

Experimental Capabilities and Achievements of the Space Environment Dynamometer (SED)

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Abstract—The Space Environment Dynamometer (SED) chamber was designed to conduct research in cryobotics; an area of study that focuses on robotic systems and rotating machinery operating in extreme cold environments including Earth, low Earth orbit, Mars, Moon, asteroids, Solar orbit, planetary orbit, or those encountered during travel among these destinations. The test chamber incorporates a modular dynamometer, consisting of a variety of brakes, torque sensors and motors to be easily interchanged between tests. Each test employs a unique test profile that incorporates different setpoints of applied torques and velocities for a given period or number of revolutions. The modularity of the dynamometer setup allows for any combination of motor, gearbox to be tested. This chamber is one of a kind and resides at the Swamp Works facility within the Granular Mechanics and Regolith Operations laboratory (GMRO) at NASA Kennedy Space Center. Other cold chambers exist, however they are project specific and do not simultaneously output real time torque, temperature and efficiency data. The modularity of this extreme cold environment test chamber, coupled with the custom software and instrumentation, makes it one of a kind.

The chamber is capable of stabilizing cryogenic temperatures and pressures to commensurate moon environments. Tests have successfully been conducted on motors and gearboxes for various cryogenic temperature set points, torques, and angular velocities. Relevant internal temperatures of the test article and chamber were recorded using a variety of temperature sensors. The temperature setpoints, on the motors and gearboxes tested, were stabilized by using PID gain scheduling of the PWM signal for the various heaters. The heat removal for the motor was provided by creating a thermally conductive path from a cryohead directly to the test article using copper straps.

A variety of strainwave gears (SWGs), also known as Harmonic drives, planetary gear systems and DC motor actuator configurations have been tested in the chamber. The experiments performed were for various projects including Bulk Metallic Glass Gears (BMGG), Volatiles Investigating Polar Exploration Rover (VIPER), In-Situ Resource Utilization Pilot Excavator (IPEX). Various upgrades have been made to the extreme cold environment test chamber for the use of cryobotic research.

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These upgrades greatly increased the autonomous capabilities of the test set up by providing redundancies in the hardware and software. The redundancies were primarily added to protect the integrity of the cryohead. A new strapping and insulation method was performed to create the thermal conductive path from the actuators to the cryohead. The software was upgraded to include temperature setpoint control, further increasing the autonomous capabilities of the test. This paper goes into detail regarding the upgrades made to the extreme cold environment test chamber, as well as highlights the results from a COLDArm acceptance test.

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1. INTRODUCTION

Accurate mechanical efficiency of gearboxes and motors is a crucial parameter in actuator design. Unfortunately, the efficiency for a particular gear system is determined in ambient conditions and does not carry over for extreme cold environments. This results in actuators being oversized for a particular space mission to compensate for the unknown drop in efficiency due to the extreme cold environment. The need for the determination of real time efficiencies at a given cryo-

genic temperature is necessary to optimally design gearboxes and motors that have stringent mass and size requirements. Low-power mechanical systems that can withstand extreme environments are needed for robotic precursor missions. [1]

The drop in mechanical efficiency of actuators at cryogenic temperatures is due to the expansion and contraction of the material, as well as changes in the properties of the lubrication. This inspired the Jet Propulsion Laboratory (JPL) to develop a new material for gearboxes that does not require lubrication. The new material, bulk metallic glass (BMG), has been used to manufacture a SWG, consisting of a flexspline, circspline and wave generator. JPL has also implemented BMG in the design and manufacturing of a planetary gear motor. JPL partnered with Swamp Works robotics lab at Kennedy Space Center (KSC) to develop a test chamber capable of determining the efficacy of the BMG material in these gearboxes, as well as calculate real time mechanical efficiencies of the gearboxes.

2. EXPERIMENTAL TEST APPARATUS

The test article (gearbox, motor, actuator) is installed onto a titanium bell within the chamber. This test article is then wrapped with copper straps and secured with band clamps. The ends of the copper straps are inserted between two copper plates and securely clamped several bolts. This clamped copperplate assembly is secured into the cryohead. The cryohead rests on the top of the chamber and is attached to the cryocooler. The cryocooler is located adjacent to the test stand and is coupled with a chiller located outside. The chamber is attached to a roughing pump, as well as a turbo pump. The coupling of the turbopumping with the cryocooling allows for ultra-high vacuum pressures (greater than $1\text{E-}12$ atm).

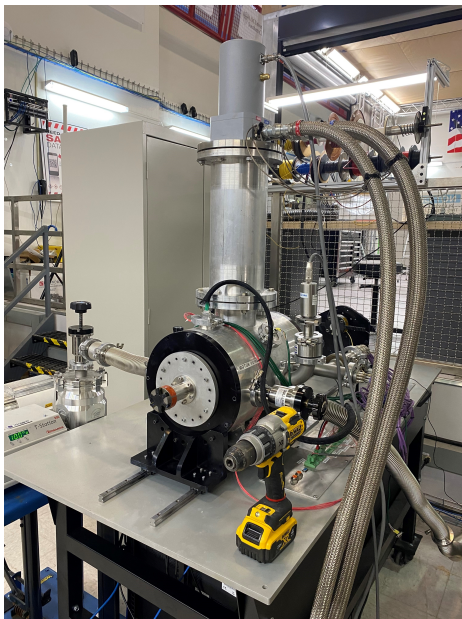


Figure 1. The complete experimental test set up (with a power drill for size reference)

The experimental test apparatus can be seen in Figure 1. SED is composed of a litany of sensors and various other hardware that are used to complete a single experiment. Each and every

sensor reading, as well as output, is controlled using a single data acquisition system (DAQ). The typical experiment uses three separate types of temperature sensors, a pressure transducer, two torque sensors, a brake, a motor (internal or external), a motor controller, two ferrofluid hermetic feedthroughs, three cartridge heaters, and two power supplies. Each test records the active current of the motor, the velocity of the motor, the motor bus voltage, the motor bus power, the motor efficiency, the mechanical power, the input torque, the output torque, the pressure, real time gear efficiency, input current of the brake, up to twenty temperatures and the time.

The test stand is able to be monitored and controlled remotely. The chamber communicates to various pieces of the hardware using RS-232, Modbus, and EtherCAT. The test apparatus performs closed loop control around a single temperature sensor using cartridge heaters. Closed loop velocity control is achieved by using a position sensor such as halls or encoders, depending on the motor being used. Finally, the torque sensor at the output and a brake are used to perform closed loop torque control.

An additional DAQ system was added to create a redundancy in the event the primary DAQ system faults. The second DAQ system is solely responsible for providing additional and separate readings of the temperature of the cryohead at various points. These additional and separate cryohead temperature readings enabled a watchdog to be created in order to ensure the cryohead is not damaged.

Vacuum Chamber

The chamber itself is approximately 15.7 L. It is internally 14.2" long and has an inner diameter of 9.2". The main portion of the chamber is 0.9" thick. The chamber and the cryohead can be seen in Figure 2.

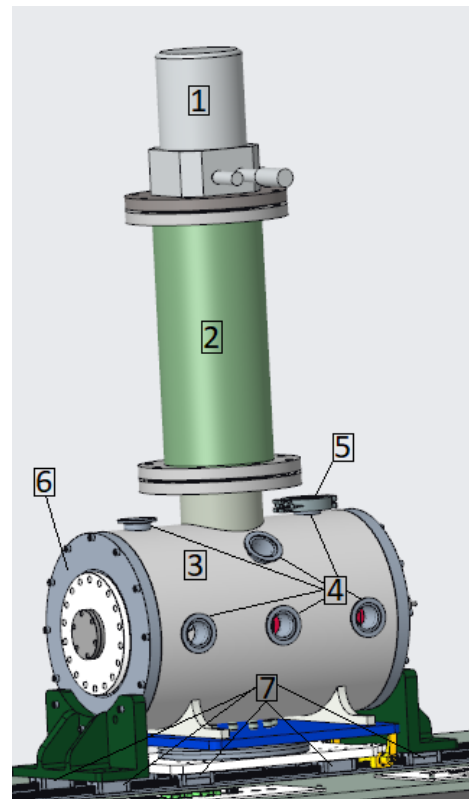


Figure 2. The chamber and cryohead of SED

Table 1 lists the major components of the chamber shown in Figure 2. The cryohead rests on top of the chamber extension. The chamber utilizes eight KF40 flanges that can be used for a variety of operations including, but not limited to: various DB connectors (used for controlling heaters, communicating with motors, reading various temperature sensors, etc.), routing thermocouple wires, installing pressure transducers, interfacing with roughing and turbo pumps, and bleeding the chamber.

Table 1. Labels for Figure 2

Label	Component Name
1	Cryohead
2	Chamber Extension
3	Chamber
4	KF40 Flanges
5	KF40 Clamp
6	Door
7	Rail Carriages

Cryogenic Subsystem

A thermally conductive path that is capable of maintaining cryogenic temperatures is required for the experiments run in this test chamber. This *cryogenic* subsystem is system is made up of five separate entities: a chiller, a cryocooler, a cryohead, a "coldplate" composed of two copper plates clamped together, and dozens of sets of copper straps.

The cryocooler (compressor) provides closed-loop circulation of helium to the cryohead; in order to achieve this, the cryocooler itself must be cooled externally using a chiller. The chiller provides a separate closed-loop system of a water/glycol mixture maintained at ambient temperature. Both the cryohead and cryocooler are manufactured by Cryomech. Haskris manufactures the chiller. However, the cryoplate is internally designed and custom to SED. The chiller is a Haskris OPC5. It has a 5 HP compressor capable of flowing 25 gpm at 50 psi.[5] Relevant capabilities of the cryocooler are shown shown in Table 2. The cryohead has a maximum temperature of 30 C, anything greater than this could cause irreversible damage.

Table 2. AL325 Specifications [4]

Cooling Capacity	100 W @ 25 K
Base Temperature	12 K
Total Cool Down Time	< 1 Hour
Helium Pressure	220 ± 5 psig @ 60Hz

For visualization purposes, Figure 3 has been included to show the cryohead assembled with the copper plates.

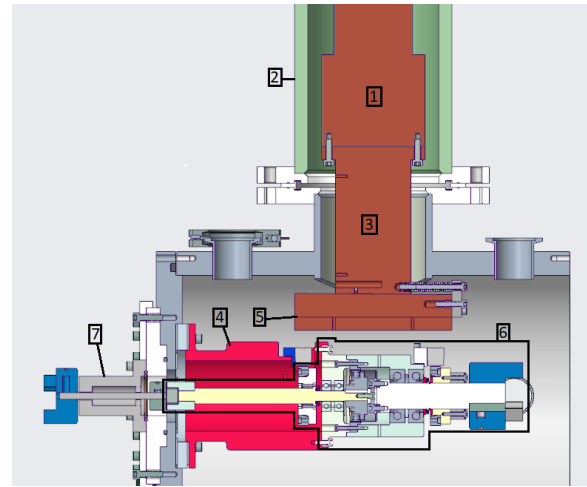


Figure 3. Cryohead and Copperplate

Table 3. Labels for Figure 3

Label	Component Name
1	Cryohead
2	Chamber Extension
3	Cryohead Extension
4	Titanium Bell
5	Copper Plate
6	Test Article (BMG Strainwave)
7	Feedthrough

A new copper strap and band clamp assembly was invented in an effort to decrease test setup time, as well as increase the efficiency of the cryogenic subsystem. The general assembly of the copper straps and band clamp is depicted in Figure 2. Each copper-strap-band-clamp (CSBC) assembly consists of a single bandclamp and anywhere from 4 to 12 individual copper straps. The primary variables that drive the thermal conductive efficiency of this experiment are the number of straps and how secure the copper straps are.



