Space Technology Mission Directorate

Game Changing Development Program

Derek Quade | Justin Scheidler | FY23 Motors for Dusty and Extremely Cold Environments (MDECE) Annual Review Presentation | 09.21.23
POC: Derek Quade | Derek.J.Quade@nasa.gov

MDECE Overview

Technology Development Needs Addressed by Project		
ESDMD Human Surface Mobility Program	Help provide safe, reliable and effective HSM capabilities via state-of-the-art magnetically-geared motors for EVA's	TX12 Materials, Structures, Mechanical Systems and Manufacturing

Project Goals	
Goal #1	Develop and demonstrate in a relevant thermal-vacuum environment, an unheated magnetically-geared motor that can operate continuously for a long duration at an ambient temperature of -243 °C (30 K)
Goal #2	Develop Proof of Concept build for an unheated piezoelectric motor that can operate continuously for a long duration at an ambient temperature of -243 °C (30 K)

Project Objectives	
Objective #1	Fabricate and assemble each prototype motor and integrate with their drive electronics for magnetically-geared motor (MG)

MDECE Team

Program Element Manager: LARC-D/Robert Parker
Project Manager: GRC-MT/Derek Quade
Technical Resource Manager: GRC-MB/Michael Anderson
Project Lead Engineer: GRC-LMR/Justin Scheidler

Principle Technologists: KSC-UBG/Angela Krenn
JSC-ER/Joshua Mehling
System Capability Team Lead: LARC-D/Danette Allen

GRC
Lead: LMR/Justin Scheidler

- LED/Aaron Anderson
- HX5/George Harpster
- HX5/Jesse Hawk
- HX5/Peter Hoge
- LMT/Adam Howard
- LMR/Thomas Tallerico
- HX5/Kyle Whitling
- MB/Michael Anderson

GSFC

- 5520/James Tuttle
- 5520/Amir Jahromi

JPL
Lead: 355N/Yoseph Bar-Cohen

- 355N/Mircea Badescu
- 355N/Louis Giersch
- 355N/Hyeong Jae Lee
- 355N/Stewart Sherrit

KSC
Lead: UBE/Drew Smith

- UBE/Bradley Buckles
- Eng. Res. & Consult./Casey Clark
- Eng. Res. & Consult./Matthew Nugent
- UBE/Drew Smith

Collaborations & Partnerships

- ➢ Contributing partners and stakeholders
  - GRC, GSFC, JPL, KSC
  - SBIR Phase 2 Lunar Sequential & Phase 1s
  - Cryogenic material testing @ AFRC & AFRL
- ➢ Infusion/transition plan
  - Target applications
    - Magnetically-geared motor: higher power, higher torque
      - Rover wheels ▪ ISRU (drills, buckets, etc.) ▪ rotors ▪ robotic arms
  - NASA mission(s) impacted
    - Search for life on Mars, Titan, Europa, Enceladus
    - High speed communication on the Moon & Lunar Gateway
    - The Moon, Mars, Others inside solar system, Foundational knowledge

NASA Centers

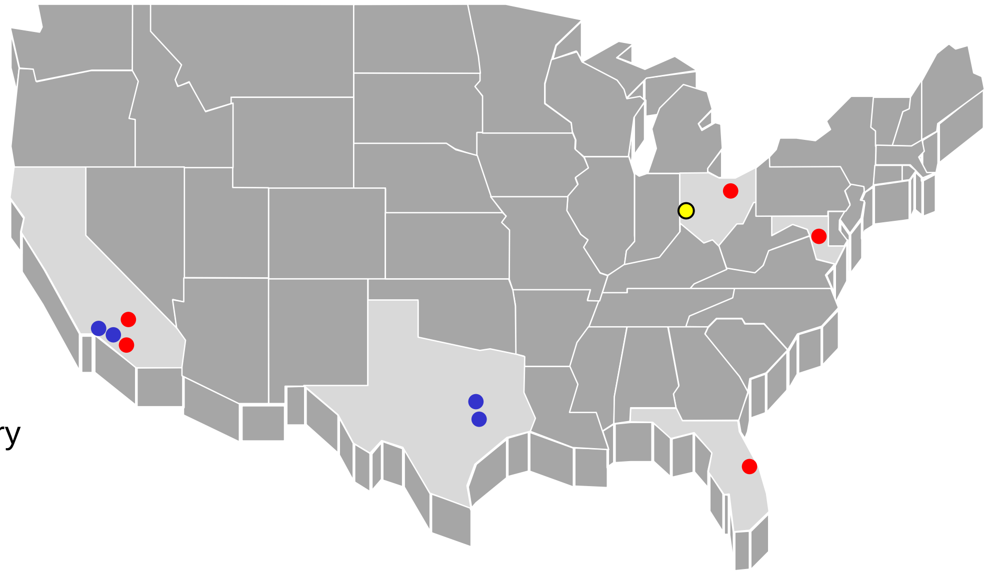
- GRC
- GSFC
- JPL
- KSC
- AFRC

SBIR/STTR

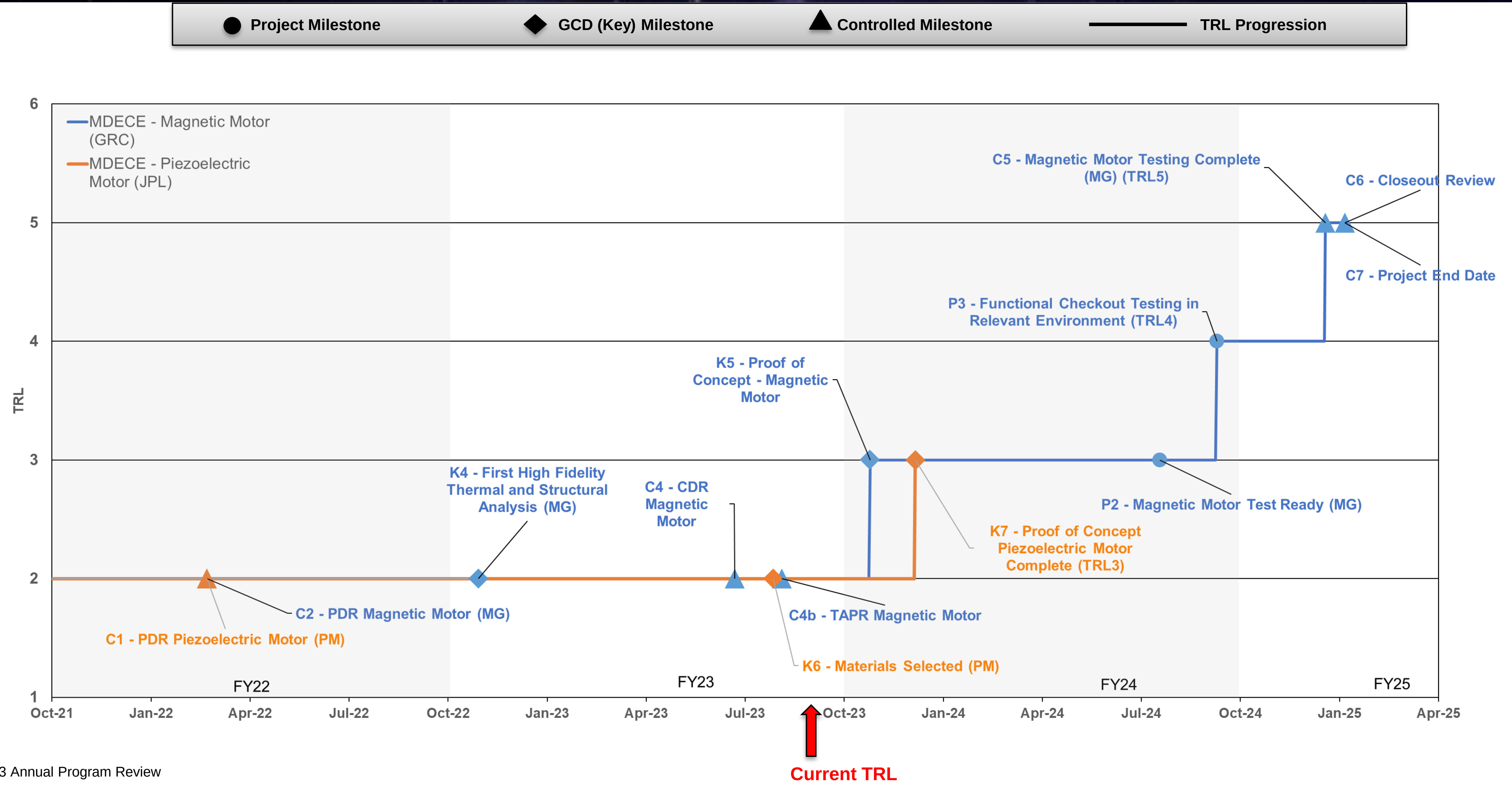
- Motiv Space Systems
- US Hybrid / Texas A&M U.
- FluxWorks / U. Texas Dallas

