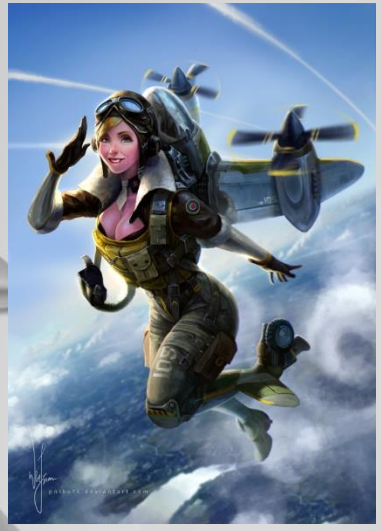
Disruptive Advance in PM Motor Technology: Higher Top Speed, Extended Range



Autonomous VTOL Technical Meeting

Mesa, AZ 01/31/2019

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Goal for Presentation

1) Increase understanding of Permanent Magnet (PM) motors and operating characteristics

2) Increase understanding PM motor field weakening technology that:
   - Extends cruise speed AND
   - Extends range for eVTOL

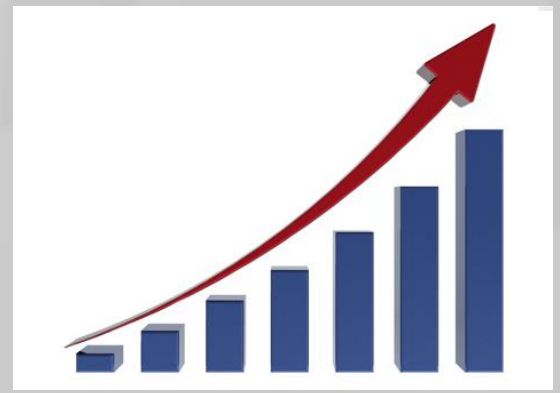
Content

Improving your Brushless PM Motor Performance

- Rise of eVTOL – Distributed Elec. Propulsion
- Not all electric motors the same
- PM motor performance curve
- DuraTrac solves PM speed limit
- Mechanical vs. electronic field weakening
- Does DuraTrac technology really work?
- Updating existing motor designs
- Safety, efficiency issues electronic weakening
- Conclusions, Q&A

Rise of eVTOL Aircraft

- Past 8 yrs. – major tech progress toward electric flight
  - PM motors
  - Battery systems
  - GPS
  - Electronic controls



- Result: diverse array of eVTOL vehicles

Distributed Electric Propulsion (DEP)

Safety thru Redundancy

- Advance work:
  - Dr. Mark Moore – NASA
  - JoeBen Bevirt- Joby Aviation and others
- Demonstration:
  - LEAPTech project
  - X-57 research aircraft
- Hardware:
  - Simplified propulsion w/ PM motors
  - Fixed pitch composite props
  - Battery, electronic control redundancy

