

DEVELOPMENT AND TESTING OF MECHANISM TECHNOLOGY FOR SPACE EXPLORATION IN EXTREME ENVIRONMENTS

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ABSTRACT

The NASA Jet Propulsion Lab (JPL), Glenn Research Center (GRC), Langley Research Center (LaRC), and Aeroflex, Inc. have partnered to develop and test actuator hardware that will survive the stringent environment of the moon, and which can also be leveraged for other challenging space exploration missions. Prototype actuators have been built and tested in a unique low temperature test bed with motor interface temperatures as low as 14 degrees Kelvin. Several years of work have resulted in specialized electro-mechanical hardware to survive extreme space exploration environments, a test program that verifies and finds limitations of the designs at extreme temperatures, and a growing knowledge base that can be leveraged by future space exploration missions.

1. INTRODUCTION

Exploring space beyond low Earth orbit presents many challenges for hardware. Hostile environments with extreme temperatures, radiation, and abrasive contamination await many of these missions. Most of these missions will utilize electromechanical systems for science, communications, mobility, and many other foundation operations that are required to operate in order to achieve mission success. The state of practice for these systems has often been wet lubrication such as grease or oils for gears and bearings. Heaters are needed to maintain these system components above critical temperatures that would cause lubricant freezing, even when these systems are not being utilized. However, this thermal protection results in mass and power penalties for the spacecraft, and adds another potential area for failure resulting in higher spacecraft complexity. The end result is heavier mission hardware and decreased mission reliability.

JPL, GRC, LaRC, and Aeroflex have combined efforts to develop improved systems that address these weaknesses, using a systems approach with goals of revolutionizing the design of next generation space systems in the area of motors, drive electronics,

gearboxes, seals and dry lubricants [1]. The benefits of this effort can be realized in reduced spacecraft power and battery requirements, reduced actuator mass, enhanced actuator performance over a wide temperature range, reduced wiring, enhanced modularity and scalability, and simplified system verification.

The environmental focus of this development was the lunar surface. In fact, the hostile environment of the moon presents as much or more of an operational challenge as any other local space environment. Due to the absence of atmosphere, the temperature varies significantly and the abrasive lunar regolith provides a challenge for mechanical systems. The temperature is expected to vary from -240 Celsius (C) to 120 C, depending on the location and time of lunar day. Also, due to the large monetary investment in exploration hardware and the difficulty in placing it on the lunar surface, it is expected that the hardware should have an operational life of at least five years. For lunar mobility solutions, this can translate into millions of revolutions on the mechanical drive train. For purposes of our development program, 450 million cycles was selected as the overall goal for life in order to meet these needs which were derived from a 10,000 km traverse life of a lunar rover. However, it was also decided that a minimum threshold of 30 million cycles was necessary for the hardware to be useful for any mission.

Some of the more demanding applications for these electromechanical systems are shown in Figure 1. These systems include robotic and manned rovers and their corresponding drive systems as well as robotic crane type systems. The actuator needs for these systems are expected to vary in size but may extend up to large 3 hp actuators. The operation of many of these planned vehicles in a lunar regolith environment will result in extensive exposure of some actuators to the abrasive soil. Therefore these devices will need to be insensitive to contamination by either preventing the migration of contamination into sensitive components or by tolerance of the system to the contamination.

All of these environmental and application challenges were used to form the foundation of our development effort and drive the goals which we are trying to achieve.



Figure 1. Lunar mobility systems which could utilize extreme environment actuators.

2. EXTREME ENVIRONMENT ACTUATORS

There are many possible areas of development that would be useful for mechanisms that are to be used in extreme environments. However, faced with a limited budget and a lack of firm user requirements, it was necessary to focus on a core technology that provides the most benefit for the adopters of the technology. For this reason, one of the primary focus areas of our technology development was in the area of extreme environment actuators. Actuators provide the core of any mechanism. Motor and gearbox combinations are by far the most common actuators used for flight mechanism applications. The goal of the effort was to develop a flexible and scalable foundation motor/gearbox combination that can be utilized by many exploration users.

