Progress in Magnetic Gearing for Aeronautics and Space Applications

Justin J. Scheidler
NASA Glenn Research Center
Rotating and Drive Systems Branch
justin.j.scheidler@nasa.gov

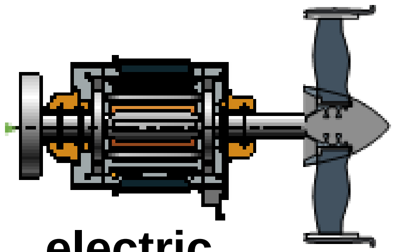
The research presented herein was conducted with multiple NASA colleagues, notably Thomas Tallerico, Zachary Cameron, and Vivake Asnani

This work was funded by:
NASA's Aeronautics Research Mission Directorate – Revolutionary Vertical Lift Technology Project
NASA's Space Technology Mission Directorate – Game Changing Development Program

Energy & Mobility Conference & Expo
September 12-15, 2023

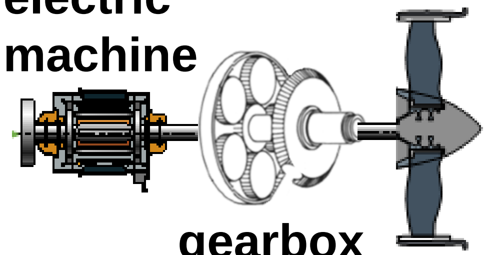
Why Gears?

Direct drive



- \+ Simpler
- − Non-optimal motor and/or fan

Geared drive

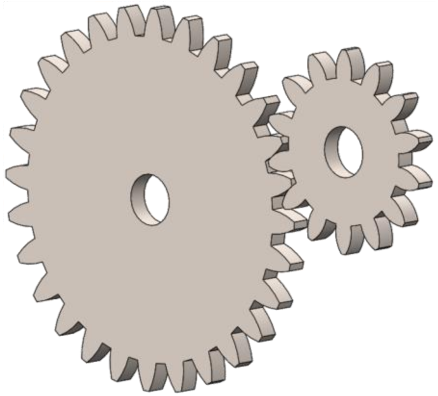


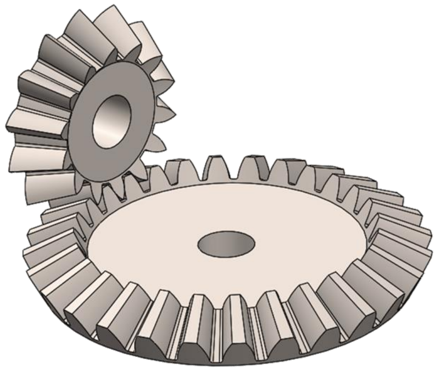
- \+ Optimized motor & fan
- − More complex
- − Potentially less reliable

Aero applications	Space applications
Electric machines optimize to high speed • Sized primarily by torque → high tip speed maximizes specific power, minimizes size	
Fans / props optimize to relatively low speeds • Higher efficiency by moving more air slower • Tip speed < Mach 1 & can't block air flow	**Strict mass & power limits**
Direct drive often heavier and/or less efficient	Direct drive very often impractical

Magnetic Gears vs Mechanical Gears

Mechanical gearing





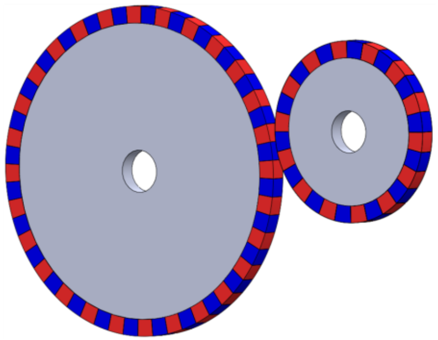
Pros

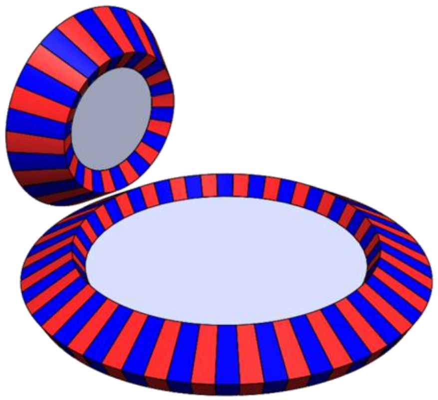
+ Mature technology
+ High to very high torque/mass (specific torque)
+ High to very high efficiency

Cons

− Contact-related wear & failure
    − **Requires lubrication system(s)**
    − Routine & costly maintenance
− Strong tonal vibration & cabin noise

Magnetic gearing





Pros

+ Non-contact
    + No lubrication
    + Low maintenance
+ High to very high efficiency
+ Easily integrated in electric machines (magnetically-geared motor)
+ Potentially low vibration

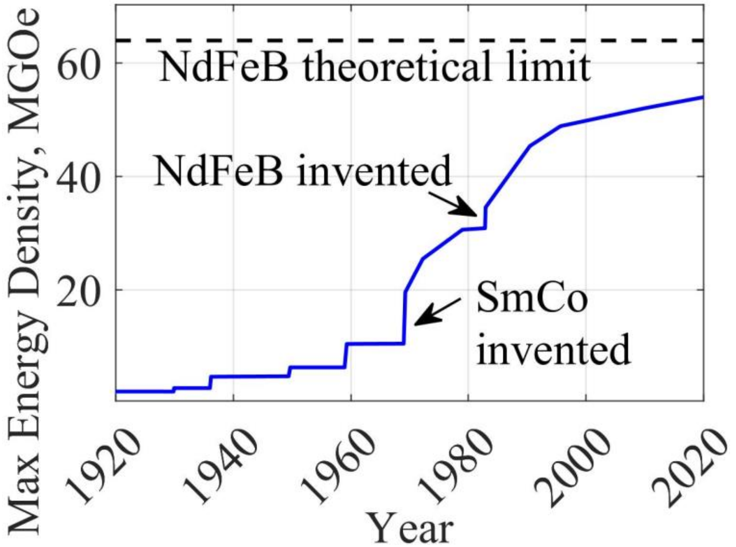
Cons

− Magnet temperature limit
− Individual magnet interaction weaker than 1 gear tooth pair
    − Specific torque lower than mechanical

