Design of a Magnetically-Geared Actuator for Extremely Cold and Dusty Space Environments

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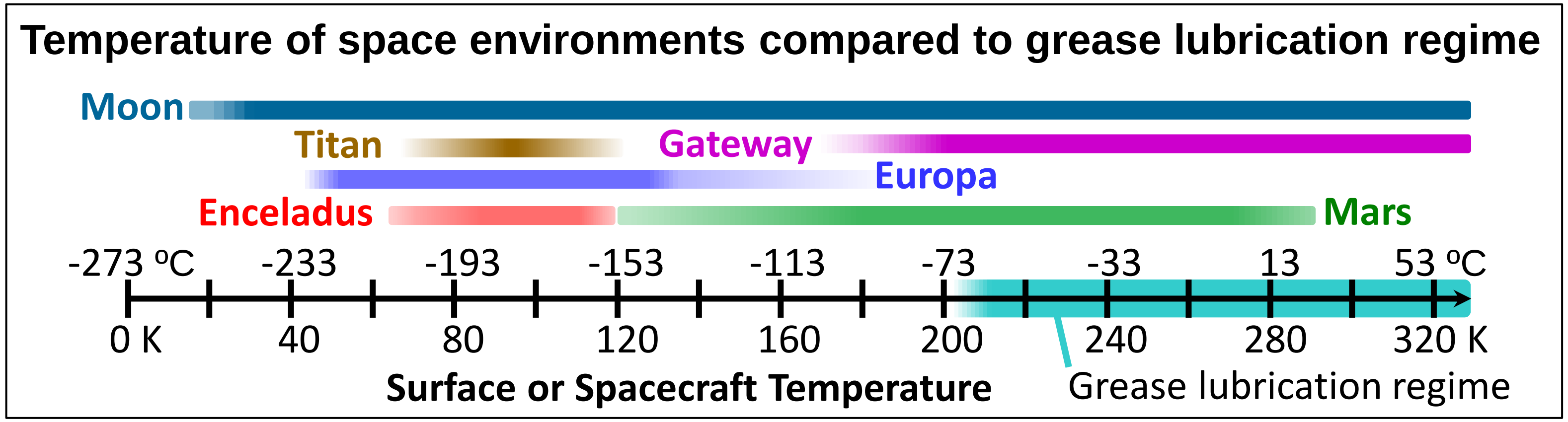
Agenda

- Motivation
- Actuator overview
- Detailed design
  - Electromagnetic
  - Bearing
  - Thermal
  - Mechanical
- Predicted performance
- Conclusions

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

Motors for Dusty & Extremely Cold Environments (MDECE) Project

- **R&D & ground test project, 2020 – 2025**
- **Goal:** Develop 2 unheated rotational actuators that can operate for a long duration in extreme cold (ambient temperature of -243 ºC (30 K))
- **Approach:** Eliminate gear lubrication:
  - 1 magnetically-geared actuator with non-contact gearing
  - 1 piezoelectric actuator with no gears (not discussed in this presentation) [1]
- **Relevant environment:** Broadly applicable, but focusing on permanently shadowed regions on lunar surface
- **Promising applications:** (magnetic actuator) rover mobility ▪ in-situ resource utilization ▪ robotic arm joints rotors for powered flight

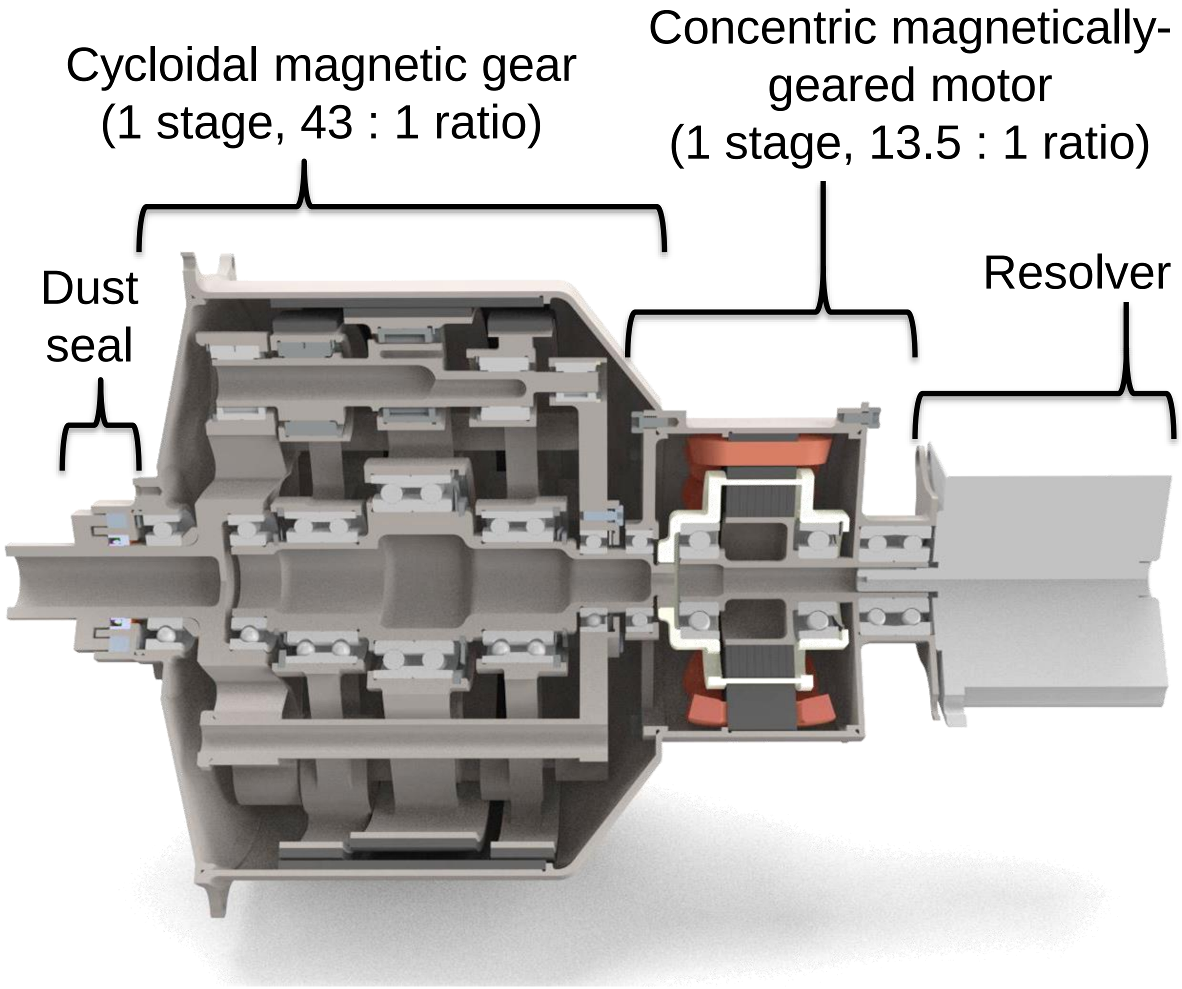
This presentation only covers the magnetically-geared actuator

1. Badescu, M. et al., "Piezoelectric motor for cryogenic applications," Proc. SPIE Smart Structures + Nondestructive Evaluation, 2024.

