National Aeronautics and Space Administration

Development and Manufacture of a Proof-of-Concept Magnetically-Geared Actuator for use in Extremely Cold Lunar Environments

Justin J. Scheidler[1] Peter A. Hoge[2] Thomas F. Tallerico[1] Kyle R. Whitling[2] Aaron, D. Anderson[1]

Jesse Hawk[2] Steven M. Darmon[2] Erica N. Montbach[1] Derek J. Quade[1] Michael D. Anderson[1]

[1]NASA Glenn Research Center, Cleveland, OH 44135, USA

[2]HX5, LLC, Brook Park, OH 44142, USA

ESMATS 2023

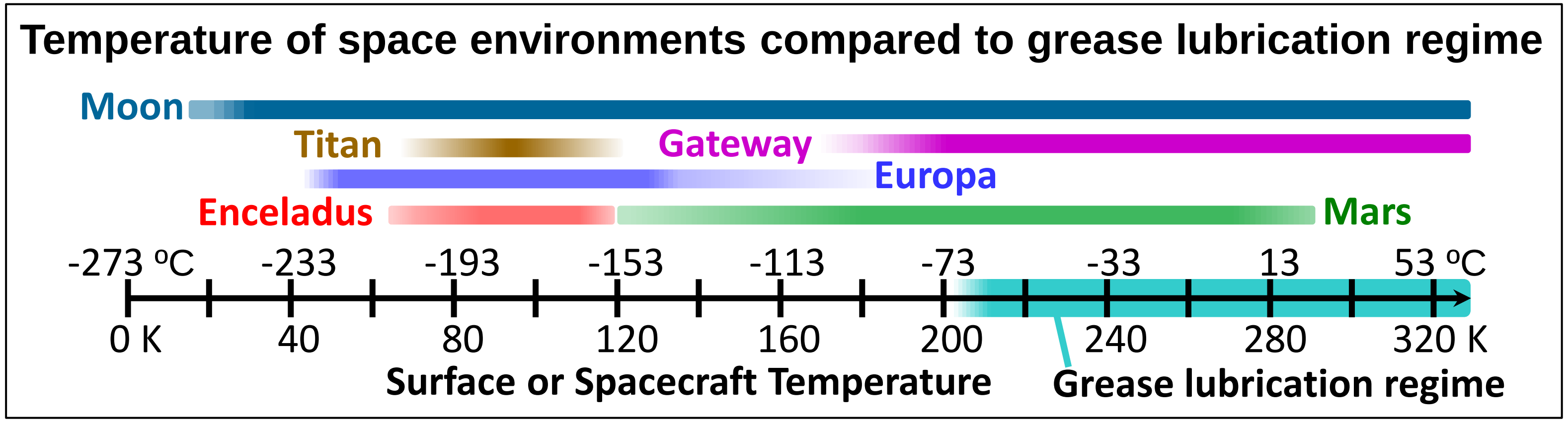
21 September, 2023

Agenda

- Motivation
- Overview of MDECE Project
- Overview of magnetically-geared actuator
- Key changes made to the proof-of-concept prototype
- Lessons learned from proof-of-concept prototype
- Conclusions & future work

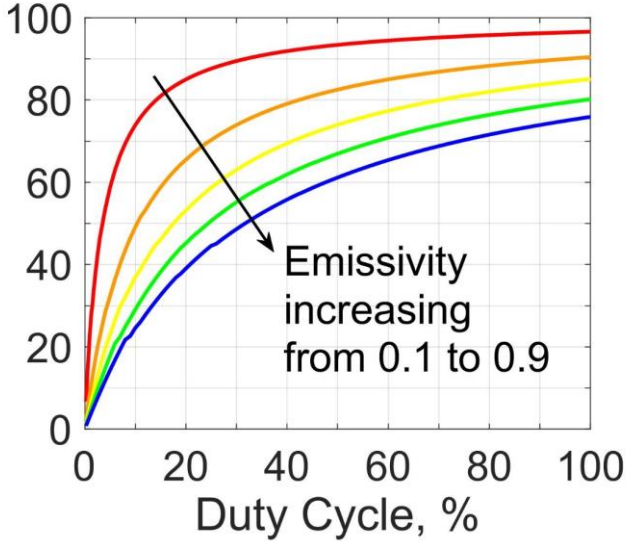
Motivation

- Rotational actuators almost always require a mechanical gearbox to meet mass, volume requirements
- Challenging to lubricate a gearbox operating in cold environments
    - Pervasive problem – *potential for big impact*



- Objective: enable operation in cold to extremely cold environments…
    - Without the mass, complexity, & energy/efficiency penalties of heating actuators
    - Without the strict design constraints & life limitations of solid lubricated gears

Theoretical limit on average total efficiency (%) of heated actuator for indefinite operation [1]