Other Government

- Air Force Research Laboratory (AFRL)



Motors for Dusty and Extremely Cold Environments
Technical Readiness Level



Accomplishments – Magnetic Actuator

C3 milestone completed (Critical Design Review and TAPR)

- Work completed (see later accomplishment slides):
  - Optimized electromagnetic design of actuator’s magnetically-geared motor and cycloidal magnetic gear
  - Optimized selection of each bearing considering full temperature range
  - High fidelity thermal analysis over every steady state operating condition & environment and critical transient conditions
  - High fidelity structural analysis at room temperature, hottest and coldest conditions, and worst case internal temperature gradients
  - Dust seal design and sub-scale testing
  - Design for manufacturing and tolerance stack up
  - Final predictions of actuator’s efficiency & bearing life

Metric		Unit	Threshold Value	Goal Value	Expected value
Actuator life (dust free)		output cycles	6,000	50,000	**46,500** (including bearings)
Avg. total efficiency in lunar PSR		%	60	80	**75 to 88**
Torque output	Continuous	Nm	≥ 105		**105**
	Short duration		≥ 208		**208***
Speed output	Continuous	rpm	≥ 2	≥ 2	**2**
	Short duration		> 0	1.5	**1.5**
Mass		kg	≤ 4.73	≤ 3.15	**4.55**† **5.30**‡
Length / diameter aspect ratio		-	0.50 to 1.75		**1.44**
Envelope volume		cm^3	≤ 1,440	≤ 960	**2,317**

* includes 10% margin on 3D predictions at largest anticipated air gap

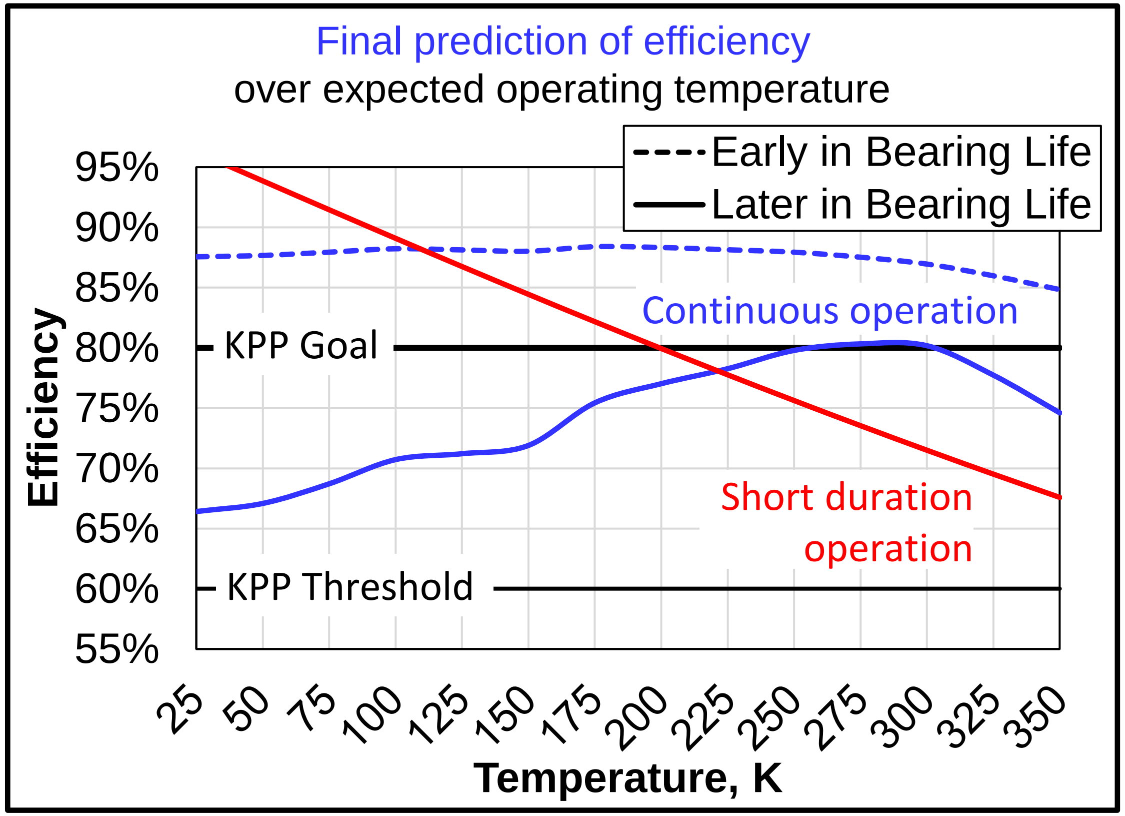
† Mass if resolver not needed, not including a brake (~0.1 kg)

‡ Mass if resolver needed, not including a brake (~0.1 kg)

Accomplishments – Magnetic Actuator

Final efficiency, power loss, and bearing life estimates obtained

- Background: The magnetic actuator has KPPs for efficiency and life, both under continuous operation. Although the life does not include the bearings, the actuator is designed to ensure meaningful bearing life
- Work completed:
  - Revised bearing design code & optimized bearing selection (see later accomplishment slide)
  - Re-optimized electromagnetic design of the cycloidal magnetic gear and magnetically-geared motor
  - Evaluated bearing losses and all electromagnetic losses in the gear and motor over full temperature range for continuous and short duration operating conditions
- Results:
  - Loss in bearings increases throughout their life due to change in lubrication from one mechanism to another
  - KPP efficiency goal should be met throughout most of bearing life and temperature range; always healthy margin to KPP threshold
  - Predicted bearing life nearly meets KPP goal