An incremental development philosophy was used to mitigate risks associated with development, isolate independent variables and to spread development costs out over a longer period of time. This incremental development philosophy resulted in a series of planned development units, each building on the previous successful achievements. To date, two development actuators have been built and tested which have been labeled as LTM0 and LTM1 with LTM1 incorporating more technology features and expanding the operational features over LTM0. These will be discussed in the following sections.

2.1 Motor and Gearbox

The brushless dc motor offers several benefits over stepper and brush motors. Brush motors do not last long in a vacuum environment due to arcing across the brushes. Brushless dc motors are capable of higher speeds compared to stepper motors. This higher speed results in higher power in a more compact package. Also, because the brushless dc motors vary current and speed with load, they can operate at a higher efficiency than steppers. Stepper motors have to continually operate at a current that represents the highest torque even when that torque is not present. Brushless dc motors do have the weakness of requiring a sensor for the commutation. However, in the event of a sensor

failure, brushless dc motors can be “stepped” and essentially can be converted into stepper motors if needed. For all of these reasons, a brushless dc motor is the most flexible motor and has been the primary focus of our development effort for exploration applications.

For the majority of actuators, a gearbox is needed to increase motor torque and decrease the rotary speed of the motor. Most actuator applications in space require only slow speeds in order to control disturbances and to minimize dynamic effects. A planetary gearbox is the best solution for wide temperature application due to the simplicity and robustness of the design. Harmonic gearboxes are also popular for flight applications due to the high ratios possible in a mass efficient package but life concerns at very low temperatures precluded the selection of this gearbox technology for our program. Planetary gearboxes also offer flexibility because the stages can be stacked to provide increasing ratios of speed and torque, thus resulting in a scalable and flexible system in which to build upon.

Because actuators are the prime movers in a system, they would be expected to be in locations that could be subjected to the full extremes of the local environment. For a lunar focus in development, the temperature could vary from -230C to 120C. In order to operate at these temperatures, dry film lubrication is required to prevent freeze-up at low temperatures. Wet lubricants such as greases and oils typically are only rated for use down to around -50 C depending on the manufacturer. Using dry film lubricants in motors and gearboxes is not new technology and cryogenic motors and gearboxes have been built before. However, a major concern is the life of the dry film lubrication since it cannot typically be replenished during operation. Therefore, a major emphasis of this effort has been to determine and verify life as well as performance in extreme environments. The life goal derived from possible mobility solutions for lunar exploration was to achieve a minimum of 30 million motor revolutions and a desired life of 450 million revolutions at temperature extremes of at least -250 to +120 degrees Celsius (C).

For both LTM0 and LTM1, Mars Science Laboratory (MSL) technology was used as a foundation to build upon. A 100 watt brushless dc motor design was selected that was developed by Aeroflex and used for the MSL wheel steering. One significant design change compared to the final MSL product was the exclusive use of dry film lubrication in the bearings to enable it to operate at significantly lower temperatures. In order to reduce evaluation variables for the LTM0 gearbox, a single stage 4:1 planetary gearbox was chosen as the design for the first generation prototype and was initially to be based off of MSL technology as well. Because of development issues and subsequent design changes for the MSL gearbox, a custom gearbox was designed by Aeroflex for our cryogenic application. This gearbox was dry film lubricated for operation at extreme temperatures and designed to

achieve a maximum possible lifetime. This is one significant change compared to other previous cryogenic actuator designs. A nother significant difference is the ability to operate at cryogenic temperatures and at temperatures up to 120C. After a successful test program with LTM0, LTM1 was built. The LTM1 gearbox ratio was increased by adding two additional 4:1 stages for a total ratio of 64:1. LTM1 complexity was also increased by adding a dust seal which was designed for lunar regolith and an improved resolver which will be discussed in the following section. LTM0 and LTM1 are shown in Figure 2 and Figure 3. Figure 4 shows the sub components of LTM1. The end goal of this actuator development program is to test and verify this technology in high power actuators up to 3 horsepower (hp).



