Refined Gearbox Design for the Chariot Lunar Rover

Steve Bauman* and David Lewicki*

Abstract

In planning for NASA's return to the moon by the year 2020, the NASA Johnson Space Center (JSC) designed and built a lunar concept vehicle called Chariot. Slightly larger than a pickup truck, it was designed to demonstrate similar utilitarian functions, but with twelve wheels for redundancy, reliability, and reduced surface contact pressure. JSC designed a motor gearbox to drive each of Chariot's six wheel pods. The pods can be independently steered over 360° for maneuverability. This paper describes the design of a second generation, drop-in replacement gearbox. The new design has a lower parts count, and is lighter than the original, which represents a step toward flight hardware.

Introduction

The goal of this work is to demonstrate a gearbox for Chariot that would be closer to what NASA could ultimately send to the moon. With fewer moving parts, it would be smaller, lighter, and have improved reliability. Helicopter gearbox designs, one of our major research areas, share the concerns for reliability and weight reduction that space hardware demands. Therefore, NASA Glenn Research Center was selected to help custom design the Chariot gearbox. As part of this effort, high-performance, aerospace quality gears were designed, specified and fabricated.

Design requirements for the new gearbox were developed to include, very importantly, that the new gearbox make use of identical motors so that direct comparisons could be made quantitatively. Like the original, two gear reduction speeds would be provided, and each would supply nearly the same output gear reduction ratio as the original. The same mounting bolt pattern to the steering box top plate would be specified so that replacement of the original gearbox would be straightforward, with minimal operational downtime. Similarly, the electrical circuits would be compatible, and the exact same electrical wire connectors used.

Description of Chariot

Chariot is slightly larger than a pickup truck and is designed for truck-type utilitarian purposes on the moon (Fig. 1). This includes the ability to carry astronauts and/or substantial loads of equipment or regolith. It can be fitted with a soil-moving blade, and the flat top deck of the vehicle lends itself to custom-configurations for different missions.

Chariot has six identical and independently motor-driven wheel pods, three on each side of the vehicle (Fig. 2). Each pod has a pair of driven wheels, so the vehicle has a total of twelve wheels total. Having numerous wheels and pods creates redundancy to assure reliability, and reduces the ground surface contact pressure. All six pods and wheel pairs can be steered independently, and to any angle (a full 360-degree capability) making the vehicle highly maneuverable. For example, it can travel a straight path or make turns while maintaining the vehicle body at any desired angle relative to the motion (often referred to as crab-motion control). Steering can also be optimized for special duties such as towing another vehicle, or conducting regolith excavating operations.

* NASA Glenn Research Center, Cleveland, OH

Proceedings of the 40th Aerospace Mechanisms Symposium, NASA Kennedy Space Center, May 12-14, 2010

NASA/CP-2010-216272

Each wheel pair is driven by a differential which is powered by a shaft that extends vertically down through the steering gears from a motor-gearbox mounted on top. This gearbox is the subject of this paper. Furthermore, each pod has its own combination of passive and active suspension. The active part allows for adjusting the chassis height, including lowering it to the ground for easy egress of the astronauts, and easier loading and unloading of cargo.

The vehicle can be operated by an on-board astronaut (Fig. 1), a remote astronaut (possibly while stationed in a lunar habitat), or remotely from earth. Some limited autonomous operation is also likely. The prototype has been demonstrated with an astronaut operation station. A suited astronaut stands on a platform which holds the operator controls, an instrument panel, and a surround railing for astronaut safety. This entire structure, controlled by the astronaut, rotates to provide the full range of visibility that a constraining suit would not otherwise easily allow.

Figure 1. Chariot with Astronaut Operation Pod (Dec-07)

Figure 2. Chariot Wheel Pods

More recently, the Chariot has been outfitted with a pressurized crew cabin that occupies most of the available mounting space. In this configuration, the vehicle is called the Lunar Electric Rover (LER). The cabin allows for shirt-sleeve operation for up to four astronauts, and includes berthing for extended occupations of up to 14 days (Fig. 3, 12, 14). Normal access to the cabin is through a door on one side of the cabin. Using Chariot's sideways crab motion ability, the cabin door can be 'docked' to a mating door, thus maintaining a pressurized environment.

There are two externally mounted lunar walking suits located on the back side of the cabin. By way of clever "suit ports", an astronaut can enter and occupy either suit from inside the cabin, and become sealed-off and disconnected from the cabin, all with no help. Following the completion of their extraterrestrial activities, the astronaut can return to the cabin using the reverse procedure. This system is intended to minimize the invasive moon regolith from entering the pressurized volume.