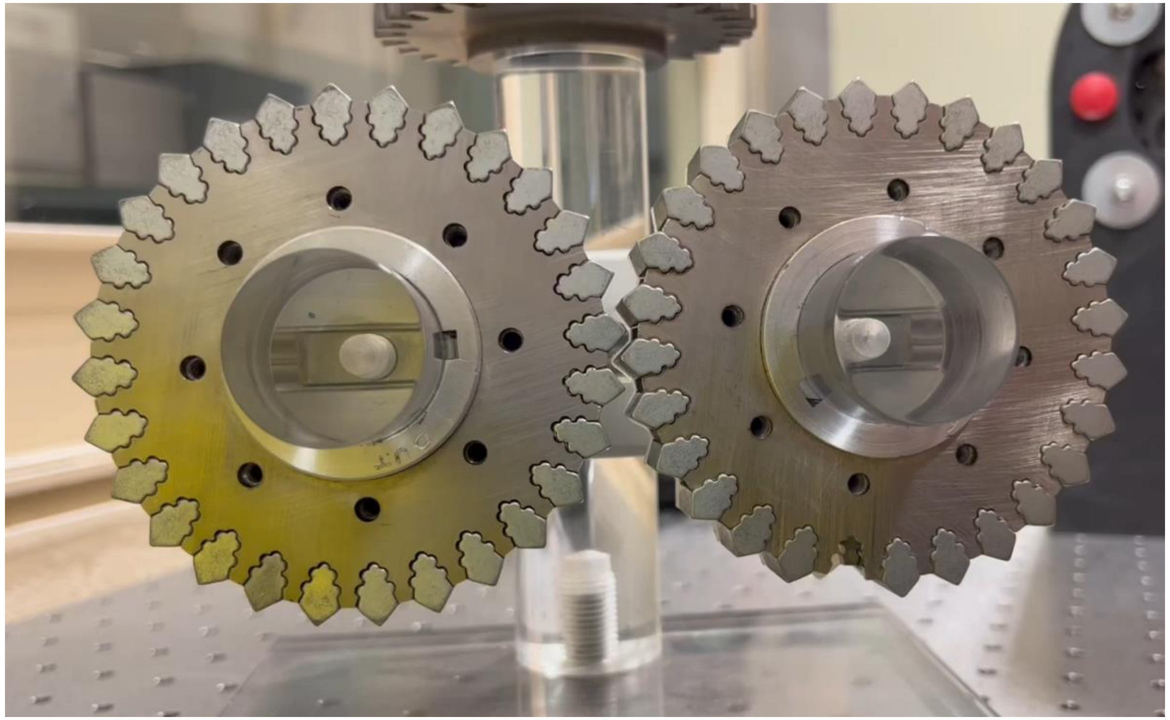
What are Magnetic Gears?

- Meshing gear teeth replaced by non-contacting permanent magnets
- 1st invented in 1901
- A stronger magnet = higher torque capacity

Historical development of permanent magnets



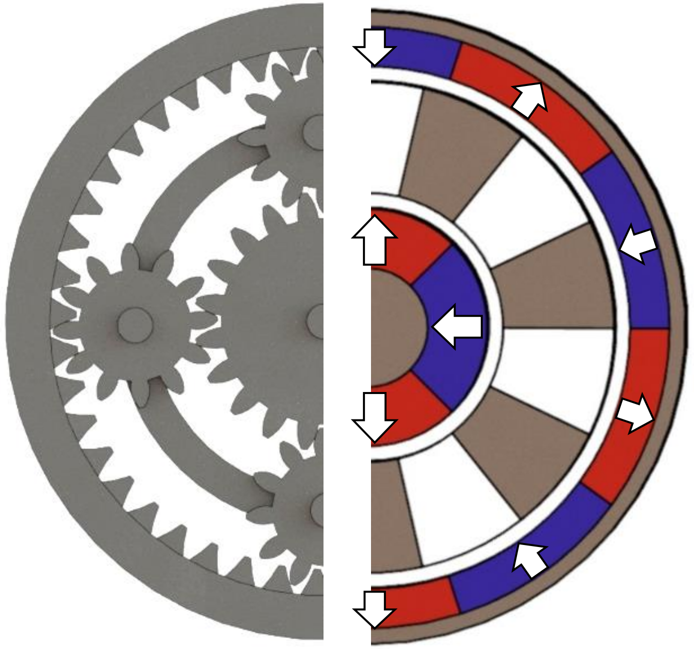
Magnetic spur gear
demo showing very low torque capacity
(magnet type/grade unknown)



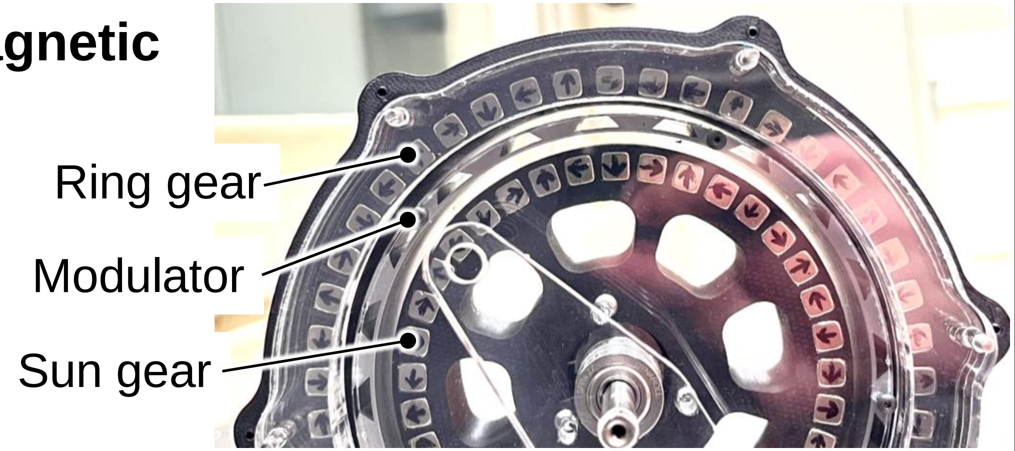
What are Magnetic Gears?