Understanding the Electric Motor

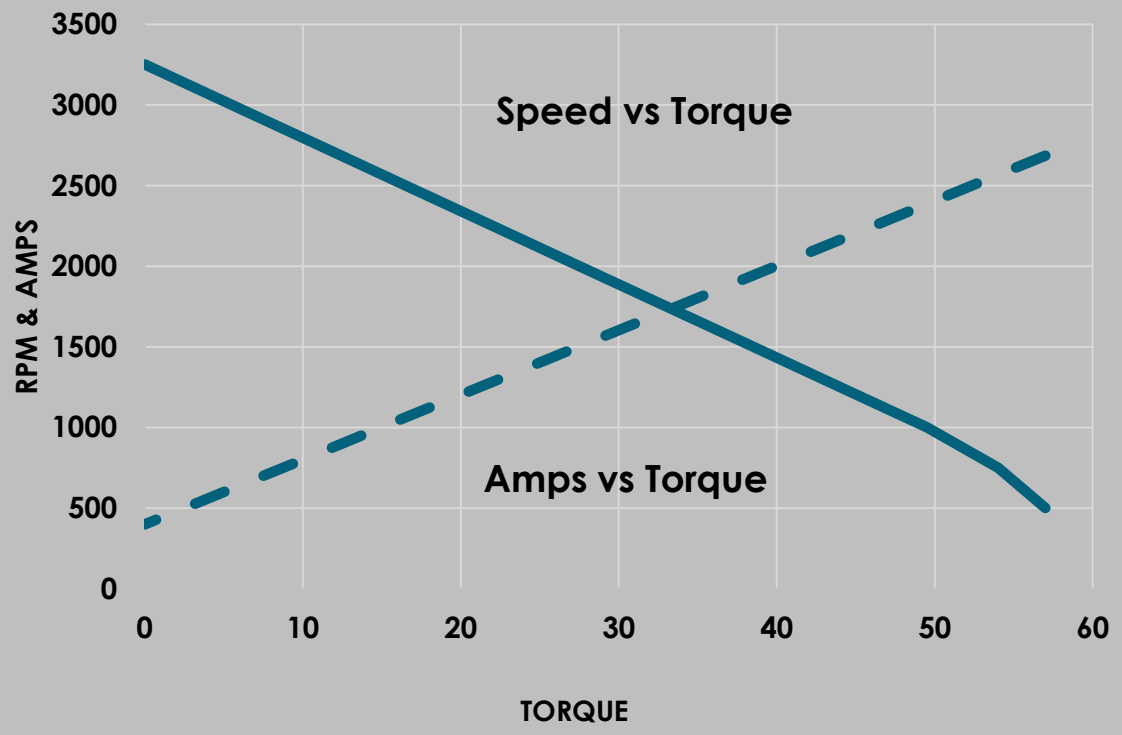
They're Not All The Same

- Many electric motors are PM brushless
- Configurations:
  - Internal magnet rotor
  - External magnet rotor

- What's best for eVTOL?
  - External rotor -- higher torque for a given size
- External rotor examples:
  - Hard disk drive
  - Computer cooling fan

Courtesy Wikipedia ; Insignia

Typical PM Motor Performance Rules



Performance Rules

- VERY linear
- As torque (Load) increases, speed decreases in straight line