Figure 3. LER Starboard Center Wheel Pod with New Gearbox

The Original Gearbox

As already mentioned, one gearbox on each pod drives the differential that turns both wheels. The original gearbox was designed and built around readily purchased off-the-shelf gears, bearings, electric clutches, and shafting. The design utilizes a total of 12 gears, 17 bearings, and 7 different shafts (Fig. 4). The design also incorporates an electric brake that prevents motion when it is de-energized, and an RPM encoder. Two selectable speed ratios are provided. The low speed provides a 16:1 gear reduction for a vehicle speed of about 4.8 km/hr (3 mph), while the high speed provides a 4:1 gear reduction for a vehicle top speed of 19 km/hr (12 mph). The speed selection is accomplished with two electric clutches.

Two concurrently operating electric motors drive the first large gear, both to generate adequate power and for motor redundancy (Fig. 5). The motors used are rated for 300 VDC, and each one draws up to 8 amps to produce 2.1 kW (2.8 hp) at peak efficiency. The resulting gearbox works very well, and is still in use on the LER prototypes today.

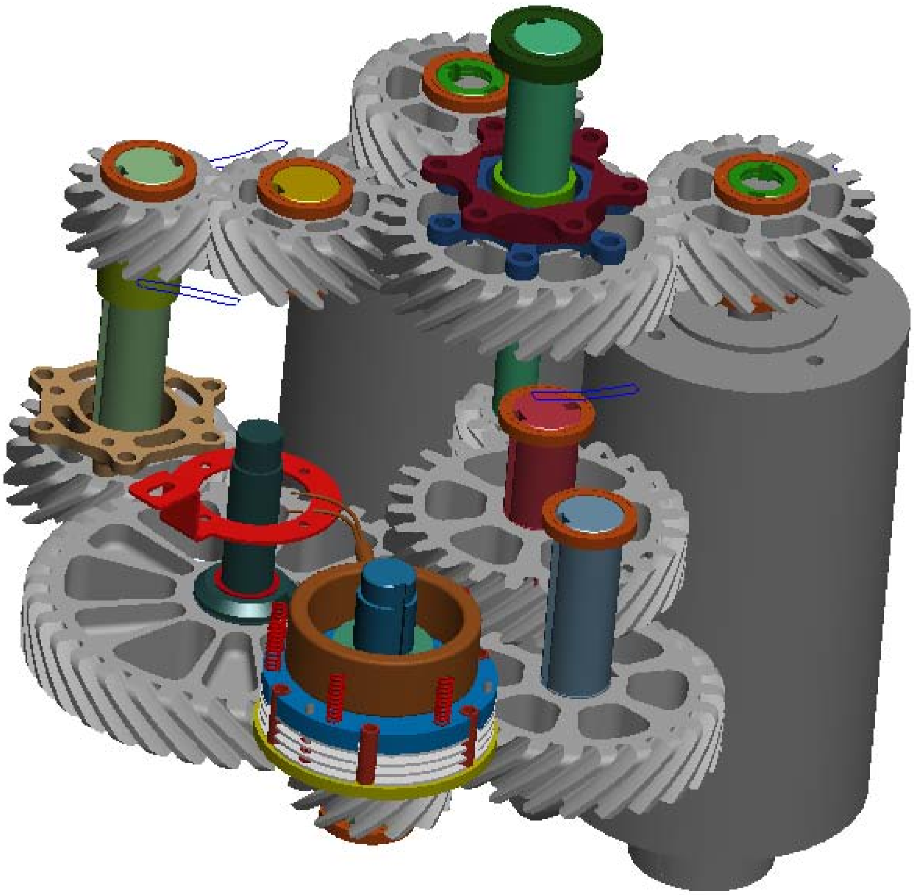

Figure 4. Illustration, Original Gearbox Gear Train

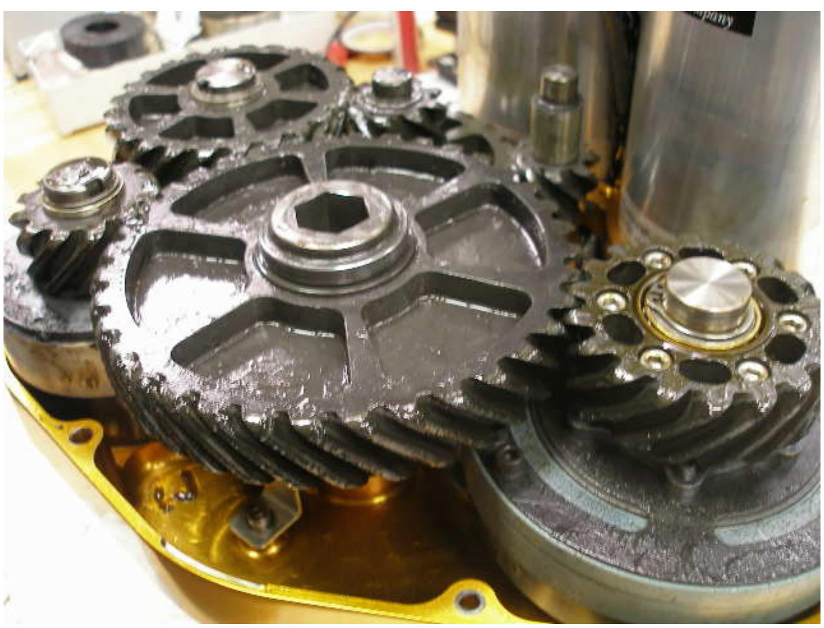

Figure 5. Original Gearbox, Lid Removed

Second Generation Gearbox, Concept

The design goal for the new gearbox was to provide a configuration which would be better suited to send to the moon. By using helicopter-grade gearing, the new design would have fewer gears, and be both smaller and lighter.

Drive Train Design

Reducing the number of gears inherently requires that each meshing gear pair accomplish more of a gear reduction than might be possible or practical when constrained by the use of catalog gears. The original design used off-the-shelf gears to meet the time and budget constraints for the fabrication of the original gearboxes. For the second generation gearbox, after considering many different gearing configurations, the simplest approach that still met the speed range criteria was adopted. Custom-made high-strength gears allowed the use of fewer (7 instead of 12) and lighter gears. Also, the gear train consists of just two parallel axes, resulting in fewer shafts (3 instead of 7) and bearings (13 instead of 17). Two electric clutches, similar to those in the original gearbox, were mounted in series on the same shaft (Fig. 6). This also allows the gear casing profile to be reduced in size, thus contributing to making a more compact and lighter final product.