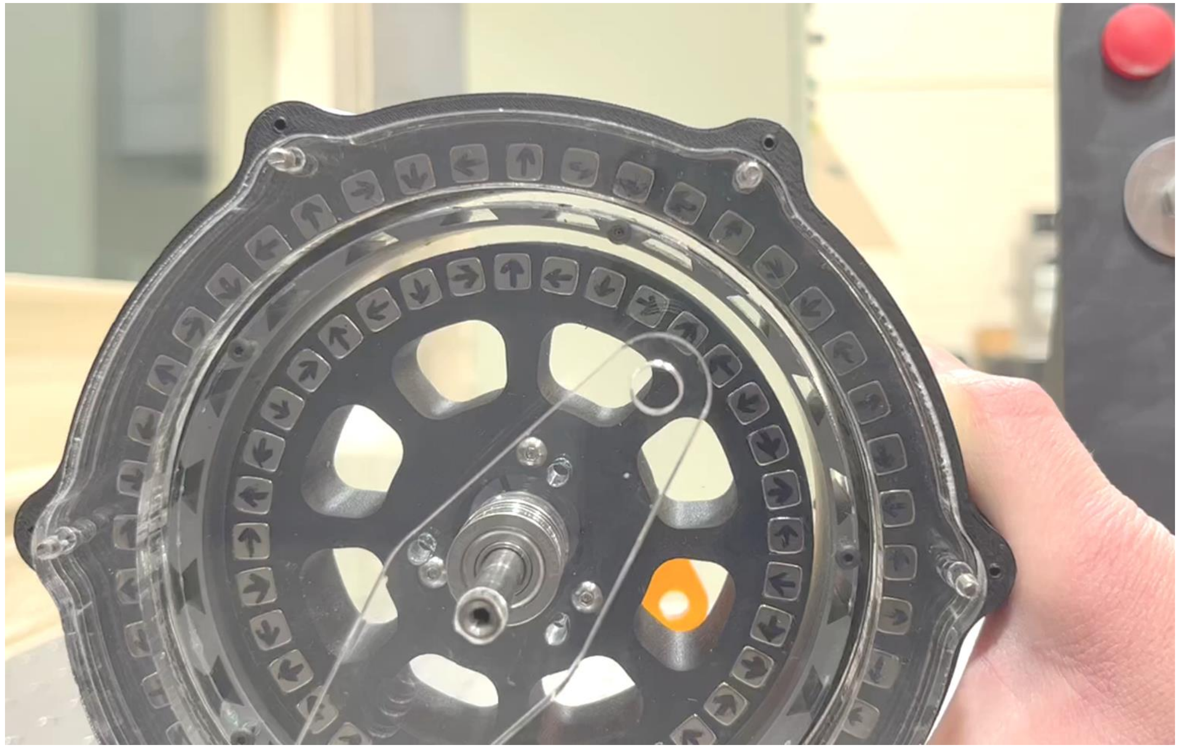
- Can only compete with mechanical gears if multiple magnets engaged simultaneously
  - Concentric-type magnetic gear invented in 2001

Analogy between mechanical planetary gear and concentric magnetic gear



Concentric magnetic gear demo





NASA's R&D for Aeronautics Applications

Phase 1
2017

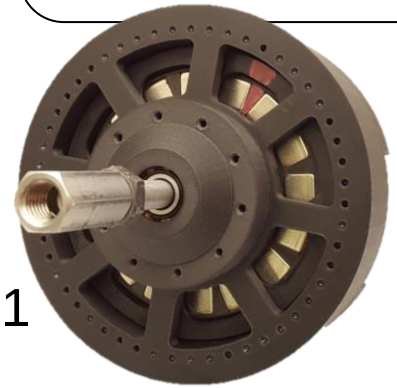
- How do they work? (PT-1)
- Can they be lightweight? (PT-2)

Phase 2
2018-2019

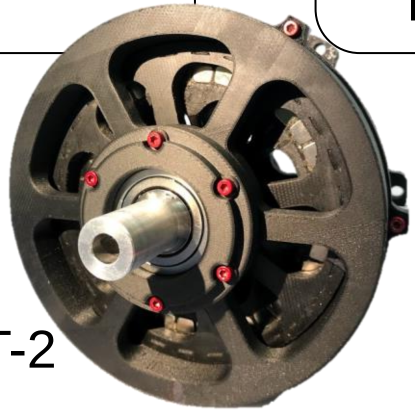
- Can they be efficient? (PT-3)
- Can they be efficient and light weight? (PT-4)

Phase 3
2019-2023

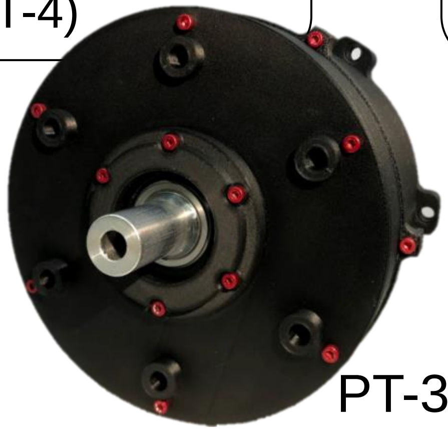
- How to pair them with motors?