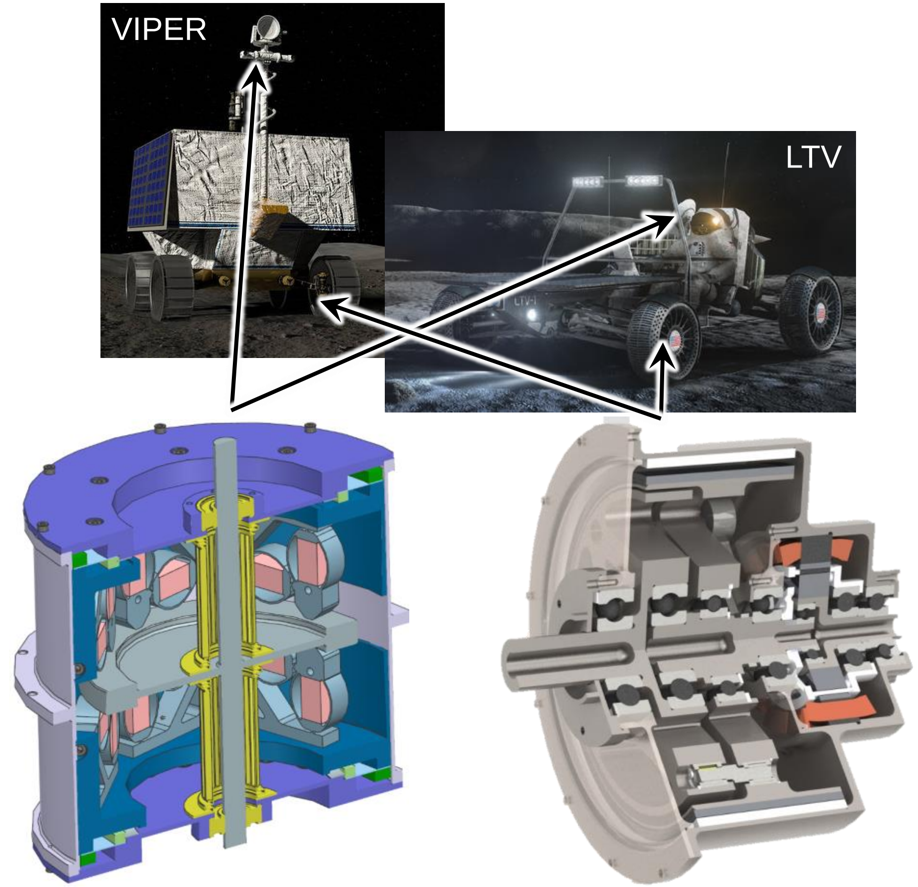


1. Scheidler, J.J. et al., in. *Proc. IEEE Aerospace Conference*, 2022.

Motors for Dusty & Extremely Cold Environments (MDECE) Project

- **R&D & ground test project, Oct 2020 – Sep 2024**
- **Goal:** Develop 2 <u>unheated</u> rotational actuators that can operate for a <u>long duration in extreme cold</u> (ambient temperature of -243 ºC (30 K))
  - Evaluate life in controlled, representative lunar dust environment with and without lunar simulant
- **Approach:** Eliminate gear lubrication – 1 actuator with non-contact gearing, 1 actuator with no gears
- **Key Performance Parameters:** Min. operating temperature ▪ dust-free life ▪ efficiency of magnetic actuator ▪ output resolution of piezoelectric actuator
- **Relevant environment:** Broadly applicable; focusing on lunar PSR
- **Promising applications:**
  - <u>Magnetic actuator</u>: rover mobility ▪ in-situ resource utilization ▪ robotic arm joints ▪ rotors for powered flight
  - <u>Piezoelectric actuator</u>: precision pointing (e.g., laser communication) ▪ low power robotic arm joints

Example mechanisms for demonstrating prototypes (NASA KSC)



Piezoelectric actuator preliminary design (JPL)
[graphic courtesy of NDEAA team / JPL / Caltech / NASA (Patent pending)]

Magnetically-geared actuator preliminary design (NASA GRC & GSFC)

Driving Requirements

Mechanical output
- Continuous 105 Nm at 2 rpm (22 W power)
- Peak 208 Nm at up to 1.5 rpm (up to 33 W) for 20+ seconds

} Match flight-qualified reference actuator

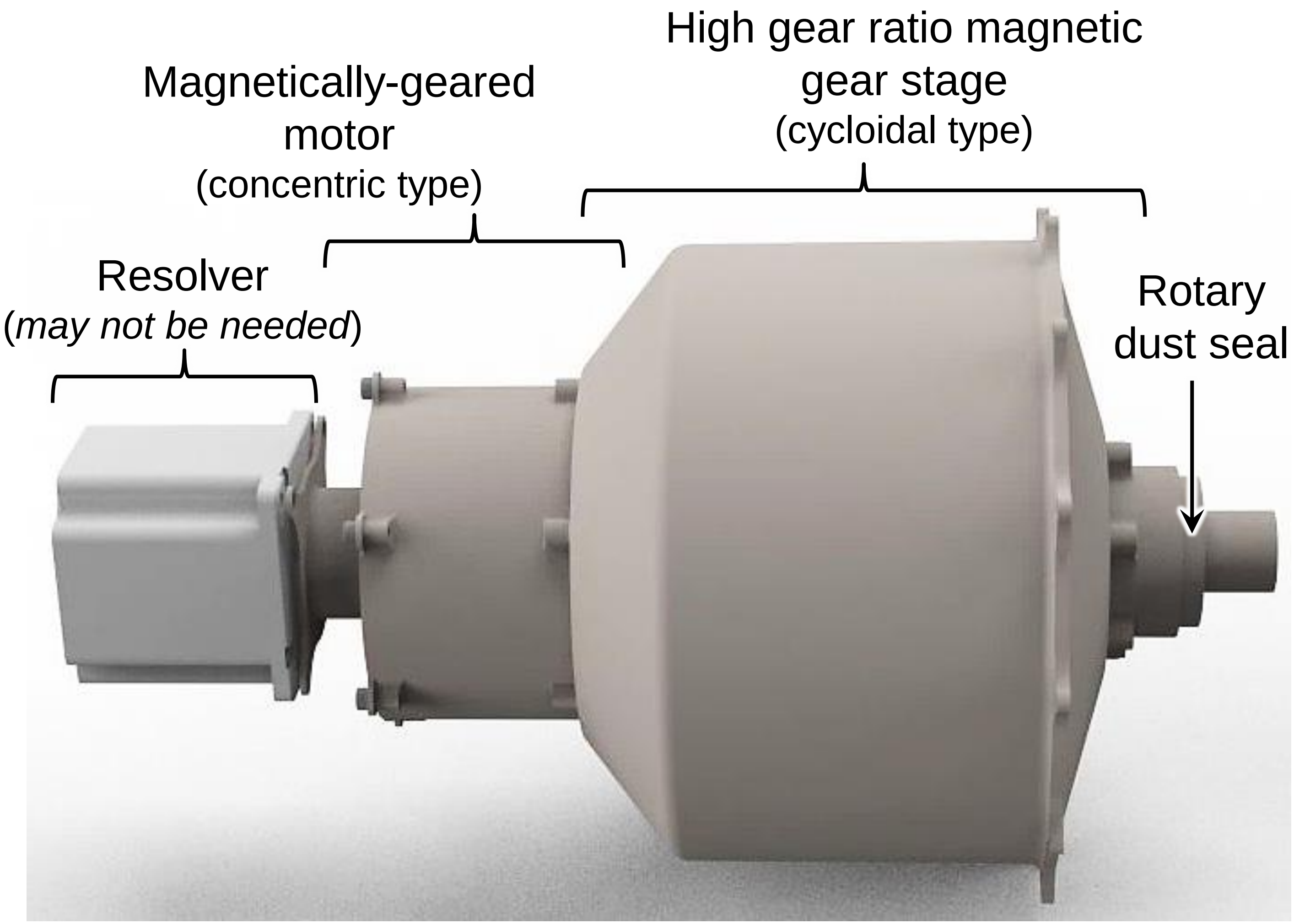
Life
- 6,000 output revolutions (min), 50,000 (goal) [dust free]