- Torque proportional to current (Amps)
- Speed proportional to voltage supply

What Brushless PM Motors Can / Can't Do

- Magnets create high torque and power
- BUT "Back electromotive force" (EMF) of magnet rotor

  - LIMITS maximum rpm
  - LIMITS top speed, even when lift motors unloaded during cruise
- **DuraTrac disruptive field weakening technology**

  - **Extends eVTOL cruise speed AND**
  - **Extends range**

Configuration Typical eVTOL Craft

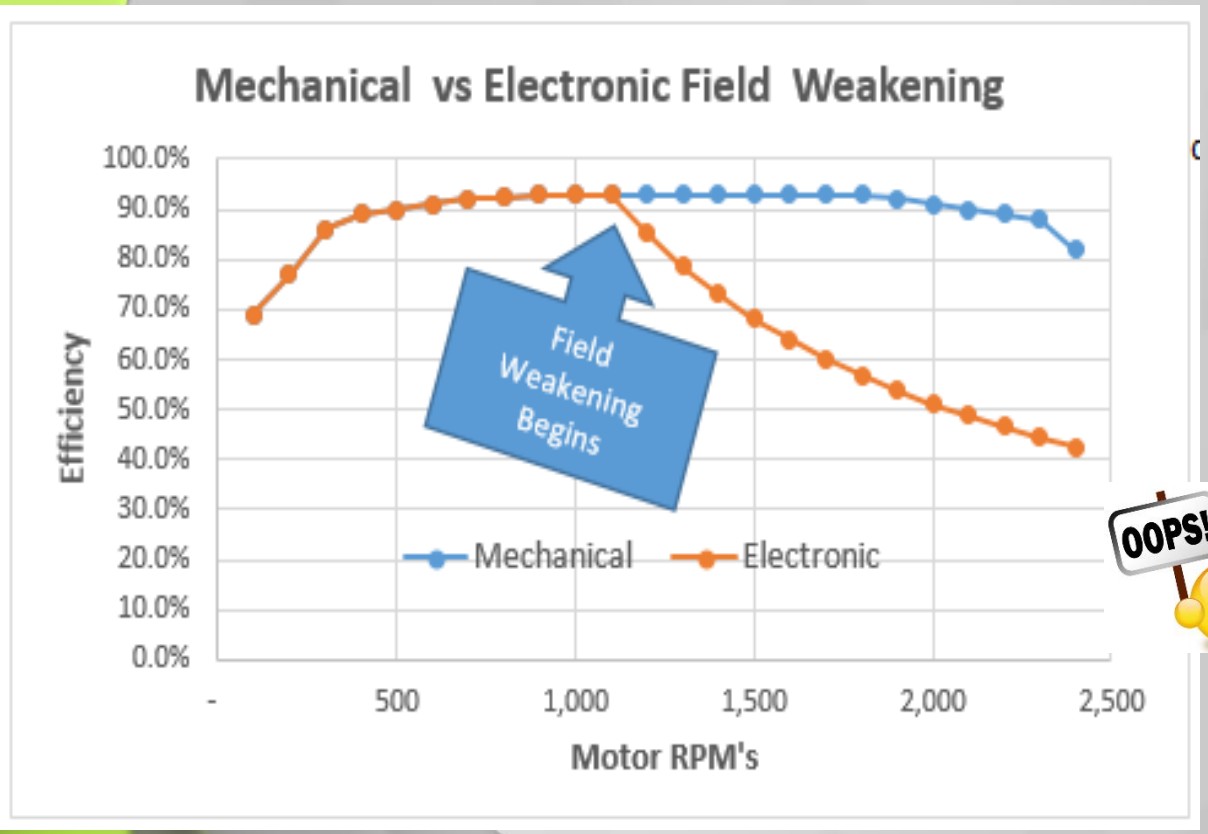
Surefly – Courtesy Workhorse Group, Inc.