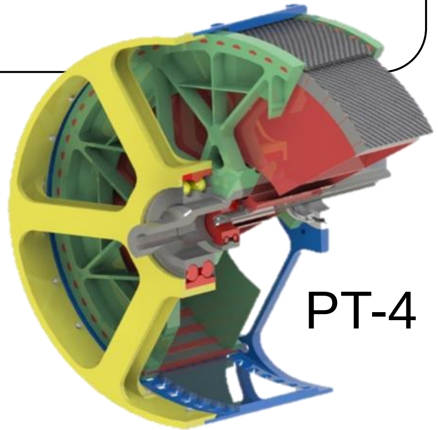
PT-1



PT-2



PT-3

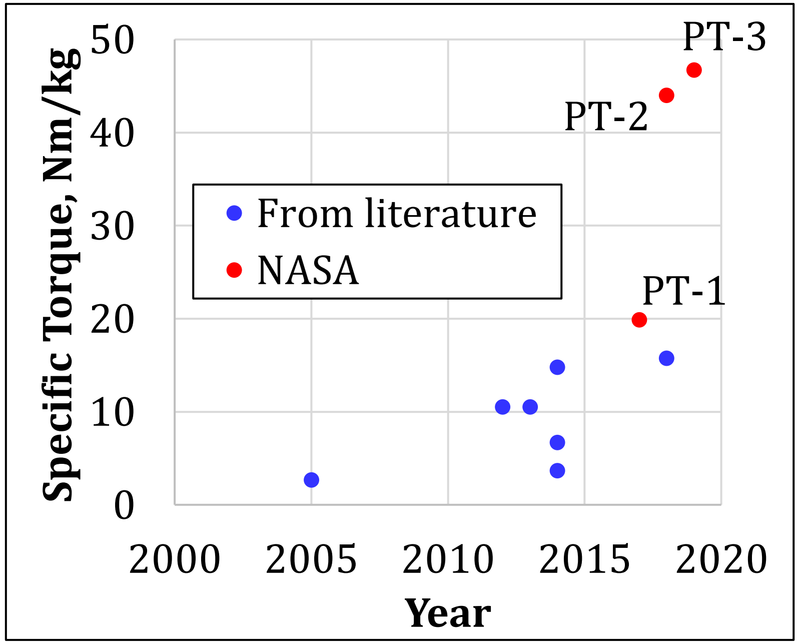


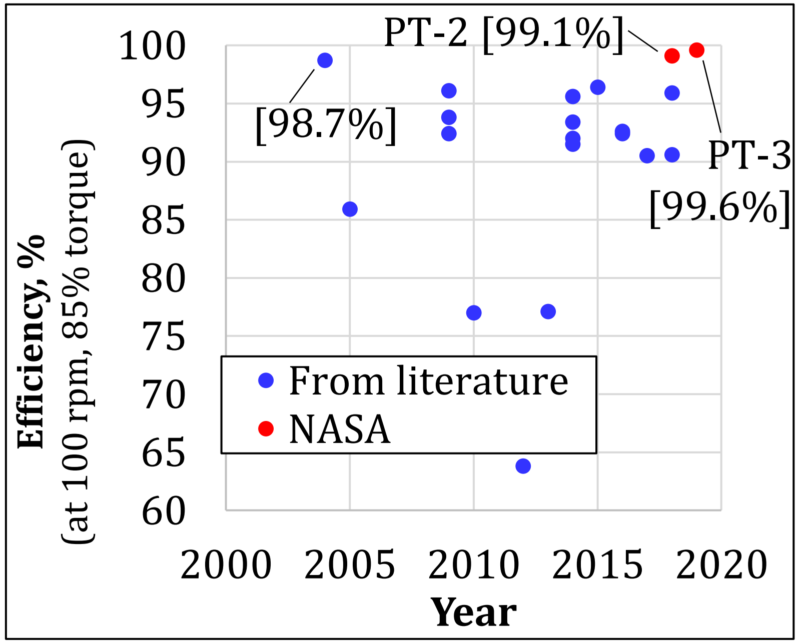
PT-4

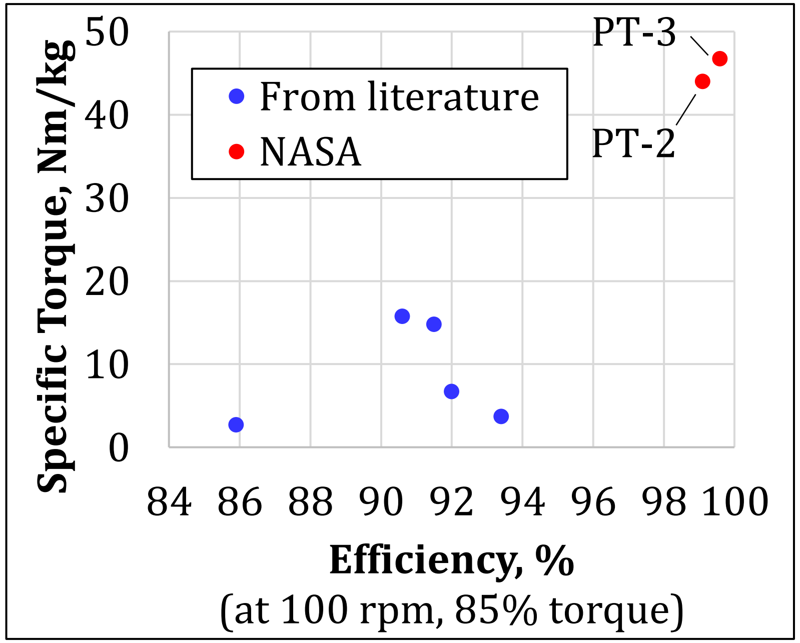
	Prototype			
	PT-1	**PT-2**	**PT-3**	**PT-4**
Magnetic Gear Type	Concentric			
Gear Ratio	4.25 : 1	4.83 : 1	4.83 : 1	12.1 : 1
Rated Output Speed, rpm	4,500	4,500	4,500	661
Peak Output Torque, Nm	34	124	112	226 (est.)
Size, mm	Ø141 x 92	Ø154 x 114		Ø212 x 131
Specific Torque, Nm/kg	20	46	42	49 (est.)

NASA's R&D for Aeronautics Applications

Historical view of NASA's advancement





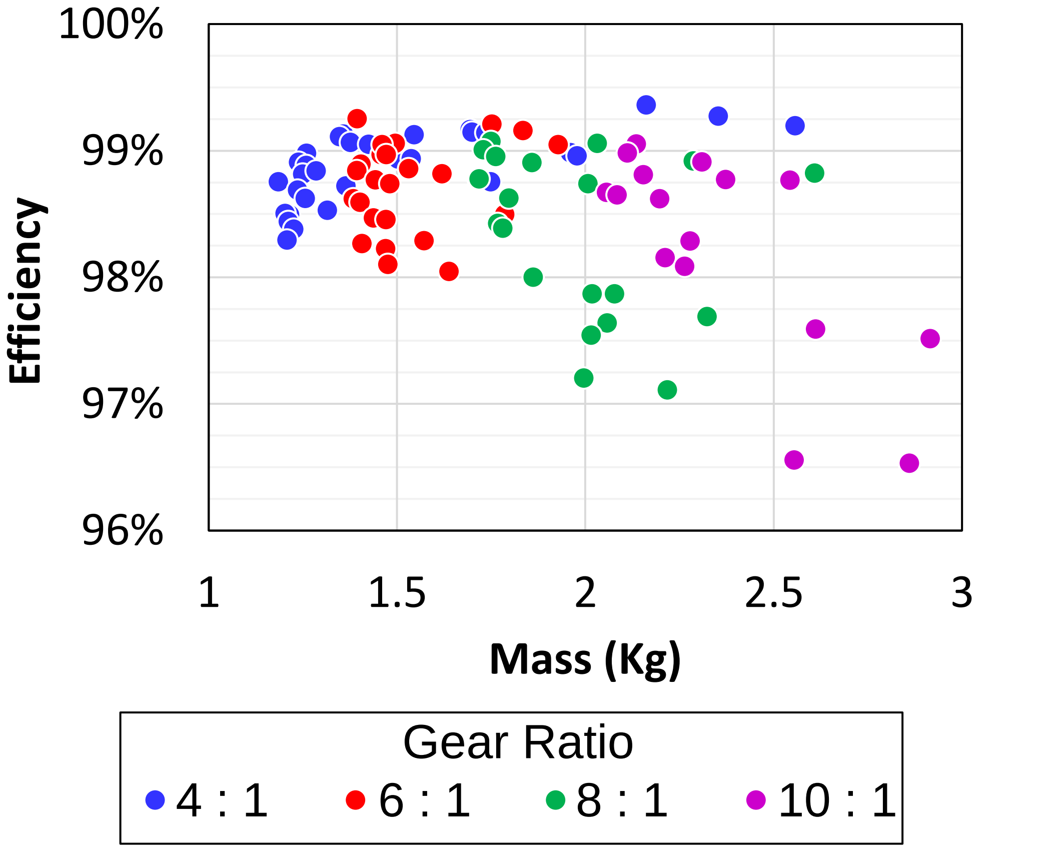


How Efficient Can They Be?

