

Electro-Mechanical Systems for Extreme Space Environments

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Abstract: *Exploration beyond low earth orbit presents challenges for hardware that must operate in extreme environments. The current state of the art is to isolate and provide heating for sensitive hardware in order to survive. However, this protection results in penalties of weight and power for the spacecraft. This is particularly true for electro-mechanical based technology such as electronics, actuators and sensors. Especially when considering distributed electronics, many electro-mechanical systems need to be located in appendage type locations, making it much harder to protect from the extreme environments. The purpose of this paper to describe the advances made in the area of developing electro-mechanical technology to survive these environments with minimal protection.*

The Jet Propulsion Lab (JPL), the Glenn Research Center (GRC), the Langley Research Center (LaRC), and Aeroflex, Inc. over the last few years have worked to develop and test electro-mechanical hardware that will meet the stringent environmental demands of the moon, and which can also be leveraged for other challenging space exploration missions. Prototype actuators and electronics have been built and tested. Brushless DC actuators designed by Aeroflex, Inc have been tested with interface temperatures as low as 14 degrees Kelvin. Testing of the Aeroflex design has shown that a brushless DC motor with a single stage planetary gearbox can operate in low temperature environments for at least 120 million cycles (measured at motor) if long life is considered as part of the design.

A motor control distributed electronics concept developed by JPL was built and operated at temperatures as low as -160C, with many components still operational down to -245C. Testing identified the components not capable of meeting the low temperature goal of -230C. This distributed controller is universal in design with the ability to control different types of motors and read many different types of sensors. The controller form factor was designed to surround or be at the actuator. Communication with the slave controllers is accomplished by a bus, thus limiting the number of wires that must be routed to the extremity locations. Efforts have also been made to increase the power capability of these electronics for the ability to

power and control actuators up to 2.5KW and still meet the environmental challenges.

For commutation and control of the actuator, a resolver was integrated and tested with the actuator. Testing of this resolver demonstrated temperature limitations. Subsequent failure analysis isolated the low temperature failure mechanism and a design solution was negotiated with the manufacturer.

Several years of work have resulted in specialized electro-mechanical hardware to meet extreme space exploration environments, a test history that verifies and finds limitations of the designs and a growing knowledge base that can be leveraged by future space exploration missions.

Keywords: cryogenic actuators; low temperature electronics; extreme environments; exploration systems

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 been centralized electronics, and even wet lubrication such as grease or oils for some gears and bearings. Heaters are needed to maintain these system components above critical temperatures that would cause electronic damage and lubricant freezing, even when these systems are not being utilized. However, this thermal protection results in weight 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, LaRC, GRC, 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. 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, 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 C to 120 C, depending on the location and time of lunar day. Also, due to the large monetary investment in exploration hardware, 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.

Extreme Environment Actuator

As a primary component of our electro-mechanical system for extreme environments, a brushless dc motor coupled to a planetary gearbox was selected, built and tested. This component provides a flexible and scalable foundation for any mechanism design. 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. The 100 watt brushless dc motor used was the same design that was developed by Aeroflex and used for the Mars Science Laboratory (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. 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. In order to reduce evaluation variables, a single stage 4:1 planetary gearbox was chosen

as the design for the first generation prototype. Due to funding issues, an “off-the shelf” Tamagawa bearing-less resolver was used for the commutation signal of the motor. The resolver will be discussed in a subsequent section.

A prototype was built and evaluated as part of this effort. Primary goals of the testing were to determine performance and life of the unit. First, the motor and resolver were tested as a separate pair to measure performance and ensure operation down to -230 C. This test was successful as shown by the torque-speed-current curve in Figure 1.