Figure 4. CSBC assembly

Depending on the test article, anywhere between 1 to 4 CSBC

assemblies are used in a single test. The ends of the copper straps of each CSBC assembly are securely fastened between the copper plates. The copper plates are clamped together using a series of bolts on each side. This configuration is shown below in Figure 2.

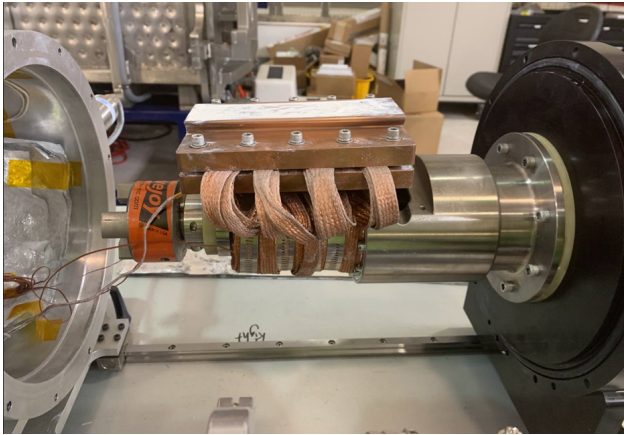


Figure 5. Copper straps secured between the copper plates

Pressure Sensor

The experiment uses the FRG-720 to determine the chamber's pressure. It is capable of measuring pressure from $3.8E - 10$ Torr using two separate technologies: Pirani and Bayard-Alpert.[2] It is monitored via a separate control module using RS-232.

The Pirani sensor exploits a heated wire to measure pressure by detecting the heat flux change from a heater to a heat sink.[3] Bayard-Alpert gauge uses a heated up filament to ionize particles in the air. The ionized particles produce current in a separate wire. The current is proportional to the number of ionized particles. The number of particles is proportional to the pressure.

Temperature Sensors

There are three different types of temperature sensor used in every experiment: thermocouples (TCs), resistance thermometer detectors (RTDs) and diodes. Different types of temperature sensors are used to produce higher confidence in the test's logic structure. Each type of temperature sensor is read by the DAQ system separately, implying that if one type of temperature reading completely fails, one or both of the remaining two will continue to function properly. All three operate based on the Seebeck principle that states a temperature displacement occurs when voltage is applied on dissimilar conductors.

E-type thermocouples are used and are capable of reading down to temperatures of -200 C.[6] They are typically used to monitor the temperature of the test article, the coldplate, and inner chamber wall. E-type have been sufficient as the lowest temperature set point required by a test thus far is -180 C. The thermocouples are read into an NI 9214 input module card.

Diodes are capable of achieving incredibly low temperature readings. A diode's voltage output is linearly proportional to temperature. However, this split between four wires, two on each lead of the diode. A Scientific Instruments Si-415 diode, depicted in Figure 6, is used to monitor the

temperature of the cryohead, as well as the test article. The Si-415 is the same shape and size of a grain of rice, and it can read temperatures from 0.5 K to 450 K with an accuracy of ± 0.5 K. It is easily the most delicate piece of equipment used in the experiments. The readings of the diode are read by a control module via RS-232.

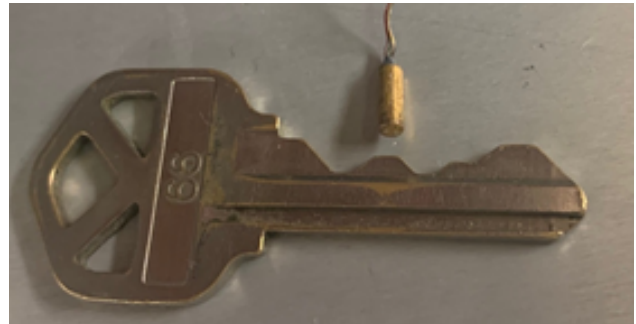


Figure 6. A Si-415 diode adjacent to a standard key for size reference

RTDs measure the change in resistance, rather than voltage. Similarly, to diodes, the signal is split between four wires, two on each lead of the RTD. Lakeshore's PT-102 is used to monitor the temperature of the cryohead. The PT-102 is capable of readings down to -259 C.[9] The readings of the RTDs are also read by a control module via RS-232.

Torque Sensors

The torque sensors that this experiment utilizes are linear torque sensors. They are internally made up of various strain gauges that output voltage proportional to the applied load (torque or force) using a whetstone bridge. The voltage output is limited to an upper and lower range. The range depends on the design of the whetstone bridge, thus it depends on the torque sensor. The voltage output is linearly proportional between the upper and lower limit of the torque sensor. Figure 7 is included as a visual aid; it depicts Interface's MRT series torque sensor.



Figure 7. An MRT torque sensor

The torque sensor capacity $\mathcal{T}_{maxTS}$ is synonymous with the full scale (FS) torque. It is the point at which the torque sensor is no longer outputting voltage linearly proportional to the torque. It can be thought of as the *effective upper limit of the torque sensor*. The nonlinearity of the torque sensor $\mathcal{T}_{minTS}$ corresponds to the *effective lower limit*, as well as the *resolution*. Table 4 displays all of the sensors currently used to run experiments in the SED chamber.

Table 4. Current Available Torque Sensors

Torque Sensor	$\mathcal{T}_{maxTS}$ (N.m)	$\mathcal{T}_{minTS}$ (N.m)
T11-0.1	0.1	0.0001
T11-0.2	0.2	0.0002
T11-1	1.0	0.001
5330-60	6.78	0.00678
5330-120	13.6	0.0136
5330-600	67.8	0.0678
5330-1200	136	0.136
MRT0.2NM	0.2	0.0002
MRT2NM	2	0.002
MRT5NM	5	0.005
MRT10NM	10	0.01

Vacuum Rotary Feedthroughs

Each experiment requires the use of either one or two vacuum rotary feedthroughs. The purpose of the feedthrough is to allow a shaft external to the test chamber to rotate with a shaft within the test chamber under vacuum. Ferrotec feedthroughs are chosen as they provide the test with this capability. The shaft capacity of the feedthrough is highly dependent on the housing diameter of the feedthrough. General information about the specifications of the feedthroughs used in the experiment can be seen in Table 5.

Table 5. Various Ferrotec feedthroughs and their specifications [11]

Model	Housing Diameter (in)	Shaft Capacity (N.m)
133601	0.63	0.69
103978	0.75	1.75
103532	1.5	1.75
103204	2.87	20.1
103359	3	X

Figure 8 shows an example of one of the feedthroughs used in the chamber.



Figure 8. A 103978 Feedthrough

The 103359 feedthrough is not only the largest feedthrough

this experiment employs, it is also the only feedthrough that does not come with its own shaft. The shaft for this feedthrough is supplied externally.

Magnetic Particle Brakes

A variety of magnetic particle brakes provide the output torque that is used in the dynamometer set up. Examples are shown in 9. The magnetic particle brakes produce torque by running current through ferromagnetic fluid.

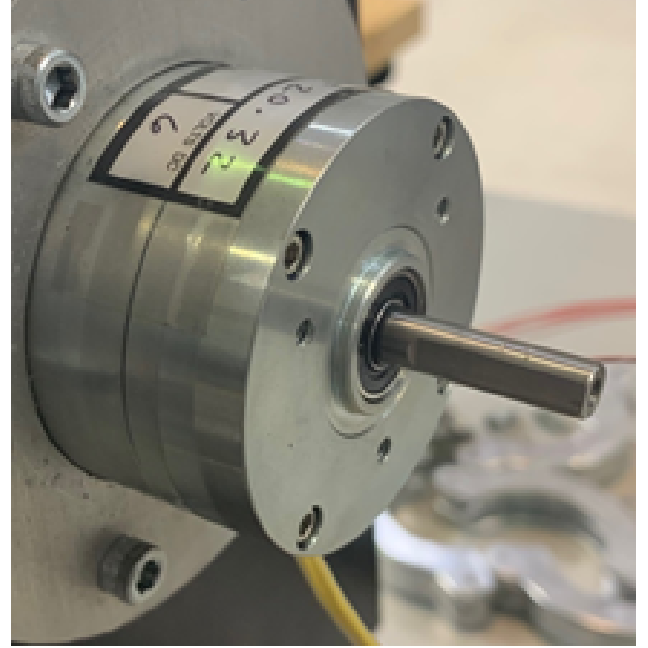


Figure 9. B Series Magnetic Particles

The output torque of the brake relative to the input current of the brake has a linearly proportional region. The maximum output of the brake $\mathcal{T}_{maxB}$ is driven by the maximum input current. The minimum output of the brake $\mathcal{T}_{minB}$ corresponds to the *effective lower limit*. The brakes that are used in tests are tabulated in Table 6. The requirements of a specific test will determine which brake is most appropriate.

Table 6. Currently Available Brakes

Brake	$\mathcal{T}_{maxB}$ (N.m)	$\mathcal{T}_{minB}$ (N.m)
B2-6V	0.28	0.0085
B15-6V	1.7	0.034
B35-6V	3.95	0.05
B60-6V	6.8	0.12
B115-6V	13	0.29
PLB-100	95	2

Custom External Drive Motor-Gearbox Configurations

There are several experiments where only a gearbox actuator is tested within the chamber. These experiments require an external motor to drive the gear box. These are referred to as external drive motors (EDMs). Each EDM is composed of a brushless DC motor, bearings, an actuator housing and a driveshaft. The actuator housings are custom designed to fit a particular DC brushless motor. The bearing placement is

Table 9. Current MC selection[8]

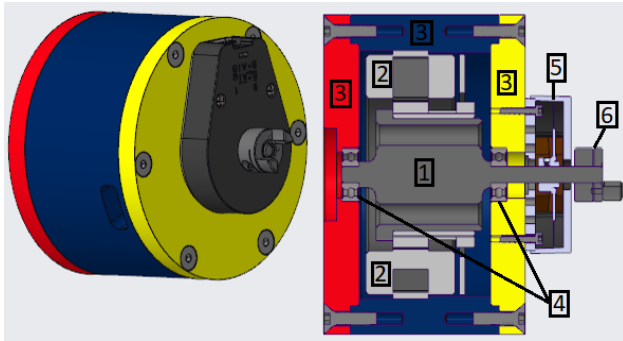
<i>Motor Controller</i>	<i>Active Current (A)</i>	<i>Bus Voltage (V)</i>
Gold Solo Twitter	3,6,10	100
Gold Solo Whistle	6	100
Gold DC Trombone	6	400

also custom. However, the bearings themselves, as well as the DC brushless motor are commercial of the shelf (COTS). The current EDMs are integrating Parker DC brushless motors with SKF bearings. Relevant parameters for each motor configuration are listed below in Table 7.

