# Magnetic Gearing Research at NASA

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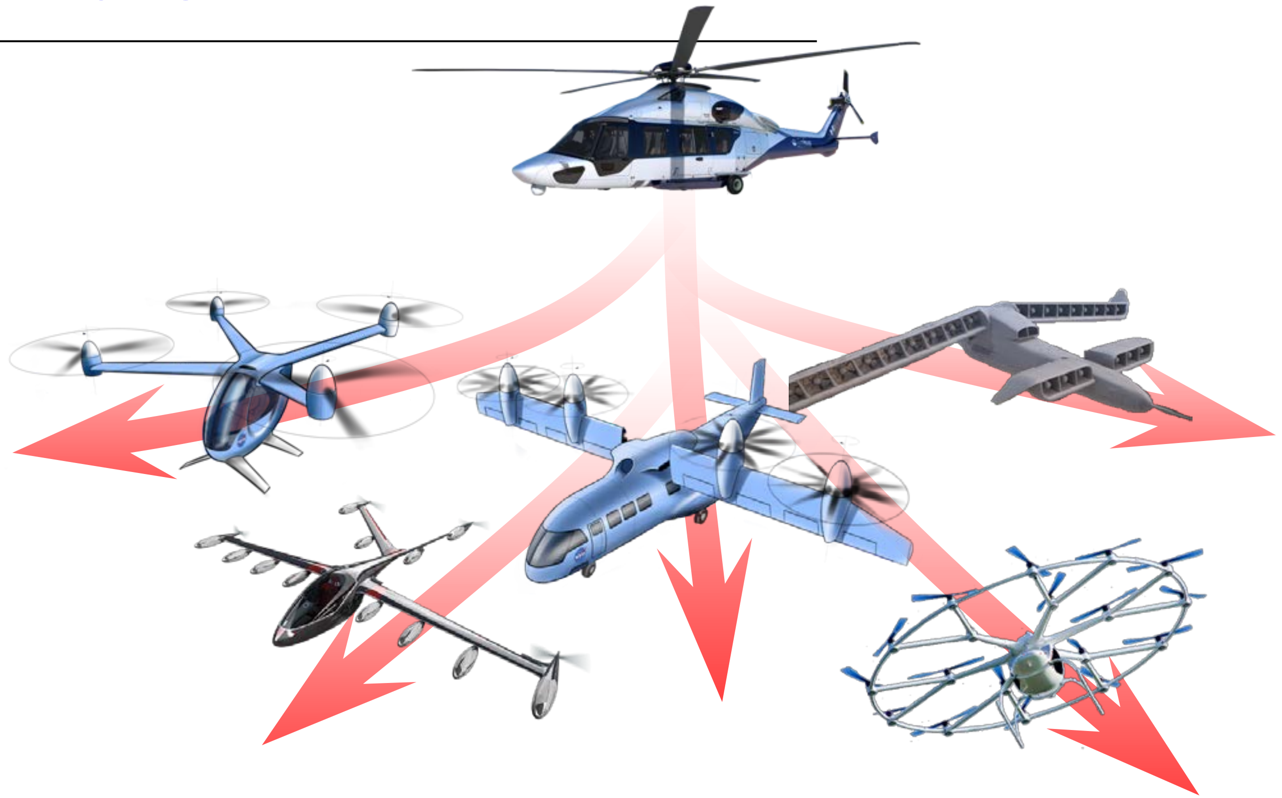
# Outline

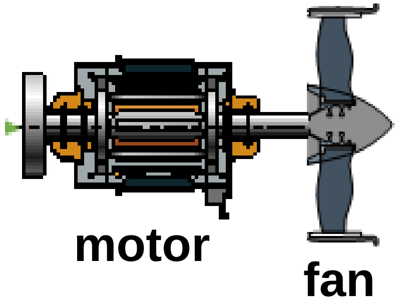
- Motivation
- Principles of operation
- Technology development at NASA
- Future work
- Conclusions

# Motivation

- Growth of short haul market & emergence of urban air mobility market
  - Enabled by electrified propulsion systems
  - Prevalence of smaller (lower torque) propulsors
- Most concepts use direct drive
- Geared drives are almost always mass optimal

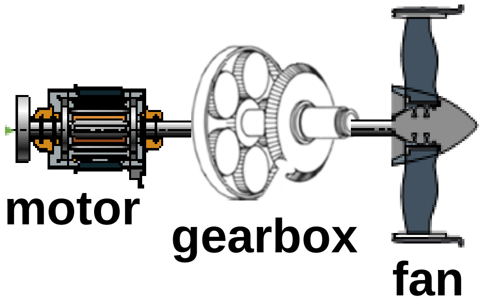


## Direct drive




+ Simpler
− Non-optimal motor and/or fan

## Geared drive




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

# Motivation

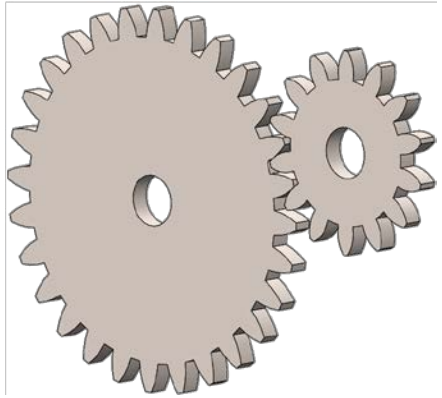
## Mechanical gearing

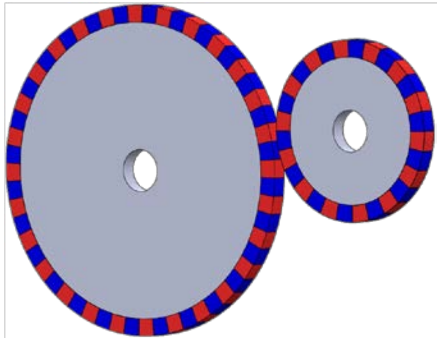
**Pros**

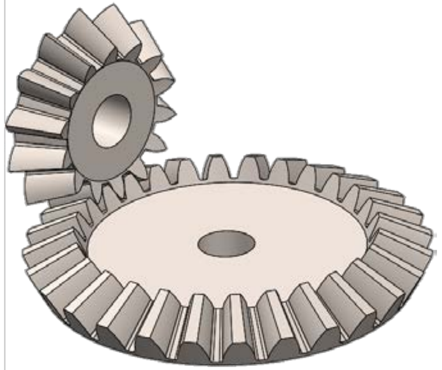
+ High / very high torque/mass (**specific torque**)
+ High / very high efficiency
+ Mature technology

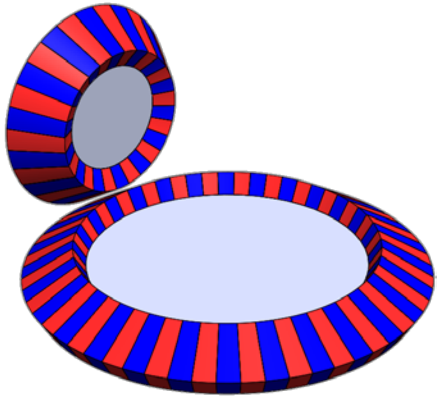
**Cons**

− 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
+ Easily integrated in electric machines
+ Potentially low vibration

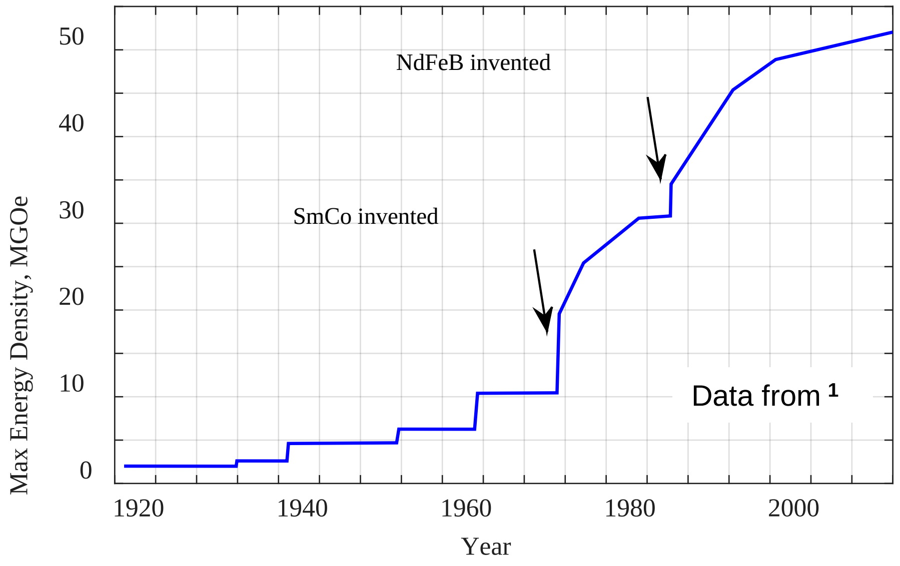
**Cons**

− Unknown limits on specific torque & efficiency
− Magnet temperature limit
− Individual magnet interaction weaker than 1 gear tooth pair