- (8) motor / prop
- 75 mph (121 km/hr) top speed
- 2 person
- Series Hybrid

- During cruise: body shape, support arms generate aero lift
- Motor back EMF limits RPM increase for faster speed
- Possible solution: transmission for faster cruise speed at lower torque

PM Motor Field Weakening

Mechanical vs. Electronic Comparison



Dura-Trac Mechanical

- Preserves Efficiency
  - Extends Speed in Cruise
  - Retains Hover Thrust

Electronic Field Weakening

- Severe Efficiency Drop
  - Limits range
  - Reduces battery pack life
- Severe safety concerns

Does Dura-Trac Really Work?

15-year history in commercial bus hybrids

- Shuttle buses require massive torque to launch
- PM motor achieved torque, but 10 mph max!

✓Dura-Trac achieved 0-35 mph (56 km/hr)

✓Acts like a variable transmission

✓Increased MPG by 25% in long-term tests

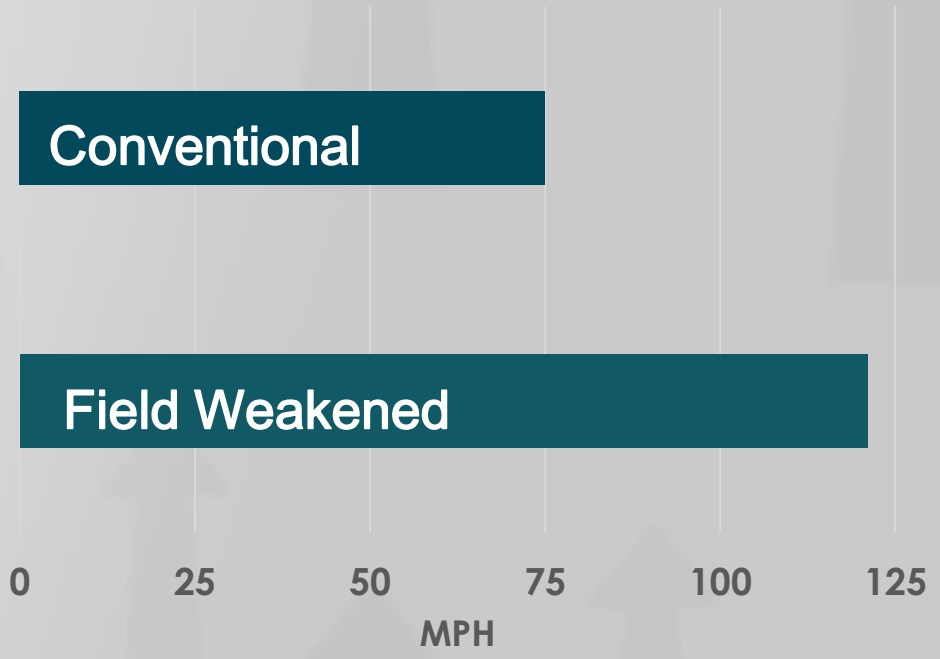
Courtesy Crosspoint Kinetics

Field Weakening for eVTOL

ASSUMPTIONS

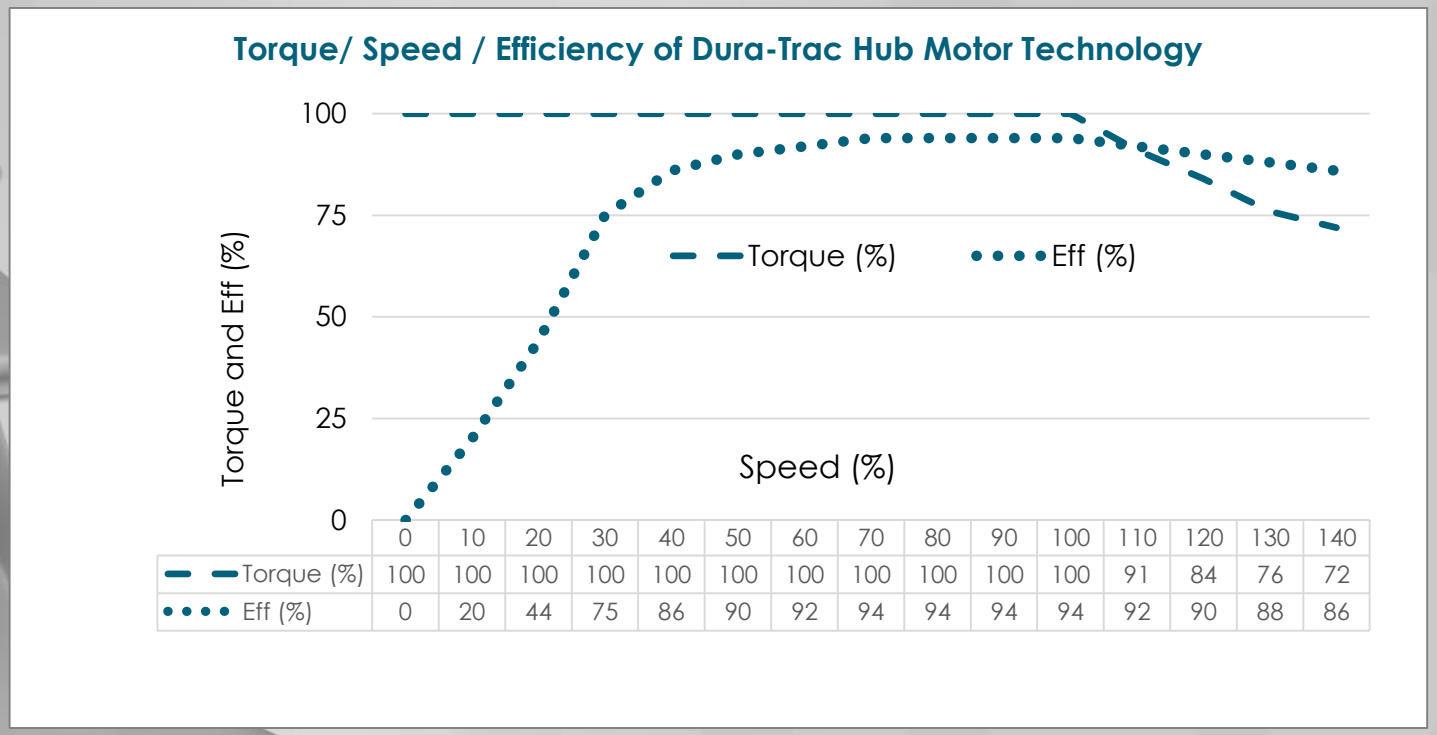
- 8 motor, 2 seat eVTOL craft
- Benefit field weakening:
  - Retain hover performance
  - Higher cruise speed – up to 40%