Size / mass
- No strict requirements (TRL 2-5)
- Mass 4.73 kg (max), < 3.15 kg (goal)
- Envelope volume 1440 cm^3 (max), < 960 cm^3 (goal)
- Aspect ratio (length / diameter) 0.5 to 1.75

Thermal specifications for operation

Parameter	Minimum		Maximum	
	Goal	Required	Required	Goal
Lunar surface temperature	30 K (-243 °C)	108 K (-165 °C)	293 K (20 °C)	313 K (40 °C)
Solar heating environment	Shadowed		–	Lunar 85° S

MDECE Magnetic Actuator Configuration



Notable characteristics:

- Gear ratios: 13:1 (motor), 43:1 (cycloidal)
- Air gaps 0.25 mm thick
- 14 ball bearings & 20 needle bearings

Predicted Performance of Fully-Functional Actuator

- Critical Design Review completed July 2023
- Expect actuator to be operable over full internal temperature range: 24 K (-249 ºC) to 371 K (98 ºC)
- Predicted actuator life (over 150 K to upper limit)
  - 46,500 output revolutions (bearing limited)

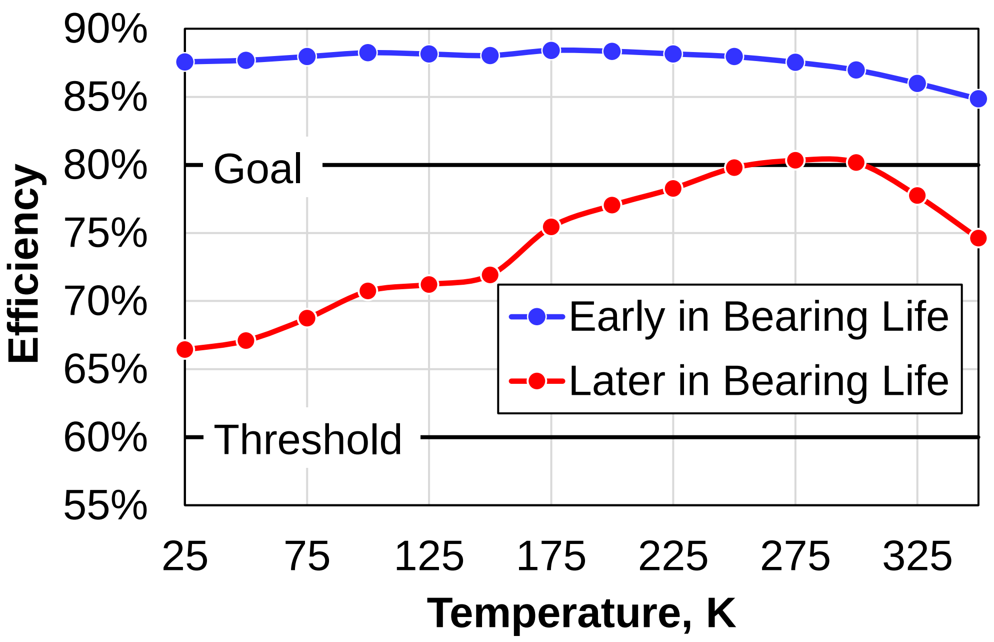
Key specs

Specification		Unit	Threshold	Goal	Predicted
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‡
Physical size aspect ratio		-	0.50 to 1.75		**1.44**
Envelope volume		cm^3	≤ 1,440	≤ 960	**2,317**