# Background

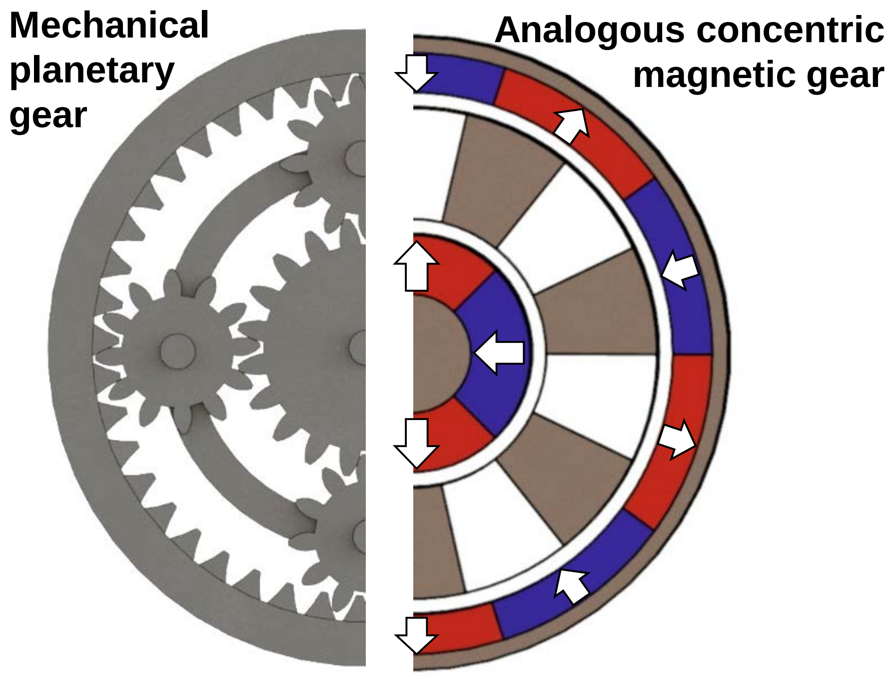
## Key historical developments

- **1901** – 1st invention
- **<1960s** – primarily electromagnets
- **1966** – SmCo magnets invented
- **1983** – NdFeB magnets invented
- **2001** – Concentric magnetic gear (CMG) mathematics



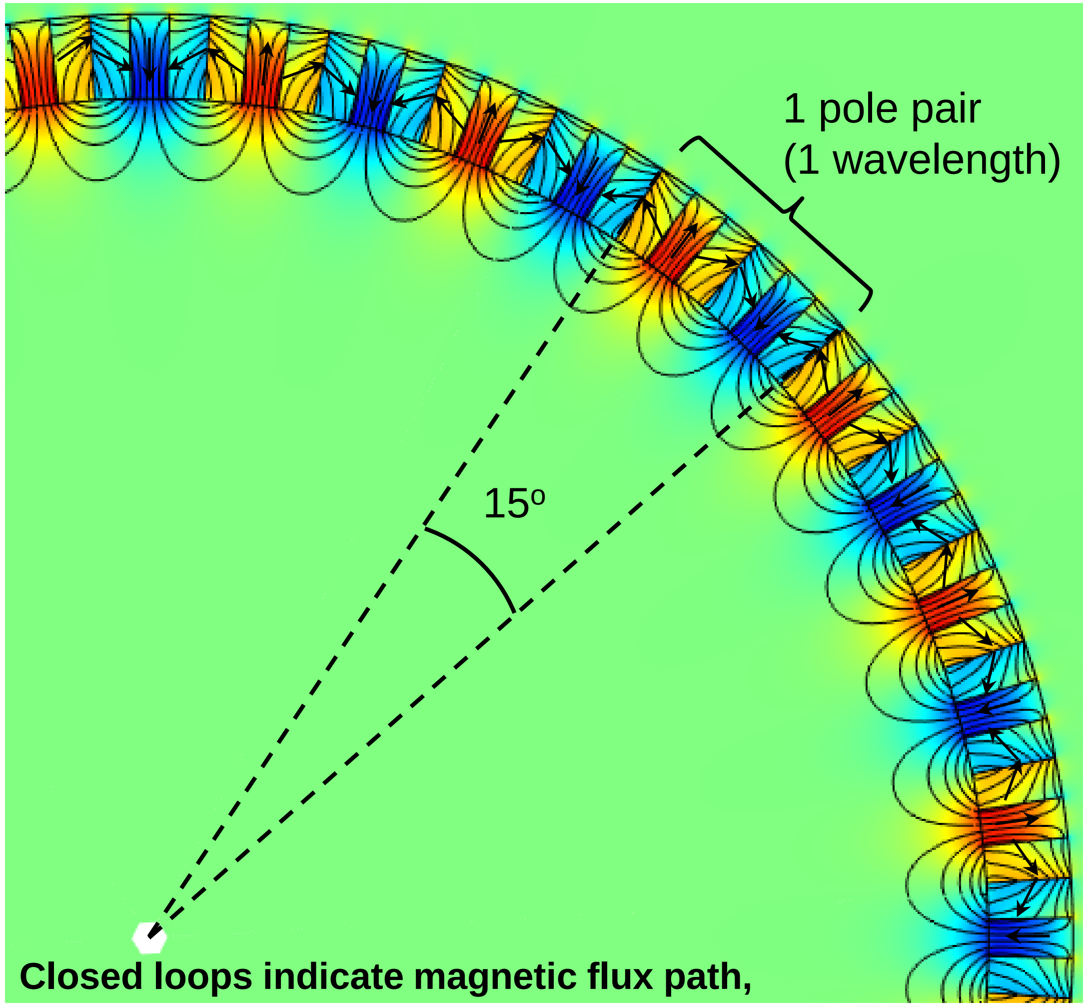

## Why we selected CMG

- High specific torque
- Potential replacement of final stage helicopter gearing (cabin noise reduction)
- Easily integrated in electric machines

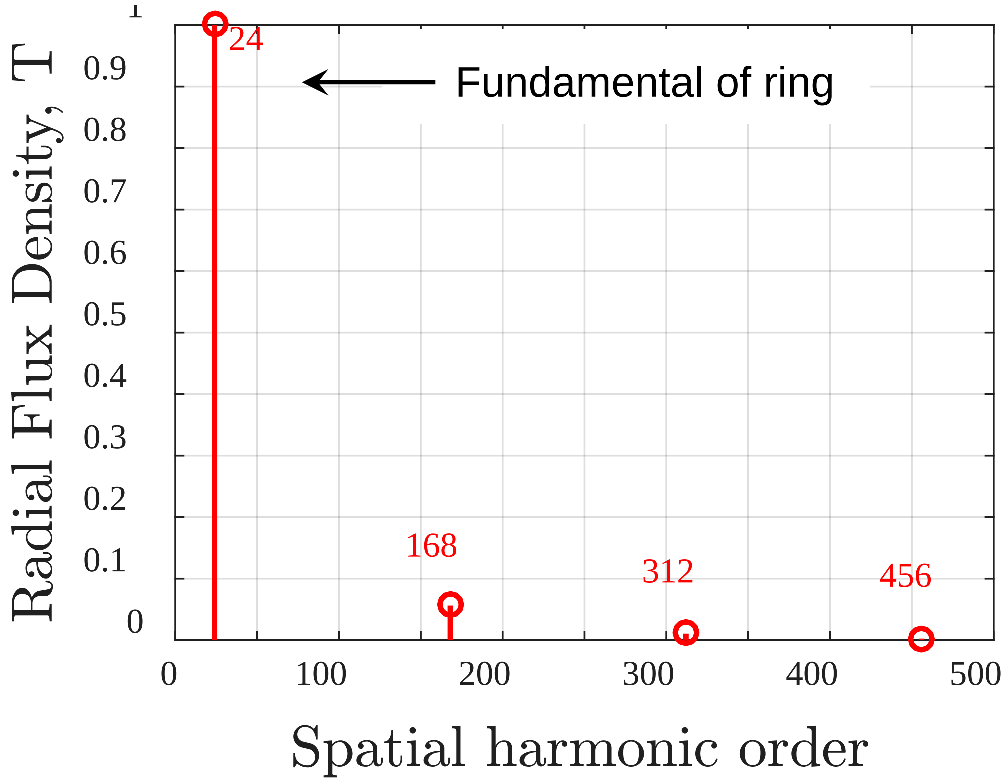


# Principles of Operation

- **Example:** 4:1 gear ratio, 24 pole pairs in ring (15º wavelength), 6 magnets per pair