Figure 4. Sub components of LTM1.



Figure 2. LTM0: First generation extreme environment actuator built by Aeroflex, Inc.



Figure 3. LTM1: 2nd generation extreme environment actuator built by Aeroflex, Inc

2.3 Resolver

Due to limited funding, a “commercial off-the shelf” (COTS) Tamagawa bearing-less resolver was used for the motor commutation for LTM0. The selected sensor offered several benefits, as it is a very compact and low mass design. It also is bearing-less with no mechanical failure points if properly installed and was a very cost effective resolver for use in a development effort.

The major disadvantage of this resolver was the unproven operation. In the course of testing, the manufacturer’s temperature specifications were far exceeded. V ery low temperatures resulted in the necessity to operate it outside of its specified limits.

Testing did prove that this COTS resolver was able to operate far below its specified limits but could not operate all the way down repeatedly to -230C without failure. Fortunately, the resolver operated well at the -180C temperature which was the normal operating temperature of the motor during testing. During the course of life testing, several resolvers failed, and a failure investigation was conducted. S ubsequent inspections revealed that the adhesive encapsulating the wiring windings had failed, most likely from thermal expansion mismatch and due to the material becoming brittle at very low temperatures. The failure of this adhesive resulted in a break of the very small diameter winding wire, as shown in Figure 5.

Due to limited funding for the development effort, it was not possible to obtain a temperature rated resolver, but realizing the potential of the Tamagawa resolver, the manufacturer was contacted regarding the failures. As a result of information shared with the manufacturer, they were able to provide a d esign change which should improve upon the temperature range. New resolvers have been built and incorporated with LTM1. Testing to date has resulted in no resolver failures.

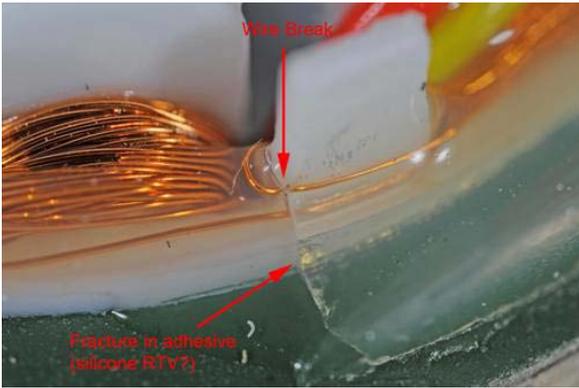


Figure 5. Optical micrograph of resolver wire break location.

3. TEST PROGRAM

3.1 Test objectives

Knowing that the actuator under development would have a limited life due to dry film lubrication and that planned missions required a very long life, test emphasis was placed on life testing. However, very little was known about the requirements of load and motion which would usually be used to develop the test plan. In the absence of these firm requirements, a generic test plan was developed that could determine life without being too stringent but also provide a point of comparison for future missions assessing the compatibility for the technology. The test schedule shown in Table 1 was developed to meet this need. This test plan increases the test severity as the life test progresses until failure is achieved.

Table 1.

	Description	Duration
Phase I	Counterclockwise (CCW) rotation at maximum torque and speed @ -180C	30 million revs at motor
Phase II	Clockwise (CW) rotation at maximum torque and speed @ -180C	30 million revs at motor
Phase III	Alternating CCW and CW motion at maximum torque and speed (5 minutes each) @-180C	30 million revs at motor
Phase IV	Positional loop: ¼ rev at output (1 rev at motor) at maximum torque @ -180C	1 million revs at motor
Phase V	Hot test at +120C at maximum torque and speed, alternating CW and CCW motion every 5 minutes	30 million revs at motor
Repeat from beginning		Repeat until failure

3.2 Test Platform

At the beginning of the effort, it was realized that a dedicated test platform was needed for extended life testing due to the length and uniqueness of the planned testing. A test chamber was needed that could provide interface temperatures down to 40 Kelvin for extended periods of time while providing a torque loading for the actuator. Using consumable liquid helium for cooling would be cost prohibited and liquid nitrogen would not provide a low enough temperature (77 Kelvin). Therefore, a test platform consisting of two integrated cryocoolers was designed and built. This test platform and chamber is shown in Figure 6. Figure 7 shows LTM1 being installed in the chamber and being prepared for performance and life testing