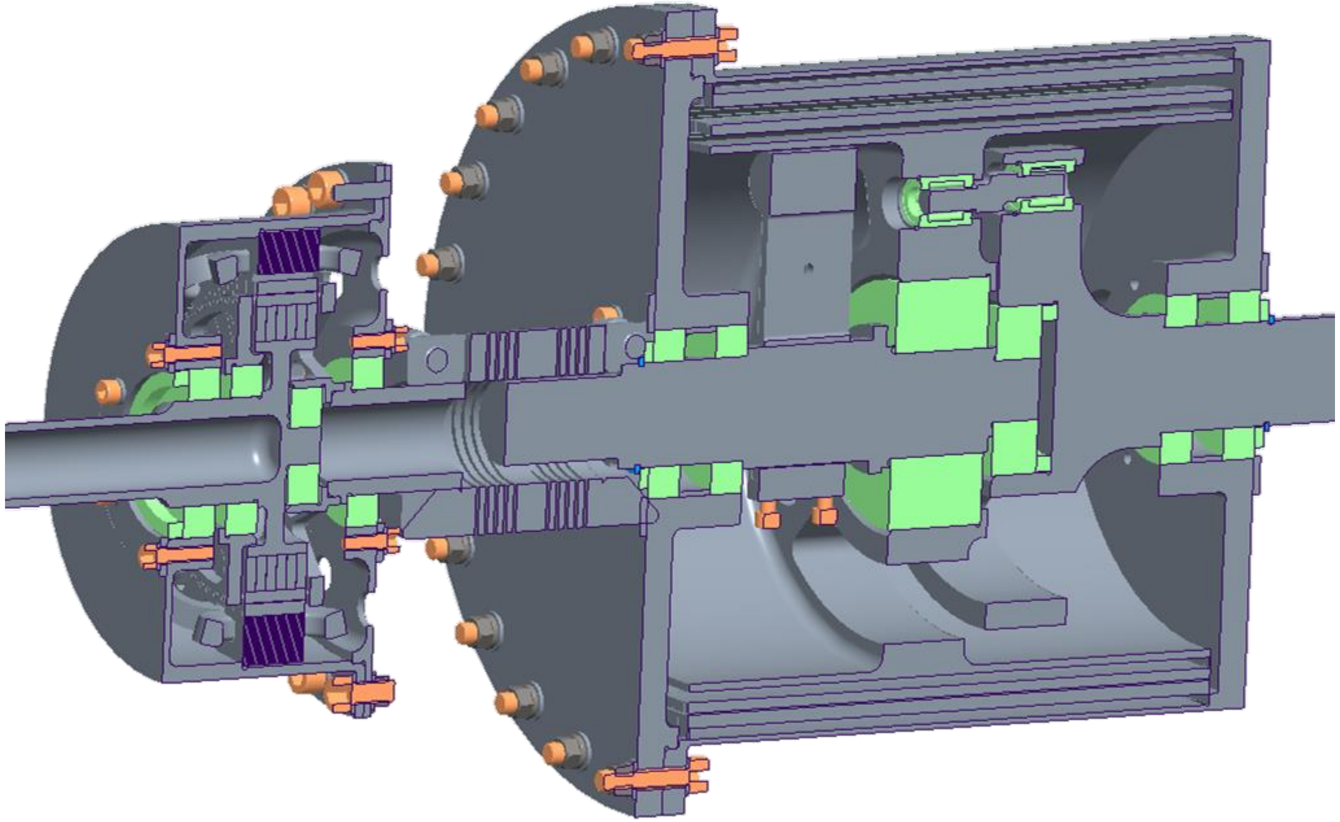
† No resolver

‡ With resolver (may not be needed)

Predicted efficiency of actuator



Proof-of-Concept Prototype



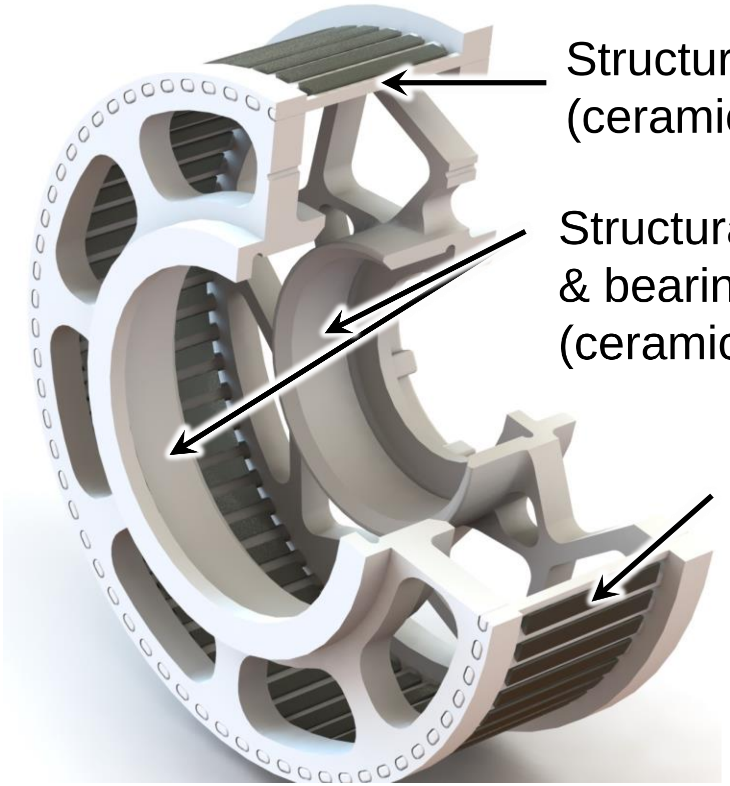
Key differences from fully-functional actuator:

- Geared motor & cycloidal gear separated to allow independent testing
- Only ambient environment
- Not light weighted – extra material & mostly stainless steel instead of titanium
- Cycloidal gear not revised to mitigate high bearing loads
  - Prototype's configuration also less stiff

Modulator Design Considerations

- Structure of the motor's "modulator" must be designed to:
  - Minimize eddy current losses
  - Be radially thin (often < 2 mm) to optimize magnetic response
  - Remove heat from magnetic "pole pieces"
- Desired material properties
  - Low electrical conductivity
  - High stiffness & strength
  - High thermal conductivity
- Ceramic considered for prototype