Table 7. Current EDM selection[10]

Motor	Rated Torque (N.m)	Rated Speed (rpm)
K089050-7Y	1.32	597
K089200-7Y	3.9	111

A cross section of one of the current EDMs show the bearings and can be seen in Figure 10.

**Figure 10. K089050-7Y****Table 8. Labels for Figure 10**

<i>Label</i>	<i>Component Name</i>
1	Rotor
2	Stator
3	Cryohead Extension
4	Actuator Housing
5	Bearings
6	Encoder
7	Coupler

Motor Controllers

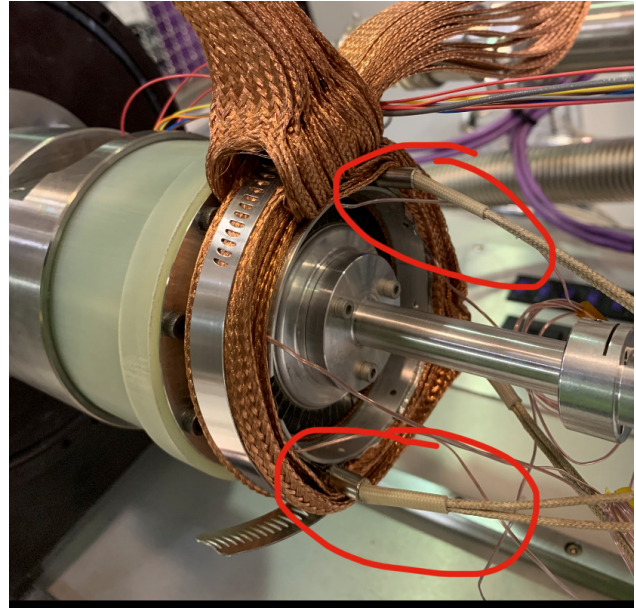
The motor controller (MC) is responsible for supplying the motor with the appropriate current and duty cycle depending on the torque and velocity setpoints. The MC is matched to a motor based on the active current and voltage of both. Depending on the test being run, different MCs are capable of running different motors. The MCs used in SED are currently manufactured by Elmo. They are controlled and read using the DAQ via EtherCAT. The current MCs available are shown in Table 9.

Heaters

Cartridge heaters are used to control the temperature of the test article. The heaters are toggled on and off using a PID controller around a specified temperature sensor. The heaters used in SED vary from 150 W to 200 W.

In general, the heaters are installed directly into the cryohead, however this presents difficulties in temperature control for temperature setpoints below -100 C and above -30 C. For temperatures below -100 C, it is difficult to get that much control without direct contact of the heaters on the test article. For temperature setpoints above -30 C, the cryohead could reach temperature above its safe operating limit of 30 C. This is due to the heaters needing to be toggled on the majority of the time in order to compensate for the heat exchanged between the cryohead and test article.

The heaters can be installed directly on the test article to mitigate the chance of damaging the cryohead. An example of this configuration is shown in Figure 11 (the heaters are circled in red).

**Figure 11. Cartridge heaters inserted between CSBC and test article**

Power Supplies

The test stand uses two separate power supplies: one for the motor, one for the brake. The brake uses the BK Precision 9172B. The output rating of the 9172B is 0-35 V and 0-3 A. The motor uses the BK Precision XLN15010. The output rating of the XLN15010 is 5-150 V and 0.04-10.4 A.

Data Acquisition System

The DAQ system is responsible for reading, writing and recording both input and output data, such as recording temperature readings, sending velocity commands to the motor, sending torque setpoints to the brake, etc. The DAQ system is composed of a National Instruments (NI) Compact Reconfigurable Input/Output (cRIO) and multiple input modules. Each input module is responsible for either reading or writing to a particular sensor or set of sensors. The input modules can either be analog or digital. The test set up makes use of the

NI cRIO-9049, as well as five separate input modules.

The first input module, the NI 9237 analog input module, is responsible for reading the torque sensors. The NI 9217 analog input module is used to read the resistance of RTDs to determine the temperature. The NI 9214 input module is used to read the voltages of the thermocouples to calculate a temperature reading, based on the thermocouple type. The NI 9474 digital output is used to toggle the heaters on and off.

Vacuum Pumps

SED is able to achieve ultra-high vacuum pressures using a roughing pump, a turbomolecular pump or turbo pump, and the cryohead. All three play their role individual role in enabling the chamber to reach pressures this low. When setting up the chamber for a cold test, the roughing pump is initially used to get the chamber down to below 50 mTorr. At this point, the roughing pump's valve is closed and the valve for turbomolecular pump is opened. The Edwards T-Station 300 turbomolecular pump allows for vacuum pressures down to approximately $4.5\text{E-}8$ Torr.[7] The turbo pump's valve is left open when the cryocooler is turned on. The pressure settles down to below $1\text{E-}10$ Torr.

3. PROCEDURE

The procedure depends on the specific test. Every test investigates the relationship between velocity, input torque and output torque regardless of the test article. There are three different types of test articles: motors, gearboxes and gearmotors. The chamber has an input side and an output side. The orientation of the input side and output side depends on the test article. The chamber's output side is invariably composed of a brake mounted to a torque sensor mounted to a sliding stand. The chamber's input side is composed of a motor mounted to a torque sensor mounted to a sliding stand, and it is only necessary when testing gearboxes independently.

The test setups for motors, as well as gearmotors, exclusively require an output side, as the input torque is calculated based on the active current and the torque constant of the motor. If the test article is a gearbox, then it must be driven externally using an EDM. An example of the test set up for testing a gearbox can be seen in Figure 12.

Table 10. Labels for Figure 12

<i>Symbol</i>	<i>Hardware type</i>
Ω	Torque Sensor
μ	External Drive Motor (EDM)
ϕ	Feedthrough
ρ	Titanium Bell
θ	Test Article
β	Brake
π	Coldplate
κ	Cryohead
ψ	Pressure Transducer
Γ	Cryocooler
Λ	Chiller

In addition to what is depicted in Figure 12 and listed in Table 10, there are an array of temperature sensors, the motor controller, the DAQ system, the heaters, the copper straps of the CSBC(s), shaft couplers, spiders, the railing system

that the sliding stands translate on, the test table the roughing pump and turbomolecular pump. Each and every one of these is also required to run a cold test.

The procedure is broken up into four portions: general test stand preparations, software preparations, assembly of the test article and installation of the test article. Examples of several of the test articles' assemblies and installations is included and discussed in the subsections of this procedure.

General Test Stand Preparations

Maintaining the integrity of the wire management between tests is paramount for the longevity, repeatability and efficacy of the test. In early 2022, the inner surface of the chamber underwent an extensive cleaning and restructure of the wiring. There are several semi-permanent temperature sensors attached to the cryohead. The wires for these temperature sensors, other temperature sensors and the heaters must be managed properly. An image of the chamber completely empty, with properly managed wires, is depicted in Figure 13.

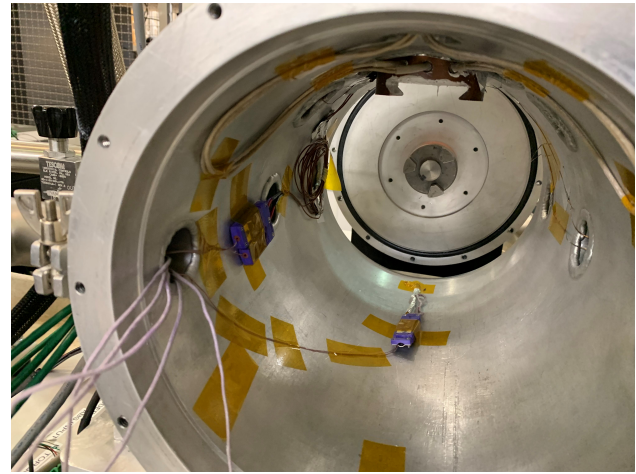


Figure 13. The chamber empty with wires properly managed

Assembly of the SWG Actuator

Both the input and output side of the SWG actuator are built independently from one another and are assembled after both sides have been built. An SWG is made up of three different components: a wave generator (wavegen), a circular spline (circspline), and a flexspline. The wave generator is fixed to the input side of the actuator. The circspline and flexspline are both fixed to the output side of the actuator.

The wave generator rotates with the drive shaft. The outer race of the wavegen is relatively flush with the inner race of the flexspline. When assembled and rotating, the elliptical shape of the wavegen forces the outer teeth of the flexspline to engage with the inner teeth of the circspline. This causes the flexspline to elastically deform to maintain contact. Hoffman et al said it best "After a 180 degree rotation, the flexspline has moved by one tooth relative to the outer spline. After a full rotation, the flexspline and the outer spline have been offset by two teeth." The number of teeth drive gear ratio of a SWG, where size drives the gear ratio in planetary and spur gears. [12]

The SWG actuator is composed of two halves: an input side and an output side. Each side is assembled individually prior

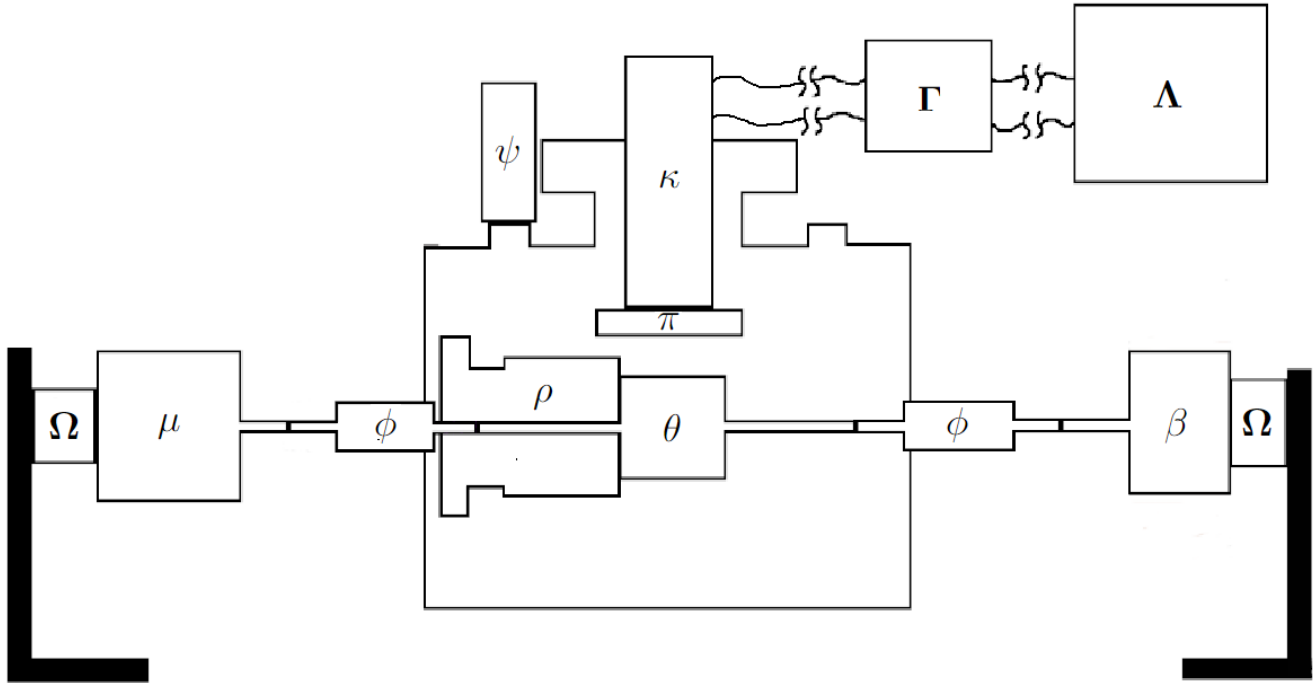


Figure 12. Experimental test set up and labeling structure

to combining both sides to form the SWG actuator.