Answer: very efficient when carefully designed

- Laminate Electrical Components
  - Laminated Electrical Steel
  - Laminated Magnets
  - Increases effective (Bulk) resistivity
- Use non-electrically-conductive (non-metallic) Structures
  - Plastics
  - Composites
  - Ceramics ($$)

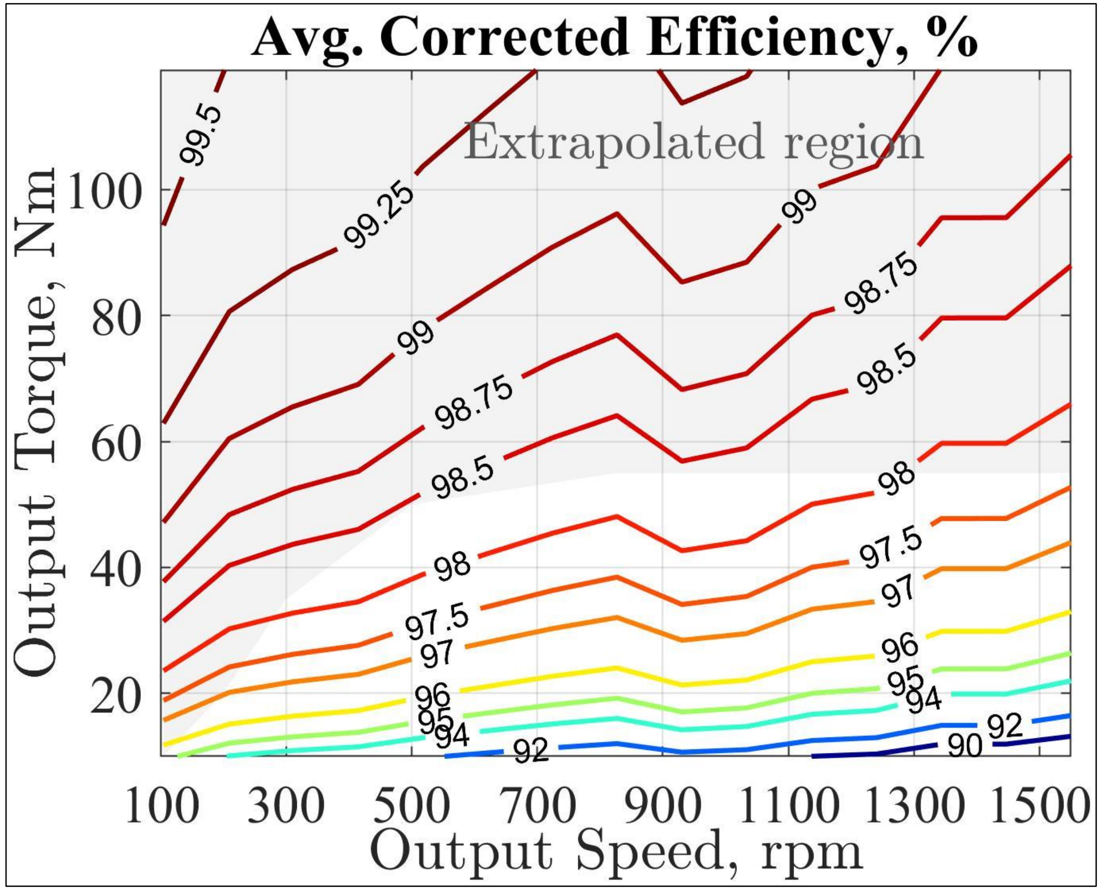
Example optimization results with 2 mm magnet laminations [1]
(gear with 120 Nm output @ 4,000 rpm [50 kW])



1. Tallerico, T.F. et al., In *Proc. AIAA/IEEE Electrified Aircraft Technologies Symposium*, 2019. https://ntrs.nasa.gov/citations/20190030509

How Efficient Can They Be?

- Measurements of NASA's prototype PT-3 [2]
  - 0.1 mm iron lamination
  - 1 mm magnet lamination
    - **Downside:** only 80% magnet fill factor
- Extrapolated efficiency exceeds 99.5% at low speeds
- > 99% efficiency up to about 1,300 rpm output speed
- ~97% efficiency at max operating torque & speed



2. Scheidler, J.J. et al., VFS Propulsion & Power Technical Meeting, 2019. https://ntrs.nasa.gov/citations/20190032574

Are They Temperature Sensitive?

- Answer: Yes
- As magnet temperature **increases**…
  - Magnets Weaken
    - Torque Decreases
    - Efficiency Increases (at a given operating point)
  - Eventually magnets demagnetize
- Losses are distributed over gear volume (not line contact)
- Lubrication/Liquid cooling not needed
  - NASA's prototype PT-4 is self cooled with centripetally-pumped flow, but magnets predicted to stay ≤ 80 ºC

Example: NASA's PT-4 with neodymium magnets [3]

Temperature (℃)	Torque, Nm (2D est.)	PT-4 Total Efficiency
20	370	98.5%
80	303	99%
100	270	-

Can mitigate the problem up to ~350 ºC with proper magnet selection

3. Tallerico, T.F. et al., In *Proc. AIAA/IEEE Electrified Aircraft Technologies Symposium*, 2019. https://ntrs.nasa.gov/citations/20190030679

How Do They Compare To Mechanical Gears & Motors?

Answer: it's complicated

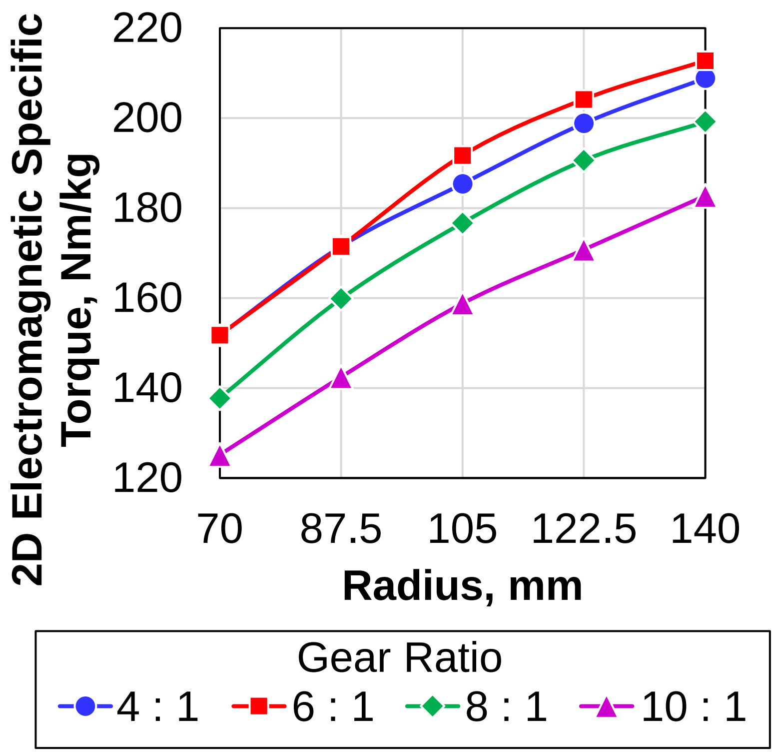
- NASA has improved SOA of magnetic gear specific torque
- Magnetic gears are light compared to electric motors
  - Magnetic gear ~ 35 kW/kg
  - Motor ~ 10 kW/kg

Prototype	Specific Torque, Nm/kg
Previous SOA	~20
PT-1	20
PT-2	46
PT-3	42
PT-4	49 (est.)