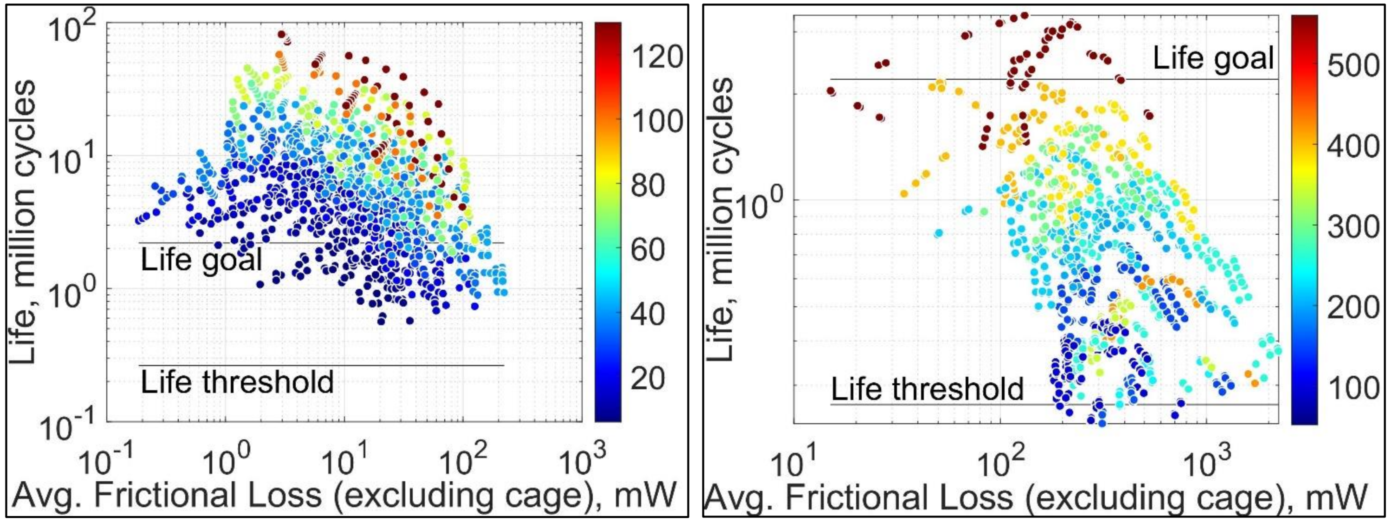


Accomplishments – Magnetic Actuator

Bearing optimization completed

- Background: to support 7 rotors, the actuator contains 34 bearings ▪ life of dry film lubricated bearings is a known limitation due to relatively large bearing loads or long life goal
- Work completed: wrote bearing optimization code that considers thermal expansion, thermal conductance, preload, geometry constraints, desired shaft & housing fits, & materials for each bearing ▪ evaluated full catalog of bearings for each instance in actuator
- Results:
  - Bearings selected to balance tradeoffs between mass, life, and power loss (efficiency)
  - Total mass of bearings = 0.73 kg (16% of actuator)
  - Avg. total loss of bearings =
    15% of actuator's loss (earlier in bearing life)
    53% of actuator's loss (later in bearing life)

Optimization results for mass (grams) of a lightly loaded (left) & heavily loaded (right) bearing



Final prediction of bearing life at continuous operating condition
(average over actuator's primary internal temperature range)

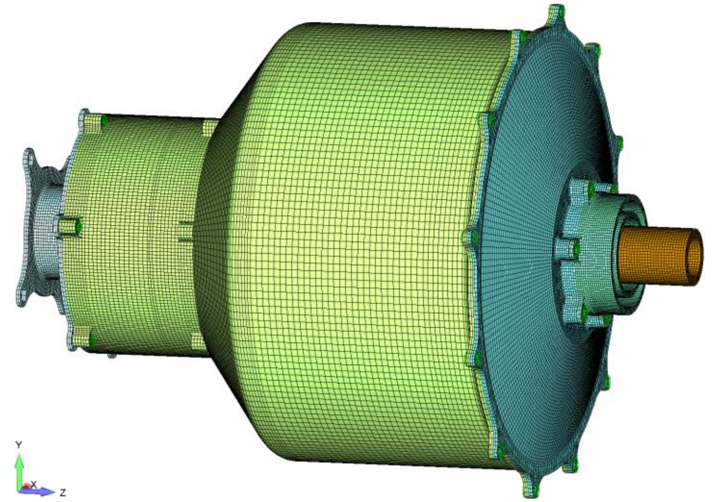
	Bearing																
	1-2	3	4	5	6	7	8	9	10	11	12	13	14	15-18	19-22	23-26	27-30	31-34
Life relative to KPP goal	0.93x	1.1x	0.97x	5.5x	4.0x	2.7x	1.3x	1.3x	1.1x	1.8x	1.5x	8.1x	>10x	4.0x	7.2x	9.3x	>10x	3.4x

Accomplishments – Magnetic Actuator

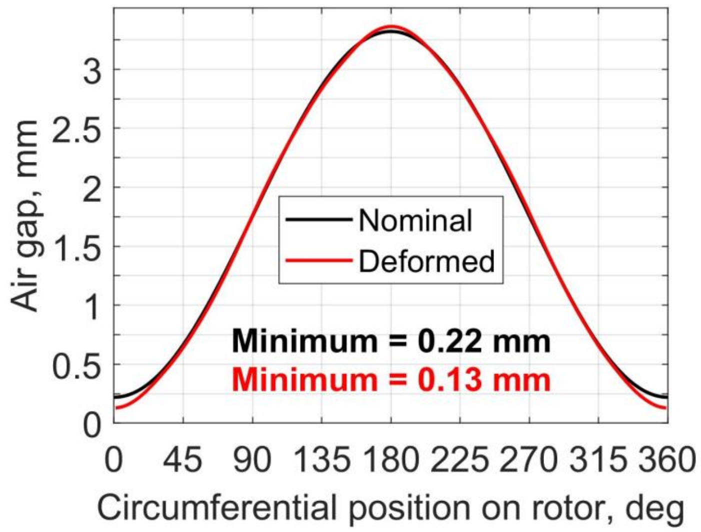
High fidelity structural model of initial critical design built

- Background: a refined structural analysis is required to ensure stress margins and deformations are satisfactory and also to accurately determine the load applied on each of the actuator’s bearings.
- Work completed:
  - Geometry carefully meshed to ensure accurate results
  - Each bearing represented by spring elements with unique stiffnesses calculated by a bearing design code
  - All constraints and loads (mechanical, magnetic, thermal) included
- Results:
  - Minimum air gaps acceptable under worst case tolerance stack up and worst case structural deformation
  - All positive margins of safety at room temperature and hottest condition
  - At extreme cold, all margins positive except for acceptable concern in small regions of epoxy

Meshed geometry of the magnetically-geared actuator



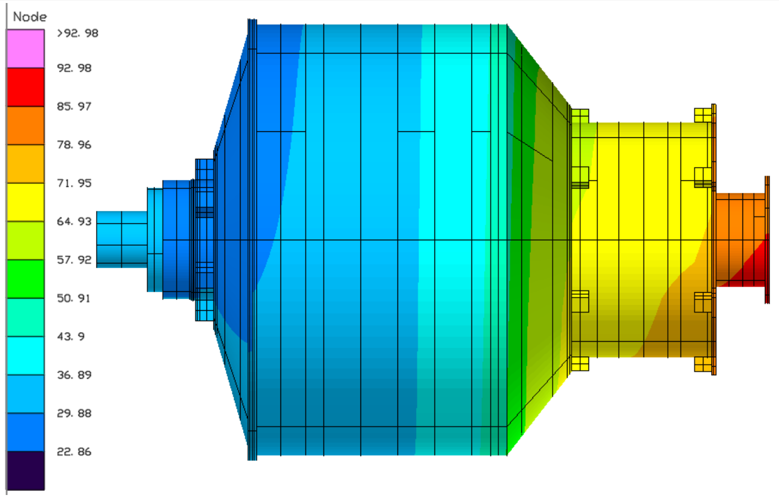
Cycloidal magnetic gear: comparison of nominal air gap (including worst case tolerance stack up) to structurally deformed air gap