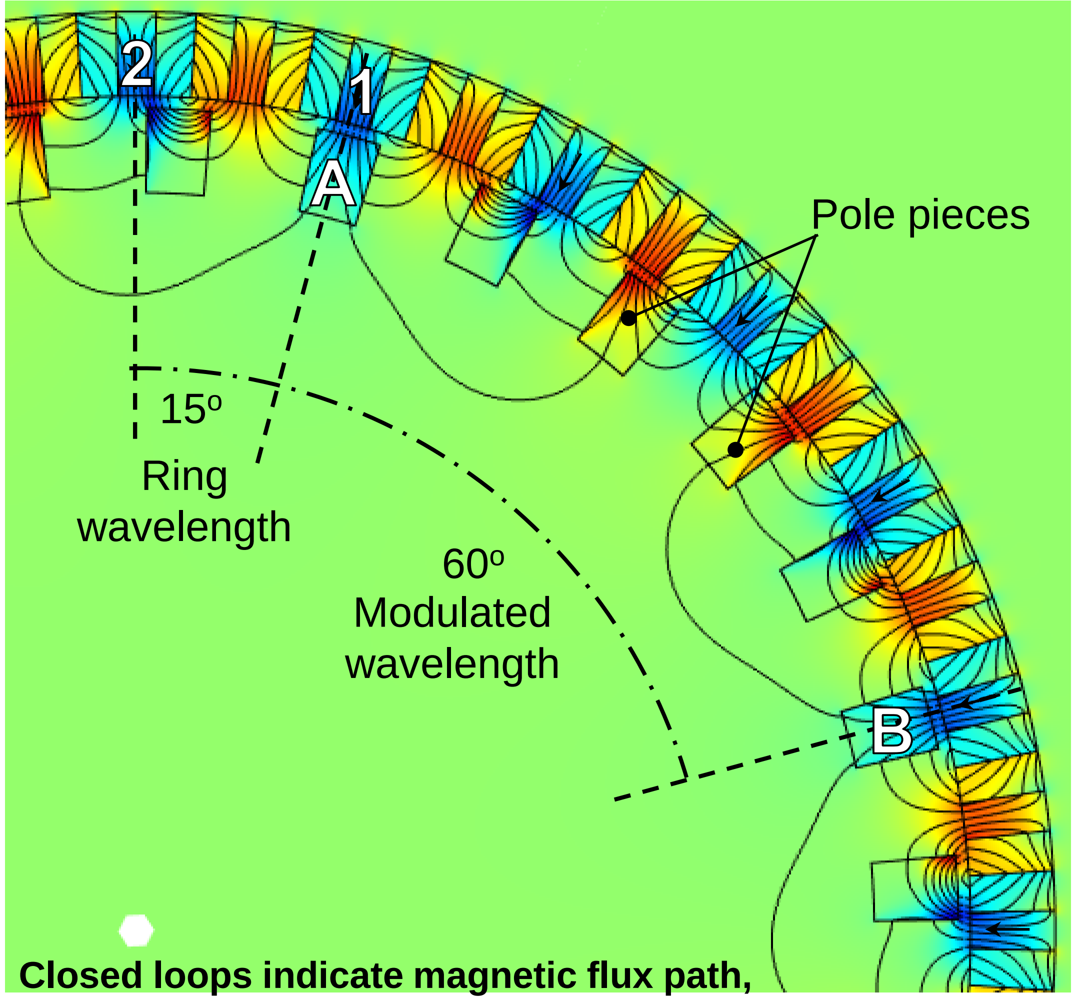



Closed loops indicate magnetic flux path, color indicates radial component of flux

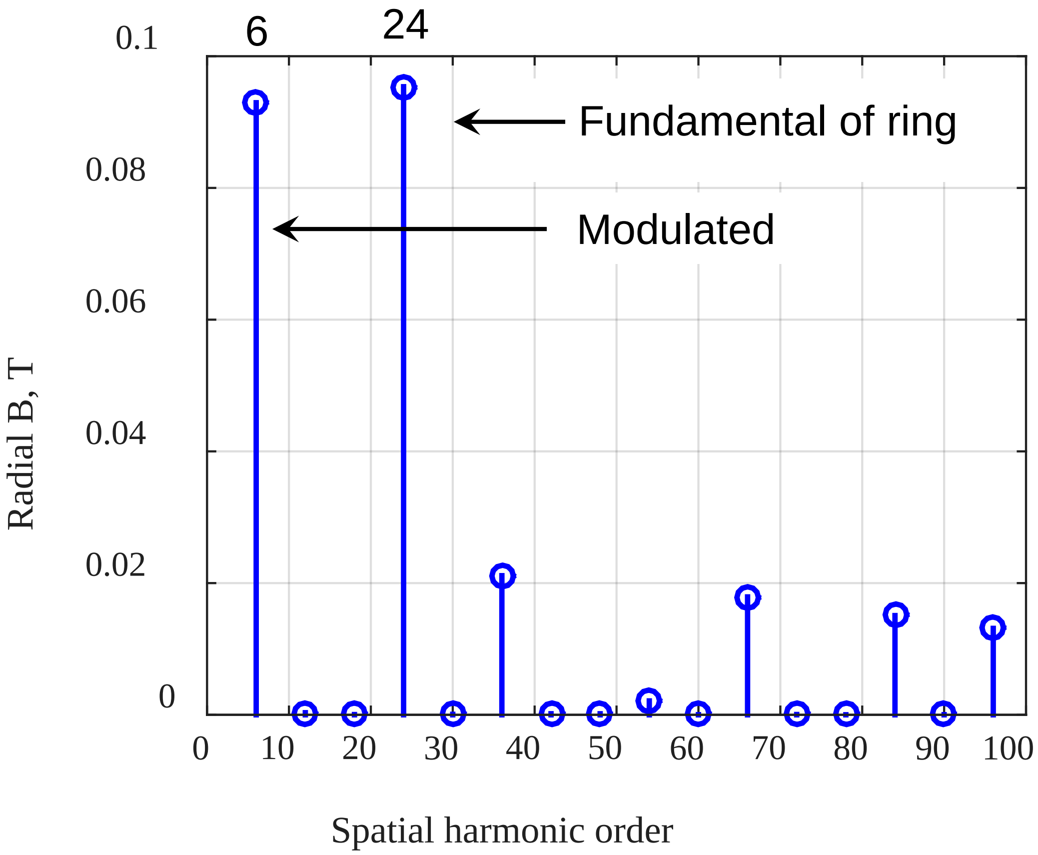


# Principles of Operation

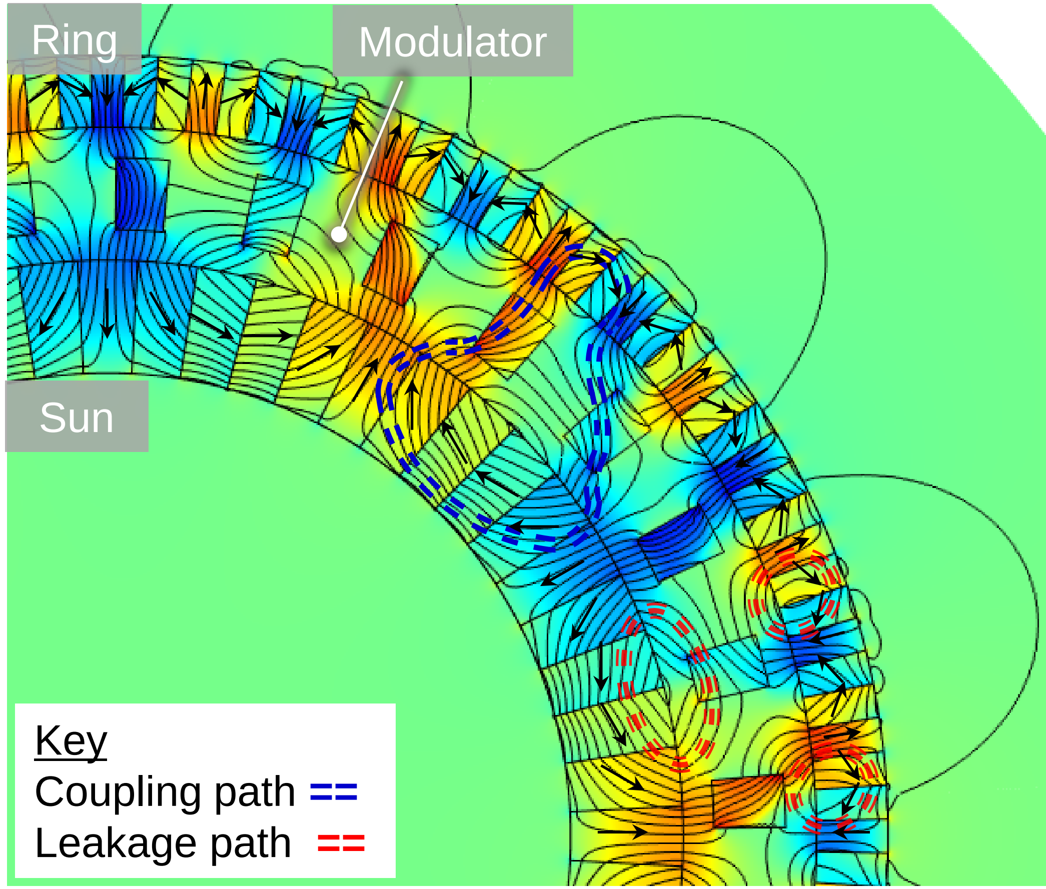
- **Example:** 4:1 gear ratio, 24 pole pairs in ring (15$^o$ wavelength), 6 magnets per pair