CRUISE SPEED



DuraTrac Field Weakening Performance Example

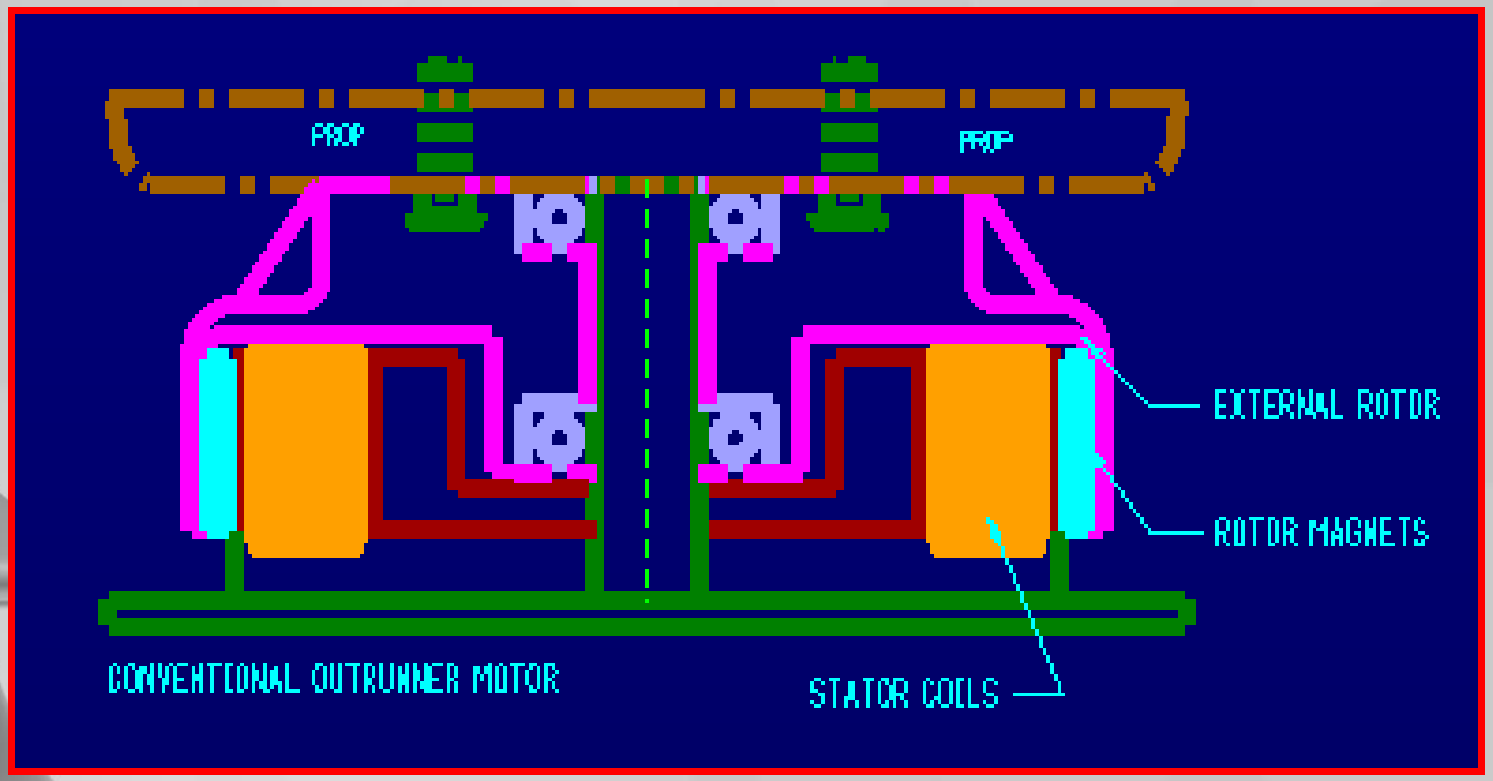
- IF 15% lift generated at cruise, THEN cruise speed extended by + 17%
- IF 30% lift generated, +40% speed increase
- This capability can be added to existing motors!



	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140
Torque (%)	100	100	100	100	100	100	100	100	100	100	100	91	84	76	72
Eff (%)	0	20	44	75	86	90	92	94	94	94	94	92	90	88	86