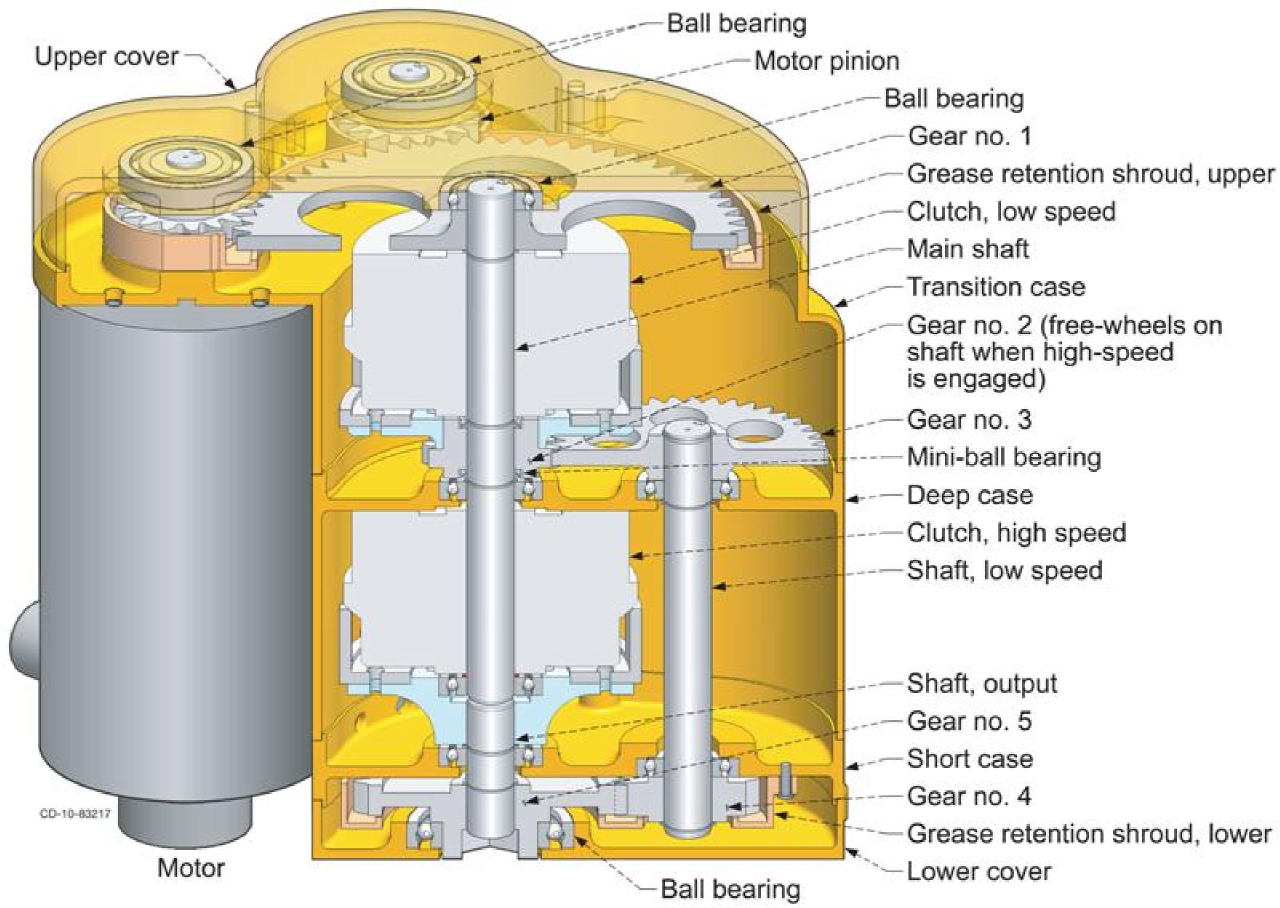

Figure 6. Chariot Gearbox Cross-Section Labeled Illustration

Like the original gearbox, the two motors both mount into their own stub shafts which are supported at both ends by ball bearings, and have integral gear pinions. This allows for the motors to be installed or removed from the assembly without opening the gearbox. Also like the original gearbox, both motors drive the same gear, but in this gearbox design, the gear must be quite large in order to achieve an immediate gear reduction of 3.94. This gear drives the main shaft which extends vertically down and drives both the low and high-speed electric clutches. When high speed is required, the low speed clutch is disengaged and the high-speed clutch is engaged. This causes the main shaft to drive the output shaft, which is located at the end of the main shaft, and gear #5. The output shaft is supported by its own bearings, one on the shaft and the other on gear #5. Gear #5 includes the female hex which is the output of the gearbox. It mates to the existing shaft hex that protrudes above the gearbox mounting plate atop the steering box of the wheel pod. Conversely, when low speed is required, the low-speed clutch is engaged and the high-speed clutch is disengaged. This causes gear #2 on the end of the low-speed clutch to drive the low-speed shaft via gear #3, and gear #4 then drives gear #5 on the output shaft and with an additional 4.1 gear reduction for a total low speed gear reduction of 16.14:1. When in high speed, gear #2 is back-driven by gear #3 and #4 and spins relative to the main shaft on its own mini-ball bearings.

Various gear sizes and pitches were considered until the final design was adopted and the exact gear ratios were established (Fig. 7). Given these, the various low and high output speeds, torques, and power were calculated for each of the motor characteristics of top speed, peak efficiency and peak power. This data was then used to select the electric clutches, mainly based on their torque capability, a maximum of 95 N-m (70 lb-ft). For high speed, this torque represents the gearbox output torque limit because the clutch is acting directly on the output shaft. For low speed, the additional gear speed reduction of 4.1 results in an output torque capability of 389 N-m (287 lb-ft).

Gearing

Gearbox Plane	Gear Pitch	lesser face width (mm)	lesser face width (in)	Gear #	no. of Teeth	Gear #	no. of Teeth	Reduction	low speed reduction
Upper	8	6.4	0.25	0	16	1	63	3.938	
Center	10	6.6	0.26	2	20	3	42	2.100	2.100
Lower	10	13	0.51	4	21	5	41	1.952	x 1.952
									4.100