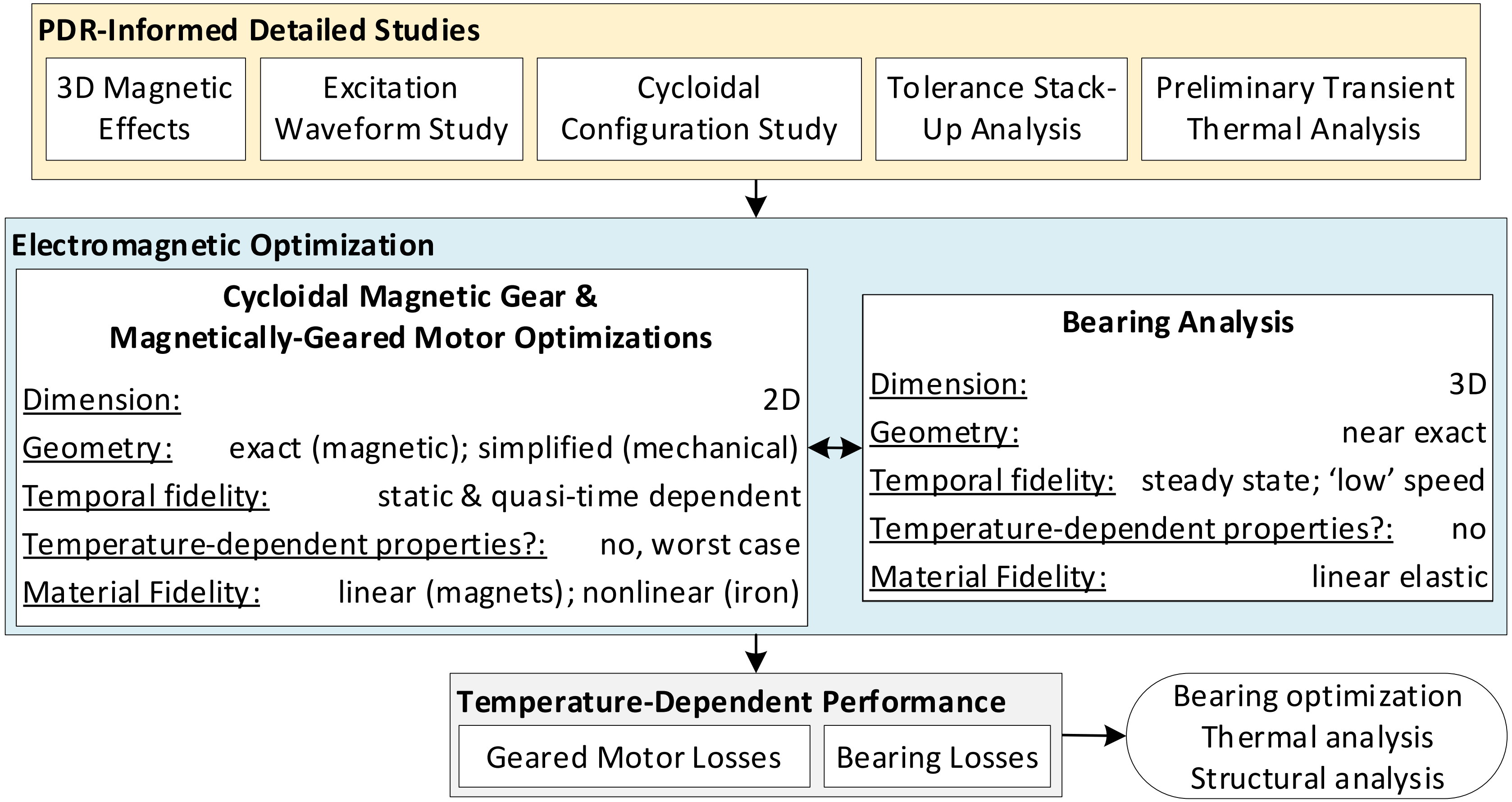
Actuator Overview

Driving requirements

- **Thermal**: Operate unheated
  -165 ºC to < -243 ºC ambient surface
- **Mechanical**: 105 Nm at 2 rpm continuous (22 W)
  208 Nm at 1.5 rpm (33 W) for 60 s
- **Efficiency**: 60% to >80% continuous
- **Life**: 6k to > 50k output revolutions
- **Size/mass**: No strict requirements (TRL 2-5)
  4.73 kg to < 3.15 kg
  1440 cm^3 to < 960 cm^3 envelope