Figure 6. Low temperature life test platform

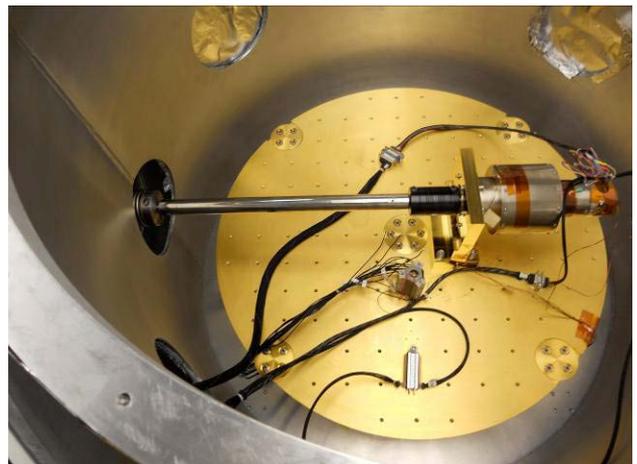


Figure 7. LTM1 being prepared for life testing in the low temperature life test chamber.

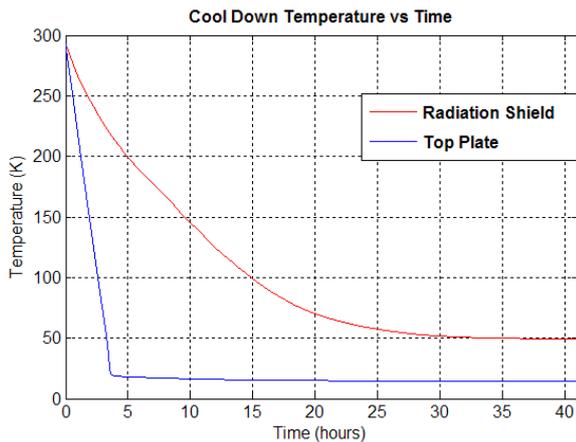


Figure 8. Temperature performance of low temperature life test chamber.

The cryocoolers provide a total cooling capacity of 90 watts at 40 Kelvin. One cryocooler is attached to an insulated radiation shield which provides a cold radiation environment for the test article. The remaining cryocooler is attached to a cold plate to which the test article is attached. This cold plate has consistently reached temperatures of 14 to 20 Kelvin during our testing. Figure 8 shows the temperature performance curve for the chamber. The test platform only requires power to operate and is very cost effective for long term operation. The test set-up also includes dynamometers to provide torque loading to the actuators during operation and a National Instruments system for data acquisition and hardware control. The entire operation of the life testing has been automated such that very little oversight is required during the 24 hour operation for 7 days a week.

3.3 Characterization methods

During long term life testing, it was expected that the actuator would degrade gradually over a long period of time. Capturing and recording this degradation was a priority of the testing. It was expected that the available actuator torque would decrease over time due to increasing inefficiencies in the gearbox and bearings as life testing progressed. Because the speed and current varied with motor load, it would be expected that the current would increase and the speed would decrease for a given output load as the actuator reached the end of its life. Fortunately, we were able to monitor these variables using the motor controller designed and built by JPL for the MSL program. However, it was previously known that these measurements can be rather insensitive to small torque changes, particularly at the output of the gearbox which is affected by a torque multiplication. Additional characterization methods were needed to provide additional insight. These separate characterizations tests were conducted by stopping the life testing at selected points and doing a characterization. These tests included performance tests that included operation

with an actuator torque load and without an actuator load. The data from these characterization tests could be compared as the test progresses to monitor changes. A third and very unique characterization test involved back driving of the actuator through a torque transducer. This test provided information from a different perspective as compared to the motor. This provided direct information from the gearbox which provided clues about gearbox wear.