The input side of the SWG actuator is shown in Figure 14 with a cross section view in Figure 15.

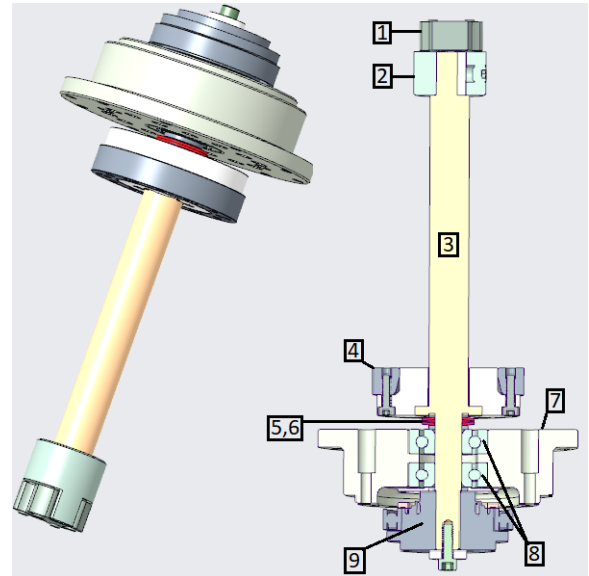


Figure 15. CAD with a cross-section view of the input side of the SWG actuator



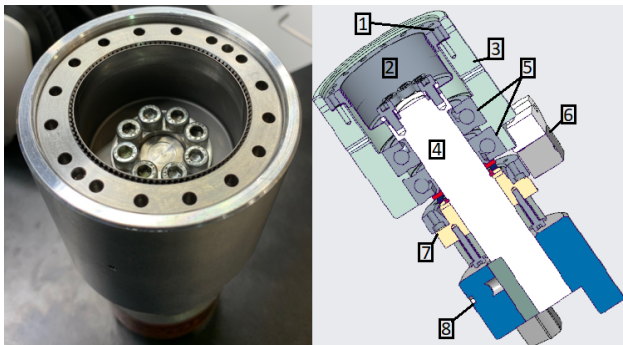
Figure 14. The input half of the SWG actuator

Table 11. Labels for Figure 15

<i>Label</i>	<i>Component Name</i>
1	Spider
2	Coupler
3	Input Shaft
4	Encoder
5, 6	Washers & Belleville Springs
7	Input Actuator Housing
8	Angular Contact Bearings
9	Wave Generator

The input side of the SWG actuator is assembled by first cleaning the input shaft, output shaft, angular bearing input mount and actuator housing with acetone and IPA. This is followed by attaching the absolute encoder assembly to the input shaft with a series of screws. The shaft coupling is then secured to the input shaft via set screw. Two shims and two Belleville disc springs are slid on the opposite end of the input shaft. One input input bearing is slid on the shaft with the large face of the inner race facing towards the shim-Belleville disc spring configuration. The input mount is installed on the shaft and press fit into the input bearing. The second input bearing is slid down the input shaft and secured into the angular bearing input mount with the large face of the inner race facing outward. The bearing shield is slid down the input shaft with the small step contacting the inner race of the bearing. The wavegen key is fit in the input shaft with the round face towards the input bearings. The wavegen is inserted onto the input shaft with the snap ring of the wave generator facing towards the input bearings. The wavegen key is secured to the input shaft with the wave input washer and a dab of Loctite on the wavegen screw. Pictures of the assembly are taken and it is set aside.

The output side of the SWG actuator needs to be assembled once the input side of the SWG actuator is finished. The output side of the actuator can be seen in Figure 16.

**Figure 16. The output half of the SWG actuator****Table 12. Labels for Figure 16**

<i>Label</i>	<i>Component Name</i>
1	Circular Spline
2	Flexspline
3	Output Actuator Housing
4	Output Shaft
5	Angular Contact Bearings
6	Encoder Reader
7	Encoder
8	Coupler

The output side of the SWG actuator is built by inserting both output bearings with the large face of the inner race facing outward into the actuator housing. The output shaft is slid into the interior of the actuator housing, through both output bearings. Two wave disc springs and two shims are slid onto the output shaft. A snap ring pushed down the output shaft until it reaches it's corresponding slot, providing the load for the angular contact bearings. The output encoder is slid down the output shaft. The coupler is slid down the output shaft. The flexspline is installed onto the shaft using a series of screws and a custom washer. Pictures of the flexspline in this configuration are taken. The circular spline is installed ensuring that the inner teeth of the circular spline have two contact points, 180 degrees from each other, with the outer teeth of the flexspline (non-diodoidle). Pictures of the assembly are taken and it is set aside.

At this point, both sides of the actuator are joined together and secured following carefully inserting the subassemblies of the actuator together by rotating the input shaft while applying slight pressure and secure them to each other with a series screws. After assembly, slowly rotate the input shaft to insure proper operation.

Installation of a Test Article for a Cold Test

The first step of preparing for a cold test is installing the test article onto the titanium bell with a series of screws. Kapton tape is then wrapped circumferentially around the test article. Several temperature sensors are installed onto this kapton tape and secured with either aluminum tape or kapton tape. An example of what the set up would look like at this point can be seen in Figure 17.

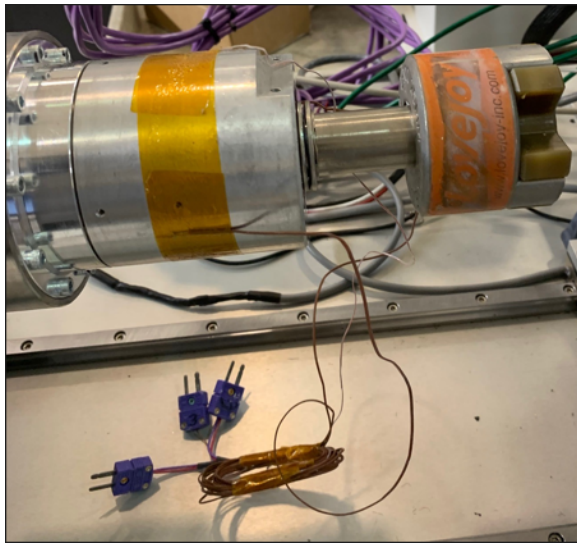


Figure 17. A SWG test article installed on the titanium bell with kapton tape and thermocouples installed

Depending on the test, one or several CSBCs are installed onto the test article. This is done by first feeding the thermocouple leads, pictured in Figure 17, through an individual CSBC. The CSBC is then positioned with the ends of the straps facing up and is lightly secured to the actuator by engaging the band clamp. Once every CSBC has been installed, the band clamps are torqued down to provide sufficient circumferential compression around the actuator. This step is vital to ensuring an efficient thermally conductive path from the cryocooling system to the test article.

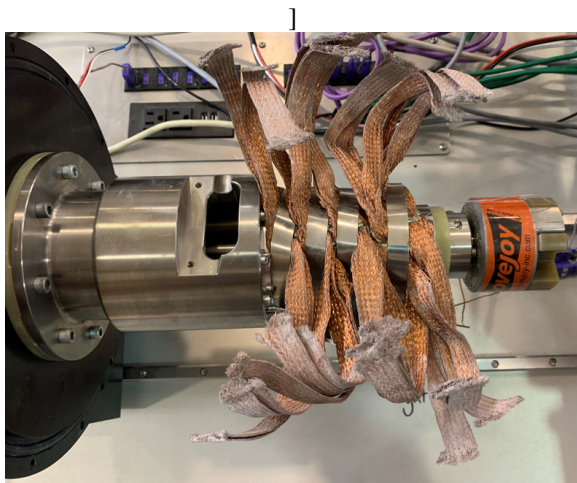


Figure 18. A SWG test article installed on the titanium bell with four CSBCs

The ends of the copper straps of the CSBCs are covered in thermal paste and inserted into the coldplate. The coldplate is meticulously clamped with a series of screws, to ensure a strong contact is made. The portion of the surface of the coldplate that makes contact with the cryohead is lathered in thermal grease.

Another portion of the surface of the coldplate is cleaned with acetone and IPA. Multi layer insulation (MLI) is wrapped

around the test article and is taped to this clean surface of the coldplate with aluminum tape. A separate MLI is inserted into the chamber and provides insulation to ensure the chamber doesn't condensate. The test article would now be ready to be inserted into the chamber. An example of what this stage would look like can be seen in Figure 3.

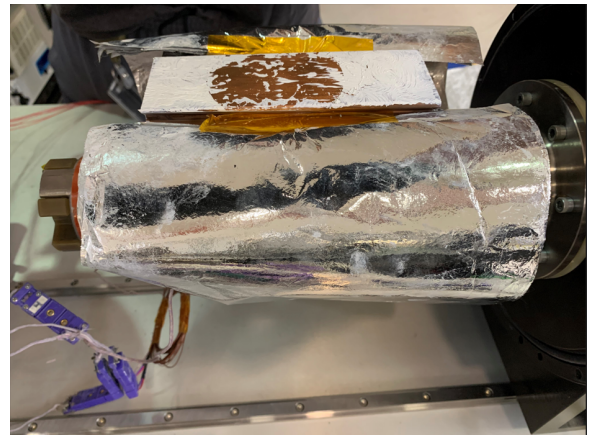


Figure 19. A SWG test article ready to be inserted into the chamber

The chamber input door is slid into the chamber carefully while the coldplate is lifted off of the surface and guided into the dovetail of the cryohead. The door is secured used several screws. A triangular piece (visible in Figure 20 and Figure 21) secures coldplate in it's proper location and ensures tolerances are met with a loaded spring. A diode is inserted into the front of the actuator, between a CSBC and the test article; this is saved for last intentionally as the diodes are incredibly fragile and relatively expensive. The chamber output door is now ready to be closed from the other side. Examples of what the inside of the chamber could look like right before the is chamber is sealed can be seen in Figure 20.



