service claims made by the HD suppliers do not appear to have been validated. As a result, during the conceptual design phase of Digger 2, which required even more muscular actuations, the team all but ruled-out the use of HD’s. The fact that there is effectively only one source for HD’s, and that there is a long lead time for orders, are also of concern for future designs.

However, HD’s provided a wide-rotation actuation range for the shoulder, and for full-rotation of the bucket, both of which provided outstanding capability that would not have been easily accomplished by any different means of actuation. The full-rotation capability of the Bucket is what enabled scooping in both forward and reverse. Plus, combined with the wide motion range of the shoulder, bucket full-rotation provided for the possibility of dumping into a vehicle top mounted hopper. These proved to be truly the most innovative features of the design.

Although the overall hardware mass was lower than the target maximum, a future edition of this design could benefit from more extensive finite element analysis to optimize the material distribution, especially within the Frame and Arms. Lighter materials such as composites or titanium should be considered. A lightweight composite-fabricated bucket could be especially beneficial, although its service life would need to be field-proven. As with any apparatus design; schedule, cost, final mass and application switch-ability need to be traded against one another for the final design decisions.

Conclusions

The design, fabrication, assembly, and early operations of the GRC Digger were a success.

All of the design requirements were met, as were most of the Goals and Objectives. Along the way, many valuable lessons were learned about how to design for this kind of application. This design was a challenge because of the high forces and clever tools that are required to deal with the widely-varied and unpredictable coarseness, abrasiveness, cohesion and density of the regolith expected to be encountered.

Beyond what was learned locally; how to seamlessly integrate our efforts, hardware and software with a distant engineering team was also of great value.

Appendix

NASA and the Moon

The United States may one day return humans to the surface of the Moon; something that has not happened since the six Apollo lunar landings between July of 1969 and December of 1972. If this does happen, unlike the Apollo missions, it will likely be in a larger, more ambitious and more enduring manner.

One ambitious goal would be to establish a permanent base where scientists could live and work (Figure 1). The base could be manned continually where, similar to the International Space Station, crews of six or more people are swapped-out routinely every six months, or perhaps much longer. To that end, the transportation architecture, meaning the takeoff and landings from both the Earth and the Moon, would need to become routine. Many of the launches to the Moon could be unmanned support launches to carry supplies and equipment. All of these journeys should be highly automated, again much like the ISS support system of today.

The Space Launch System (SLS) (Ref. 6) is a new, heavy-lift rocket that is currently being developed by NASA using Shuttle-derived hardware and manufacturing technologies. This could become a workhorse of the Moon transportation architecture. Unmanned missions would deliver equipment to the Moon, while other SLS launches could carry astronauts in the Orion Multi-Purpose Crew Vehicle.

On the Moon, specialized vehicles would be required to build the home-base, to move supplies about, to mine the resources and to explore. While these vehicles could be modeled after those that accomplish similar tasks here on Earth, they would also be designed very differently; light weight for launch yet specifically built to endure the journey to the Moon, and to operate in the lunar environment.

Centaur 2

The NASA Johnson Space Center (JSC, in Houston, TX) has designed and built many mobile robots, including one known as Centaur 2 (C2). This is a follow on to the original Centaur, and like it, C2 is designed as a mobile platform for Robonaut (Figure 19). (The Centaur name comes from Greek mythology for a creature with the head, arms, and torso of a man joined to the body of a horse.) Robonaut is an anthropomorphic (man-like) robot that was designed to conduct certain astronaut-designated functions. It has the shape and size of a human torso, with a head, arms and hands, but does not initially have legs. It is intended to be mounted in one place, or mounted on the ISS robotic arm. Similar to Centaur, Robonaut has been advanced into a second model, Robonaut 2, or R2, which is faster, more compact, more dexterous, and has increased sensory capabilities. The first R2 was delivered to the ISS by STS-133 on February 24, 2011, and it was first powered up on August 22, 2011. For terrestrial functions, R2's can be mounted to C2.

Centaur 2 is a very sophisticated design with an amazing level of capability. It is about the size of a golf cart. It has four wheels, all four are in-hub electric motor driven, and each can be independently steered. This allows the vehicle to travel in any direction, regardless of the chassis orientation, such as crab motion (Figure 16). It can also turn within its own footprint (Figure 20). In addition, each wheel is mounted on a bogie (or arm) that is both actuated, which allows for the raising/lowering and tilting of the chassis relative to the ground, and has passive suspension springs as well. The actuation allows, for example; the chassis to be kept level while the wheels traverse a hill, or for the chassis to be lowered to the ground, "belly in the dirt" (Figure 21).

Figure 19.—Robonaut 2 mounted on Centaur 2.