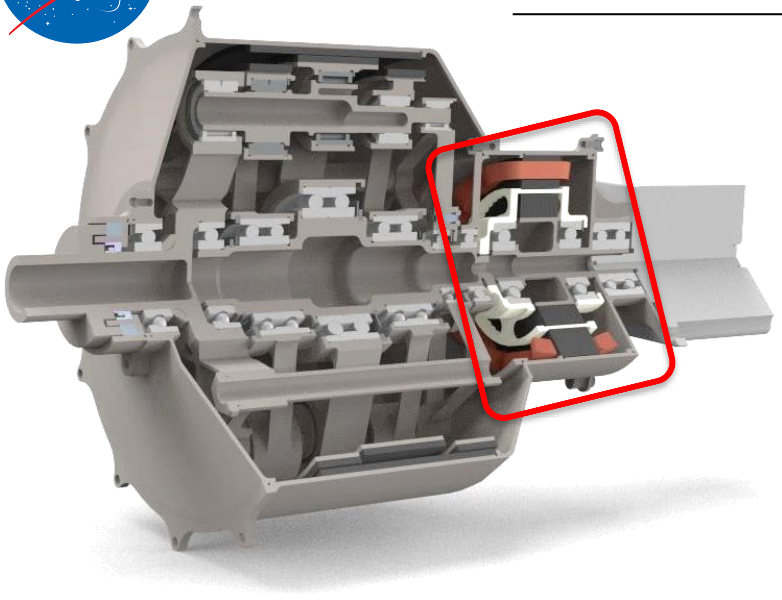


Electromagnetic Design



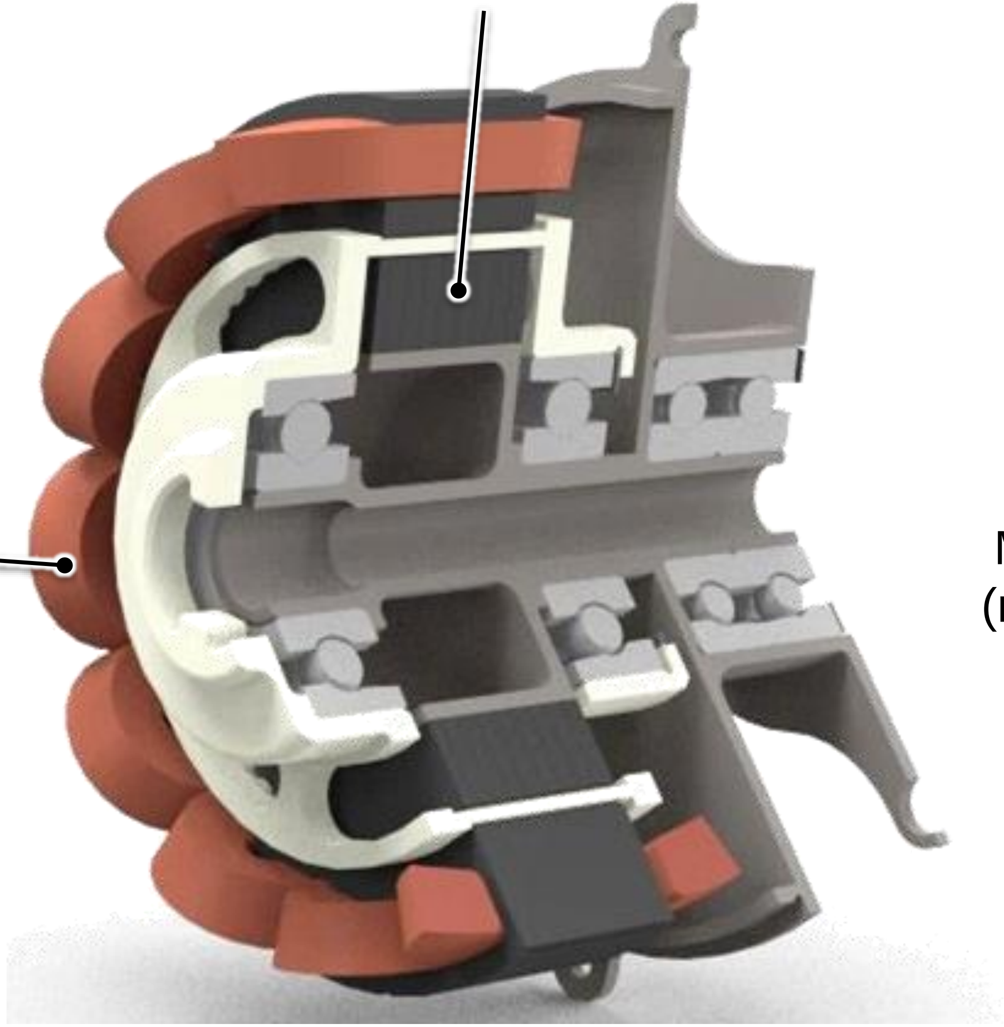
- Cycloidal gear optimized then its gear ratio & efficiency input to motor optimization
- 0.25 mm air gaps selected, but sized magnetically for 0.4 mm gaps based on initial prediction of air gap tolerance (± 0.15 mm)
  - Additionally, 15% and 20% torque margin on gear and motor

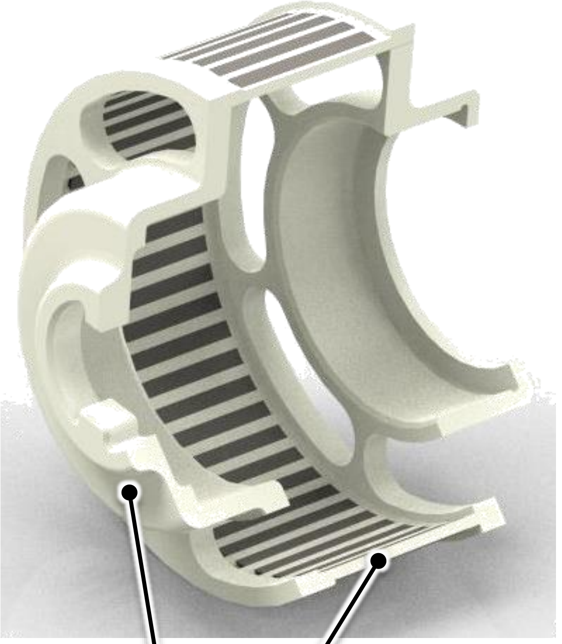
Electromagnetic Design



Concentrated winding for simplicity & higher efficiency
+
field oriented control for reduced resistive loss & torque ripple