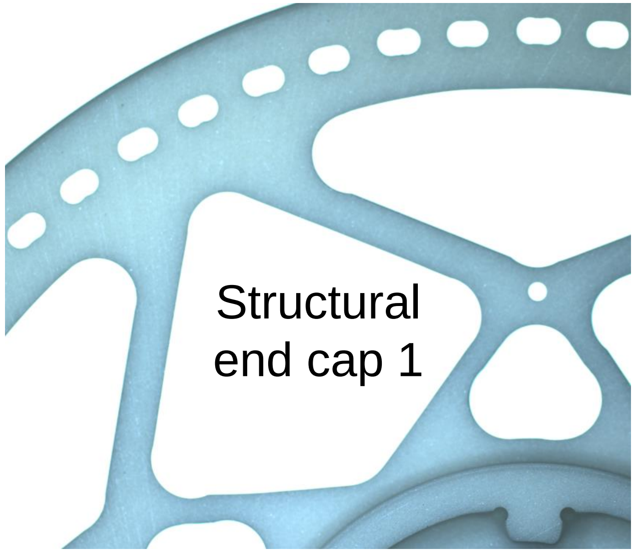
Modulator subassembly in the motor

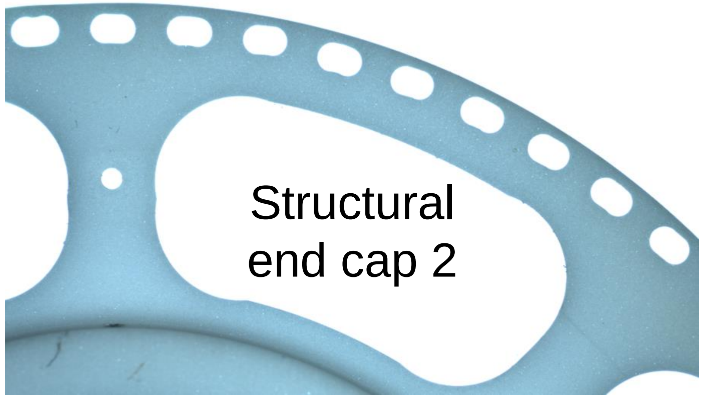


Prototype Manufacture – Ceramic Structures

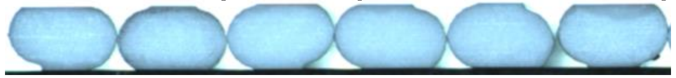
- Combination of trying to eliminate eddy currents in modulator and achieving 0.25 mm air gap found to be a difficult challenge
- No ceramic machine shop or manufacturer would commit to fabrication tolerances less than ±0.025 mm to ±0.05 mm (±0.001” to ±0.002”)
- Ceramic parts received unable to be assembled
- For the prototype, ceramic parts replaced with G10 ones
  - Received G10 parts have high quality

Errors in form of slot interface in ceramic parts





Structural posts (view from end)

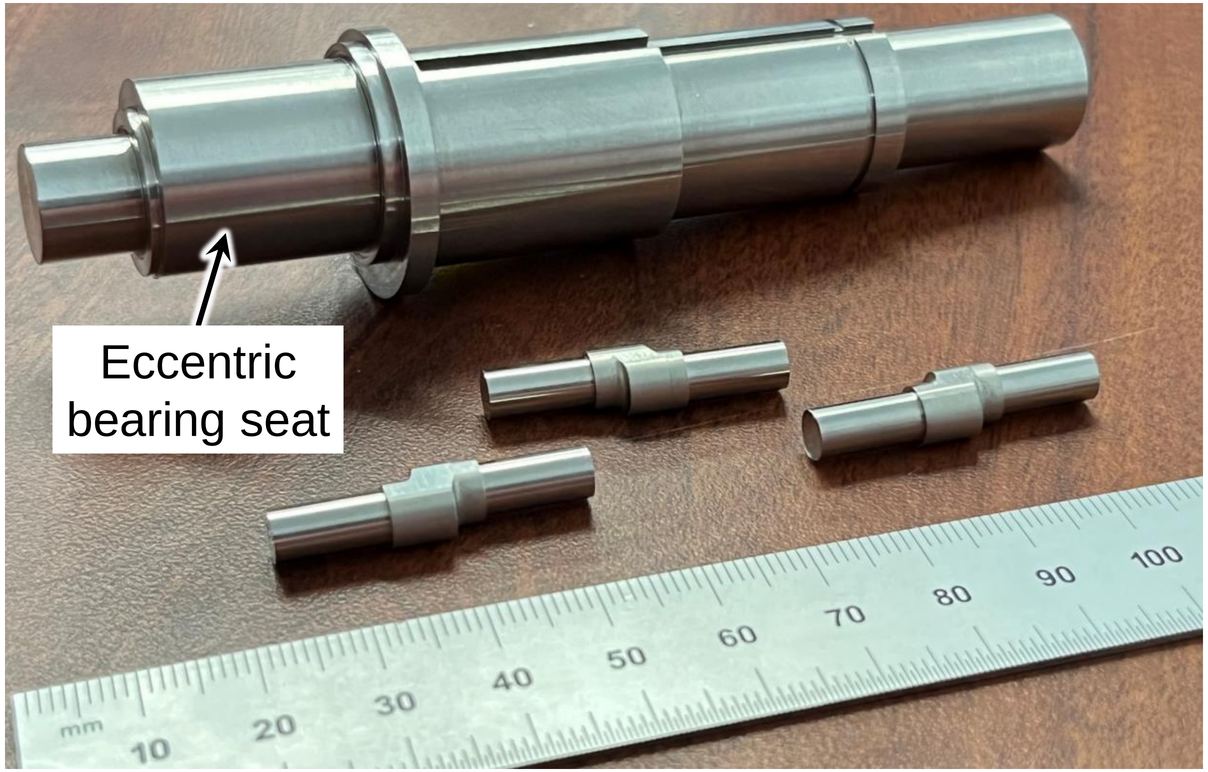


<u>**Lessons learned**</u>

- Achievable tolerances of ceramic bearing seats may compromise bearing functionality or performance
- Larger mating interfaces or round features would improve manufacturability of ceramic structures
- G10 is a viable structural alternative to ceramics