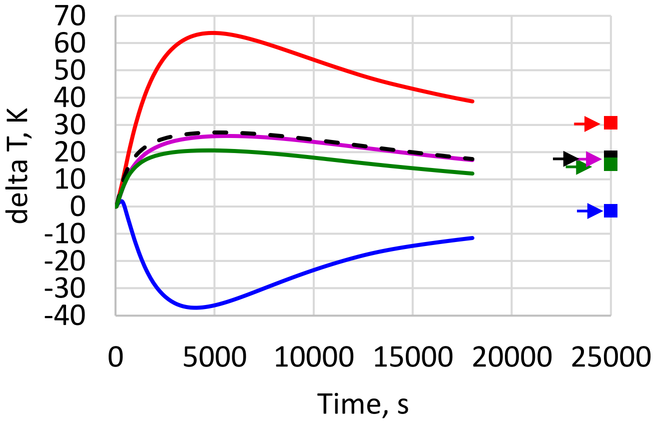
Accomplishments – Magnetic Actuator

Final thermal analysis completed

- Background: Thermal analysis is required to determine min and max temperature of each component, temperature gradient across each bearing (to refine life & power loss predictions), & temperature distributions for quantifying thermal stresses
- Work completed: built model of entire actuator, regolith, & solar heating in commercial software ▪ included temperature-dependent heat loads, material properties, and bearing thermal conductances ▪ simulated steady-state response for every specified thermal condition & transient response for warm up & cool down to/from every important condition
- Results:
  - In general, temperature gradients across air gaps and bearings are significantly larger than predicted at PDR due to considerable temperature dependence of loss, increased loss at low temperatures, and smaller (but more realistic) bearing thermal conductances
  - No material limits exceeded, although preferred epoxy may soften too much at upper end of temperature range
  - Operating (op) conditions to consider in structural analysis: worst-case hot* ▪ room temperature ▪ worst-case cold** ▪ coldest
    - * end of transient peak op starting at steady continuous op, 85 deg S latitude, in sun, on 21º slope inclined toward sun
    - ** ~4,000 seconds into continuous op warm up starting at survival in permanently shadowed region with 30 K regolith



External temperatures (deg C) at steady state for continuous operation at the goal hot operating condition (85 deg S latitude, in sun, on 21 deg slope inclined toward sun)

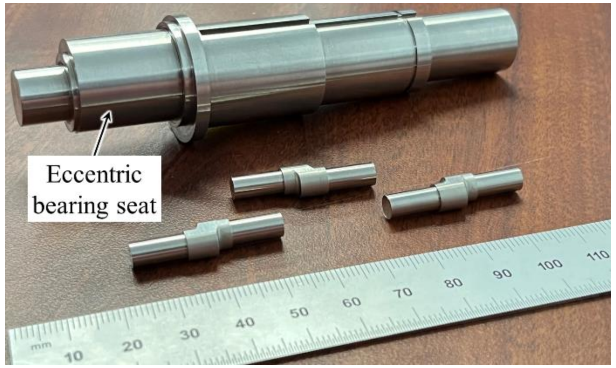


Example results: temperature difference across each air gap during worst-case warm up (start at 25 K cold soak, 20 second peak operation, then 300 minute continuous operation)

Accomplishments – Magnetic Actuator

Proof-of-concept cycloidal magnetic gear assembled

- Background: A proof-of-concept prototype is being built and tested to verify the manufacturing and assembly processes, to test functionality, and to measure its performance at speed. Leveraging prior aero work for the motor half of actuator, but cycloidal magnetic gear half is completely new to GRC team.
- Work completed:
  - Procured fabricated parts and magnet subassemblies
  - Assembled complete cycloidal magnetic gear, including structural and magnetic parts and bearings
  - Completed initial functionality test
- Results:
  - Magnets & iron lamination stacks had very small thickness-to-length aspect ratio and required delicate handling – led to 1 rework & elevated magnet scrap rate during assembly
    - Eliminated these lamination stacks in final actuator
  - Cycloidal gear's input shaft & pins (precision parts) met drawing specifications & functioned as planned
  - No issues aligning & assembling rotating components
  - Lathe successfully used for final assembly step where strong magnetic forces encountered
    - Can't use this for final actuator (assembly in controlled environment required), but simple alternative seems likely to work
  - Internal components move as expected & seem to produce desired gear ratio
  - Faint, grinding-like noise needs investigation; expectation: fine magnet debris in the 0.25 mm thick air gap



Input shaft & pins

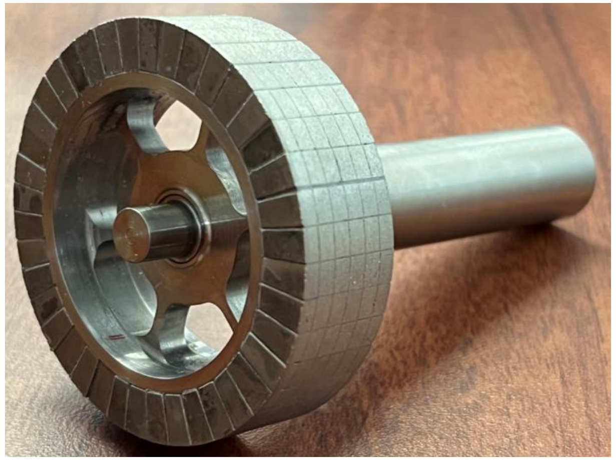
Assembly of rotating components

Assembled prototype cycloidal magnetic gear

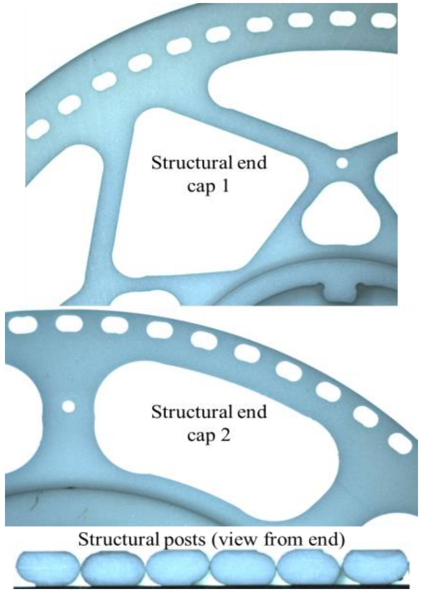
Accomplishments – Magnetic Actuator

Proof-of-concept magnetically-geared motor approaching final assembly

- Background: see previous slide
- Work completed:
  - Procured fabricated parts and magnet subassemblies
  - Finished epoxy impregnation of stator coils
  - Inspected ceramic parts to identify geometry errors
- Results:
  - Fabricated ceramic parts exhibit errors in geometry that prevent assembly (see pictures on right)
    - Revising design for final actuator to improve manufacturability of ceramic parts & identified replacement vendor
    - Replacement G10 parts procured for prototype
  - Completed magnet subassemblies seem well made – increased trust in vendor for final actuator