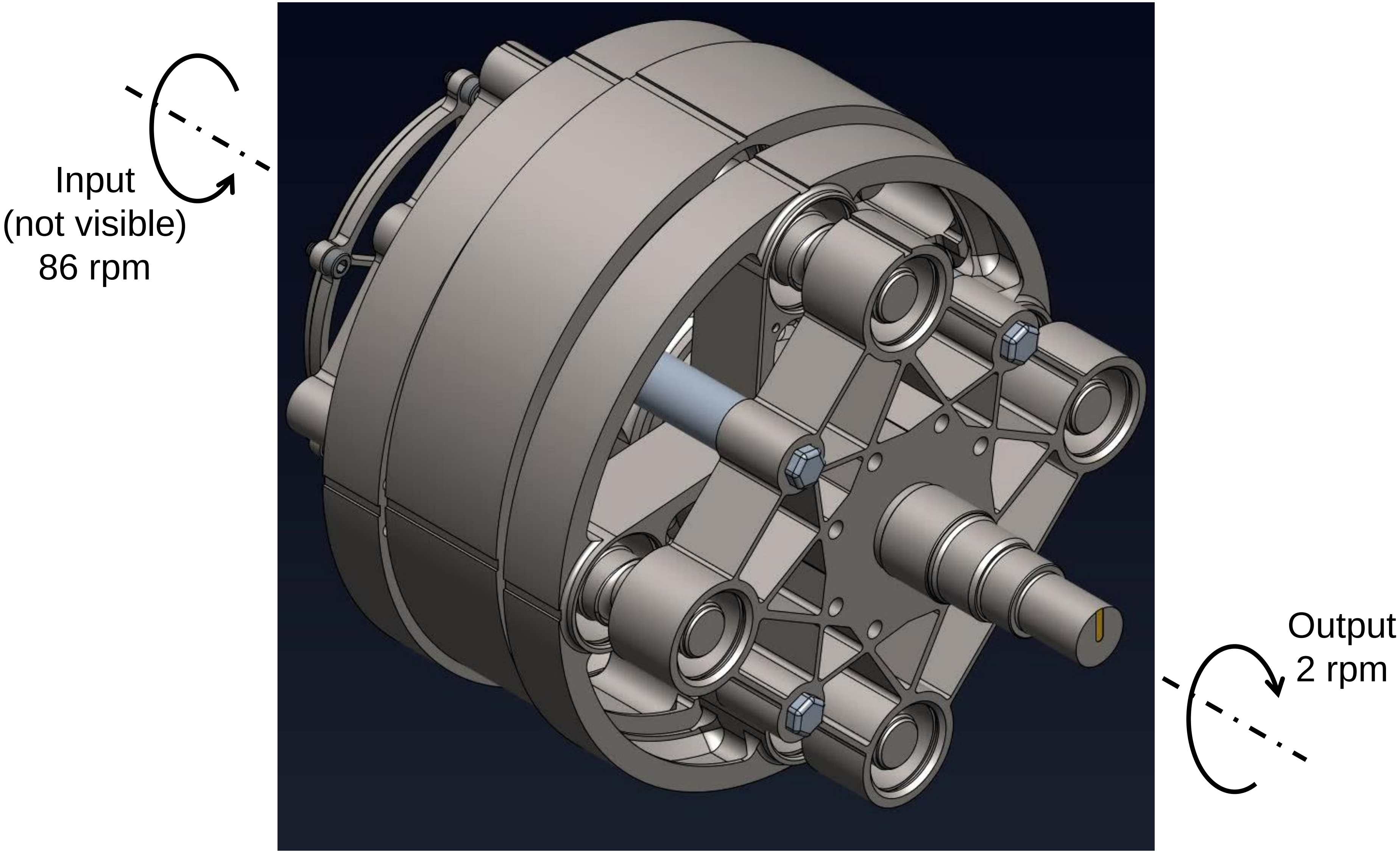
Laminated sun gear magnets



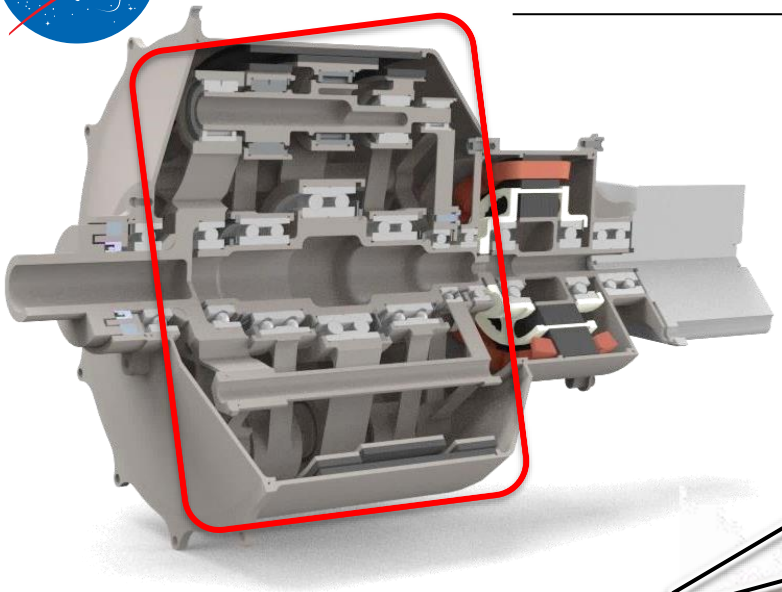


Modulator structure (magnesia-stabilized zirconia)