Output	Reduction
High Speed	3.938
	x 4.100
Low Speed	16.144

Motors and Gearing

Motor: Magmotor/SatCon Product no: 730420001

Motor	Torque				Speeds			Power
	One Motor N-m	2 X motor N-m	High Speed N-m	Low Speed N-m	motor rpm	High Speed rpm	Low Speed rpm	watts
Top speed	0.0 (0.0 lb-ft)	0.0 (0.0 lb-ft)	0.0 (0.0 lb-ft)	0.0 (0.0 lb-ft)	2439	619	151	0 (0 hp)
max efficient	9.18 (6.77 lb-ft)	18.34 (13.54 lb-ft)	72.3 (53.3 lb-ft)	296.4 (218.6 lb-ft)	2185	555	135	4202 (5.63 hp)
peak power	28.24 (20.83 lb-ft)	56.5 (41.7 lb-ft)	222.4 (164.0 lb-ft)	911.9 (672.5 lb-ft)	1657	421	103	9805 (13.15 hp)
stall	88.10 (64.98 lb-ft)	176.2 (130.0 lb-ft)	693.8 (511.7 lb-ft)	2844.6 (2098.0 lb-ft)	0	0	0	0 (0 hp)
					Approx. motor speed at clutch torque maximums			
Clutch static maximums:			95 (70 lb-ft)	389 (287 lb-ft)	2105.4	535	130	5314.4 (7.127 hp)

Figure 7. Chariot Gearbox – Gear Ratios and Torques, Speeds, Power

The motor speed was approximated being loaded to these torque limits, and this was used to estimate the maximum low and high-speed output RPM and power-out before either clutch would be expected to begin slipping. If a clutch should start to slip, the output power would drop dramatically because the slipping friction of the plates would provide a much lower output torque. This could also damage the clutch because it is not designed to slip for long periods, or to dissipate the resulting heat. Currently, the power to the drive motors of the Chariot control system should not provide enough current to the motors to exceed the clutches' torque rating.

Gears

The gear teeth pitch and face widths were selected based on the anticipated operational loads and speeds. Traditional formulas were used to calculate gear tooth stresses, and to help decide the required gear pitch and face width. The width of the smallest of the two meshing gears at all three gear meshing planes is 1.5 mm (0.06 in) larger, which allows the gears to tolerate some axial misalignment due to dimensional tolerance stack-ups during assembly. The smaller gear was selected to have the larger width in order to keep the overall weight minimized, and to bolster wear duration of the faster turning gear. For example, while the large gear #1 has a face width of only 6.4 mm (0.25 in), which is enough from a gear tooth-strength standpoint, both motor pinions have a face width of 7.9 mm (0.31 in) to ensure that, after final assembly, the entire 6.4-mm (0.25-in) width of gear #1 is engaged. Similarly, gear #2 has a larger face width than gear #3, and gear #4 is larger than gear #5. Also, both gear #1 and #3 are large enough to be lightened-up by the addition of a pattern of holes, again in an attempt to minimize the weight of the final product. The gears are designed to helicopter-grade quality, or an American Gear Manufacturers Association (AGMA) gear tolerance Class 12.

Casing Design

It was a design goal for the case to shroud the gears as tightly as possible to minimize both the size and weight of the final product. It should be noted again that for compatibility, the same motors as used in the original gearbox were also used in the second generation gearbox. Due to time constraints, commercial off-the-shelf clutches were used that were very similar in size and capability to those in the original gearbox. Although the main drive gears were sized and optimized for minimum weight, the overall gearbox size was largely dictated by the size of the motors and clutches. Slightly taller than the original, the new gearbox is not nearly as broad, and is therefore smaller and lighter. Considerable effort went into fine-tuning the gearbox design so that the mounted height of the motors would only be slightly above the mounting plate (Fig. 8).

A stacked-component approach was used in the design of the case. This helped keep the size profile minimized because it allowed the top gear plane, with the two motor pinions and large gear, to be shrouded closely by way of the Top Cover before transitioning to the majority smaller profile required for the main body which encompasses the rest of the gears and both electric clutches (Fig. 6). A total of five parts make up the complete case: The Upper Cover, Transition Case, Deep Case, Short Case, and Lower Cover. Having a multi-part casing also reduced the machining risk on each separate part. The fit between all parts was kept flat (planar) for machining simplicity.

There was no seal designed between the casing interfaces. Like the original gearbox, no oil containment was required because grease lubrication was planned. However, a full perimeter lip was designed into the face-fits between each casing part. This serves to hold the required relative positioning between each of the casing parts for shaft and bearing alignments, and to make assembly easier. It also serves as a partial seal to help keep dirt out, and extraneous grease in. The final wall thicknesses were determined in part through the limited use of finite element analysis. The analysis indicated that the casing thicknesses could have been reduced further, but 3.18-mm (0.125-in) thickness for most of the walls was determined to be the minimum from a standpoint of machining comfort, stiffness, and warpage concerns.