Sun gear assembly



Errors in geometry of slot-shaped interface in ceramic parts

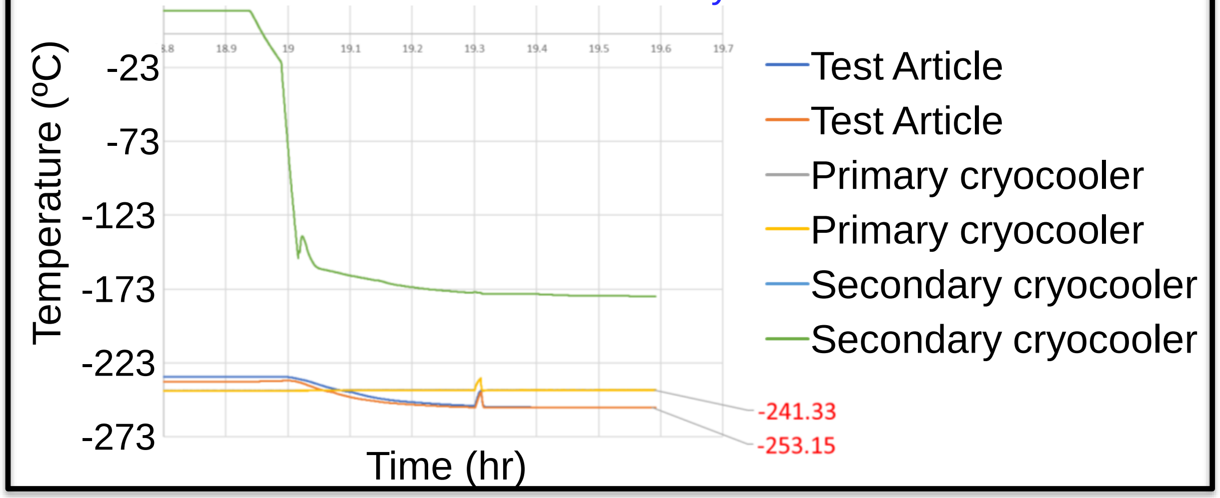
Epoxy impregnated stator

Accomplishments - Testing

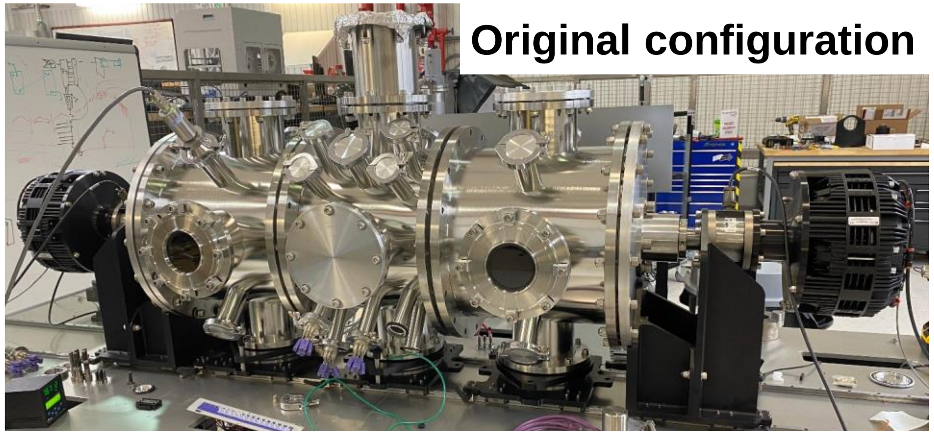
Improved cryocooling capabilities

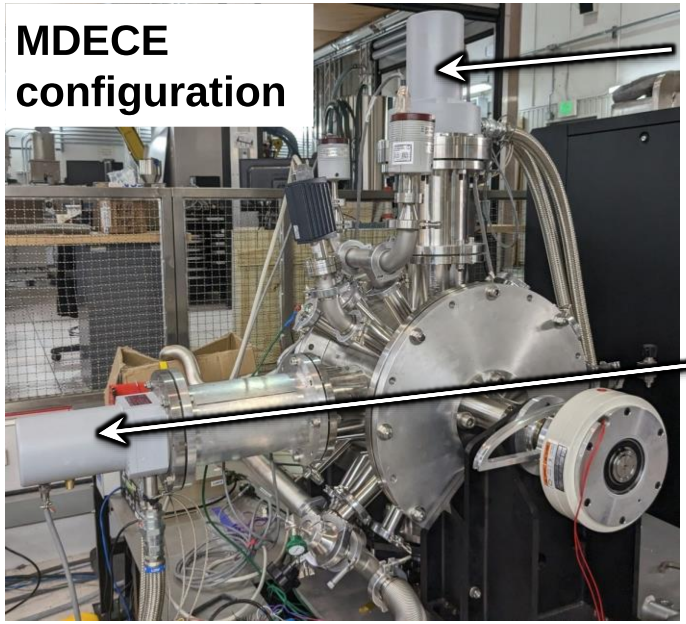
- Background: The amount of heat that cryocoolers can remove decreases significantly with temperature, which can limit how cold a test article can be cooled
- Work completed:
  - Disassembled, rearranged, and re-assembled test chamber to reduce the volume to the minimum chamber size needed to perform test
  - Procured 2nd cryocooler & demonstrated its rated performance on chamber
  - Completed cool down test of a dummy test article with no internal heat generation
- Results: Reached steady-state chamber pressure of < 10^{-6} torr and test article temperature of -235 ºC (primary cryocooler only) to < -253 ºC (both cryocoolers)

Cool down test of dummy test article



KSC's dusty Space Environment Dynamometer in the Granular Mechanics and Regolith Operations Laboratory





Secondary Cryocooler for radiant shroud and heat leak paths

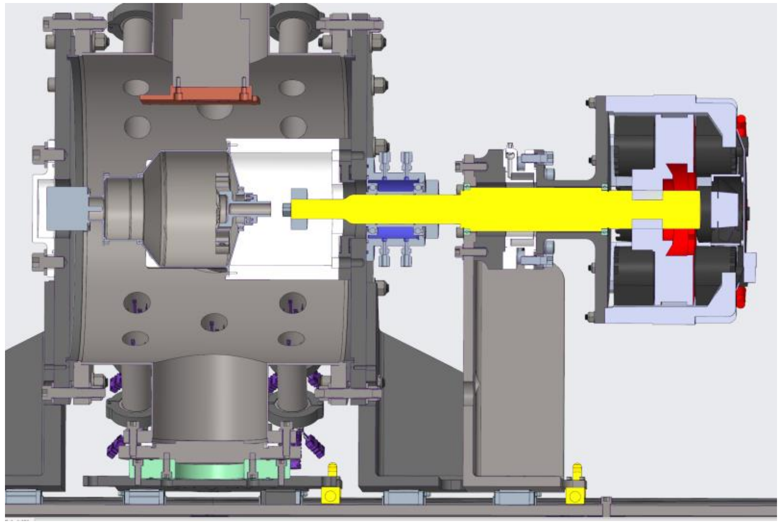
Primary Cryocooler for Test Article

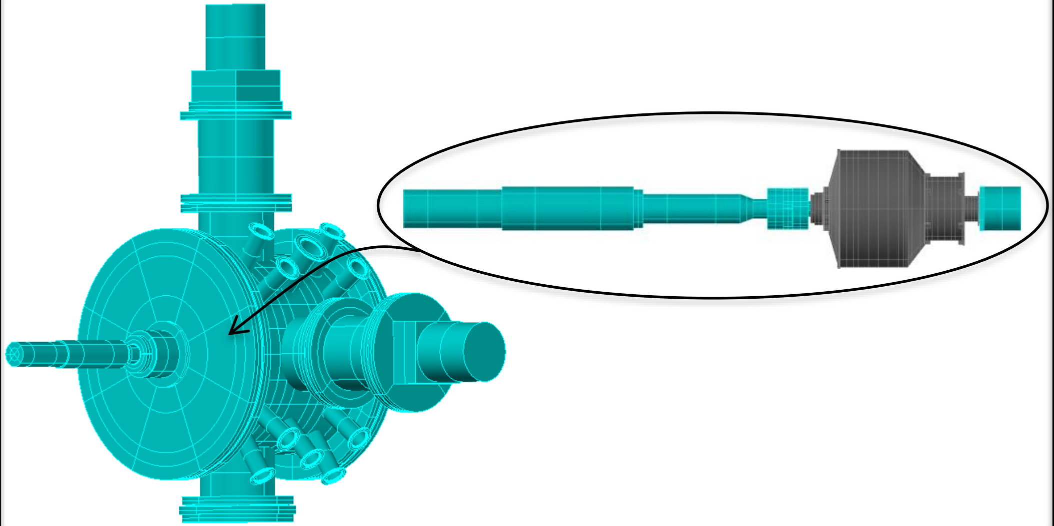
Accomplishments - Testing

Progress on improving thermal design of cryogenic vacuum chamber

- Background: Cryocooling a test article to low cryogenic temperatures requires careful thermal design of structures to minimize the heat leak into the cryogenic system
- Work completed:
  - Heat leak reduction
    - Reviewed data collected to date during cold operations to determine heat leak sources
    - Completed preliminary design of new mounts to improve thermal isolation of test article
  - Thermal conduction path improvement
    - Completed preliminary design of new thermal straps to improve heat conduction from cryocooler's cold head to test article
  - Nearing completion of thermal model of magnetic actuator in chamber
    - Will use to finalize design of mounts & thermal straps and the con-ops of the test