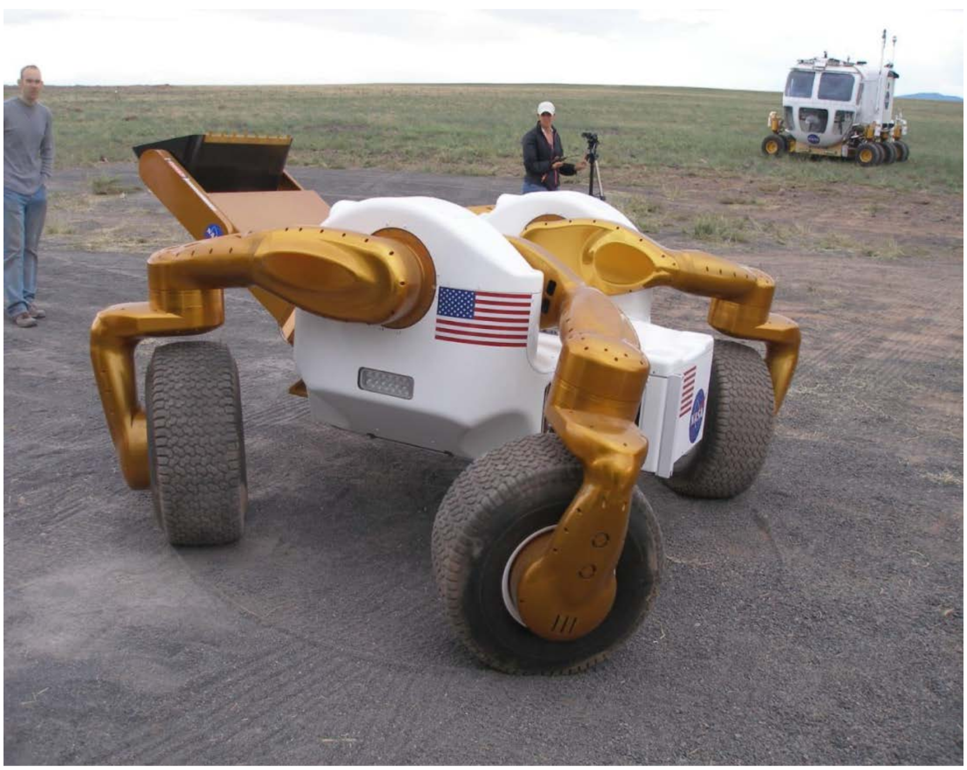

Figure 20.—Centaur 2 can turn on its own footprint.

Figure 21.—Using its articulated bogies, Centaur 2 can lower its chassis to the ground, even with the wheels turned for crab-travel.

The chassis of Centaur 2 is a welded tubular structure, and the flat front and back surfaces are identical vertical accessory mounting surfaces. Included is a pattern of six threaded ½-in. bolts holes that are for the mounting of any accessory, along with access to sockets for the 300 V DC power supply and data channels. The accessories include Robonaut and the Digger, and can even support both of these at opposite ends at the same time.

Lunar Considerations

Hardware that is to be sent to the Moon must be designed as light and efficiently as possible to minimize launch mass and still function as expected once it arrives. It must also withstand Earth launch and Moon landing accelerations and vibrations, and certain landing impact levels.

To operate on the Moon, the peculiarities of the Moon environment must be fully accounted for. There is no atmosphere on the Moon. With no air, clouds or haze, the sunlight is very intense while the sky is otherwise very black. Large temperature extremes are normal; the result of either direct sunlight (hot) or radiation heat loss (cold). At the lunar equator, temperature can vary between –280 to 305 °F. What is liquid in the atmosphere of Earth becomes vaporized in the vacuum of space, and the Moon. And with no atmosphere, the radiation from space reaches the Moon’s surface unabated. This, by itself, is hostile to long-term human presence. One lunar day is the equivalent of 29.5 days on Earth. This means that night time, with no sunlight, lasts nearly 15 days, followed by a sun slowly moving across the sky for the next 15 days. And, much like on Earth, near the north and south poles there can be near constant sunlight (with the sun very near the horizon), or constant darkness, particularly within large craters.

Moon dust is everywhere, and it is very fine and very abrasive. This is the result of a 4.5 billion year history of meteorite impacts breaking surface rocks into finer and finer granules, all in the total absence of any of the weathering agents that we are accustomed to here on Earth. Gravity is much lower, 1/6th that of Earth. This will be advantageous for many activities by literally lightening the working loads. But also, our experience with humans in long-term weightlessness suggests that there are health risks to low gravity as well.

Harmonic Drive Torque Ratings

Based on the HD Inc. literature, and on conversations with a HD technical representative, the various ratings can be characterized as follows:

Rated Torque

The most conservative, or lowest, of the ratings, this is the allowable continuous load torque at 2000 rpm input speed. Comparable to other gear-drive rated torques, this is a bench mark for comparison. It is based on the life of the wave generator bearings, with a 2000 rpm input and projected life of 35,000 to 50,000 hr.

Limit for Average Torque

Based on an average duty-cycle torque, when load torque and input speed vary. This limit is set with particular attention to the lubricant; not overheating it, or exceeding its limits of deterioration.

Limit for Repeated Peak Torque

This is the acceleration torque limit due to the moment of inertia of the output load. This limit relates to staying below the endurance fatigue-life limit of the constantly-bending flexspline. (It is commonly about 2.5 times the Rated Torque.)

Limit for Momentary Peak Torque

This is an emergency-level figure, intended to be reached only very occasionally, such as during a collision or emergency stop.

It has been observed that for light duty cycle, low use applications such as experimental robotics, designing to 75% of the Repeated Peak Torque (which results in being close to double the Rated Torque) can be routinely done with only occasional difficulties (e.g., Desert RATS 2010 spline slip damage).

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