For LTM0, an additional step was taken of inspecting the unit at regular intervals during the testing. It was not practical to inspect the motor and bearings without substantially altering the test article but the gearbox was partially disassembled to provide additional information about how the life progressed. The inspection was limited to non-destructive techniques such as dowel measurements of gear teeth and microscope inspection but the additional information was very valuable in assessing how the gear lubrication was wearing. Figure 9 shows a view of the gears after 30 million revs. The surfaces are still in excellent condition.

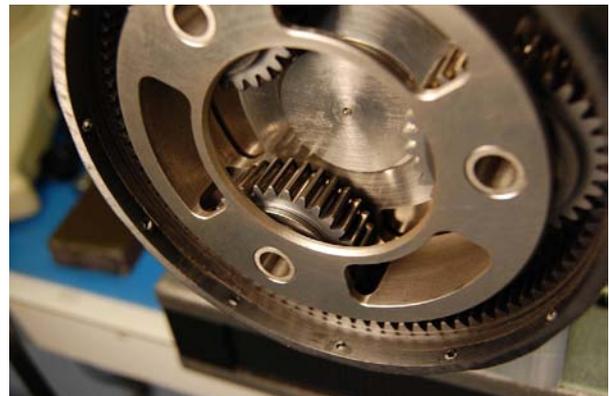


Figure 9. LTM0 gearbox during inspection after 30 million revs (at motor)

4. RESULTS

Testing began for LTM0 with just the motor and resolver and without the gearbox. This provided more insight as to what was happening at the motor at low temperatures down to -230C. These series of tests were successful and the results are shown by the torque-speed-current curve in Figure 10.

This data shows the motor actually becomes more efficient at a low temperature and the speed does not drop off as much for increasing torques as at ambient temperatures. The reason is that the resistance drops in the motor windings at cryogenic temperatures and the magnetic process becomes more efficient.

Next, the motor/resolver and gearbox were integrated and the life test program started for LTM0. The prototype actuator (or motor, gearbox and sensor combination) successfully operated at interface environmental temperatures down to as low as -256 degrees Celsius and also at 120 degrees Celsius. Due to the thermal conductance between the gearbox mounting interface and the motor housing, it was

actually difficult to maintain the motor at a reasonably low temperature, and duty cycling was utilized in order to keep the motor cold. Since the motor was initially designed for Mars, it was designed to be lightweight and employed titanium as a material. However, titanium is a poor conductor of heat and contributed to the thermal resistance of the actuator. Due to this thermal performance issue, the motor test temperature was around -180 C for the majority of the life testing, even with duty cycling of 15 minutes of cool down for 5 minutes of operation. For low temperature environments, it could be a good idea to build thermal resistance into your actuator in order for the actuator to self heat better in those cold environments. However, additional problems could be caused such as detrimental thermal gradients, poor performance in hot environments, and thermal noise issues if used in the vicinity of infrared sensors. Many applications will still require cold starts anyway so the unit will still require a low temperature rating. For our testing, it made it difficult to verify components for low temperature operation but was beneficial in keeping our resolver above temperatures of failure.

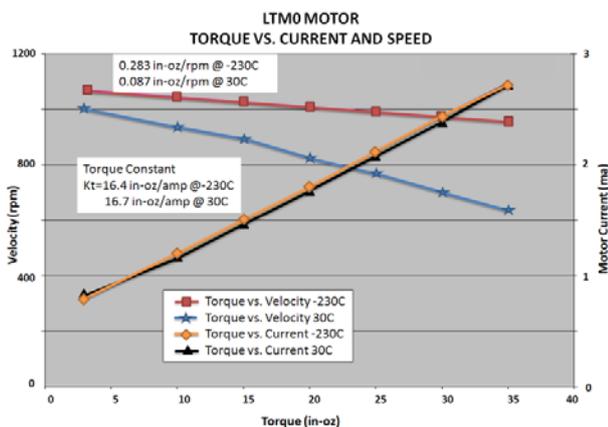


Figure 10. Speed versus torque curve for LTM0 motor at ambient and -230C.