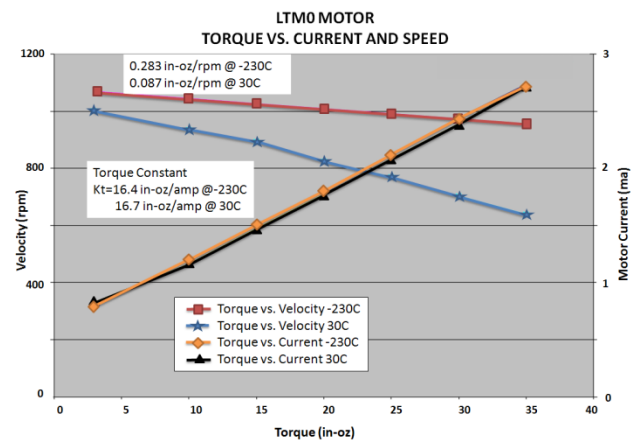


Figure 1 - Torque versus current and speed.

Next, the motor/resolver and gearbox were integrated and tested. A primary objective of the integrated testing was to determine the realistic life at a -230 and 120 degree Celsius environment and how the unit performance changed over this life. 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. Due to this thermal performance issue, the motor test temperature was around -180 C for the majority of the life testing. As a result of the life testing, it was found that a reasonable life for our prototype unit was approximately 120 million revs at the motor, or 30 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. Additional testing would be needed to determine how this end of life performance would progress.

Low Temperature Distributed Electronics

Many such as the automotive industry have gone to distributed electronics in order to save cost and weight. Distributed electronics could also provide major benefits for flight missions where adopted. The primary benefit would be eliminating many of the wires associated with a centralized controller. Wiring is a major contributor in most missions to weight, volume, and complexity in integration and checkout. Centralized controllers are also more susceptible to Electro Magnetic Interference (EMI) and other noise concerns because of long wiring runs carrying low voltage signals. A distributed controller could be located close to the site of operation and utilize binary communication with the primary controller, thus limiting noise concerns and reducing the number of wires. However, the major challenge to a distributed controller scheme results from placing the distributed controllers close to or in the extreme environments.

Therefore, another element of this effort was to characterize the low temperature limitations of a Distributed Motor Controller (DMC). The DMC selected was developed by JPL as part of Mars Focused Technology (MFT). The JPL DMC was designed to be located on or adjacent to the actuator being controlled, and was designed to be folded into a compact cube. This first generation DMC design was characterized at low temperatures to identify electrical components not capable of operating down to -230 C. The results of this characterization are shown in Figure 2. The primary temperature limitations were determined to be in the DC-DC convertor, the voltage reference diode and the high side gate driver. Replacement components have been identified but not yet

integrated and tested. As part of this effort, this DMC design has also been successfully upgraded with a high power winding driver. The goal is to operate actuators up to 2.5 KW with the low temperature DMC rated for -230 C.

Sensor Evaluation in Extreme Environments

As previously stated, a commercial off-the-shelf (COTS) Tamagawa bearing-less resolver was integrated with the prototype actuator as a sensor for motor commutation. In the course of testing, the manufacturer's temperature specifications were far exceeded. The selected sensor offered several benefits, as it is a very compact and light weight 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. Very low temperatures resulted in the necessity to operate it outside of its specified limits and the electronics added complexity to commutate.

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. Subsequent 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 3.