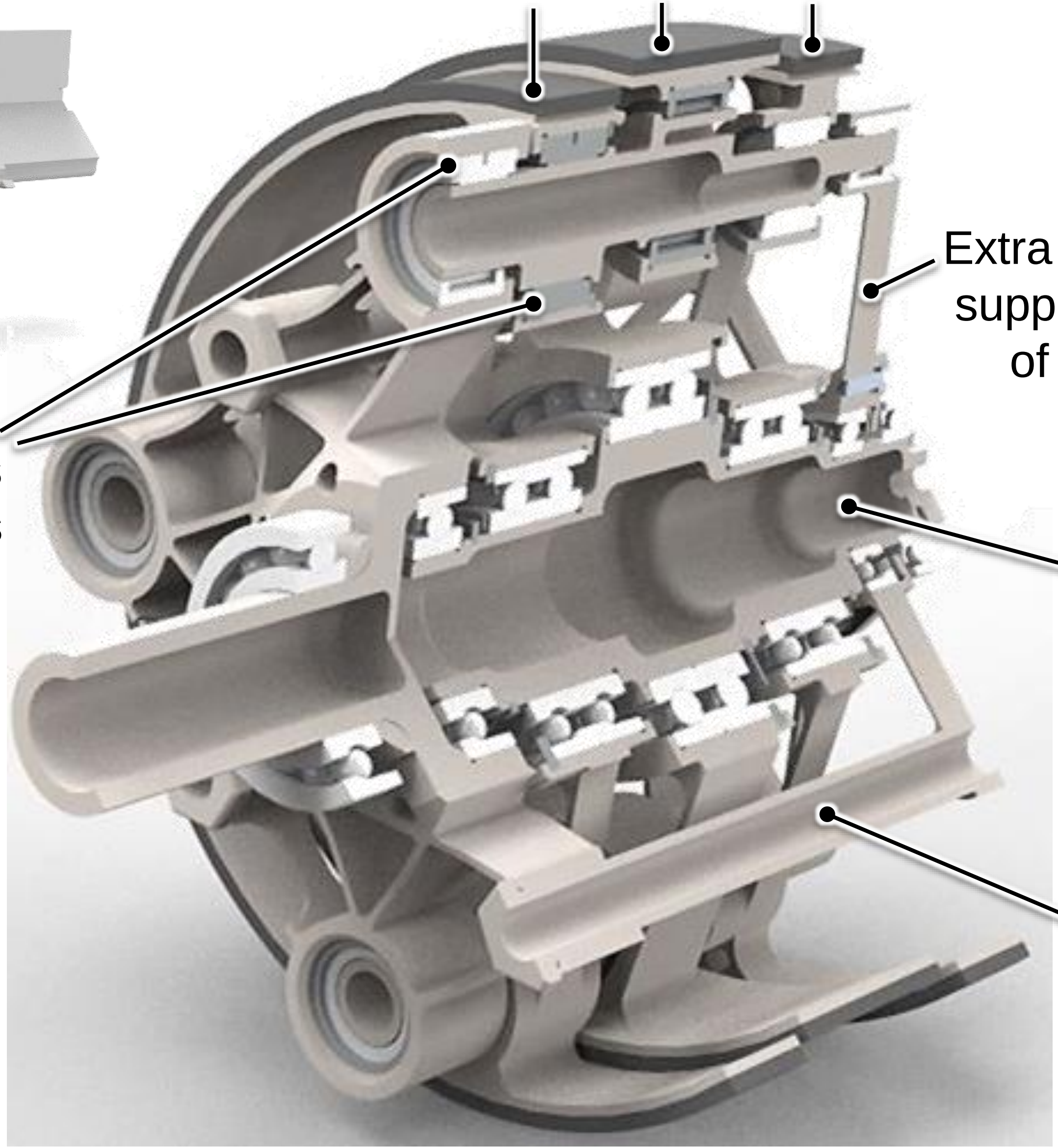
Electromagnetic Design



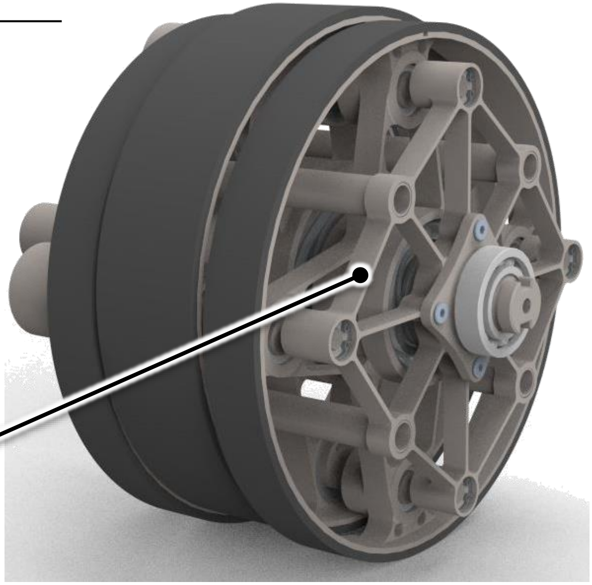
Electromagnetic Design



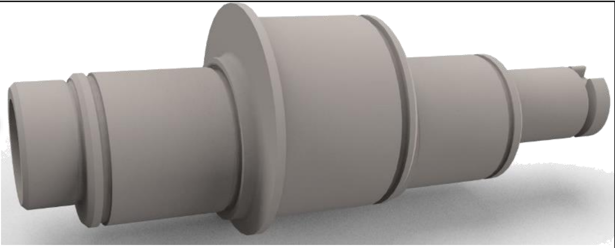
3 eccentric rotors to yield 1.3 kg reduction relative to 1 rotor



Extra rotor to support end of pins



Needle bearings to reduce losses & mass



Cycloidal gear’s input shaft (Ti-6Al-4V)

4 cycloidal pins (440C stainless) found to optimize mass, loss

1 of 4 tie rods to mechanically link support rotor to output shaft

Electromagnetic Design

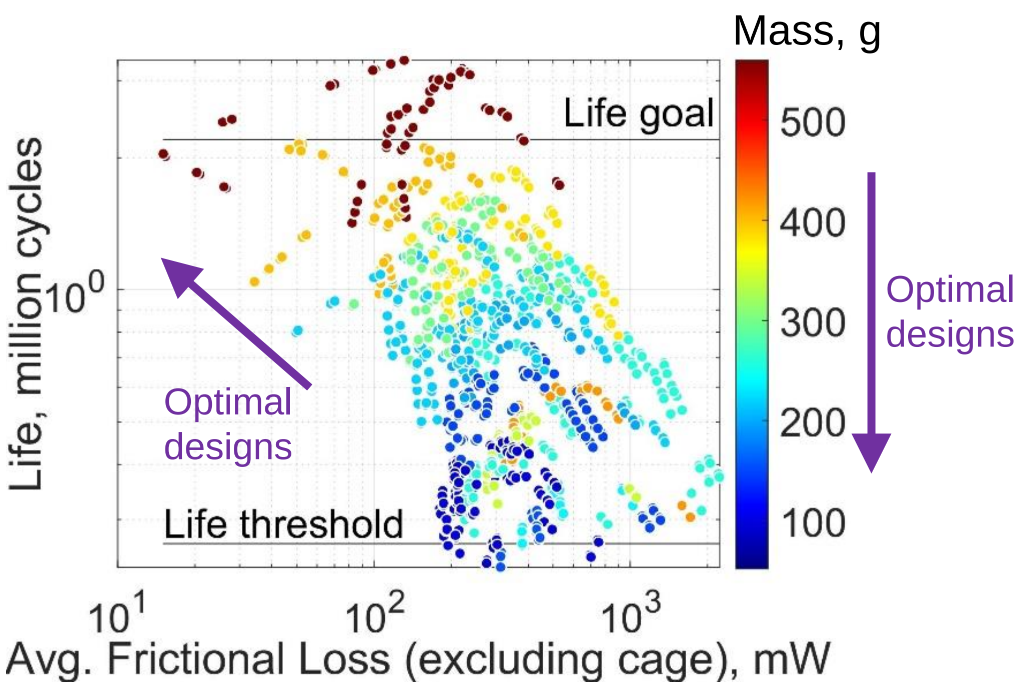
Magnetic losses & magnetic efficiency (continuous operation)

Loss [W]		Temperature [K]				
		50	***150***	***250***	***350***	***450***
Eddy currents	Sun magnets	0.1	0.09	0.08	0.07	0.06
	Modulator	0.15	0.14	0.14	0.14	0.13
	Ring magnets	0.07	0.07	0.06	0.05	0.05
	Stator iron	0.77	0.77	0.76	0.74	0.71
Winding losses	Proximity	0.86	0.05	0.03	0.02	0.01
	Ohmic	0.06	0.84	1.65	2.54	3.53
Efficiency		91.7%	92.0%	89.2%	86.3%	83.2%

- Magnetic forces simulated then input to bearing & structural analyses

Bearing Design

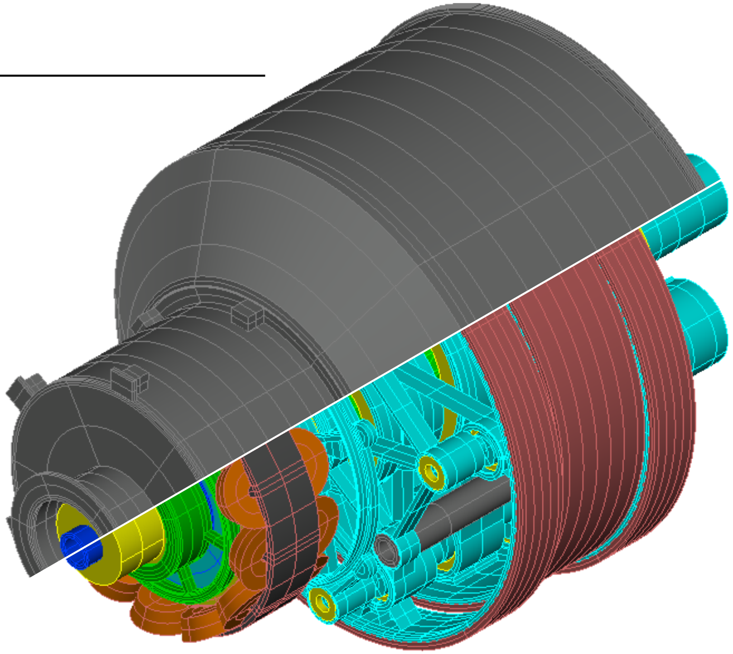
- Bearing design dictated by life and sliding friction of the solid lubrication
- For each bearing in the actuator, the whole catalog of bearings was evaluated, and the best was selected
- Evaluation was based on time-dependent analytical calculation of:
  - Load distribution on each ball/roller
  - Contact area & contact stress
  - Sliding friction power loss
- Included effects of
  - Temperature-dependent material properties
  - Fits to mating hardware
  - Thermal expansion
  - Bearing preload variation
- Stiffness matrix of each bearing calculated & input to structural analysis