Figure 20. A CSG-20 SWG set up for a cold test

As previously stated, the difference between testing a gearbox and testing a motor/gearmotor is that there is no input side when testing a motor. Figure 21 and Figure 22 exhibit an examples of a setup for testing a motor.



Figure 21. An LSI 75-12 set up for a cold test

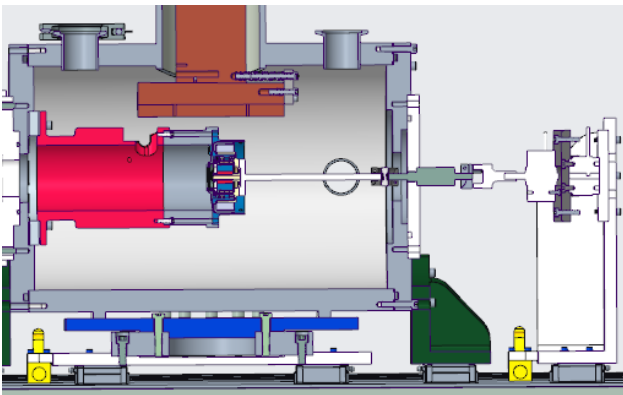
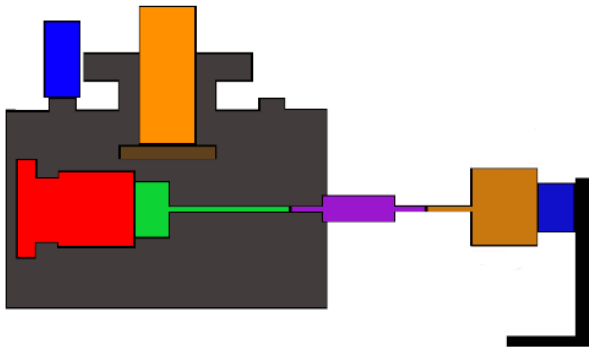


Figure 22. An LSI 75-12 set up for a cold test



Installation of a Test Article for a Vacuum Only Test

The procedure for installing the actuator for vacuum tests is identical for the cold test procedure, up until installation of the CSBC(s). Vacuum only tests do not require the cryogenic subsystem at all. The cryohead remains on the chamber for these tests, however it remains inactive, along with the cryocooler and chiller. Though the cryohead remains on the chamber for convenience, the coldplate and CSBCs are not

installed on the test article. Examples of a vacuum only test of a gearbox and vacuum only test of a motor can be seen in Figure ??

Installation of a Test Article for an Ambient Test

The test stand is occasionally used without the chamber to conduct ambient tests. The chamber can be moved to one side of the table and the sliding stands can be consolidated to one side of the table. This test configuration is used for a number of reasons including, but not limited to tuning the motor under load, interfacing and verifying new motor controllers, verifying test operations in general. The procedure for setting up a motor to be tested should be intuitive based on Figure 23.

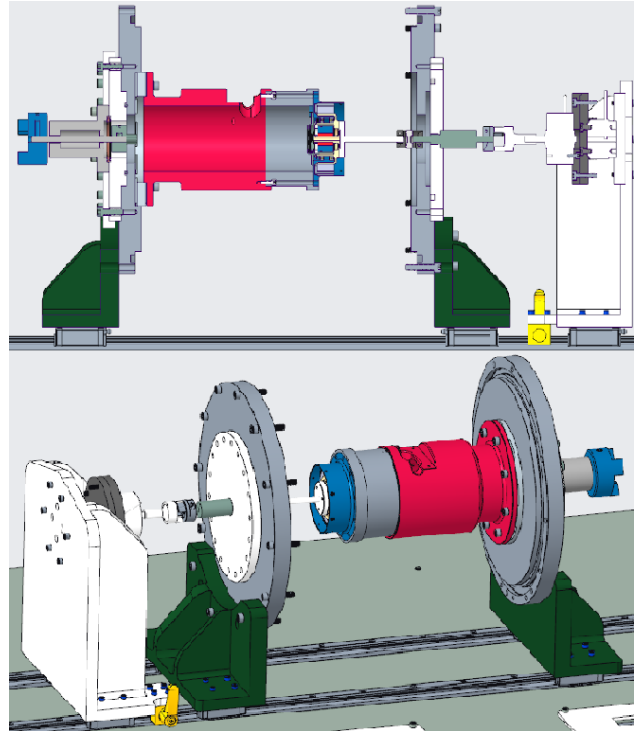


Figure 23. CAD of a thingap LSI 75-12 set up for an ambient test outside of the chamber

Software Preparations

The software is equipped to handle and automate complicated tests that require different torque profiles be run with different velocities at different temperature setpoints for either a set number of time or revolutions. The time and thought that has gone into the software permits minimal required modification/preparation of the software between tests. The software procedure for operating the software is discussed in detail in the User Interface section of this paper. It can be done before, during or after the physical installation of the test article.

4. USER INTERFACE & SOFTWARE

The UI is used to verify functionality of the various subsystems of SED. It enables the user to program unique tests based on velocity profiles, torque profiles and temperature profiles. The UI provides extensive monitoring and control capabilities of the various subsystems. The DAQ software for the system was created using National Instruments LabVIEW. The software controls all aspects of the test, including

motor control, PID output torque, data logging, health monitoring and reporting, and stop criteria. A real-time C-Rio chassis was used to provide the data logging and automation. The software allows for manual control of the motor and data logging as well as an automated tests. The automated tests control the motor, torque set point, temperature setpoint, data logging, and stop criteria. All setpoints are controlled through a scheduler based upon revolutions or time intervals. The front panel is accessible remotely to support multi-day test.

All the data is converted to engineering units real-time and is normally logged at 0.2 Hz, but the software allows for up to 10 Hz. The sampling rate can be changed during operation at any time. During velocity, temperature and torque changes the logging rate automatically changes to 2 Hz and set back to the normal rate. The torque sensors are measured using a NI-9237 C Series Strain/Bridge Input Module, which has a 24-bit resolution and a ± 25 mV/V input range. The software performs all the unit conversions real-time. The variables that are recorded are as follows: records temperature, input and output torque, real-time gear efficiency, motor revolutions, motor velocity, motor amperage (active current), motor bus voltage, motor bus current, motor bus power, real-time motor/motor controller efficiency, high-resolution input and output revolutions, time, vacuum pressure, Sample Rate (Hz), and Elapsed Time (minutes).

Input Torque & Output Torque Indicator

The input and output torque plots enable the the torque to be monitored in real time. This allows the user to infer what went wrong based on any anomalies viewed in the plots.

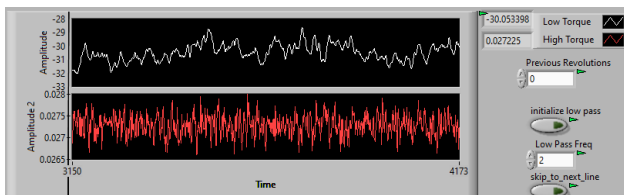


Figure 24. Input and output torque display on the UI

A recording of torque data can be seen in Figure 24. The accuracy and resolution of the torque is dependent on the torque sensor used. There are various anomalies in the laboratory that can cause misreadings. The cryocooler introduces vibrations and shifts the values once it is turned on and running. A person bumping the table or even a curious lizard could impose enough force on the table to shift readings. For this purpose, the test is typically gated and inaccessible during testing.

Temperature Monitor

The temperature monitor is typically pulled up and monitored often during a test. The temperature updates on the display every 0.25 seconds on a high-speed display, and every 1 second on the standard display.

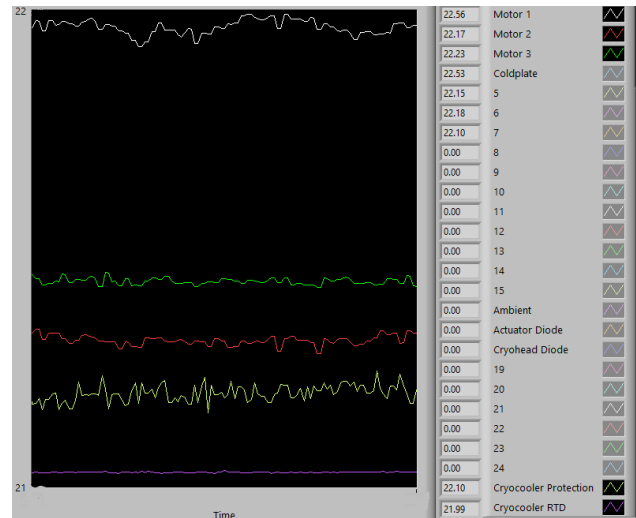


Figure 25. Temperature Monitor on the UI

Figure 25 shows an example of the standard display and various temperatures recorded in a typical test. Keep in mind, every temperature sensor slot is not required by every test.

Motor Indicator & Controller

EtherCAT is the communication protocol used to communicate with the Elmo MCs. The user is able to update the state of the motor directly from the UI, as well as poll and set the acceleration, deceleration (in rpm), the continuous current, and peak the current. The column on the right provides information about the current functionality of the motor, such as if it is connected to the system correctly or if there is an error that needs attention

Brake Controller & Indicator

Verification of the connection between the PS of the brake and the brake can be seen here. The PS of the brake can be powered on or off here. The brake can switch between closed loop torque control (used during tests) versus open loop current control. If the PID controller becomes over saturated then we are able to reinitialize the PID controller.

Exit Criteria Selector

The user can define exit criteria based on hardware limitations in the test setup such that if a condition is met, the test will exit and prevent the hardware from being damaged. The exit criteria can be one or any combination of the following: gear eff limit, velocity limit, output torque limit, input torque limit and temperature limit.

Heater Controller

The temperature sensor that closed loop control of the heaters is selected from a drop down on this portion of the UI. The heaters are toggled on & off using a PID controller that effectively outputs duty cycle of a PWM signal to the heaters. The user is able to set the cryocooler max temp and select the cryocooler protection sensor so that we do not damage the cryocooler.

Motor Power Supply Controller & Indicator

From this portion of the UI, the user will verify the connection exists between the motor power supply and the DAQ system. It is also where the user will turn the power supply on or

off, set voltage and current, and read the actual voltage and current off of the motor.

Data Names

Different tests call for different data to be logged. The label names of the data file's columns can be changed from the UI rather than hard-coding it. This enables a more streamlined process when a new test requires data to be logged that previously was not.

Test Selector

The test selector is used set important constants that are specific to a particular test set up. The values are stored and saved, as often times other tests with a similar test setup will require some of the constants remain the same between tests. Important constants of the equipment used are entered into the Test Selector.