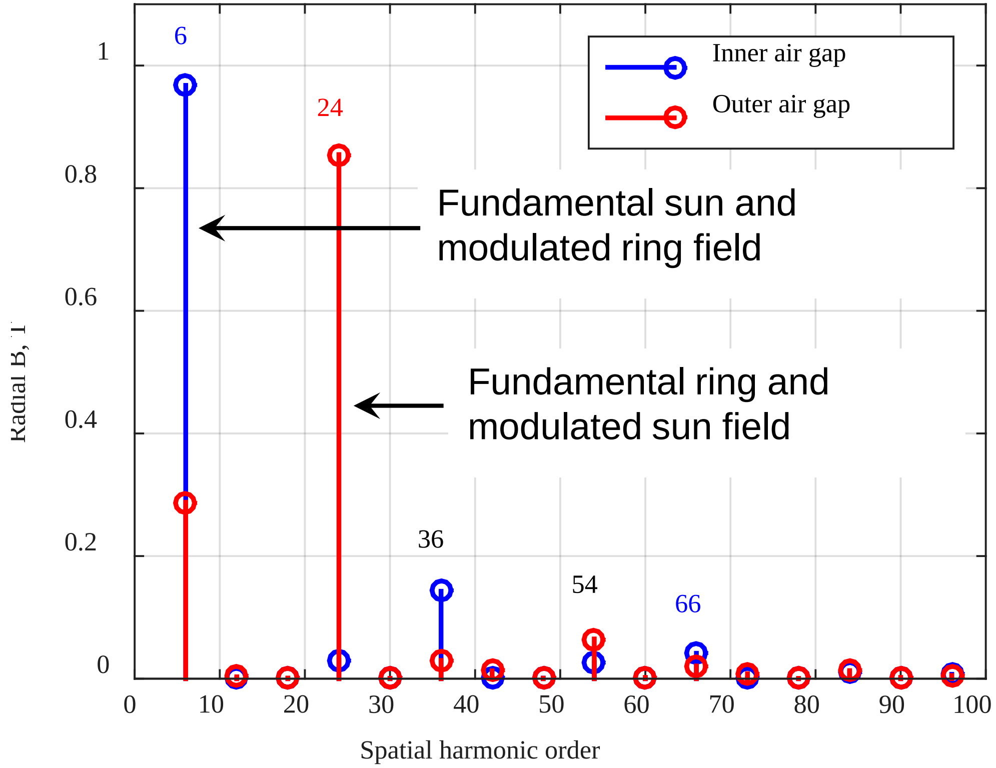



**Closed loops indicate magnetic flux path, color indicates radial component of flux**

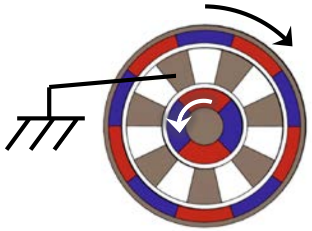


# Principles of Operation

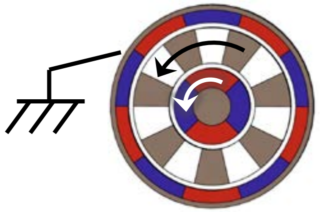



- Key design variables
  - # of magnetic pole pairs ("teeth")
  - # magnets
  - Radial thickness of components & air gaps



$$GR = \frac{N_{\text{ring}}}{N_{\text{sun}}}$$



$$GR = 1 + \frac{N_{\text{ring}}}{N_{\text{sun}}}$$

# Technology Development at NASA

2-1/2 year project

- Create fundamental understanding
- Compare to mechanical gearing for aerospace applications

Focus areas

- Phase 1 – specific torque
- Phase 2 – efficient high-speed operation
- Phase 3 – motor/gear integration

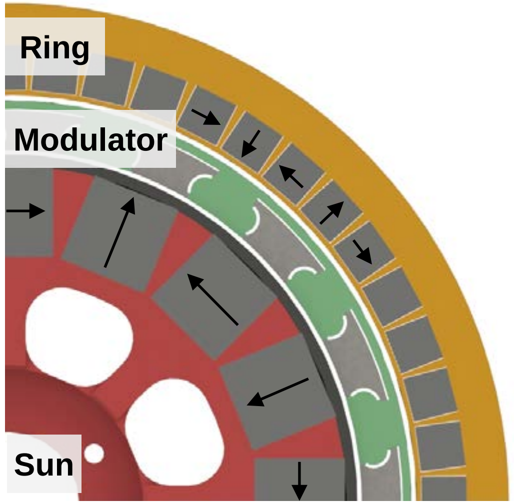
Progress

- Phase 1 was recently completed.
- Two prototypes were developed to understand specific torque

# Design and manufacture of Prototype 1 (PT-1)

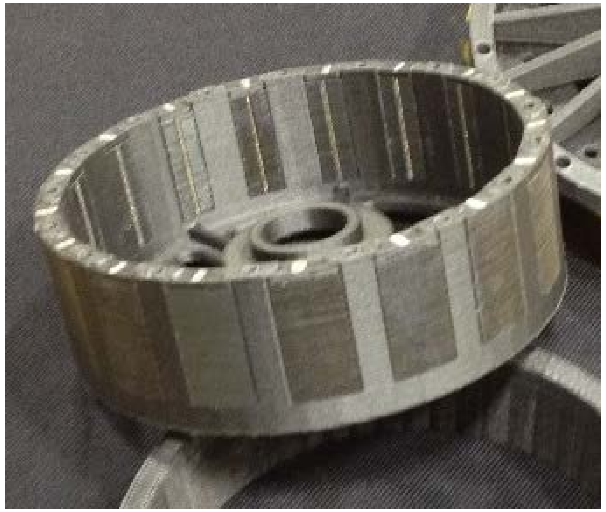
- Goal:  To gain design & manufacturing experience
- Electric aircraft propeller specifications:  152 mm (6 in ), ~4:1 speed reduction, 4500 rpm
- Static/2D magnetic FEA: Off-the-shelf magnets / Limited design optimization
- Printed structures
  - Rapid production
  - Nylon-carbon fiber composite material
  - Not suitable for heat dissipation in long-duration tests

**Design**




**Sun**

**Modulator**



**Ring**

# Results from PT-1

Specific torque

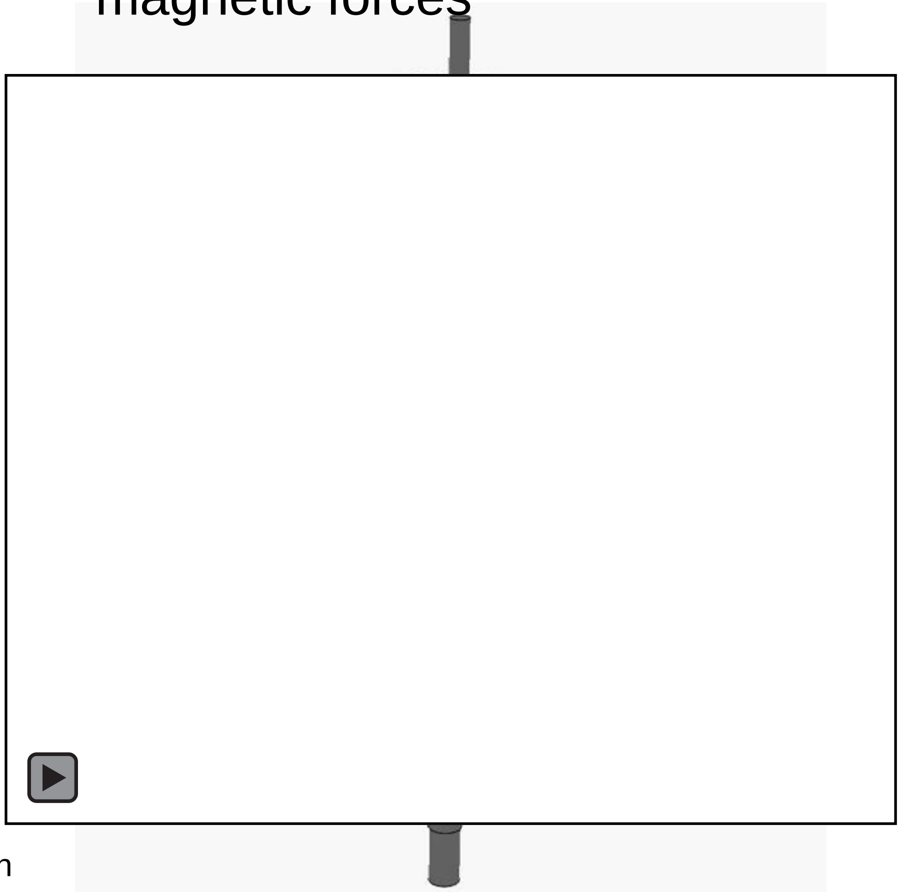
- 2D simulation: **31 Nm/kg**
- Measurement: 20 Nm/kg
- 36 % reduction

Lesson

- Magnetic forces can deform/damage the structures during assembly

Successful assembly procedure

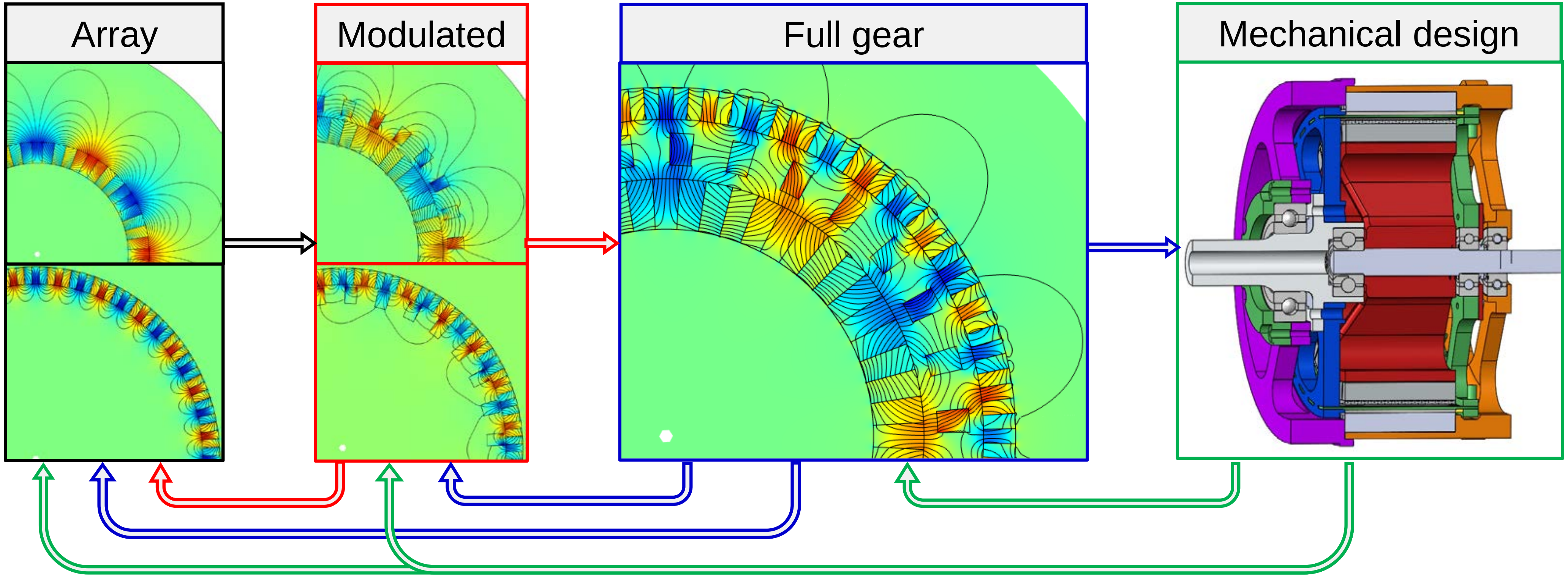
- Fully construct the sun, modulator, and ring → full hoop stiffnesses
- Use shims in air gaps to keep members centered → reduces magnetic forces