Prototype Manufacture – Cycloidal Gear

Input shaft and eccentric pins in cycloidal magnetic gear



- Cycloidal magnetic gears contain two parts with unusual features that are required to create the gear ratio
  - Input shaft and pins have bearing seats on two axes
- Careful tolerance stack up analysis and dimensioning needed
- Parts received met requirements without the need for rework

Lessons learned

- Dimensioning approach was successful and tight tolerances specified were achievable without excessive cost
- Requirements outside capability of some vendors

Prototype Manufacture – Magnetic Components

Magnetic lamination stacks

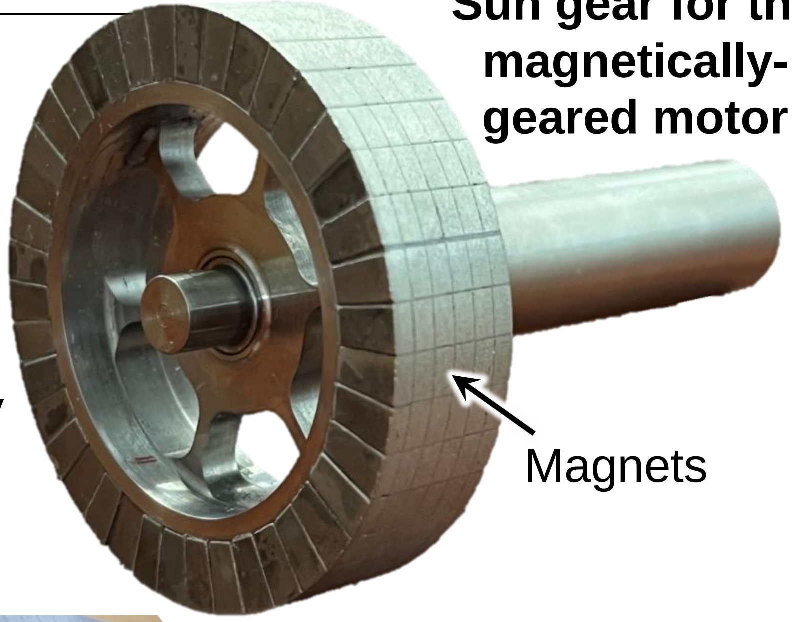
- 2-3 mm radial thickness at limit of vendor capability
    - No laser welding → stack more fragile
- Desired part precision pushed tolerance limit for stacking
- Minor machining of a mating structure required to enable assembly

Magnet arrays

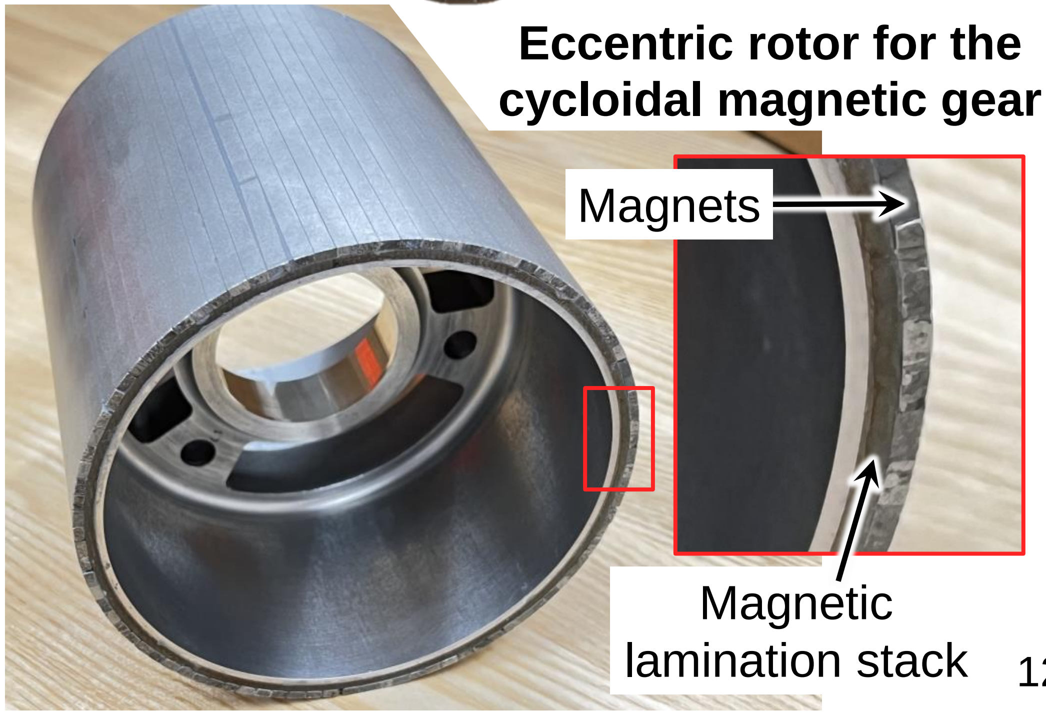
- Laminate thickness required for high efficiency well within vendor capability
- Scrap rate for cycloidal magnets high than expected

<u>Lessons learned</u>

- Eliminate backiron in cycloidal if possible
- Thin, high-precision modulator lamination pushes existing manufacturing capabilities
- Magnet array assembly & finish grinding have similar difficulty to conventional motor