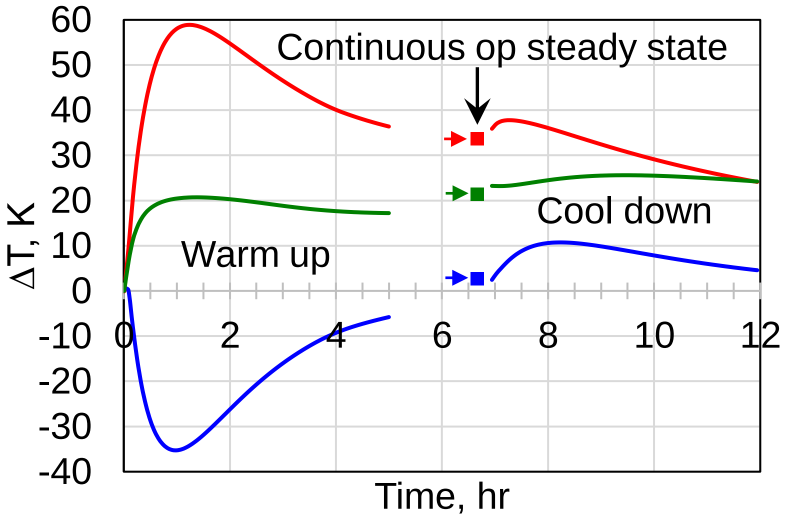
Example optimization of a heavily-loaded bearing

Thermal Design

- Finite difference + finite element (FE) model of actuator used to predict steady state and transient responses
  - Only radiation to environment
  - Contact conductances of bearings & mechanical contacts
  - Temperature-dependent heat loads, thermal conductivity, and specific heat
  - Measured optical properties
- Ability to operate cold eliminates typical tradeoff with housing's external finish/coating → can optimize for hot, sun lit environments
- Predicted max internal temperature of 101 ºC
  - Hot thermal margins >140 ºC except cryo-vacuum rated epoxy (34 ºC margin)
- Bearing & structural analyses use temperature distribution & gradient across bearings & air gaps