MDECE magnetic actuator in KSC chamber: geometry (top), thermal model (bottom)

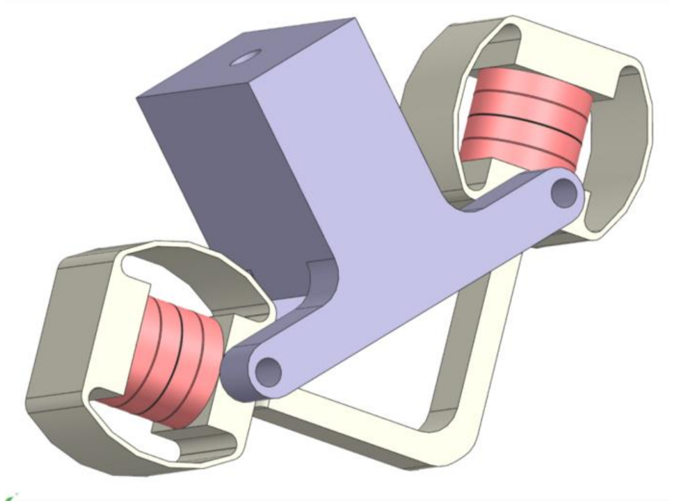




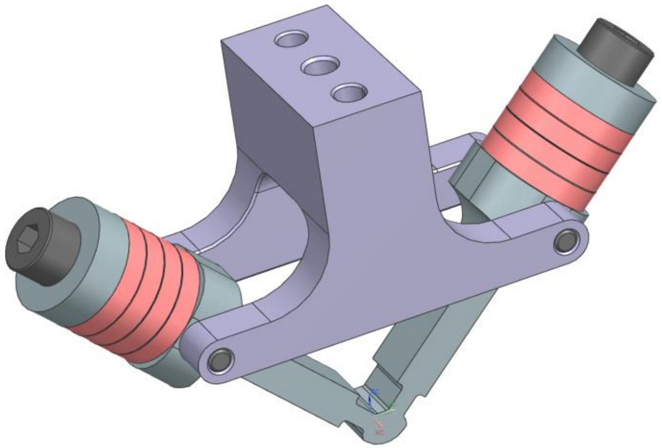
Accomplishments – Piezomotor

The V-shape Configuration

- Circular piezo-stack elements have been chosen and harmonic analyses were done to determine the resonant modes.
- The design configurations were modified to include available PZT disks and rings.
- The following configurations were considered:



Configuration 1
flexure transducer, PZT disks

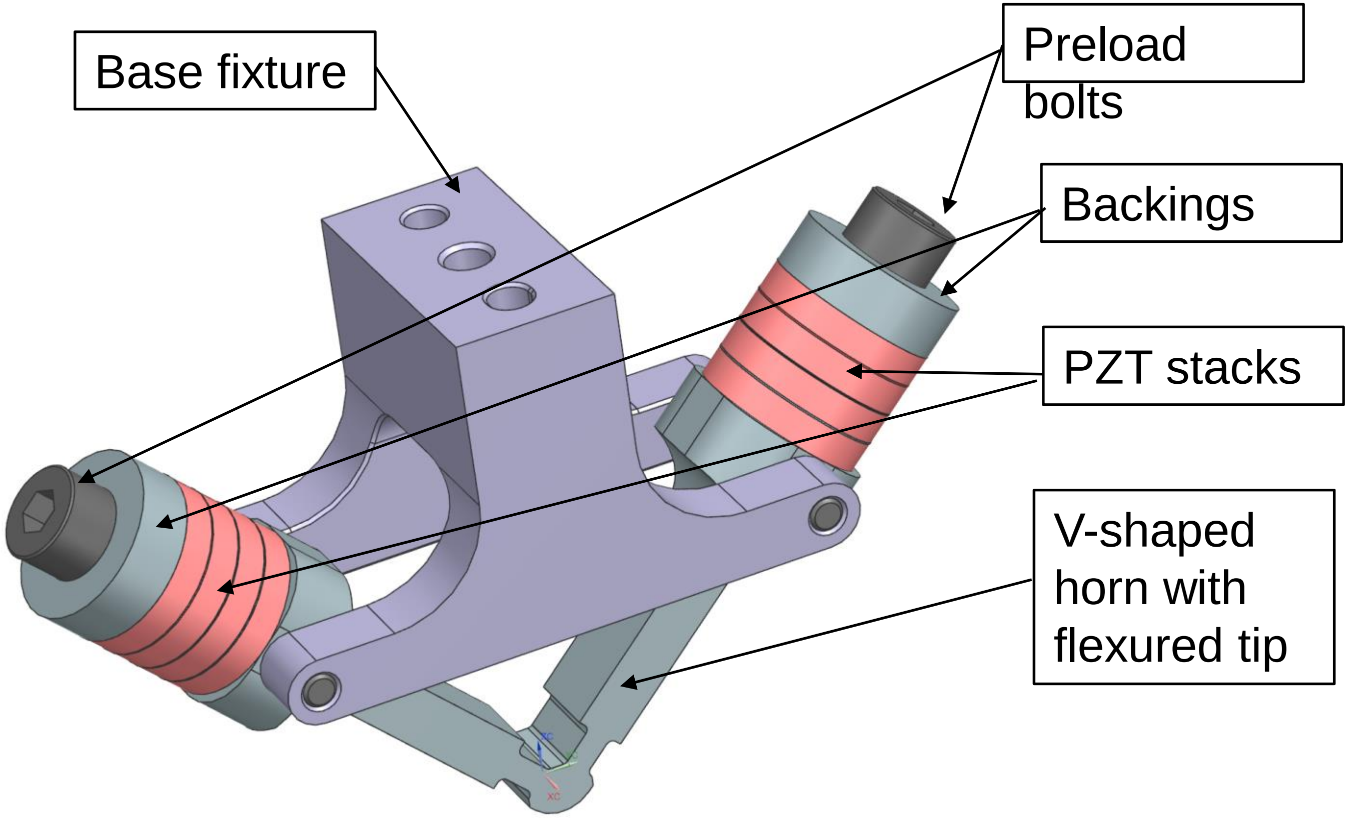


Configuration 2
Bolt preload transducer, PZT rings

- V-shape without flexure may be easier to implement
- Initial modal analysis showed resonances in the drive frequency region for using the bolt and thin flexures.