Sun gear for the magnetically-geared motor



Eccentric rotor for the cycloidal magnetic gear

Prototype Assembly – Magnetically-Geared Motor

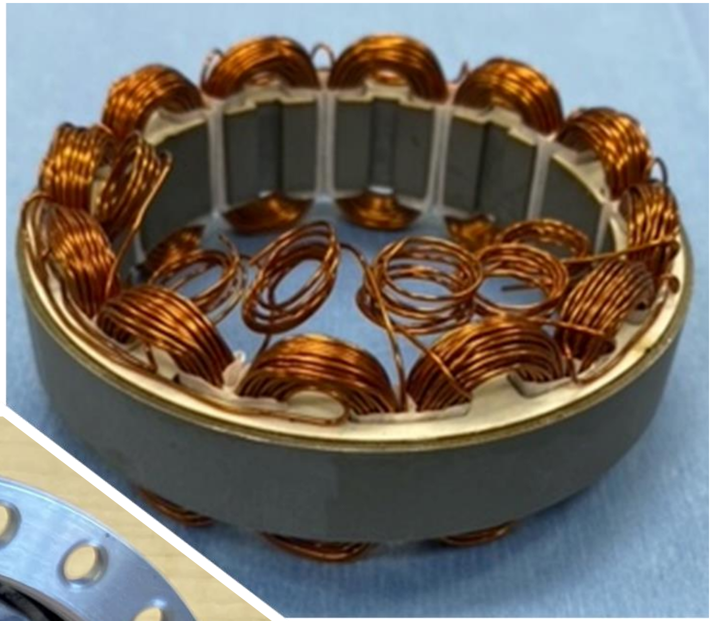
Combined stator / ring gear

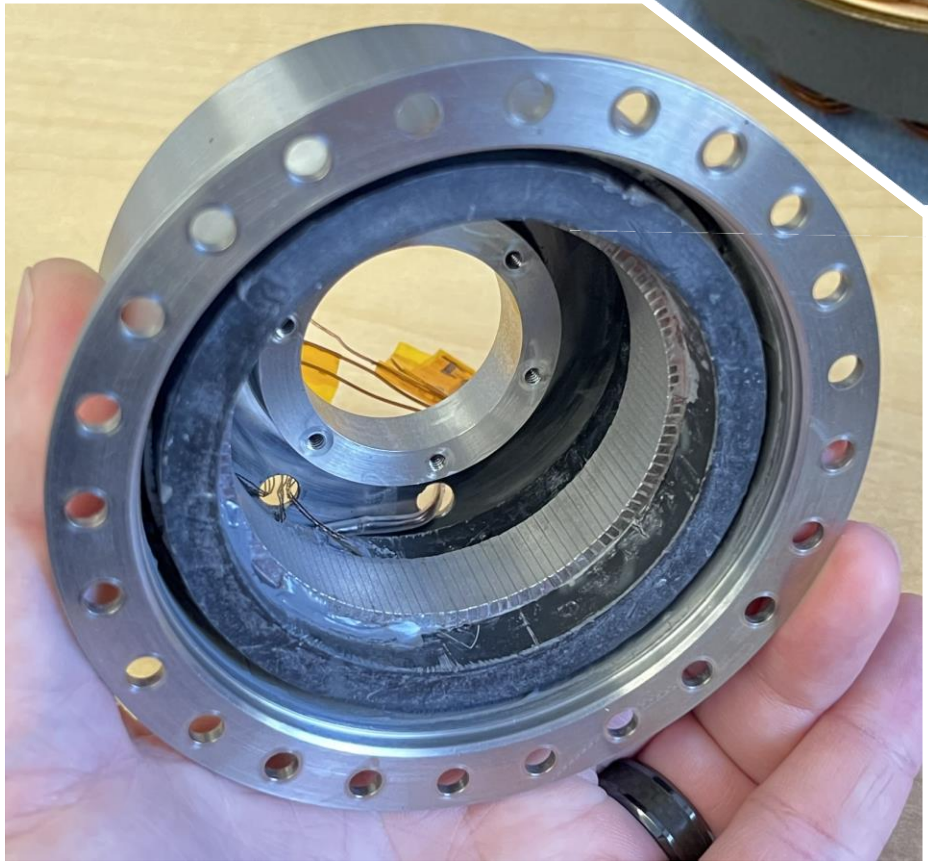
- Stator fabrication follows conventional practices until ring gear magnets installed
- Need slot wedges or epoxy to fill gap between stator teeth

Lessons learned

- No manufacturing or assembly challenges identified

Practice coil winding





Completed stator / ring gear assembly in motor's housing

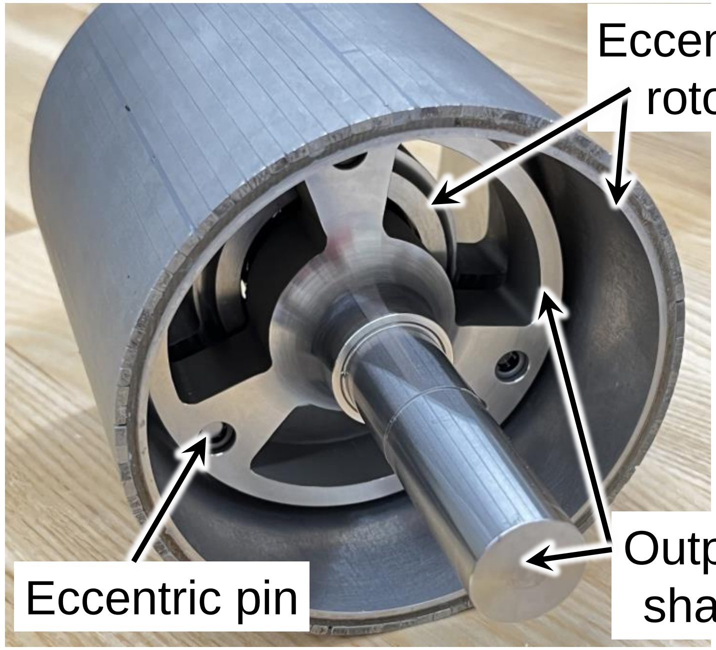
Prototype Assembly – Cycloidal Magnetic Gear

- No influence of magnetic forces observed during subassembly of rotating components
- Aligning output shaft, eccentric pins, and eccentric rotor easier than expected
- Rotating subassembly had adequate off-axis backlash & stiffness
- Strong magnetic forces during install of rotating subassembly into housing (used lathe)
  - Forces tend to axially disassemble the rotating subassembly