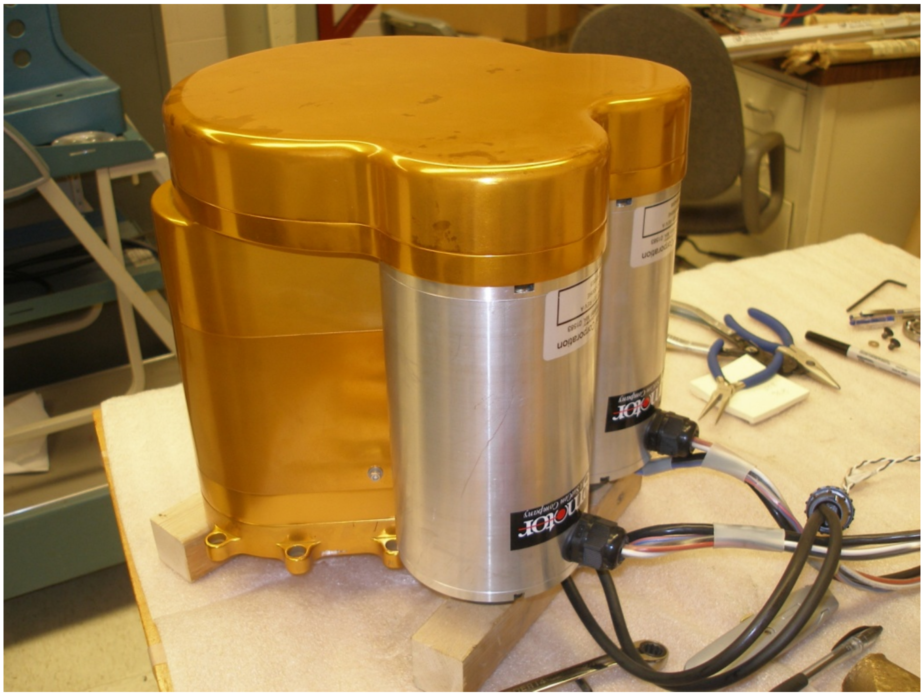

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Figure 8. New Gearbox on Bench

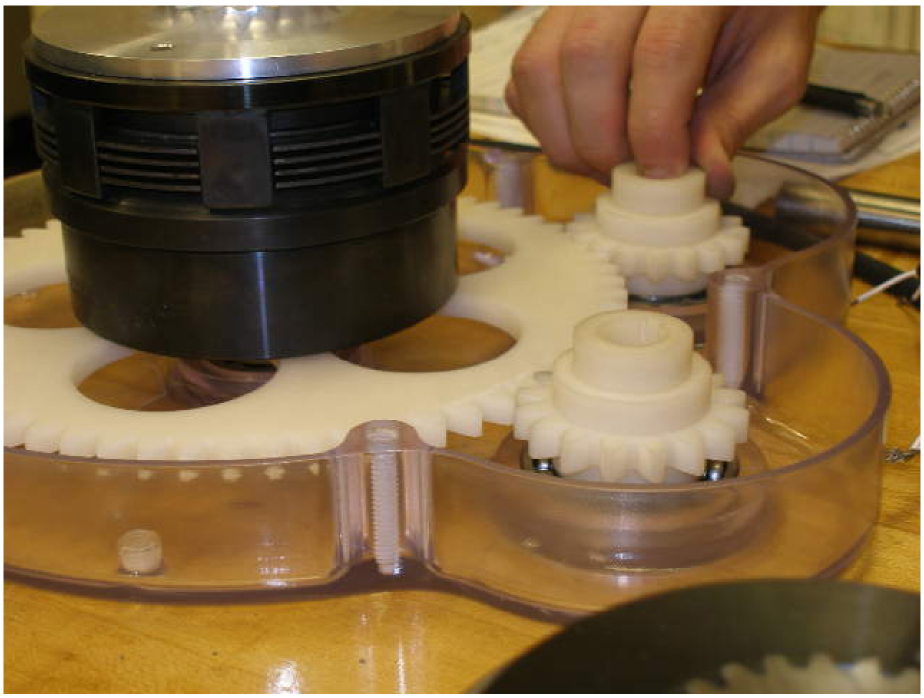

Figure 9. Rapid Prototype Gears in Clear RP Lid

Rapid prototypes (RP) were made of all the casing parts and gears before the design was finalized (Fig. 9) to allow for practicing the assembly sequence. The transparent casing parts were helpful during the trial assemblies. Some important changes to the final case design details resulted, and a detailed assembly procedure was initiated.