String is where the user would input the name of the test setup. *Gear Ratio* is used to calculate the gear efficiency. *Input Torque Scalar* and *Output Torque Scalar* are the scalars specific to the individual torque sensors in N.m/V. They are roughly the same for torque sensors of the same model number, however they change slightly and therefore need to be recalculated during an annual calibration process. *Input Torque Offset & Output Torque Offset* are calculated prior to starting every test and are dependent on the various systematic errors of the test. *Input Drag Offset & Output Drag Offset* are calculated based on the measured drags of the feedthroughs. *No Load Motor Current* is the active current of the motor when zero output torque is applied. *Torque Constant* is the torque constant of the motor in N.m/ A_{RMS} . *Brake Voltage Level* is the voltage level of the brake. *Max Brake Current* is the maximum current the brake can handle. *PID Max Output* is equivalent to τ_{maxB} . *Gains* refer to the gains of the PID controller responsible for controlling the output torque, as the brake's current is adjusted real time based on the torque reading for the torque sensor.

Test Logic

The test array is half of a two-part logic system for creating a completely self-sufficient and self-sustaining test; the other half is the test scheduler.

The test array is in charge of assigning a designator to a specific task that a test calls for. In general practice, a designator is unique and only executes a single task; this task can be one of the following: set a velocity, set a torque (and specify how it is discretized), set the exit criteria (time or number of revolutions), set a temperature, and turn the cryocooler on or off.

The test scheduler is in charge of creating a logic sequence based on the test array. It is able to be repeated and there are an infinite amount of ways to utilize the relationship between the test array and the test scheduler.

Exit Criteria Record

The exit criteria record is populated if one of the contingencies that was selected in the exit criteria selector is met during a test.

Relevant Test Variables

The relevant test variables would be checked often during a test. They are an indication as to what step the test is currently on.

CPU Loads

The CPU loads can be monitored real time from the UI to provide a reference when a test or the software in general exhibits abnormal behavior. *Total (%)* reaches above 85% then there is generally an issue that needs to be investigated.

Heater Gain Scheduler

The heater controller incorporates gain scheduling. This is due to different gains being essential to maintain temperature requirements. The gains change depending on the temperature setpoint, which results in different modulation of the heaters.

Elmo Error Record

If the motor controller faults, then a code will be read on the Elmo Error indicator. This code can be looked up in the Elmo manual if further investigation is needed to alleviate the fault.

Cryocooler & Chiller - Status & Controller

The cryocooler status and controller indicates the temperatures and pressures of both the input, as well as the output, of the water/glycol lines and the helium lines. It can be remotely powered on and off from here. The chiller status and controller, indicates a specific alarm if any is triggered. The temperature setpoint of the water/glycol can be changed here. The pressure and unit status is also able to be viewed here.

5. PROJECTS AND EXPERIMENT OVERVIEW

The chamber has been used to perform a variety of tests for several different missions. Cold Operable Lunar Deployable Arm (COLDArm), Bulk Metallic Glass Gears (BMGG), and Volatiles Investigating Polar Exploration Rover (VIPER), have all had actuators tested in the SED.

Cold Operable Lunar Deployable Arm (COLDArm)

COLDArm is a NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) project that is creating a robotic arm capable of surviving and operating during the lunar night. The operational conditions can be less than -173 degrees Celsius. The use of greases and oils to allow the bearings and gears to survive the mission would require heaters on each of the actuators. With limited power resources available, the use of heaters is undesirable for mission success. The COLDArm actuators required qualification and testing under lunar like conditions to ensure their designs can meeting the mission requirements. This qualification testing was completed at KSC in the DEE chamber. COLDArm is targeted to fly as a technology demonstration on a NASA Commercial Lunar Payload Services (CLPS) flight.[13]

Bulk Metallic Glass Gears (BMGG)

The components within the COLDArm project actuators contain another technology demonstration called Bulk Metallic Glass Gears (BMGG). The BMGG project is a NASA STMD GCD project that is focusing on creating geared mechanisms to withstand the low temperatures of -180 degrees Celsius. Typical mechanisms on earth and in space contain wet lubricants combined with electric heaters to withstand the extreme environments at the cost of using more power. The BMGG team is creating a new metallic glass with unique composition and atomic structure to create a tougher, stronger, and more elastic material that does not need lubricants to withstand a

harsh vacuum and extremely low temperatures. The BMGG project tests all their gearboxes and actuators in the DEE chamber at KSC.[14]

Volatiles Investigating Polar Exploration Rover (VIPER)

With an approaching launch date to the moon in 2024, the NASA Artemis Lunar rover called the Volatiles Investigating Polar Exploration Rover (VIPER) is performing tests on specific mechanisms to reduce risks in the highest probability of failure areas on the rover. VIPER's mission is to search for ice and other resources on the lunar south pole. The data that is collected during the resource mapping will be used by NASA for a future long-term presence on the surface of the Moon. One of these areas of concern is with dust intrusion into the mobility actuators. The VIPER team came to KSC with their knowledge of the capabilities of the DEE chamber to test their mobility actuator in a high vacuum, cold temperature, and dusty environment while applying load to the gears and motor.[15]

6. DATA ANALYSIS & RESULTS

The tests ran during 2021 and 2022 have consisted of both BMG and COTS strainwave gearsets, a three stage planetary BMG gearmotor, a motor and dust seal for VIPER, and a motor for IPEX.

BMG Strainwave Test

A litany of strainwave tests were performed. These tests ranged from COTS to BMG, and incorporated the lightweight version of the harmonic gearset.

The strainwave test ran for BMG SN3 provided an exceptional example of SED's precise temperature control. Figure 27 exhibits a ΔT of ± 2 C across 4 separate sensors. The ΔT of each individual temperature is less than ± 1 C.

The test ran at ± 100 rpm for just over two and a half hours. The test endured several load profiles and just over 15,000 input revolutions before a failure occurred. A fracture developed at the edge of one of the teeth of the flexspline and propagated to one of the other teeth; this can be seen in Figure 26. The failure is observed in the peak that exceeds 100% at the end of the gear efficiency plot of Figure 27.

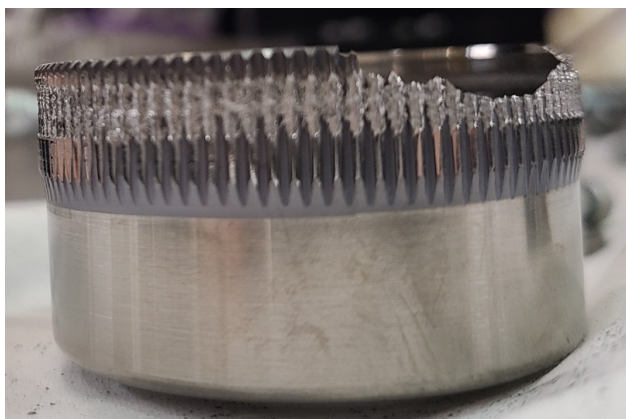


Figure 26. BMG flexspline failure post SN3 cold test

Figure 28 shows the second flexspline failure

For clarification, the gear efficiency was not below 20% for the portion of the test before 6,000 input revolutions; in fact, the calculation of the gear efficiency for a no load case is erroneous as the gear efficiency is directly proportional to the output torque. If the set output torque is zero, then output torque sensor will only record noise of the test set up, and that noise will drive the gear efficiency calculation.

It is clear that as soon as the harmonic is loaded at around 6,000 input revolutions, the gear efficiency gradually decreases until the failure occurs.

COLDArm Acceptance Test

The COLDArm acceptance tests provided interesting results. They focused on testing the lightweight version of the CSG-20 strainwave gearset. The lightweight version of the harmonic has a more compact oldham coupling. It required a completely new actuator housing design.

The first acceptance test failed before it was started due to an enigmatic anomaly. An abnormal amount of resistance of the input shaft was noticed after installation of the actuator into the chamber. Upon deliberation, the decision was made to disassemble entirely and restart the installation process. It was hypothesized that the bearings could have been the culprit, but procedure was followed so it was ultimately eliminated and the source of the friction in the input shaft was never found.

The second acceptance test ran for nearly seven days straight. The test provided a monumental achievement to the SED chamber by verifying several innovative and recent additions to the test set up. The test automated the power cycling of the cryocooler, and changed the temperature set point, as the test requirements (shown in Figure 29 provided by JPL called for various temperature set points.

The temperature was not as tightly controlled during this test. It is suspected that the CSBCs and/or the heaters were installed improperly, as the deviation in the temperature of the test article was closer to ± 5 C. In addition to a less resolute control of temperature, the COLDArm acceptance test provided a large deviation in the individual temperature sensors along the actuator.

The condensed version of the requirements of the COLDArm acceptance can be seen in Figure 29. The test incrementally increased the output torque by 10 N.m for a various number of input revolutions. The number of input revolutions at each load is based on the conops of the COLDArm mission.

The COLDArm acceptance test were performed at ± 10 rpm, a load of 0 to 60 N.m, and consisted of three temperature set profiles (seen best in Figure 30): ambient, -100 C and -180 C. Once again, the gear efficiency is seen to gradually decrease once the harmonic is loaded. The random peaks in the gear efficiency plot are due to direction changes.

Figure 31 shows the data from all three temperature setpoints during the sixth cycle of the second COLDArm acceptance test. Each cycle took roughly 24 hours to complete (including cool-down and warm-up times.