How Do They Compare To Mechanical Gears

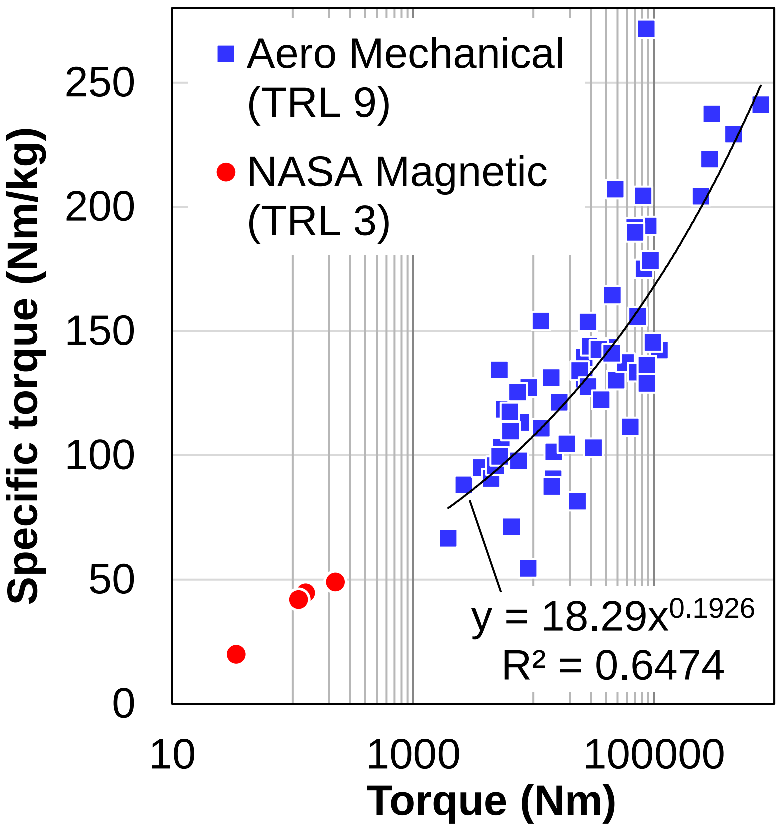
Scaling with size [4]

Magnetic specific torque (torque / magnetic mass) scales linearly with radius



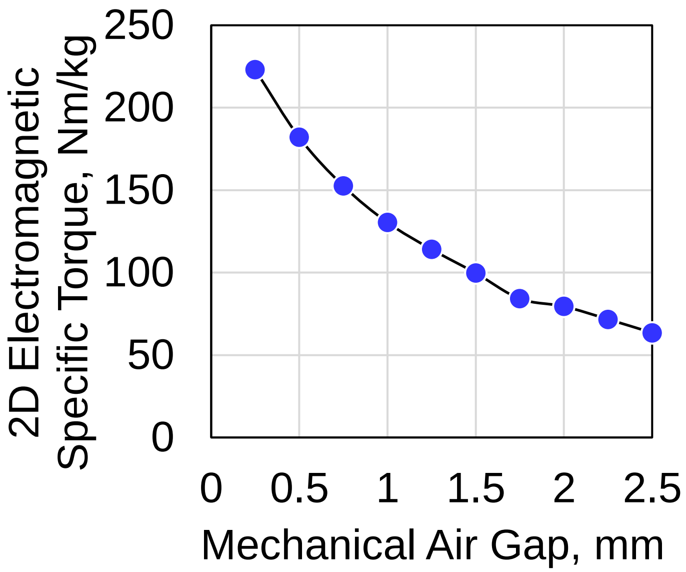
Scaling with torque

Specific torque (torque / total mass)



Scaling with air gap [3]

Magnetic specific torque



4. Tallerico, T.F. et al., VFS Propulsion & Power Technical Meeting, 2019. https://ntrs.nasa.gov/citations/20190033112

How Do They Compare To Mechanical Gears

Example: magnetic gear vs mechanical gear [4]

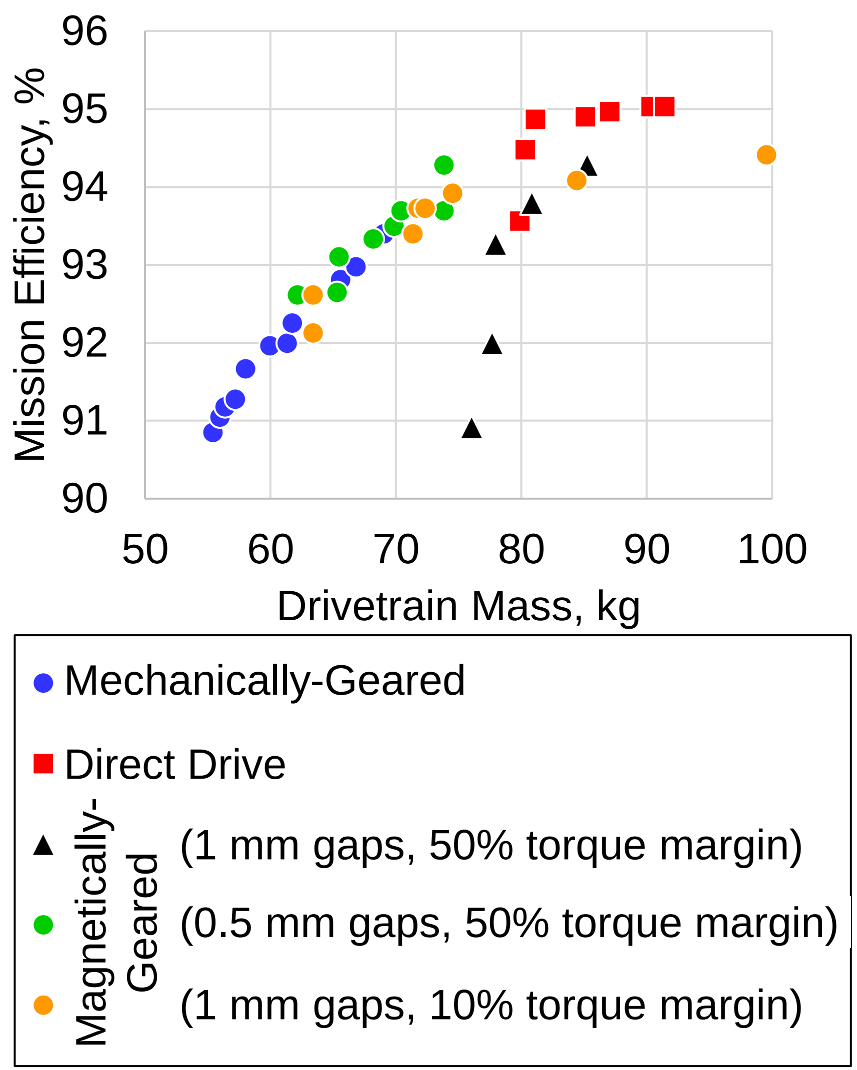
(OH-58 helicopter, final planetary stage)