Grease Retention Shrouds

Enclosures around the gears were added to help hold the applied grease close to the teeth to extend the re-grease service lengths. Referred to as grease retention shrouds (GRS), similar enclosures have been used in certain commercial products such as heavy-duty hand drills. Of the three gear meshing planes of the design, a GRS was designed for two of them; the upper area where the two motor pinions engage gear #1 (Fig. 10), and at the lower output end where the low speed gear #4 engages with the output gear #5. The center gear plane of gear #2 and #3 was not shrouded because it would have made final assembly difficult, and the space between gear #3 and the housing was prohibitively small.

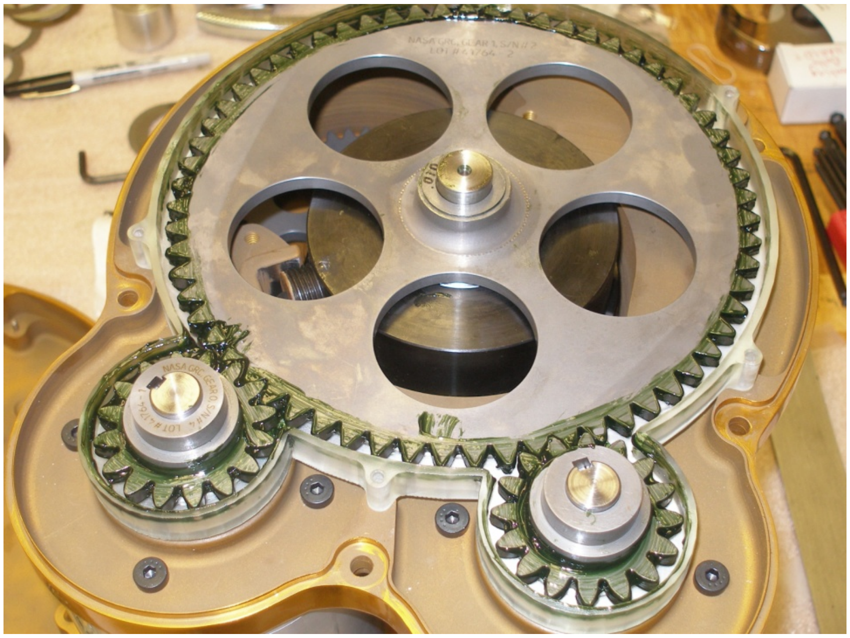

Figure 10. New Gearbox, Motor Pinions and Gear #1, with GRS

For quick and inexpensive fabrication, the GRS's were made by rapid prototyping. Exposure tests were conducted using coupons of three different RP materials and two kinds of grease because of concern whether commonly available RP materials might degrade when in contact with the anticipated hydrocarbon based greases. The results indicated that the material used by a laser stereolithography machine showed excellent property resistance to the grease exposure, therefore, work continued using the same material and process.

The Lower GRS is positioned over gears #4 and #5, and is screwed to the Short Case. This occurs just before the Lower Cover is installed and the lower four case parts are fastened (sandwiched) together by long screws. The Upper GRS was originally designed similarly, to be screwed to the Upper Cover, because this worked well with the topside-down order of assembly that is used. However, as a result of trial practice assemblies with the rapid prototype case, it was demonstrated that there is a great advantage in being able to remove the Upper Cover after the gearbox assembly was otherwise complete.

Removing the Upper Cover is the only way that, after the assembly is otherwise complete, a final check of whether the top gear meshing plane of gear #1 to the motor pinions is adequately centered (usually done by way of adding shaft shims). The Upper Cover is fastened on separately from the other four casing parts, making its post-assembly removal possible. Removal of the Upper Cover also serves as a convenient way to grease the gears initially, and to occasionally inspect the area for grease distribution and gear wear. The motors can even be run with this cover off, although only slowly and unloaded because all three shafts are not properly supported since their secondary support bearings are pressed into the Upper Cover.