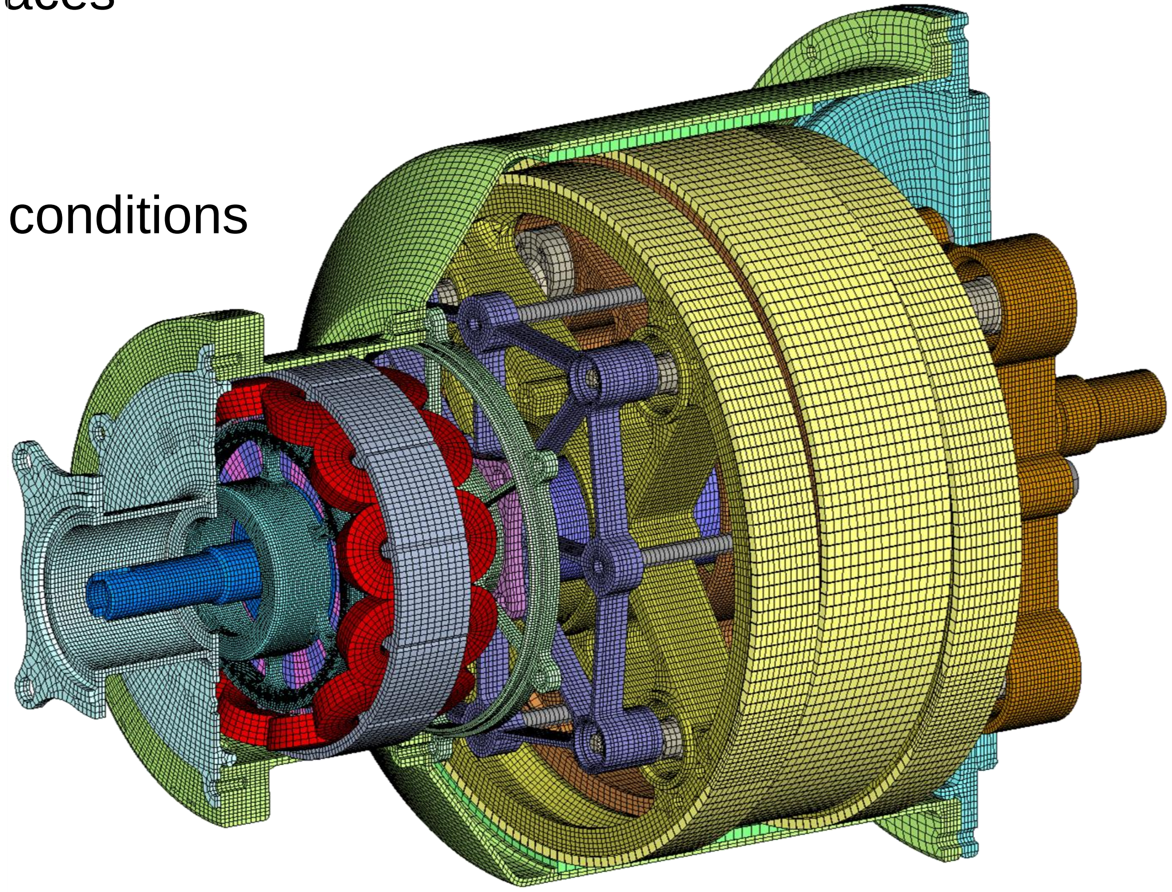
Thermal model



Temperature gradient across 3 air gaps

Mechanical Design

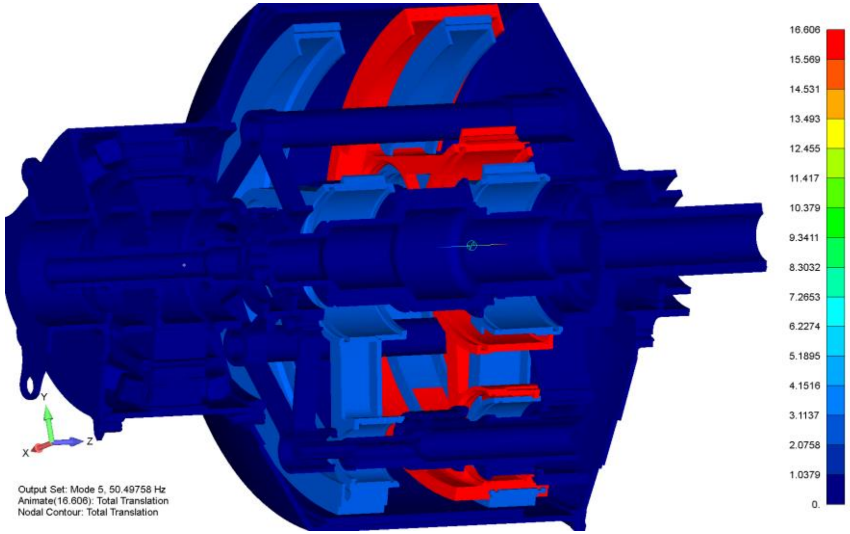
- Designed based on bearing design, tolerance stack-ups, manufacturability, & structural FE model
- Structural FE model
  - Mechanical contact at non-bolted, non-glued interfaces
  - Explicitly modeled epoxy around magnets
  - Thermal stress from temperature distribution & temperature-dependent expansion for 4 operating conditions
  - Worst-case magnetic forces (0.1 mm air gaps)
  - Worst-case position of eccentric rotors
- Predicted change in cycloidal's minimum air gaps
  - At peak torque: *increases* by 0.01 to 0.08 mm
  - At zero torque: *decreases* by 0.06 mm



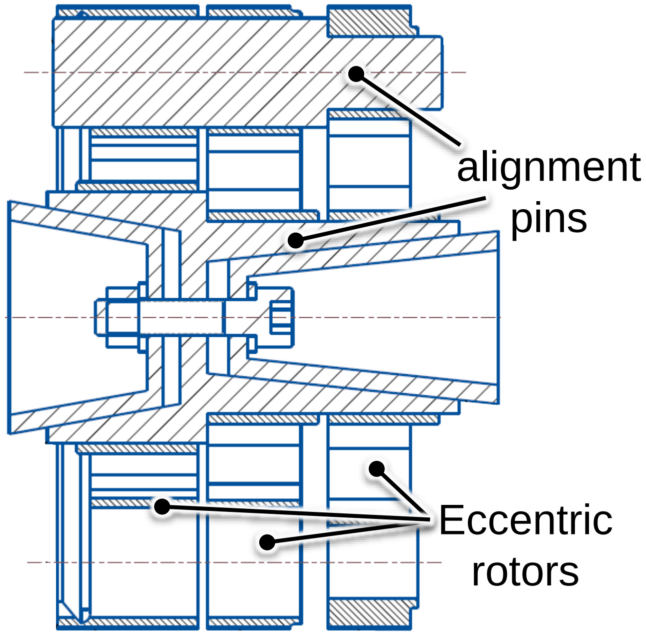
Structural model of as-built actuator

Mechanical Design

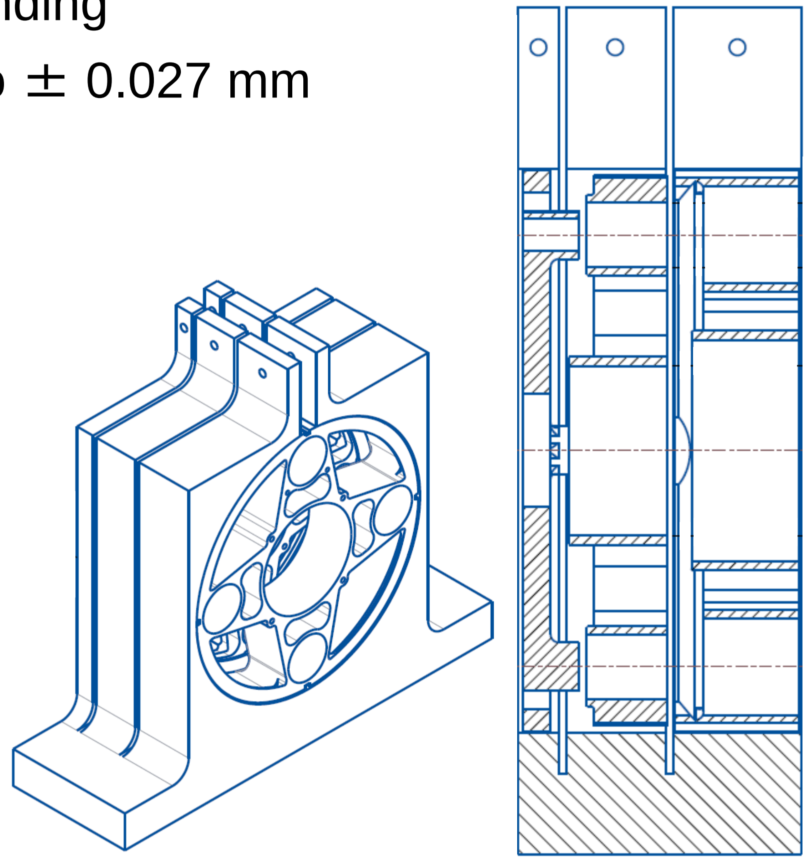
- Modal analysis confirmed that vibration modes can't be excited (bearing preload springs aren't too compliant)
- Challenges with 3 eccentric rotors addressed
  - Angular misalignment reduced using 4 grooves spaced 90º apart, 1 used as datum during match grinding
  - Match grinding to reduce air gap tolerance to ± 0.027 mm



Vibration mode with lowest frequency (51 Hz)



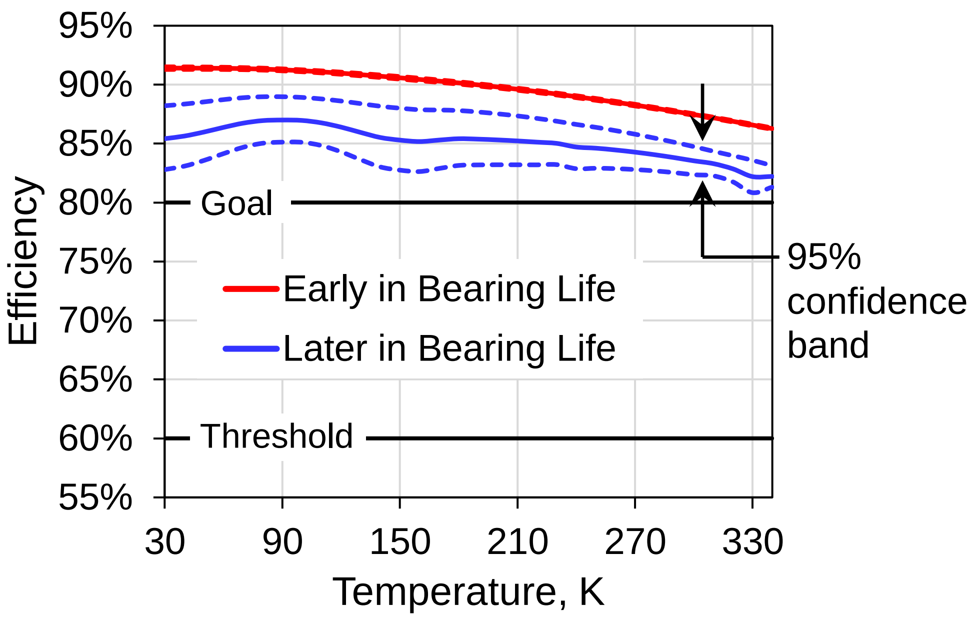
Fixturing to match grind OD of eccentric rotors