Accomplishments – Piezomotor

The V-shape Configuration



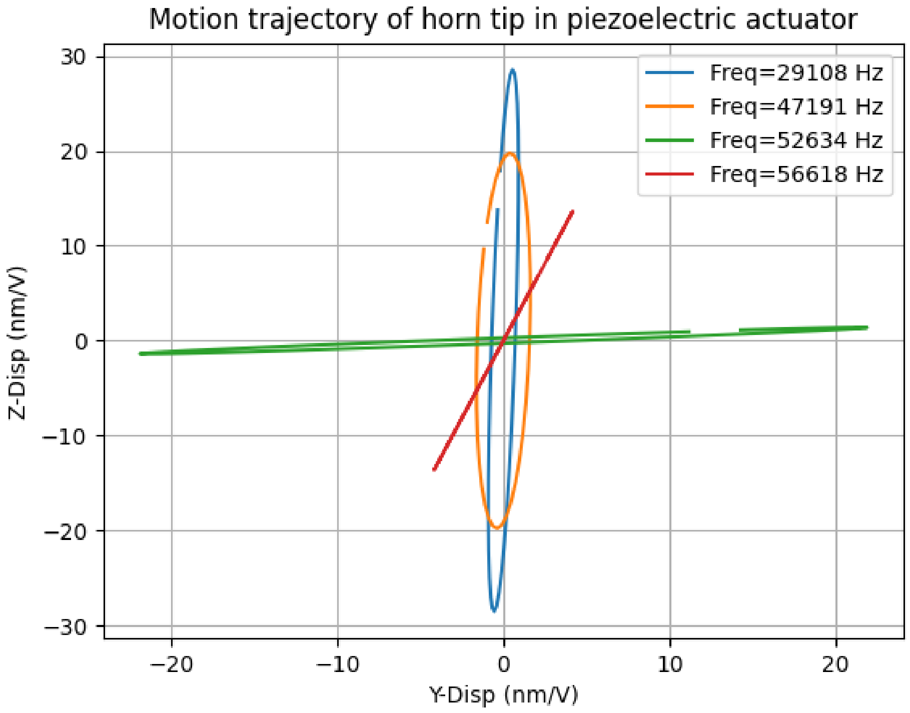
Size envelope:
70.5W x 43.5H x 22.5T

Accomplishments – Piezomotor

Motor Performance Simulation

Motion trajectory of the tip driven at 1V (horn length = 30mm)

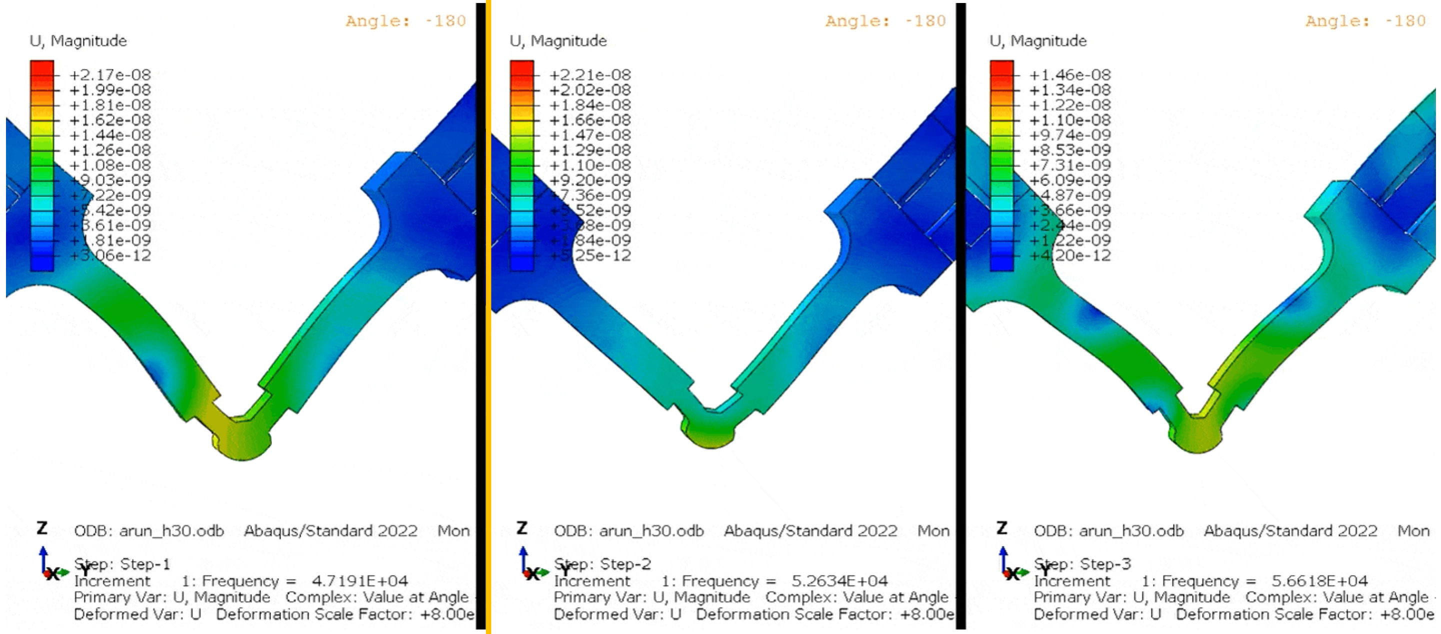
Horn Length = 30mm



47.2kHz

52.634kHz

56.618kHz

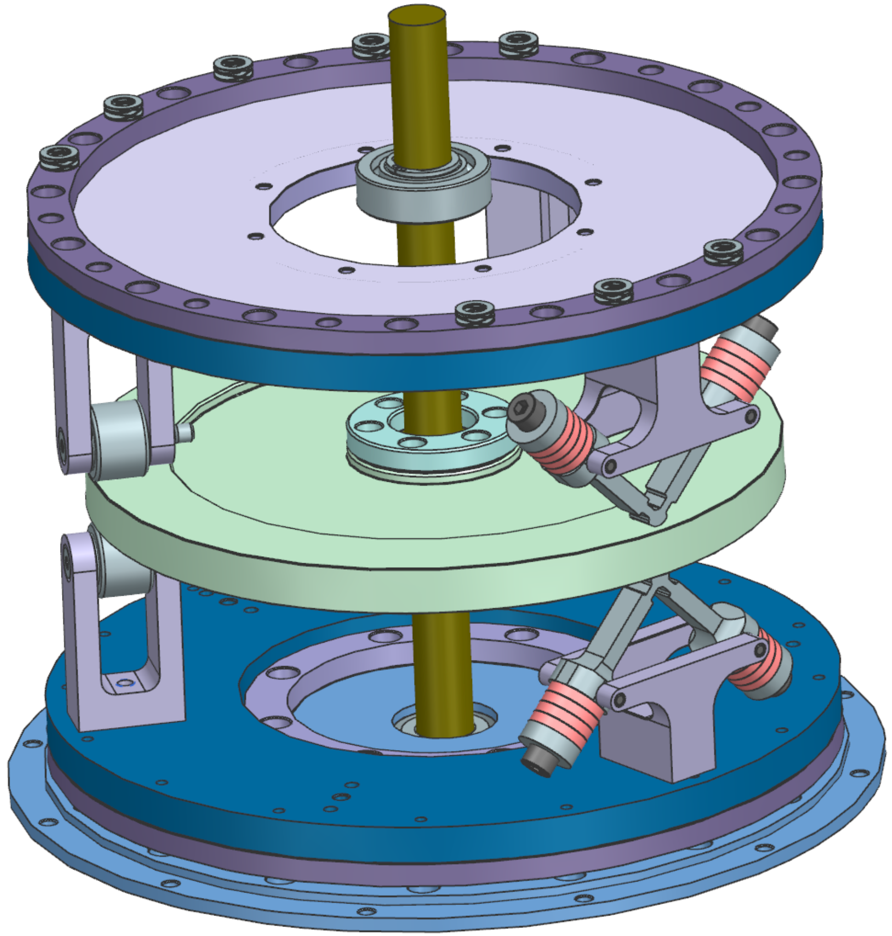


The operating frequency of 47.2kHz has been determined to provide elliptical tip motion