- Mechanical active mass: 8.0 kg (gears + planet bearings)
- Active mass 2-3 x heavier with current capabilities
  - Improve by: thinner modulator or air gaps, stronger magnets

OH-58 Magnetic Gear			
Level of Tech	**Mechanical Airgaps**	**Modulator Thickness**	**Magnetic Mass**
NASA Current Aero Prototype	1 mm	2 mm	22.0 kg
Improved Modulator Design	1 mm	1.3 mm	20.3 kg
Improved Manufacturing	0.5 mm	2 mm	16.4 kg
Improved Manufacturing & Design	0.5 mm	1.3 mm	12.0 kg
Highly Improved Manufacturing	0.25 mm	1.3 mm	8.7 kg

Example: magnetically-geared motor vs alternatives [5]

(Quadrotor, 100 kW hover, 1,000 rpm)



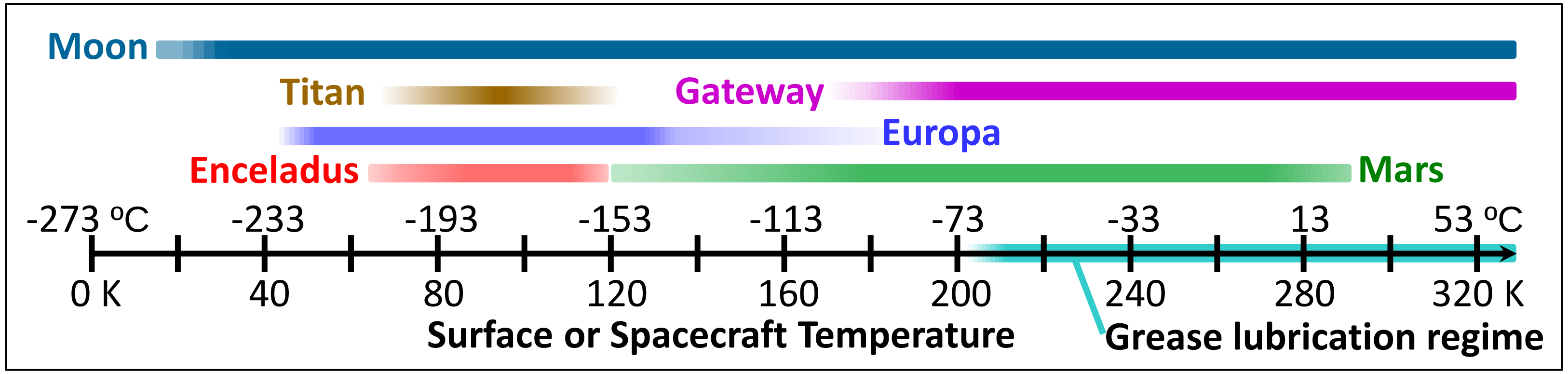
5. Tallerico, T.F. et al., In *Proc. AIAA/IEEE Electrified Aircraft Technologies Symposium*, 2023. https://ntrs.nasa.gov/citations/20230006121

Magnetic Gearing for Space Applications

- Lack of gear lubricant in magnetic gears is a significant benefit for space applications

Current approaches	Current penalty
Use dry film lubricant on contacting surfaces	(often significant) reductions in life & efficiency
Heat the gearbox/motor to ≥ -60 °C & use grease lubrication	Increased complexity & mass; less power for science

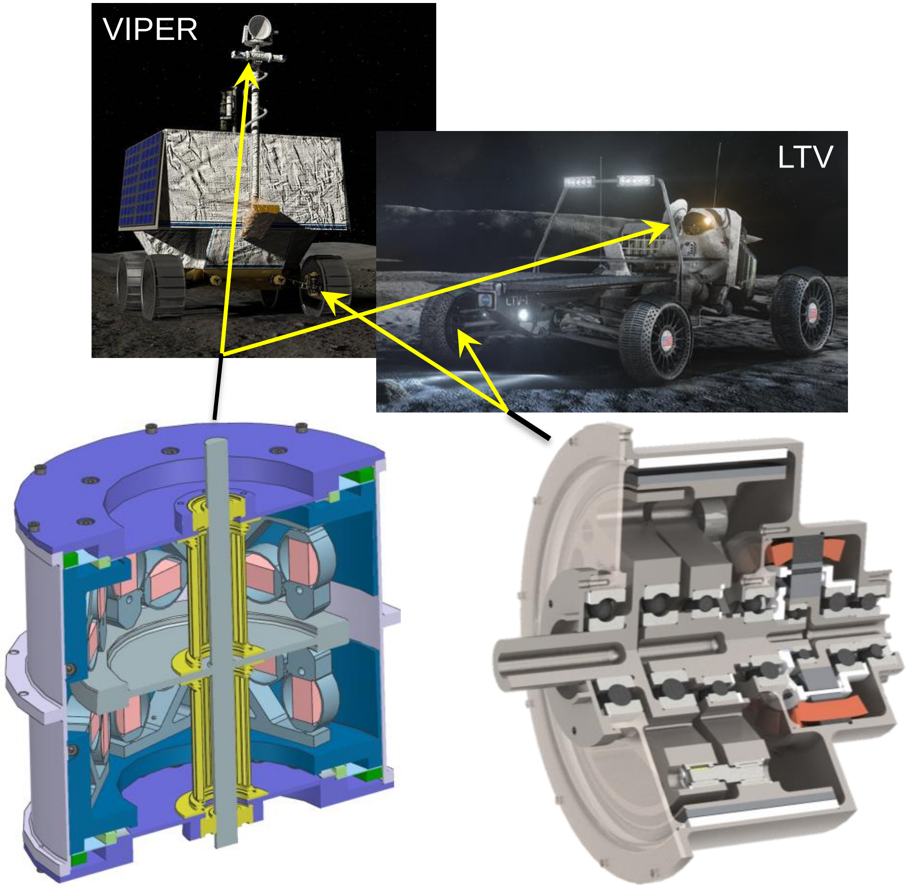
Temperature of space environments compared to grease lubrication regime