With the GRS screwed to the Upper Cover, removing this cover required that the motor pinions and Gear #1 also come off, trapped and pulled by the GRS. While this is theoretically possible, in practice, these gears usually do not remove easily, and since the GRS is not very strong, it could easily break while attempting this. Therefore, instead of using screws, the design was changed so that holes in the GRS would fit onto pins from the case. Because it was desired to either remove the Upper Case and have the GRS remain in place on the Transition Case, or during initial assembly, place the GRS on the Upper Case and add the Transition Case to it, locating pins were provided on both cases (Fig. 11). Supports were designed into both case parts to help hold the GRS in its final trapped position, although a precise final position is actually not required. This approach appeared to work well.

Figure 11. New Gearbox, Lid Removed

Gearbox Fabrication and Assembly

Two functional gearboxes of the same design were fabricated in-house and assembled. One was ultimately adapted and mounted to the Chariot prototype while the other was kept for dynamics testing and modeling. A combination of 6061 and 7075 aluminum alloys were used due to their availability in the required starting stock sizes, and since either one suited the structural needs of the housing. The end result was that the Upper Cover, Transition Case and Deep Case were made of 7075, while the Short Case, Lower Cover, and the later Adapter Spacers were made of 6061.

Three case parts were primarily machined using a CNC 2-axis milling machine, while two were completed on a more sophisticated CNC machine that directly used the solid model data. After all five parts were close to completion, the assembly was placed into a boring machine to accurately locate and precisely precision machine the bearing pockets. Two additional parts were designed to allow the gearbox to easily adapt to Chariot; a new steering-box top plate on which the gearbox mounts, and a spacing plate to raise the mounted height of the new gearbox to accommodate the more shallow mating female hex.

The “Assembly Procedure” that was developed during trial assemblies with the RP casings was used for assembly, but with many changes and a great deal more added detail. One of the main lessons learned during the build was the need to pay attention to how the gears were to be axially aligned. Shaft shims were used to accomplish the aligning, but decisions of how to determine the shim size, what measurements were needed, and in what order to perform all the operations proved to be a challenge. Although the final assembly procedure does capture the process very well, it was more time consuming than originally thought.

Conclusions, Gearbox Mounted to Chariot

The new gearbox was completed and mounted on the center starboard pod of the Chariot, in LER form, for an inaugural drive (Fig. 3, 12-15). Software adjustments within the Chariot main drive controller were required to accommodate the slightly different gear ratio outputs. Also, the motor forward and reverse functions, due to the different gearing, had to be swapped for the High Speed function to work correctly. Beyond these issues, the gearbox appears to have operated well.

Figure 12. Chariot in LER Form, Starboard Center Wheel Pod with New Gearbox

Figure 13. LER Starboard Center Wheel Pod, New Gearbox Close-up

Figure 14. LER with New Gearbox Climbing a Steep Grade

Lessons Learned

1. Document the complete “Design Requirements” early, and revisit them regularly. While the project intent was to supply a smaller, lighter “drop-in replacement” gearbox with all the capabilities of the original, in the casing design process, both the rotary encoder and electric brake were dropped. JSC agreed to allow us to not provide these features, since they use the encoders integral to the motors, and not every gearbox has to have an electric brake.

2. While assembly is one thing, serviceability is quite another. Although it was possible to fully assemble the gearbox as designed, it would be highly beneficial if the Upper Cover could be removed without disassembling most of the unit. This led to an alteration in the way the Upper GRS was secured, allowing removal of just the Upper Cover.

3. Even in high precision work, account for tolerance stack-up by design. For instance, leave room on drive axles for spacing shims. Given the tolerance stack-up of any gearbox assembly, shims may be needed.

4. When possible, build contingency time into the schedule. Even in-house manufacturing shops may miss an estimated completion date, or number of hours to completion, as occurred with the gearbox casing parts. Due to Constellation Program driven priorities, the in-house shop started in August 2008 and was to be complete in October, but was not completed until December.

5. When schedule and budget allow, particularly for “high visibility” activities, minor resources devoted to “quality finish” of a product can be beneficial. Not all viewers appreciate seeing the “engineering details” hanging out. In this case, in order to match the original parts' finish, the original gearbox anodizing vendor was utilized after local vendors proved unable to match the required polished color finish.

Summary

A second generation “drop-in replacement” gearbox was designed and built for the concept vehicle called Chariot. State-of-the-art aerospace gear design and manufacturing practice were taken advantage of to produce optimally light weight gear sets, which were incorporated into a smaller, lighter gearbox with otherwise conventional components. The “lessons learned” in this gearbox build are broadly applicable.