Demonstration of gear ratio

# Design of Prototype 2

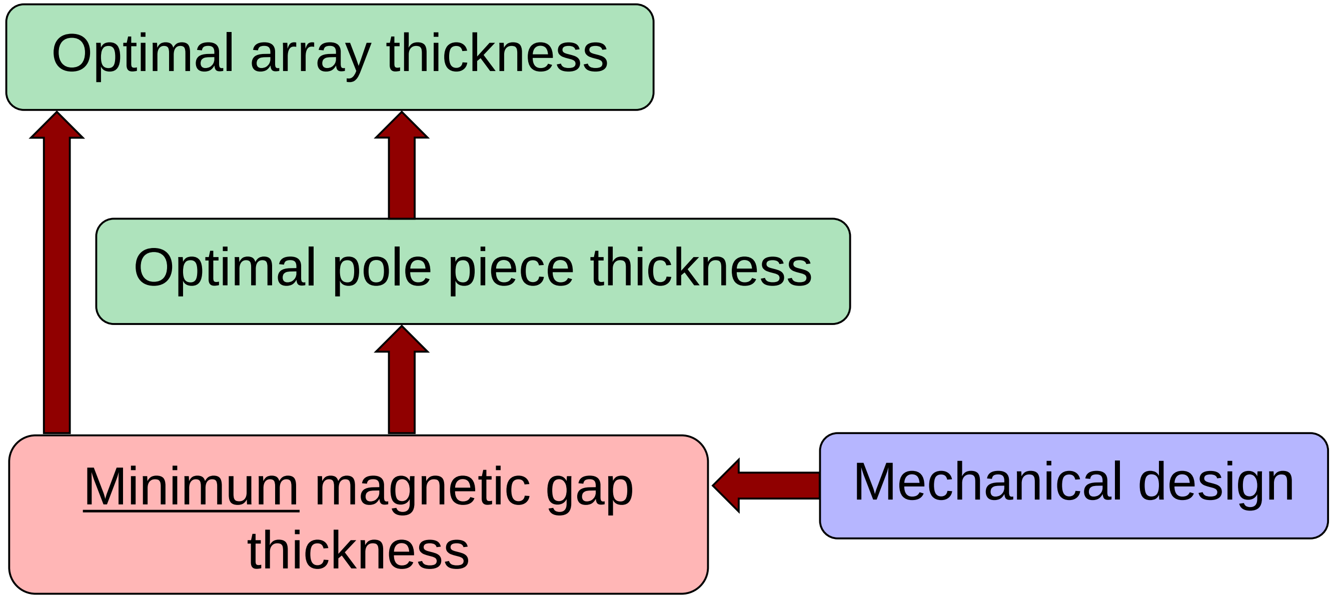
- Goal: Maximize specific torque
  - Geometric optimization of magnetic and pole piece geometry.
- Incremental / iterative design process
  - Provides clearer understanding of the role of sub-components.
  - Sub-component simulations reduce number of full gear simulations required.
  - Mechanical features are fed back to constrain the magnetic geometry



# Key results from the design of PT-2

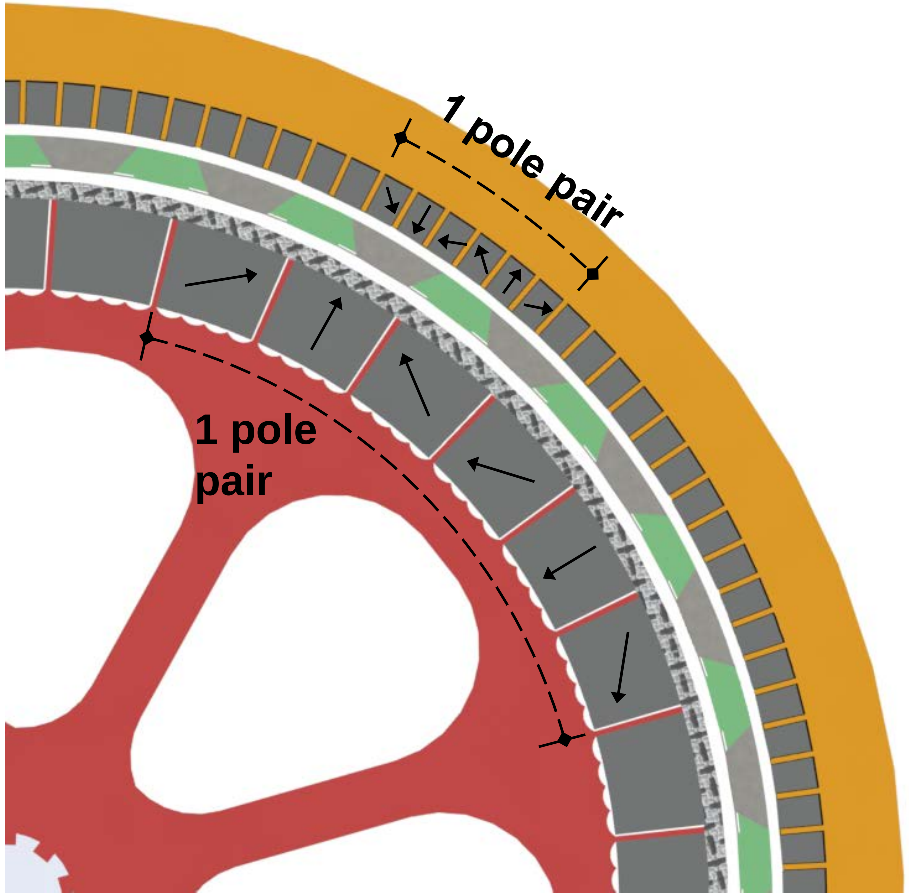
## Specific torque

- 2D simulation: **61 Nm/kg**, roughly 2x PT-1
- Magnetic gap thickness fundamentally limits specific torque




- Mechanical design features that enable thinner magnetic gaps can improve specific torque

## Magnetic configuration



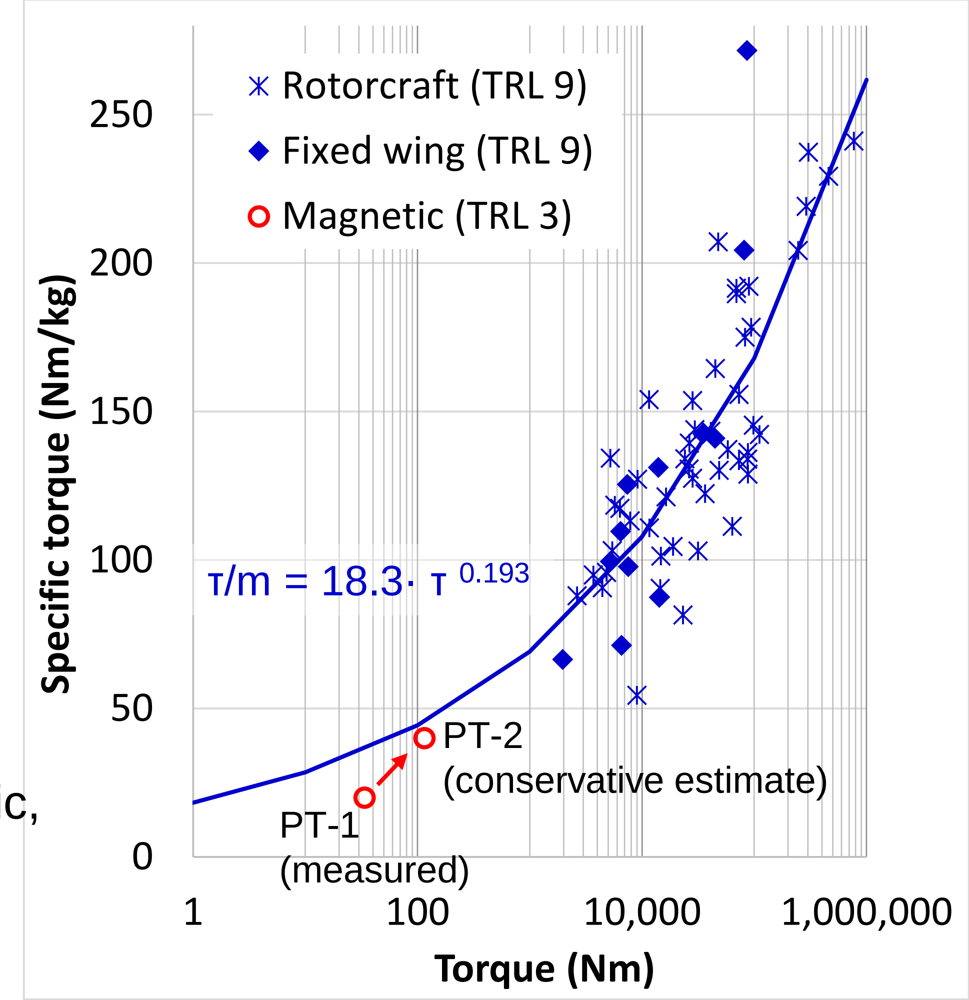
# Prototype Performance

- Fabrication of PT-2 is in progress
- Prototype specific torque is estimated by de-rating prediction by 36 %

| | PT-1 | PT-2 |
|---|---|---|
| **Torque (Nm)** | | |
| 2D simulation | 53.0 | 178 |
| Measurement | 34.0 | N/A |
| **Mass (kg)** | | |
| Active | 1.0 (59 %) | 1.7 (59 %) |
| Structural | 0.7 (41 %) | 1.2 (41 %) |
| Total | 1.7 | 2.9 |
| **Specific torque (Nm/kg)** | | |
| 2D simulation | 31 | 61 |
| Measured | 20 | >40 (est.) |