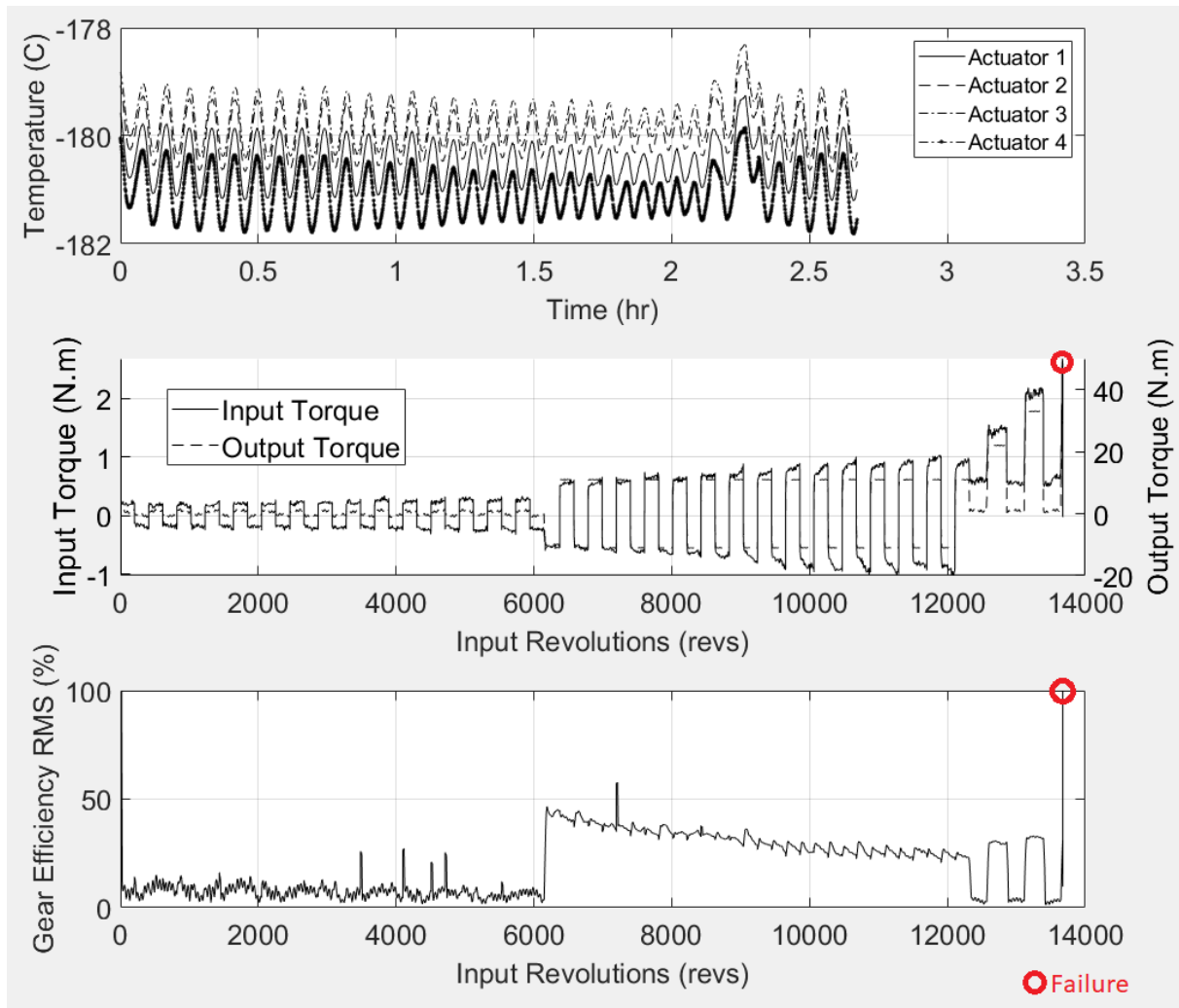


Figure 27. Temperature, Input Output Torque, and Gear Efficiency of BMG SN3 cold test

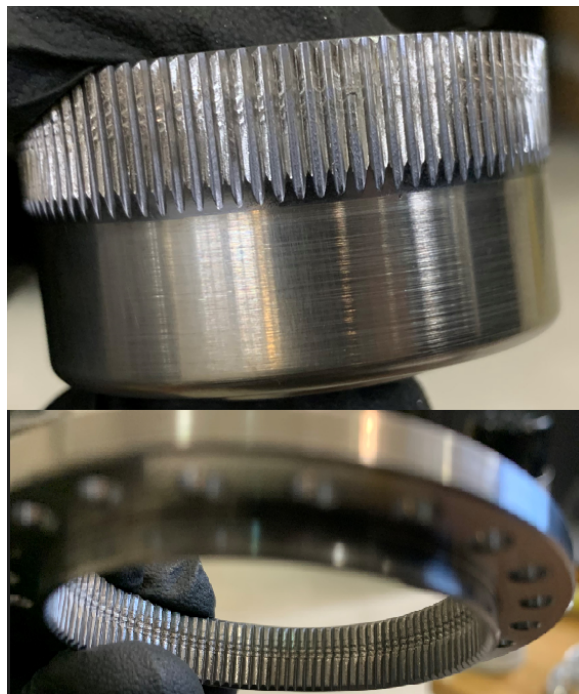


Figure 28. BMG flexspline failure post COLDArm Acceptance Test 2

The test gear efficiency eventually dropped to a point such that the generated input torque was above the capacity of the input torque sensor. The test unfortunately had to be disassembled without breaking the test BMG strainwave test article. The wear of the outer teeth of the flexspline, as well as the wear of the inner teeth of the circspline, can be seen in Figure 28.

This unfortunate event did prompt a much needed upgrade and thus a torque sensor was ordered. This new torque sensor has a higher capacity and the ability to integrate with future strainwave tests.

Other Tests

The motor for the VIPER test, as well as the gearbox, was properly maintained at the designated environmental conditions throughout the entire test. The introduction of dust into the motor-gearbox configuration caused the motor to seize after a short time, each iteration the direction of the velocity changed.

The tests performed for IPEX thus far have been preliminary torque constant verification tests for one of the actuators. It is suspected that the torque constant, is not constant at all and varies noticeably with temperature. This relationship has

Step	Load (Nm)	Speed (rpm)	Ramp (rpm/s)	Duration (input revs)	Duration (output revs)	Temperature (deg C)	Notes
1	No Load	+/- 10	5	100	2	25 +/-25	Change direction every 50 input revs
2	10	+/- 10	5	2200	44	25 +/-25	Change direction every 50 input revs
7	60	+/- 10	5	500	10	25 +/-25	Change direction every 50 input revs
8	No Load	+/- 10	5	100	2	25 +/-25	Change direction every 50 input revs
Total Ambient Input Revs: 4,280 Total Ambient Output Revs: 85.6							
Cool to -180 deg C +/-10 deg C; Reverse initial rotation direction at start of each new cold series.							
9	No Load	+/- 10	5	100	2	-180 +/-10	Change direction every 50 input revs
10	10	+/- 10	5	440	8.8	-180 +/-10	Change direction every 50 input revs except only 40 input revs for last cycle
15	60	+/- 10 (+/- 5)*	5	20	0.4	-180 +/-10	Change direction every 10 input revs
16	No Load	+/- 10	5	100	2	-180 +/-10	Change direction every 50 input revs
*Speed change from 10 rpm to 5 rpm to complete 2nd step 15.							
Total Cold Input Revs: 760 Total Cold Output Revs: 15.2							
Warm to 25 deg C +/- 25 deg C and repeat steps 1 through 16							

Figure 29. Test Procedure for the COLDArm Acceptance Test

begun to be delved into, though it needs to be investigated further.

A BMG gearmotor was tested in the SED chamber.

7. SUMMARY

Cryobotics is an important field of research that requires complex hardware integration. The SED chamber offers a solution to testing motors, gearboxes and actuators at temperatures and pressures equivalent to that of the moon. The testing of motors, gearboxes and actuators in a simulated space environment is crucial as key motor parameters, such as the gear efficiency and the torque constant, change with deviations in temperature and pressure.

The SED chamber is able to run virtually any test profile that calls for any array of temperature setpoints, velocities, torque setpoints and exit criteria (time vs. revs). This capability is due to SED's implementation and integration of the vacuum chamber with the cryogenic subsystem, being able to be monitored by the pressure transducer and various temperature sensors. The modularity of the torque sensors, feedthroughs, brakes, EDMS and motor controllers allow for most tests to be set up and performed in short time spans. The DAQ system, coupled with the UI & software, provide the test with a robust and powerful test potentiality. The various innovations, such as the EDMs and the CSBCs, allow for efficient and effective tests to be performed. The comprehensive procedure ensures that every test is treated with attentive detail.

The tests performed thus far in the chamber have been

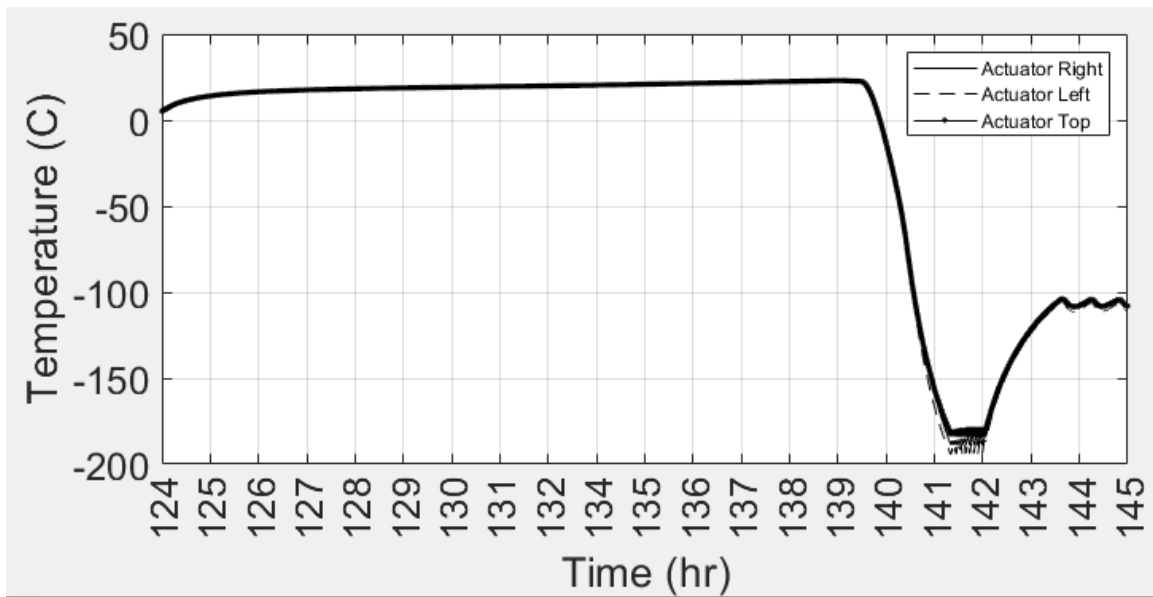


Figure 30. Temperature, Input & Output Torque, and Gear Efficiency of COLDArm Acceptance Test 2