Fixturing to match grind bearing seats in 3 of 5 rotors

Predicted Performance

Category	Description	Current model prediction	Objective
Thermal	Internal *operating* temperature range	-249 ºC to +101 ºC ✓	< -243 ºC
Efficiency	Considering full temperature range & actuator life	81% to 91% ✓	>80%
Magnetic	Peak torque	252 to 262 Nm ✓	105 Nm continuous 208 Nm peak



Impact of air gap on torque & specific torque

Air gap [mm]	Magnetic gear: *Peak torque [Nm]*	Magnetic gear: *Specific torque [Nm/kg]*	Geared motor: *Peak torque [Nm]*	Geared motor: *Specific torque [Nm/kg]* – *With resolver*	Geared motor: *Specific torque [Nm/kg]* – *No resolver*	Actuator: *Peak torque [Nm]*	Actuator: *Specific torque [Nm/kg]* – *With resolver*	Actuator: *Specific torque [Nm/kg]* – *No resolver*
0.1	282.6	78.7	-	-	-	282.6	53.3	62.1
0.25	257.0	71.6	7.56	4.4	7.9	257.0	48.5	56.5
0.4	231.2	64.4	5.62	3.3	5.9	231.2	43.6	50.8

Predicted Performance

Category	Description	Current model prediction	Objective
Mass	Total mass	4.55 kg ✓ (initial design script: 4.63 kg)	Target: <4.73 kg Stretch goal: < 3.15 kg
	Specific torque	47.5 to 49.5 Nm/kg	
Size	Envelope	153 mm dia, 240 mm length = 4,412 cm^3 ✗	Target: 1440 cm^3 Stretch goal: < 960 cm^3
Life	Output revolutions, dust free	46,500 ✓	Required: 6,000 Goal: > 50,000

Mass breakdown (without resolver)

Component	Magnetic (stator) [kg]	Magnetic (other) [kg]	Structure [kg]	Bearings [kg]	Hardware / other [kg]	Total [kg]
Geared motor	0.31	0.30	0.20	0.14	0.01	**0.96**
Magnetic gear	n/a	1.11	1.78	0.59	0.11	**3.59**
Actuator	0.31	1.41	1.98	0.73	0.12	**4.55**

Conclusions

- Actuator predicted to operate at internal temperatures of -249 ºC to +101 ºC, have efficiency > 80%, and a useful life
- Lightweight magnetic design enabled by 0.25 mm air gaps
  - Achieving this is difficult due to complexity of cycloidal gear, but solution found that achieves air gap tolerance of -.09 / +.11 mm across all operating conditions
- Actuator's size and mass largely driven by sizing of solid lubricated bearings

Acknowledgements

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Space Technology Mission Directorate

Game Changing Development Program

MDECE Project

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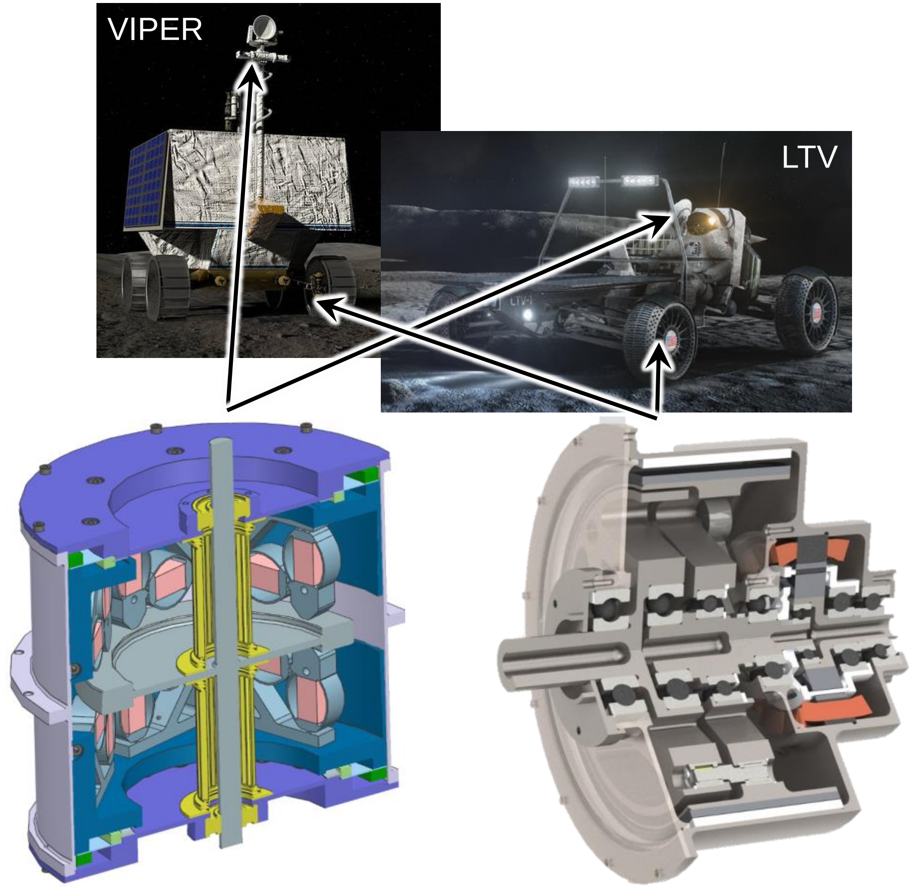
Motors for Dusty & Extremely Cold Environments (MDECE) Project

- **R&D & ground test project, 2020 – 2025**
- **Goal:** Develop 2 unheated rotational actuators that can operate for a long duration in extreme cold (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:**
  - Magnetic actuator: rover mobility ▪ in-situ resource utilization ▪ robotic arm joints ▪ rotors for powered flight
  - Piezoelectric actuator: 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 60 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