- Specific torque is expected to be similar to an aircraft gearbox
    - o **Structural mass may increase** considerably as thermal, dynamic, and other engineering considerations are added
    - o But, **magnetic mass can be reduced** by reducing air gap size
- o *Scaling to other torque levels is unknown at this point*

Performance compared to aircraft transmissions

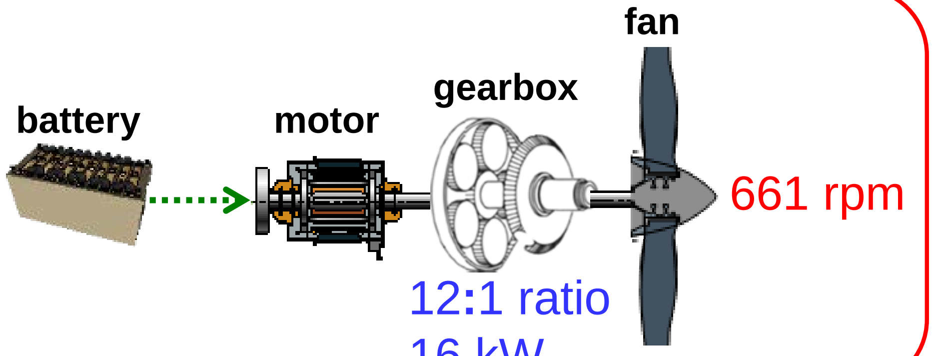



Data courtesy of Dr. Tim Krantz (NASA GRC)

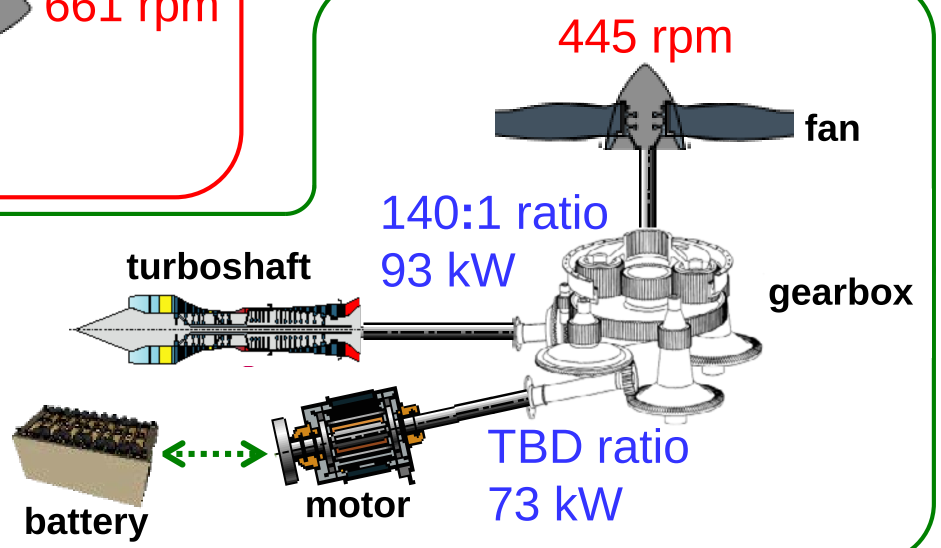
# Future Work

- Target NASA's eVTOL reference aircraft [2]

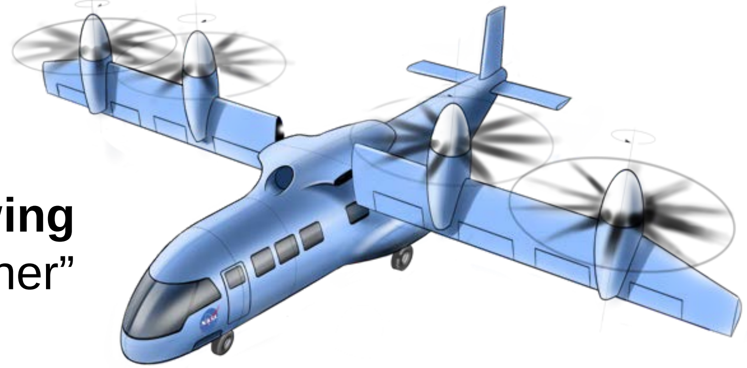
**Quadrotor**
"Air Taxi"

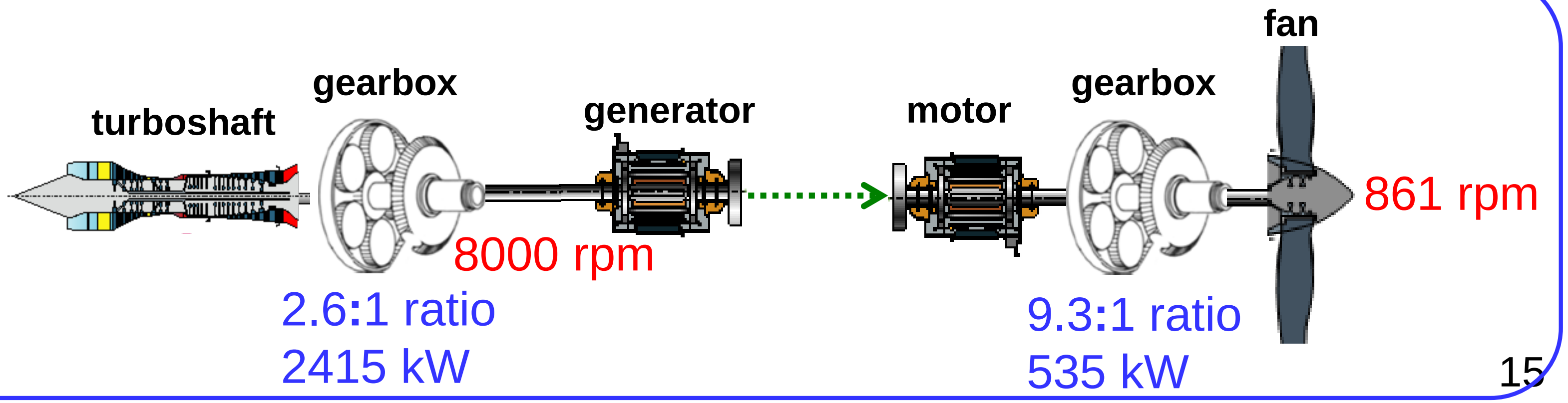



**Side-by-Side**
"Vanpool"




**Tiltwing**
"Airliner"





# Future Work

**Phase 2** – enable high efficiency at high speeds

- **Data**
  - Speed dependence of torque, efficiency, vibration, & temperature
- **Design**
  - Reduce driving mechanism for eddy currents
  - Unconventional solutions for magnet & pole piece containment
- **Materials**
  - Alternative or laminated magnetic materials
  - Electrically-insulating, thermally-conductive structural materials

**Phase 3** – integration in electric motors

- Focus**:** motor-to-rotor stages of the quadrotor and tiltwing
- Explore several topologies from literature

# Conclusions

**Key conclusions from NASA's Phase 1** (understand & improve specific torque)

- **Strong coupling between mechanical & magnetic designs**
  - Magnetic performance limited by mechanical features & min. gap size
- **Concentric magnetic gears are viable, at least for lower torque applications** (e.g., emerging eVTOL aircraft)
- Improvement relies on reducing air gaps, better integration, lighter structures

**R&D needs in the field**

- **Understand scaling**
- **Thermal management**
- Data at higher speeds – efficiency, continuous operation
- **Enhanced high-speed efficiency**
- Advancement of other configurations
  - Shaft angle change
  - Combining inputs
  - Higher ratios

Acknowledgements

- NASA Revolutionary Vertical Lift Technology (RVLT) Project
- NASA Internal Research & Development Project

## References

1. Constantinides, S., “The demand for rare Earth materials in permanent magnets,” Proc. of 51st Conf. of Metallurgists, Niagra Falls, Canada, 2012.
2. Johnson, W., Silva, C., and Solis, E., “Concept Vehicles for VTOL Air Taxi Operations,” American Helicopter Society Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, Jan 16 – 19, 2018.