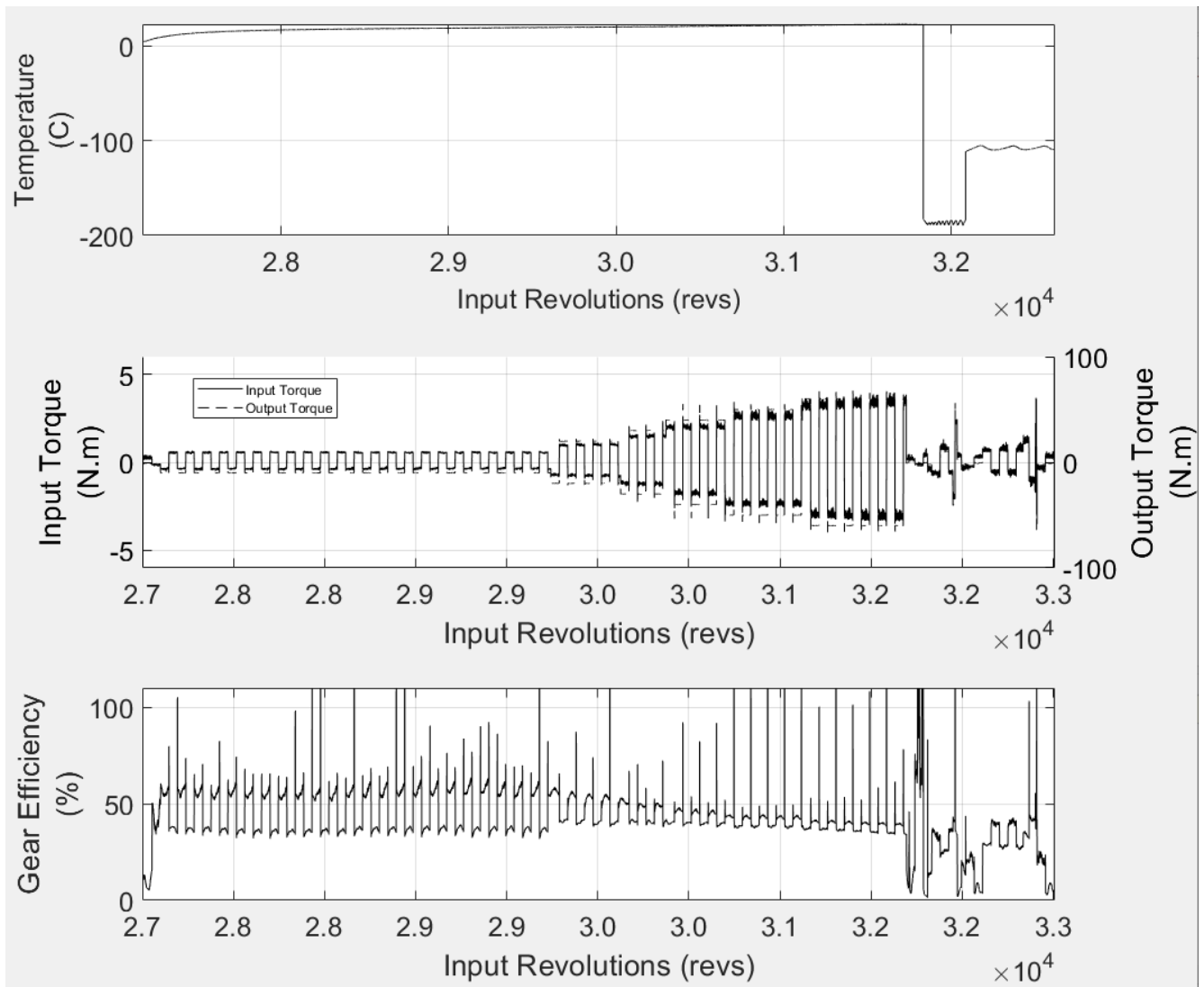


Figure 31. Temperature, Input & Output Torque, and Gear Efficiency of COLDArm Acceptance Test 2

beneficial to a variety of projects. In addition, the tests have provided insight into shortcomings and limitations of SED. These limitations were thoroughly investigated and were ultimately mitigated before moving on to a next test. This research project has provided a fantastic insight into the area of cryobotics and will continue to conduct experiments for a variety of NASA's upcoming missions.

8. LESSONS LEARNED

The method and structure of the assembly of the copper straps and band clamps is paramount for meeting temperature set point requirements. A sparse amount of copper straps, as well as inadequate clamping of the copper straps into the coldplate, can lead to insufficient heating; where as an uneven distribution of the copper straps wrapped on the test article, as well as inadequate circumferential compression force of the copper straps around the test article, can lead to uneven temperature distribution of the actuator.

The fragility of the temperature diodes created problems incorporating them into monitoring the temperature of the test article. The test article is wrapped with several layers of copper and metal. These layers often damage the 36 AWG leads of the diodes, as well as damage the diodes themselves. To mitigate this, the diode isn't installed until the very end of the test set up, immediately before closing the chamber. Leaving the installation to the end eliminates several potential hazards that the diode was exposed to in previous tests.

9. FUTURE WORK

Additional torque sensors and brakes would increase the experimental capabilities of SED. An in depth analysis of the systematic errors and calculus-based error propagation would add fidelity to the test results. Installing a touch screen on the test stand to monitor and control the the test via the UI would be useful for explaining the test set up to vistors of Swamp Works.

The chamber will be updated and modified and accordingly to accommodate any and all tests that need to be performed to qualify all of the motors used by IPEX.

ACKNOWLEDGMENTS

The authors thank each and every one of the various technology companies that provide the hardware that integrates together to create this convoluted test set up. The authors would also like to thank the various personnel at KSC who are not on this paper, but offered a helping hand throughout the years the project has been in use.

REFERENCES

- [1] J. D. Smith, A. J. Nick, J. M. Schuler, A. Kennett, and R. P. Dillon, "Cryobotics: Extreme cold environment testing of strain wave gear sets," *2019 IEEE Aerospace Conference*, 2019.
- [2] "High Quality Gauges and Controllers for Accurate Vacuum Measurement," *Agilent*. [Online]. Available: <https://www.agilent.com/en/product/vacuum-technologies/vacuum-measurement/vacuum-transducers>. [Accessed: 29-Sep-2022].
- [3] A. DeHennis and J. Chae, "Pressure sensors," *Comprehensive Microsystems*, pp. 101–133, 2008.
- [4] "Gifford-McMahon cryocoolers," *Cryomech*, 10-Mar-2022. [Online]. Available: <https://www.cryomech.com/cryocoolers/gifford-mcmahon-cryocoolers/>. [Accessed: 29-Sep-2022].
- [5] "OPC-Series," *Haskris*, 30-Oct-2020. [Online]. Available: <https://haskris.com/products/outdoor-process-chillers-opc-series/>. [Accessed: 29-Sep-2022].
- [6] "Types of Thermocouples," *Omega*. [Online]. Available: <https://www.omega.com/en-us/resources/thermocouple-types>. [Accessed: 29-Sep-2022].
- [7] "T-station 300 pumping stations Edwards," *Edwards*. [Online]. Available: <https://www.edwardsvacuum.com/en/our-products/turbomolecular-pumping-stations/T-station-300>. [Accessed: 29-Sep-2022].
- [8] "Servo Drive Gold Family," *Elmo*, 09-Jun-2022. [Online]. Available: <https://www.elmome.com/products/industrial-environment/servo-drive-gold-family/>. [Accessed: 29-Sep-2022].
- [9] "Platinum," *Lakeshore*. [Online]. Available: <https://www.lakeshore.com/products/categories/overview/temperature-products/cryogenic-temperature-sensors/platinum>. [Accessed: 29-Sep-2022].
- [10] "Frameless Motors," *Parker*. [Online]. Available: <https://ph.parker.com/us/en/division-engine-mobile-hydraulic-and-fuel-filtration-division/frameless-motors>. [Accessed: 29-Sep-2022].
- [11] "Feedthrough model: SSL-005-NN part number: 133601 - ferrofluidic seals %," *FerroTec*, 15-Nov-2018. [Online]. Available: <https://seals.ferrotec.com/products/ferrofluidic-vacuum-rotary-feedthroughs/133601/>. [Accessed: 29-Sep-2022].
- [12] D. C. Hofmann, R. Polit-Casillas, S. N. Roberts, J.-P. Borgonia, R. P. Dillon, E. Hilgemann, J. Kolodziejaska, L. Montemayor, J.-ook Suh, A. Hoff, K. Carpenter, A. Parness, W. L. Johnson, A. Kennett, and B. Wilcox, "Castable bulk metallic glass strain wave gears: Towards decreasing the cost of high-performance robotics," *Scientific Reports*, vol. 6, no. 1, 2016.
- [13] M. Guerges, "Cold operable lunar deployable arm (COLDArm)," *NASA*, 11-Jan-2022. [Online]. Available: <https://www.nasa.gov/feature/cold-operable-lunar-deployable-arm-coldarm>. [Accessed: 29-Sep-2022].
- [14] E. Vitug, "Bulk Metallic Glass Gears (BMGG)," *NASA*, 07-Apr-2020. [Online]. Available: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/BMGG/. [Accessed: 29-Sep-2022].
- [15] R. Chen, "Viper mission overview," *NASA*, 05-Feb-2020. [Online]. Available: <https://www.nasa.gov/viper/overview>. [Accessed: 29-Sep-2022].

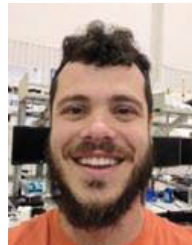
BIOGRAPHY



Casey Clark received a B.S. and M.S. in Aerospace Engineering from Florida Institute of Technology in 2016 and 2018, respectively. He is the lead test engineer at Swamp Works NASA Kennedy Space Center. His interests include nonlinear control systems, multivariable feedback control systems, cryobotics and robotic design.



Drew Smith graduated in 2009 with a B.S. in Mechanical Engineering from the University of North Florida. Upon graduating, he was hired into the NASA Engineering Safety organization. In 2011 transferred to the Granular Mechanics and Regolith Operations (GMRO) laboratory and is a co-founder of Swamp Works at KSC. He has designed and tested multiple percussive excavation end effectors for NASA's Jet Propulsion Laboratory, Glenn Research Center, and Johnson Space Center. He is also an inventor of patented extraterrestrial mining robots for in situ resource utilization. Drew is currently the Lead Design Engineer for Swamp Works.



Andrew Nick received a B.S. in Mechanical Engineering from Florida Institute of Technology in 2007. He was a contractor for NASA at the Kennedy Space Center for over 13 years before converting to civil servant in 2020. As a founding member of Swamp Works at KSC, he has spent most of his career developing control systems for exploration and utilization of planetary surface.



Victoria Ortega received a B.S. in Mechanical Engineering from Carnegie Mellon University. She was a Pathways Intern in 2021 at Swamp Works NASA Kennedy Space Center for the project Mini RASSOR and was converted to a full-time position in 2022. She now supports mechanical design, testing, and analysis for ISRU Pilot Excavator in Swamp Works.



Robert "Peter" Dillon received a BSc. in Materials Engineering from CalPoly, SLO and MSc. and PhD in Materials Science and Engineering from the University of California, Irvine. He started at NASA's Jet Propulsion Laboratory in 2008 as a Technologist in the Advanced Electronic Packaging Engineering group and is currently the Technical Group Supervisor of the Materials Development and Manufacturing Technology Group. Since 2015 he has also been the project manager for the NASA Game Changing Development Program's Bulk Metallic Glass (BMG) Gears project, leading the development of unheated cryo-capable actuators.



Andrew Kennett received a B.S. and in Mechanical Engineering from MIT as well as an M.S. from UCLA. He is currently involved in the development of the Mars Sample Return Lander Platform as well as a handful of technology development tasks. He was previously the Mechanical Systems Engineer for the Mars 2020 Motion Control Subsystem, where he was responsible for delivering motion control performance for all of the rover actuator applications (excluding payloads).



Bradley Buckles is a Robotics Engineer in the Granular Mechanics and Regolith Operations Laboratory (GMRO) at the NASA Kennedy Space Center. He has a background in mechanical engineering and computer science, and began his career in control systems and automation. He is interested in all things robotics and autonomy.