During LTM0 life testing, three inspections were done at approximately 30 million, 60 million and 90 million cycles. During the first 30 million cycles, a significant amount of dry film lubricant material migrated out of the output bearing of the gearbox as shown in Figure 11. The majority of this debris was generated during the initial part of the test program and migrated out of the bearing primarily due to the multiple chamber vacuum pump downs that occurred during the testing. As a result of the life testing, it was found that a reasonable life for our first prototype unit, LTM0, was approximately 130 million revs at the motor, or 32 million revs at the gearbox output. This far surpassed our minimal goal of 30 million cycles, but did not reach our desired goal of 450 million cycles which corresponds to a lunar mobility mission of 6 years. Performance of the actuator was found to be very consistent during life testing until the dry film lubrication failed.

However, it is important to note that the failure was not catastrophic. The end of life was determined by a significant drop in efficiency and inconsistent operation at low speeds. Due to the gear material selection by Aeroflex, it was still possible to operate the actuator even with these decreased efficiencies. Additional testing would be needed to determine how this end of life performance would progress.

LTM1 testing is now underway and is progressing well. The three stage gearbox on LTM1 has added to the thermal resistance issue and resulted in an even longer duty cycle time. The unit now cools for over 30 minutes for every 5 minutes of operation resulting in an average motor temperature of approximately 100 Kelvin even with an interface temperature at or below 20 Kelvin.

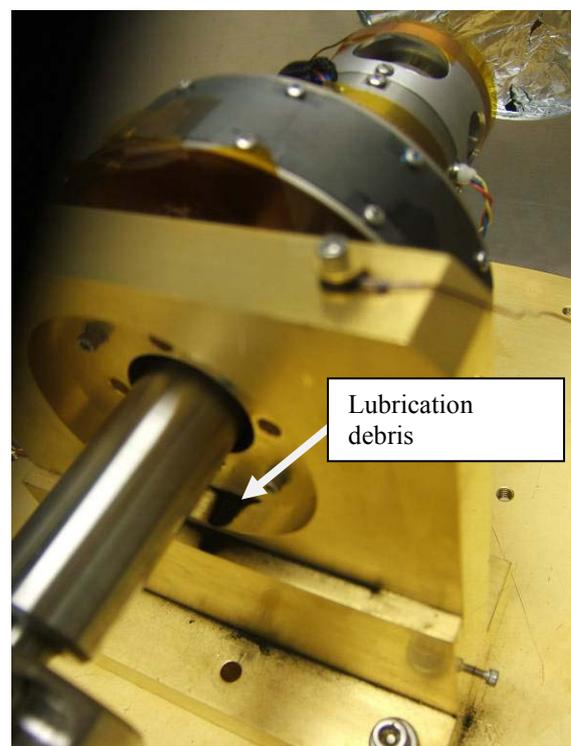


Figure 11. Lubrication debris generated during first 30 million cycles of life test.

5. SUMMARY

Several years of work have resulted in specialized actuator hardware to meet extreme space exploration environments, a verification test history that also identifies design limitations, and a growing knowledge base that can be leveraged by future space exploration missions.

There are limitations that have to be considered when selecting systems for extreme environments. There are life issues to be considered for the mechanical components that operate in extreme environments, but this effort has shown that reasonable lifetimes can be achieved with proper design. For our first generation actuator, 130 million cycles were achieved when

measured at the motor. Unfortunately, these lifetimes may still not rival those of liquid lubricated systems, and this technology may not be adequate for long duration missions without additional development work. Fortunately, this design did not fail catastrophically but would still be able to continue limited operation with reduced efficiency.

Only the first phase of this effort is complete. A second generation Aeroflex actuator is undergoing testing now which builds on the first generation design, but also has a three stage gearbox and a dust seal designed for the abrasive lunar environment. Also, an improved resolver has been integrated with the motor. The end result of this effort should be a family of scalable systems to operate in extreme environments that are reliable and meet the requirements of exploration systems.

6. REFERENCES

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