# QUESTIONS ?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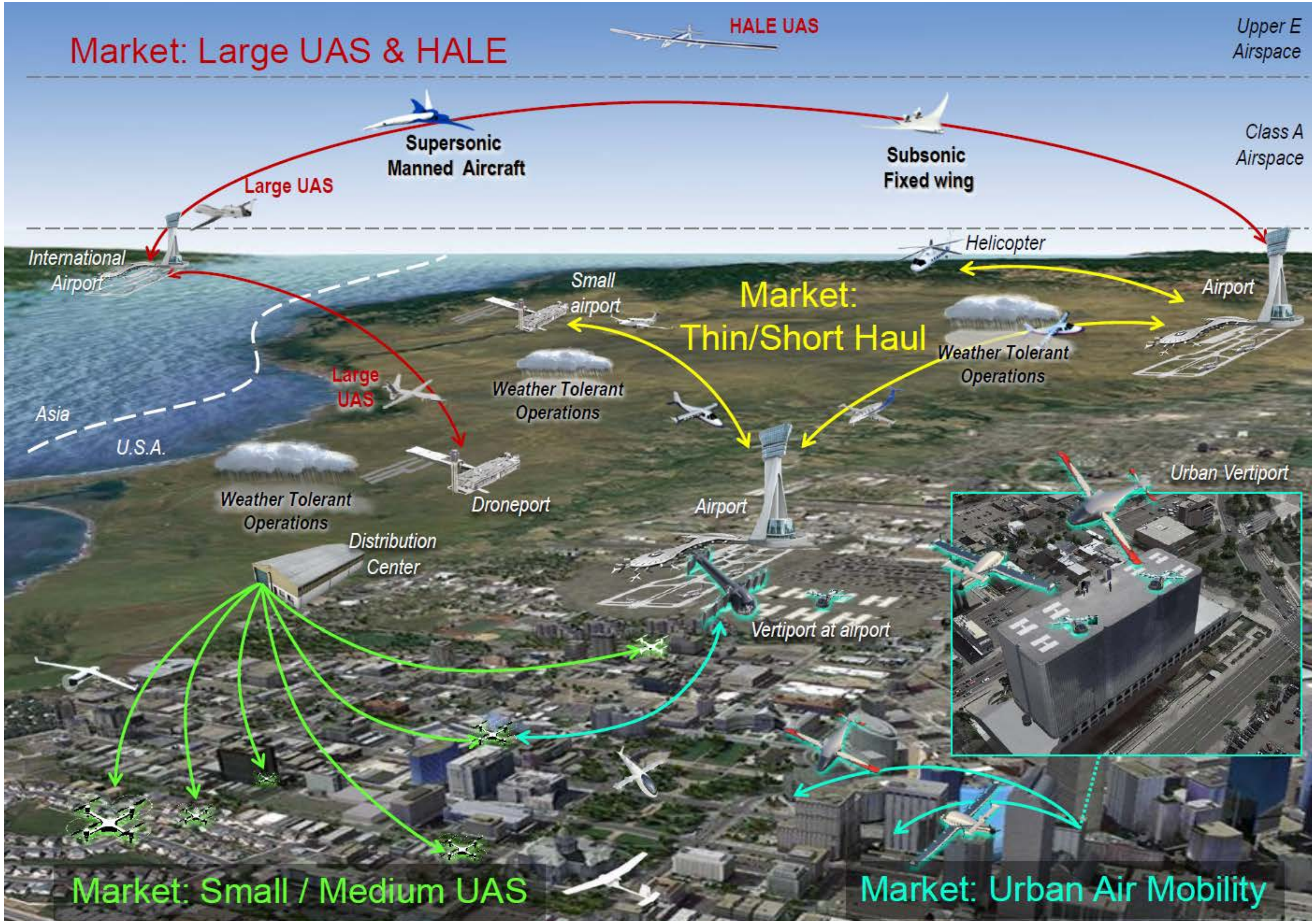
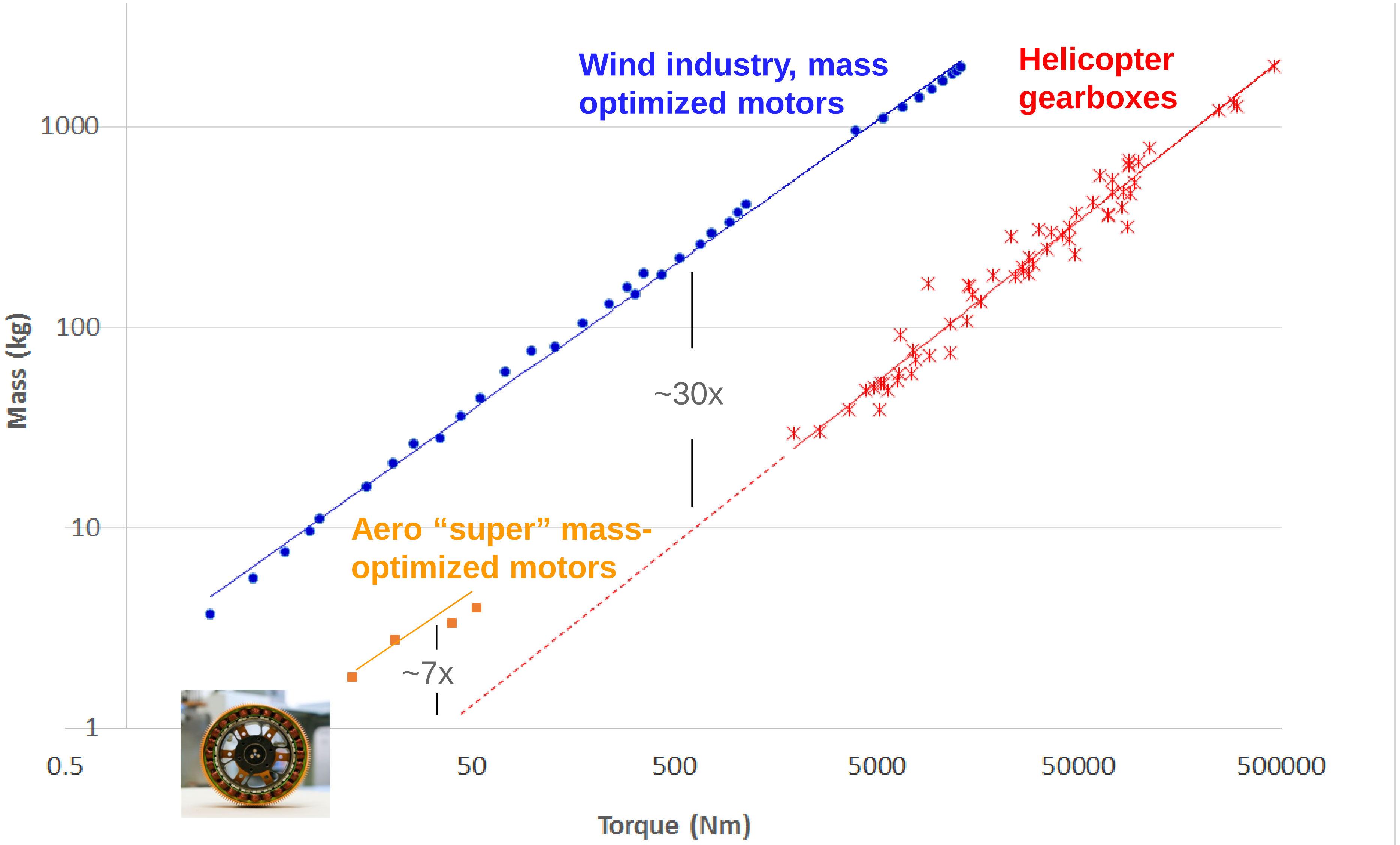
# Future Work

| | Quad | Side-by-side | Tiltwing |
|---|---|---|---|
| **Propulsion configuration:** | Electric<br>4 rotors<br>4 EM | Par. Hybrid<br>2 rotors<br>2 TS, 1 EM | Turbo elec.<br>4 rotors<br>4 EM |
| **Gear stage** | EM-rotor | TS-rotor | EM-rotor |
| **Ratio** | 12.1 | Up to 140 | 9.3 |
| **Load (kW)** | 15.9 | 92.6 | 535 |
| **(rpm)** | 661 | 445 | 861 |
| **(Nm)** | 229 | 1987 | 5928 |
| **Gear stage** | N/A | EM-rotor GB | Genset |
| **Ratio** | | TBD | 2.6 |
| **Load (kW)** | | 73.2 | 2415 |
| **(rpm)** | | 445 | 8000 |
| **(Nm)** | | 1,569 | 2,883 |