Accomplishments – Piezomotor

Design Configuration – Drive Components

- PZT transducers integrated with mounting bases
- Drive fixtures integrated with the floating stators
- Rotor – rotor disk clamped onto the shaft flange
- Shaft constrained by preloaded angular contact bearings mounted in a back-to-back configuration
- The motor design configuration: compliant membrane, preload springs, floating stator, base stator, housing, bearings
  - PZT disks received
  - PZT fixture parts drawings released (expected delivery: end of September)
  - Order for fabrication placed
  - Identified the required bearings, sized the preload springs sized, and other off-the-shelf components



Accomplishments - Programmatic

Assignee	RFA#	Description	Status
Justin Scheidler	1	Confirm/Assess bearing race conformity	Open – 8/11/23
Thomas Tallerico	2	Assess bearing radial loads	Open – 8/31/23
Tallerico, Scheidler, Whitling	3	Assembly plan with consideration of magnetic parts	Open – 8/31/23
Tallerico, Scheidler, Whitling, Harpster	4	Interfaces to Final Design Cross-Check	Open – 9/15/23
Justin Scheidler	5	KPP Requirements verification and Validation	Open – 10/31/23
Thomas Tallerico	6	Clarification of loads included in MGM bearing analysis and selection	Open – 8/18/23
Kyle Whitling	7	Balance of High-Speed Assemblies	Open – 8/18/23
Peter Hoge	8	Beam bending loads in singular angular contact bearing	Open – 8/25/23
Justin Scheidler	9	Procurement of mission critical bearings from standard industry	Open – 10/15/23
Tallerico, Scheidler	10	Bearing pre-load not readily apparent	Open - 8/18/23
Thomas Tallerico	11	Missing geometry in the upper-level assembly	Open - 8/18/23
Tallerico, Scheidler, Whitling, Hoge	12	Dynamic interaction of internal components with motor	Open – 8/31/23

Critical Design Review (6/27/23)

- Successful CDR
- 12 Requests for Action
- Prerequisite for transition from design to build (TRL 2 → 3)
- Majority of RFA's completed at this point in time

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year	G	G	G	Y	**Technical** – No technical issues at that time. **Cost** – CR changes approved and put into effect. **Schedule** – CR changes approved and put into effect. **Programmatic** – Change in PM and various other positions within program added minor pause to schedule and workflow overall. Technical leads are still present and maintaining appropriate schedule via TRL/MRL progression.
Annual	G	Y	G	G	**Technical** – Progression on Magnetic Actuator TRL continuing; Piezoelectric design also continuing at scheduled pace. **Cost** – No issues at this time. **Schedule** – Critical Design Review and Technical Annual Performance Review slid back on schedule. No major effect on TRL progression; two major purchases not yet ordered. **Programmatic** – No issues at this time.

Plans Forward and Transition / Infusion Plan

Plans Forward:

- **Magnetic actuator**
  - Complete assembly of proof-of-concept actuator
  - Procure and assemble fully-functional actuator
  - Conduct Limited check out testing at GRC
  - Complete moderate-fidelity design study of alternative magnetic gear configuration
  - Explore internal collaboration to build cryogenic, dusty bearing life test rig
- **Piezoelectric motor**
  - Complete piezomotor design
  - Finalize parts schematics/drawings
  - Fabrication/Assembly/Performance testing of developed piezomotor breadboard
- **Integrated Testing**
  - Conduct relevant environment testing of magnetic actuator at KSC

Plans Forward and Transition / Infusion Plan

Infusion/transition:

- Submitting NTR soon to GRC Legal to explore patentability
- Potential industry customers
  - Stated interest in MDECE: Honeybee Robotics ▪ Maxar Loral Robotics ▪ Motiv Space Systems ▪ Blue Origin ▪ FluxWorks
  - Interest expected: Astrobotic Technology ▪ Lunar Outpost ▪ Lunar Resources ▪ US Hybrid Corp ▪ FluxMagic
- Leverage SBIR Phase 2 lunar sequential
  Motiv Space Systems – Distributed Extreme Environments Drive System (DEEDS)
  - Integrate magnetically-geared actuator with the awardee's cryogenic motor drive/controller to form an unheated cryogenic actuation system
  - Discuss MDECE during site visit(s)
- Leverage SBIR Phase 1
  FluxWorks – Scalable Magnetically Geared Actuator for Future Missions in Dusty & Extremely Cold Environments

Education/Public Outreach

EPO Involvement

Dissemination

- 2023 IEEE Aerospace Conference – paper & presentation
  Topic: detailed design of magnetically-geared actuator
- 2023 Energy & Mobility Conference – presentation
  Topic: progress in magnetic gearing for aerospace
- 2023 European Space Mechanisms and Tribology Symposium – paper & presentation
  Topic: development and manufacture of proof-of-concept magnetically-geared actuator
- (abstract submitted) 2024 Worldwide Advanced Manufacturing Symposium – paper & presentation
  Topic: development of piezoelectric motor

Outreach / Infusion

- Discussed MDECE technology with 2 mechanisms and tribology engineers from Blue Origin. Blue Origin staff conveyed interest in the technology and desire for follow-up discussion with other engineers to explore collaboration opportunities.

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead	
2023 European Space Mechanisms and Tribology Symposium (ESMATS)	September 20 – 22
LSIC Fall Meeting	October 10-11
Abstract deadline – Aerospace Mechanisms Symposium	November 15
2024 Worldwide Advanced Manufacturing Symposium (WAMS)	February 19-23

Summary

Design
- TAPR completed
- CDR for magnetic actuator completed; design finalized
- Piezomotor activity restarted; configuration down selected & refined

Hardware
- Proof-of-concept magnetic actuator undergoing final assembly
- Drawings of final magnetic actuator completed; many procurements initiated
- Design of proof-of-concept piezomotor nearing completion; procurements initiated

Testing
- Low temperature capability of KSC cryo-vac chamber improved
- Design of text fixtures & thermal straps nearing completion

TechMat
- TRL start / current / end: 2 / 3 / 5 (magnetic actuator), 2 / 2 / 3 (piezoelectric actuator)
- Ramping up IP and internal/external infusion activities

Come see our booth

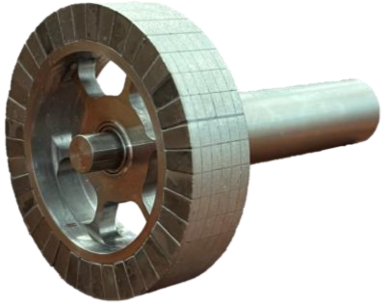
Project Name – Annotated Cover Pictures

Annotated Cover Slide Images

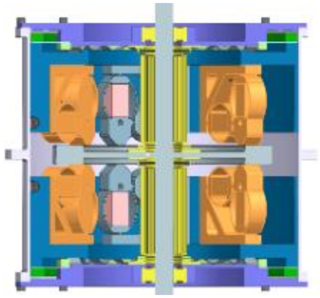
GRC's magnetic gear for aeronautics

Proof-of-concept cycloidal magnetic gear

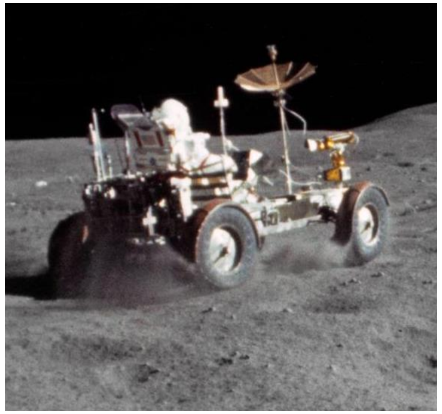
Illustration depicting astronaut in dusty lunar environment



Sun 'gear' in the proof-of-concept magnetically-geared motor, showing magnets bonded onto the rotor



Cross section of the preliminary piezomotor



Lunar Roving Vehicle (LRV) spraying dust, Apollo 16 (NASA Photo S72-37002)