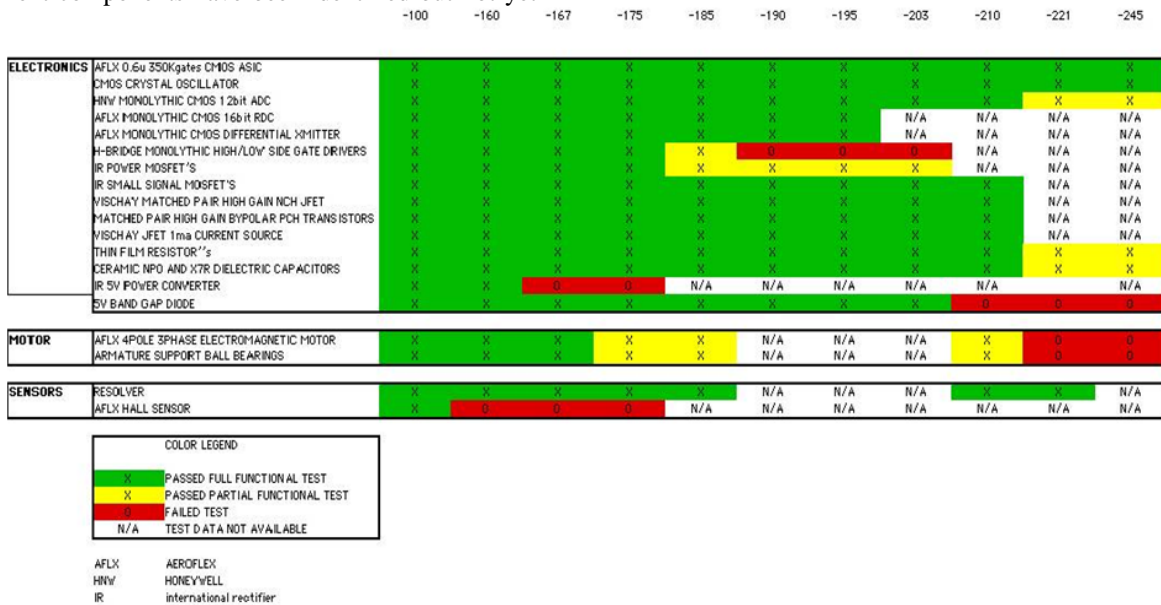


Figure 2 - Limit temperatures for JPL prototype controller components.

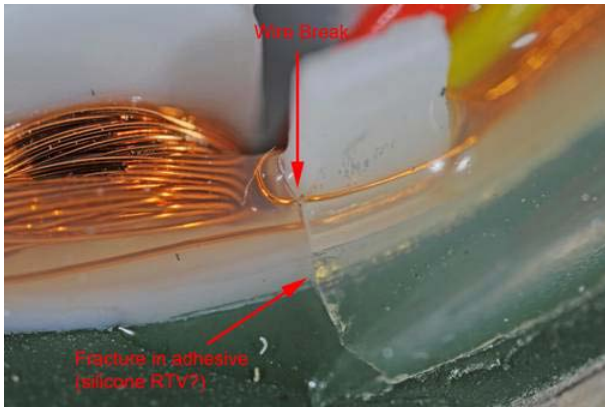


Figure 3 - Optical micrograph of wire break location.

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 design change which should improve upon the temperature range. Several resolvers with the new design have been procured but have not yet been tested.

Mitigation Technologies

The limited life of cryogenic rated mechanical systems was recognized as a possible risk to this technology development effort, particularly in the area of gearboxes. Previously encountered issues with MSL gearboxes had accentuated this concern. In order to mitigate the risk, other technologies that could improve gearbox life were investigated. Three low TRL development areas were identified to mitigate the risk in cryogenic gearboxes and bearings, and GRC monitored SBIR results were leveraged for this purpose.

Ionic liquids are a possible lubrication solution with the potential to extend the low temperature limit of liquid lubricants, allowing gearbox operation to much lower temperatures¹. Ionic lubricants promise a “mix-n-match” range of properties which can be tailored for functions such as basic lubrication, extreme pressure additive, antioxidant, anticorrosive, surfactant, etc. Work in this area is ongoing.

Another relevant technology area investigated was novel design, high pressure angle (HPA) gears². HPA gears have a more tangential tooth contact interface than traditional gears, resulting in reduced sliding between gear teeth. The advantage is a potential for increased life, particularly for gears that are dry film lubricated. Lower sliding motion also can result in higher gearbox efficiencies.

The third research area considered which offers potential advantages to the extreme environment electromechanical system work was the use of Nitinol 60 as a material for bearing and gear fabrication. Nitinol 60 promises a lighter

weight, non-galling, high hardness, non-corroding material potentially well suited for cryogenic use³.

Summary

Several years of work have resulted in specialized electro-mechanical 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. Environmentally rated electronics are the most challenging components to develop. 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. 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 actuator has been constructed by Aeroflex 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, improved resolvers are to be integrated with the motor. Additional testing is planned with cryogenic actuators from other vendors which will provide comparison points for life and performance. 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.

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