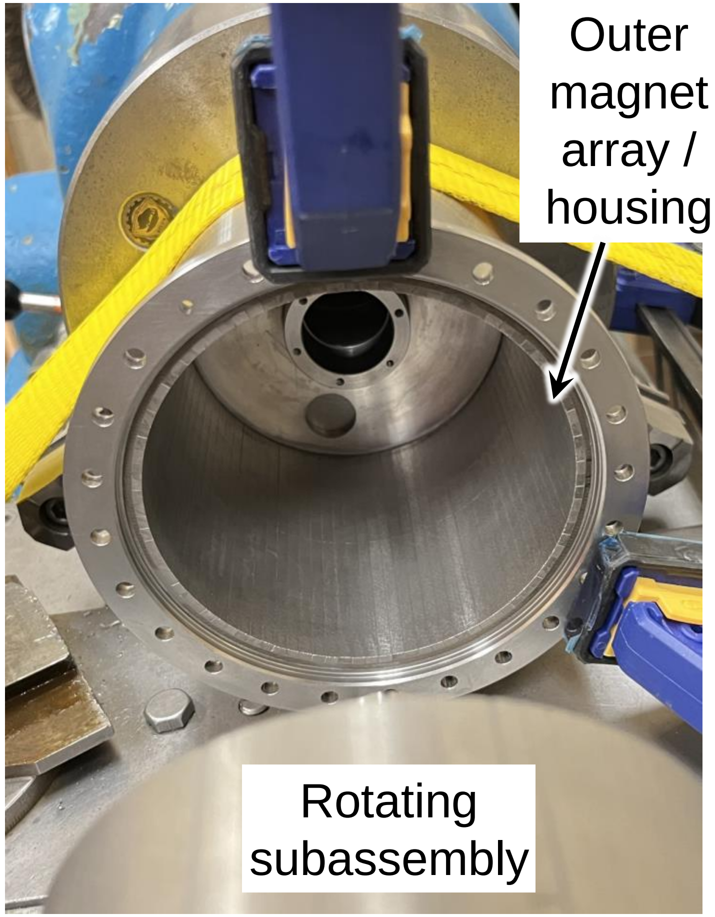
Lessons learned

- Need temporary method to axially secure input shaft to output shaft
- Sufficient assembly conditions
  - Fixed housing
  - Axial positioning of output shaft

Subassembly of rotating components



Installation of rotating subassembly into housing



Testing to Date

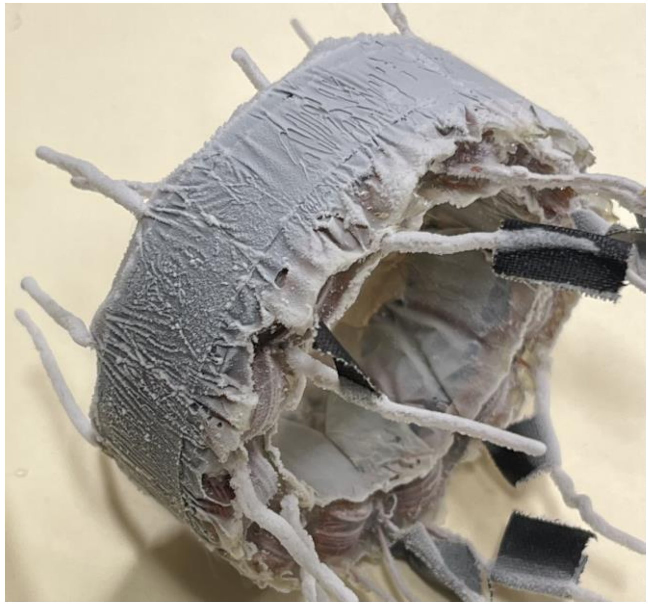
Cycloidal magnetic gear

- Cycloidal magnetic gear functions and exhibits expected gear ratio
- Debris in 0.25 mm air gap
- Measured maximum torque 3% greater than design requirement (6% less than predicted)

Magnetically-geared motor

- No coils shorted after cold soak at 77 K

Stator after cold shock and cold soak at 77 K



Assembled cycloidal magnetic gear (left) mounted for testing (right)

Trial	Slip Torque, Nm
1	217.0
2	215.5
3	212.9
Mean	**215**

Lessons learned

- More thorough cleaning of magnetic debris off magnets needed in final actuator
- Quasi-static performance of cycloidal gear matches design

Conclusions & Future Work

Conclusions

- Predicted performance of final actuator**:** operable from 24 K to 371 K ▪ ≥ 208 Nm peak torque ▪ 4.55 kg ▪ life of 46,500 output cycles ▪ > 85% efficiency earlier in bearing life
- 0.25 mm air gaps achievable in terms of manufacturability and structural deformation under all loading conditions
- Either design changes to the motor's modulator structure or ceramic manufacturing improvements are needed to enable the use of ceramic modulator structures, but G10 may be a viable alternative
- No significant concerns uncovered during assembly & functionality testing of cycloidal magnetic gear

Based on manufacture of prototype & design of final actuator, magnetically-geared actuators are viable for space mechanisms & ready for cryo-vac demonstration

Future work

- Final design modifications to fully-functional actuator
- Procurement of fully-functional actuator underway
  - Ground testing in relevant cryogenic-vacuum-dust environment expected to start March 2024

Acknowledgements

This work was funded by the Motors for Dusty & Extremely Cold Environments (MDECE) Project

Space Technology Mission Directorate
|
Game Changing Development Program
|
MDECE Project

Contact Info

{justin.j.scheidler, peter.a.hoge, thomas.tallerico, kyle.r.whitling, aaron.d.anderson-1, jesse.hawk, erica.n.Montbach, derek.j.quade, michael.d.anderson-1**}@nasa.gov**

THANK YOU

Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
NASA
Glenn Research Center
FOR THE BENEFIT OF ALL

NASA