# Emerging Aeronautics Markets



# Magnetically-Geared Motors



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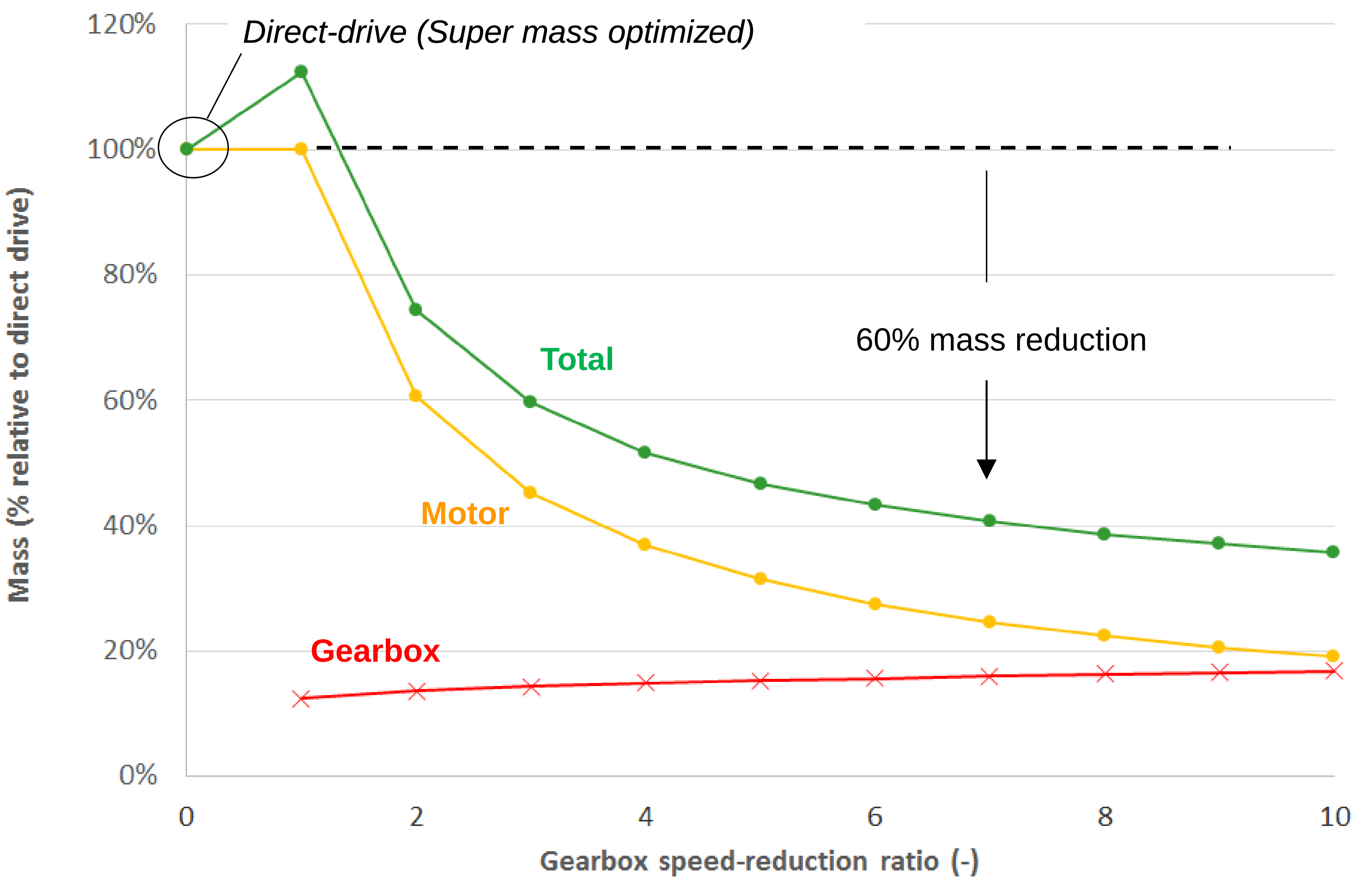
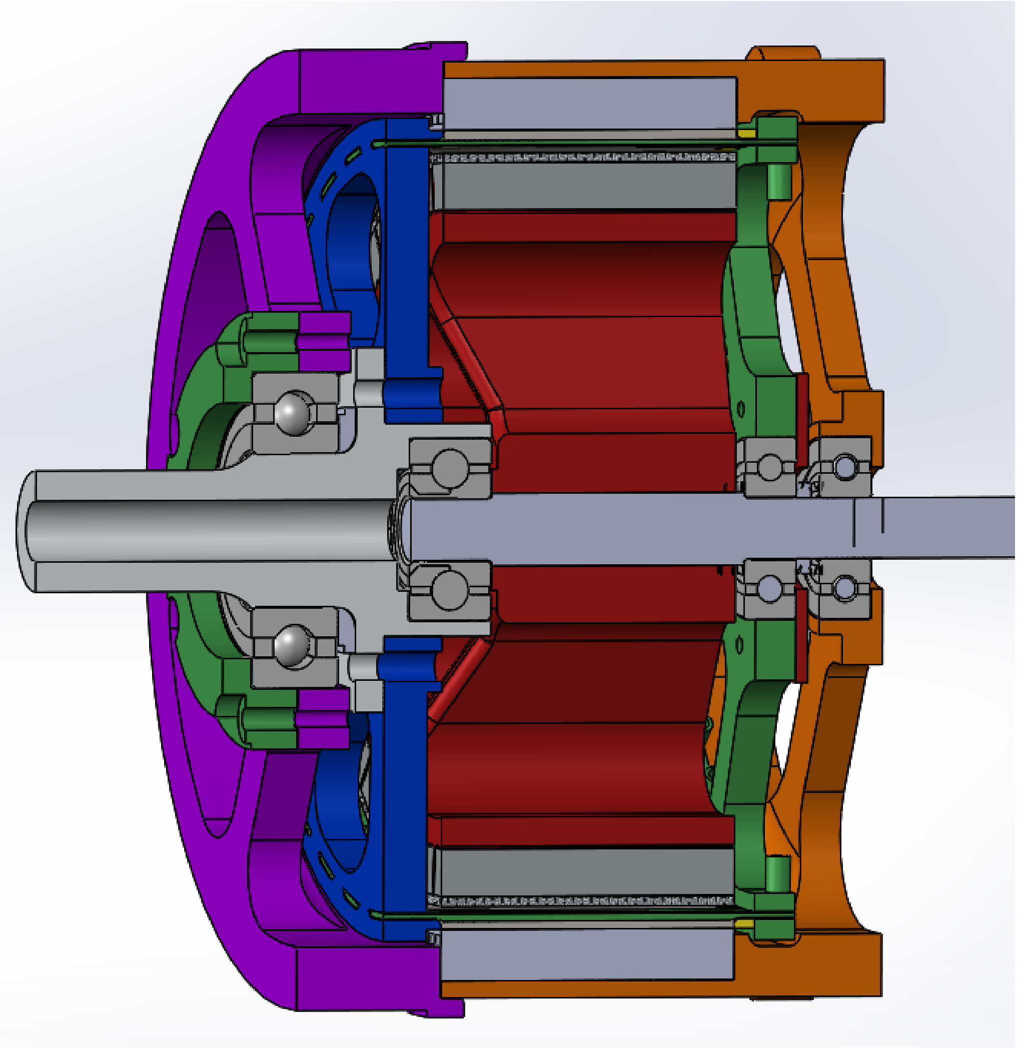
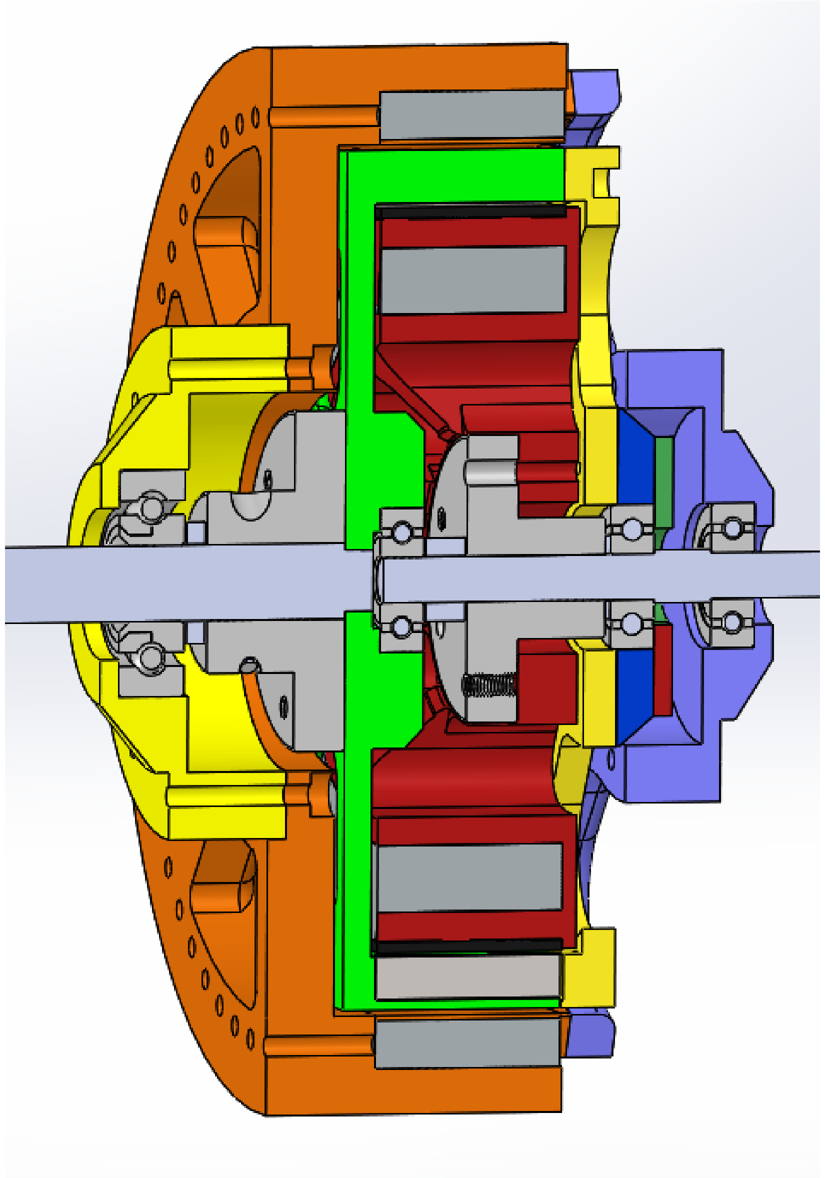


# Prototypes – Mechanical Configuration





# Test Rig