NASA's 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

Preliminary designs & example mechanisms



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

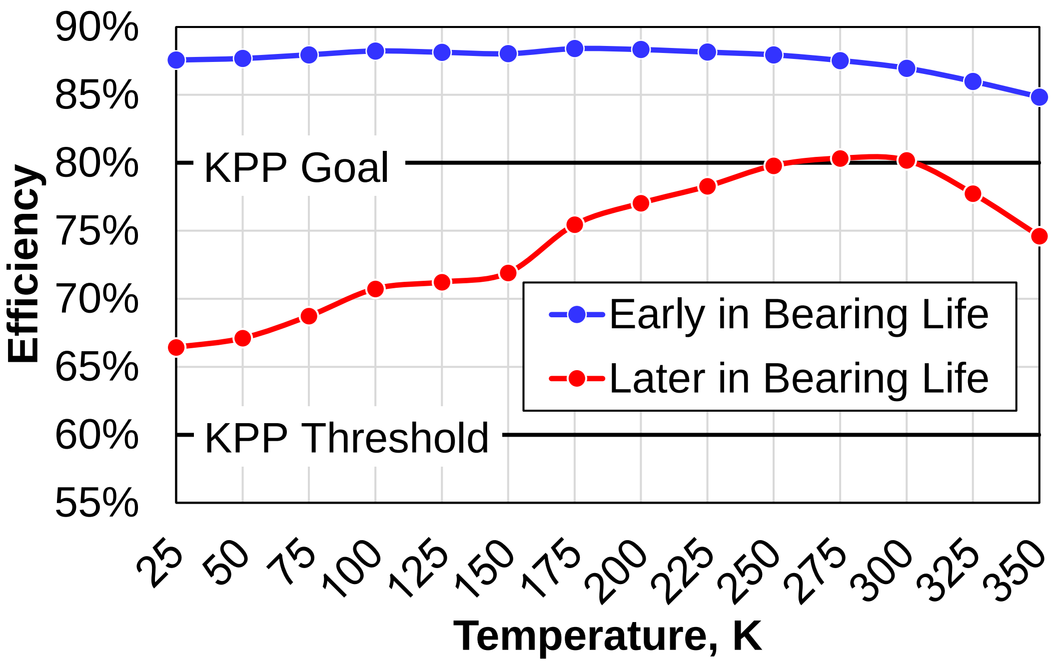
Magnetically-geared actuator preliminary design (NASA GRC & GSFC)

NASA's Motors for Dusty & Extremely Cold Environments (MDECE) Project

- Expect actuator to be operable over full predicted internal temperature range: -249 ºC (24 K) to 98 ºC (371 K)
  - Notional mission to lunar south pole in and out of permanently shadowed region
- Materials selection
  - Strongest permanent magnets (NdFeB) susceptible to radiation- & cryogenic temperature-induced degradation; SmCo better choice
  - Eliminate or carefully design composite materials
    - Anisotropic and non-homogeneous thermal expansion
  - Epoxy/varnish selection not trivial
    - Outgassing, cryo rating, softening at above room temperature, thermal expansion
- 0.25 mm air gaps are achievable with careful structural & mechanical design
- Cryo-capable bearings are life limiting component, but magnetic gear design can have strong influence on bearing loads

MDECE Project – Development Status

- Critical Design Review completed July 2023
- 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

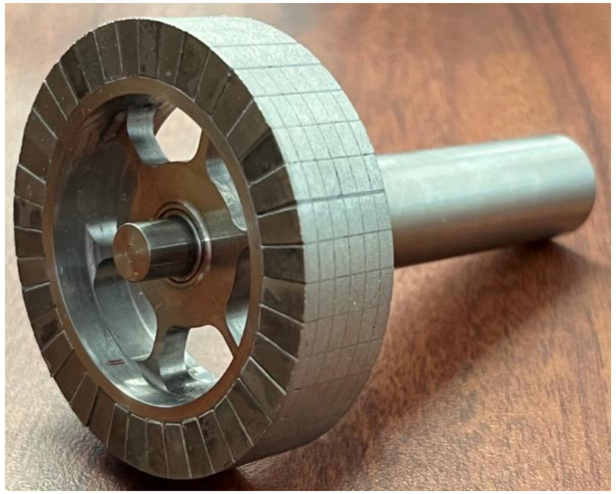
‡ With resolver (may not be needed)

Steady state condition	Efficiency	
	Early in life	Later in life
Goal cold operation (-243 ºC regolith, shadowed)	88.4%	78.3%
Goal hot operation (40 ºC regolith, in sun at 85 ºS)	85.1%	75.4%

MDECE Project – Development Status

- Assembly of proof-of-concept actuator in progress [6]
- Procurement of hardware for fully-functional actuator in progress

Sun gear for proof-of-concept actuator's magnetically-geared motor



proof-of-concept cycloidal magnetic gear

5. Scheidler, J.J. et al., In *Proc. European Space Mechanisms Symposium*, 2023.

SBIR Projects on Aerospace Applications

Aero applications

- **2019-2020 / Phase 1** / FluxMagic, Inc. & Portland State University
  - Magnetically Geared Aircraft Drivetrain [1]
  - Design, manufacture, & testing of magnetic gear with 12.1 : 1 ratio
- **2019-2020 / Phase 1** / US Hybrid Corp. & Texas A&M University
  - Robust, Compact, and Low-Maintenance Magnetic Gear System [2]
  - Design of magnetically-geared motor for electrified aircraft propulsion

Space applications

- **2020-2021 / Phase 1** / US Hybrid Corp. & Texas A&M University
  - Magnetic Gearing Applications for Space [3]
  - Design magnetic gearbox with 1000 : 1 ratio for extremely cold space environments [4,5]
- **2023-2024 / Phase 1** / FluxWorks LLC & University of Texas at Dallas
  - Scalable Magnetically Geared Actuator for Future Missions in Dusty & Extremely Cold Environments [6]

1. https://sbir.nasa.gov/SBIR/abstracts/19/sbir/phase1/SBIR-19-1-A1.04-3853.html
2. https://sbir.nasa.gov/SBIR/abstracts/19/sbir/phase1/SBIR-19-1-A1.04-3812.html
3. https://sbir.nasa.gov/SBIR/abstracts/20/sbir/phase1/SBIR-20-1-Z5.05-5968.html
4. Praslicka, B. et al., 2021 IEEE International Electric Machines & Drives Conference (IEMDC), Hartford, CT, 2021. https://doi.org/10.1109/IEMDC47953.2021.9449504
5. Hasanpour, S. et al., 2023 IEEE International Electric Machines & Drives Conference (IEMDC), San Francisco, CA, 2023.
6. https://sbir.nasa.gov/SBIR/abstracts/23/sbir/phase1/SBIR-23-1-Z13.05-1119.html

Conclusions

Comments on feasibility

- Feasible for aero applications, although some applications will hinge on mechanical design & manufacturing improvements or better understanding of required torque margin
- More feasible for space applications, because it enables cold actuation

Technical barriers to adoption

- Need to demonstrate life & eventually reliability
- Need to mitigate life limitations of cryo-capable bearings
    - Improve bearing tech or further evaluate alternative magnetic gear configurations

Potentially fruitful areas of future research

- Design & demonstration of high efficiency with minimal reduction in magnet fill factor
- New magnetic gear configurations (e.g., ones tailored for high gear ratio that avoid high bearing loads)

THANK YOU


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