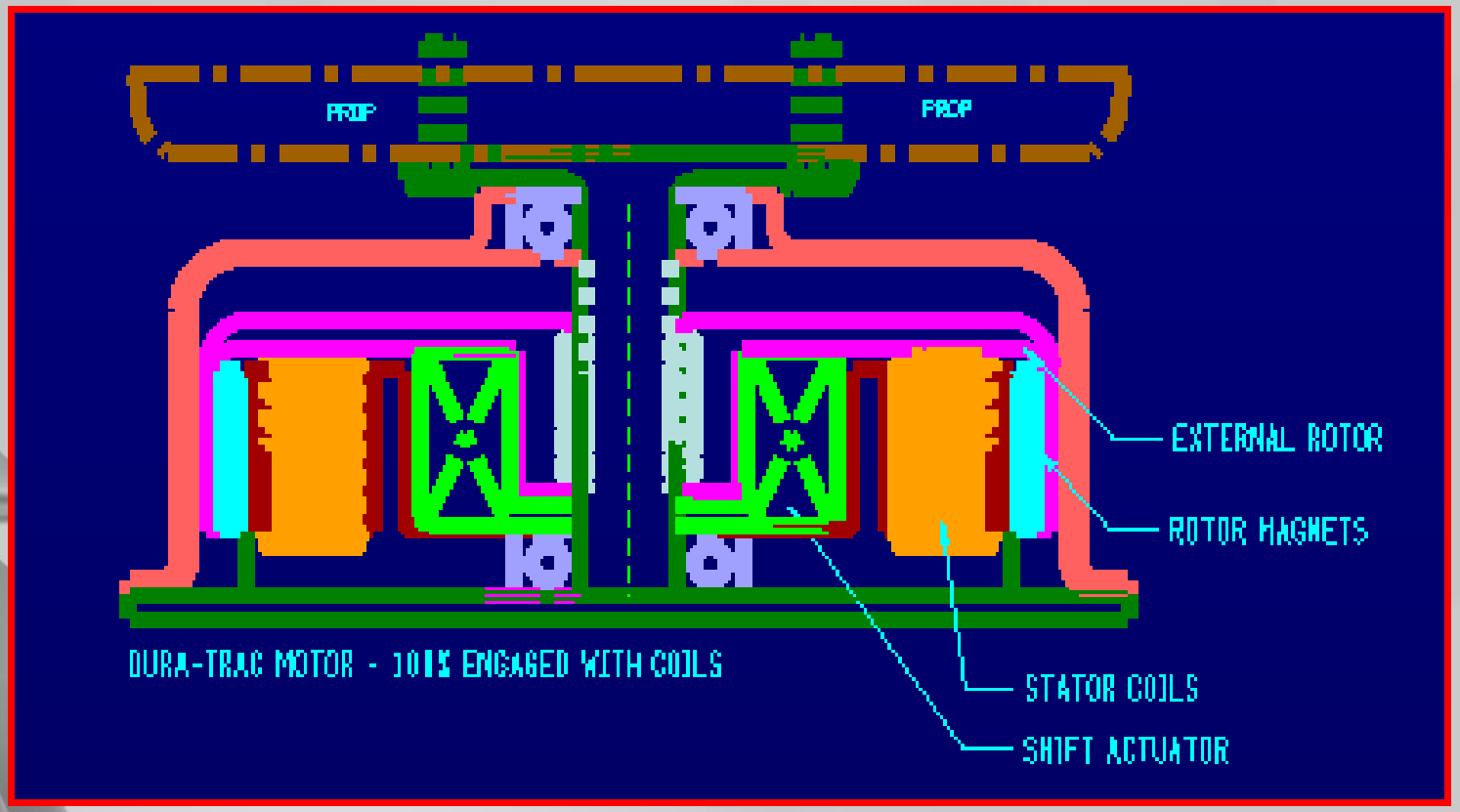
Adding Field Weakening Technology

To an Existing Motor Design



Conventional outrunner motor for eVTOL

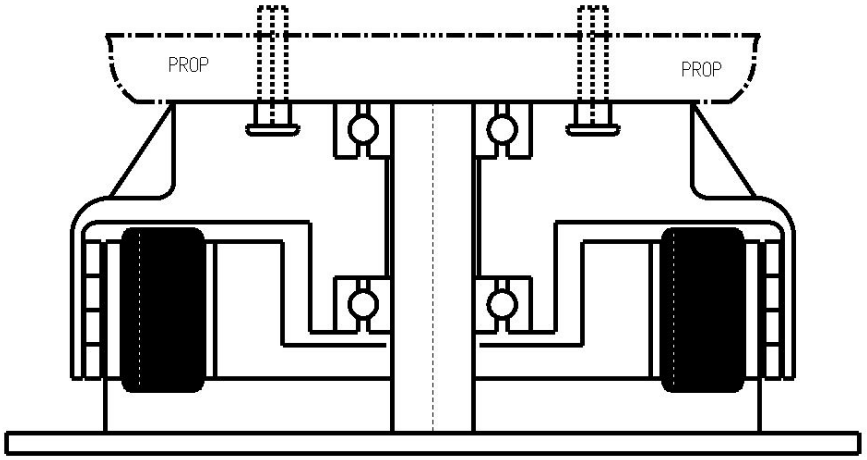
Adding DuraTrac Axial Shift Technology



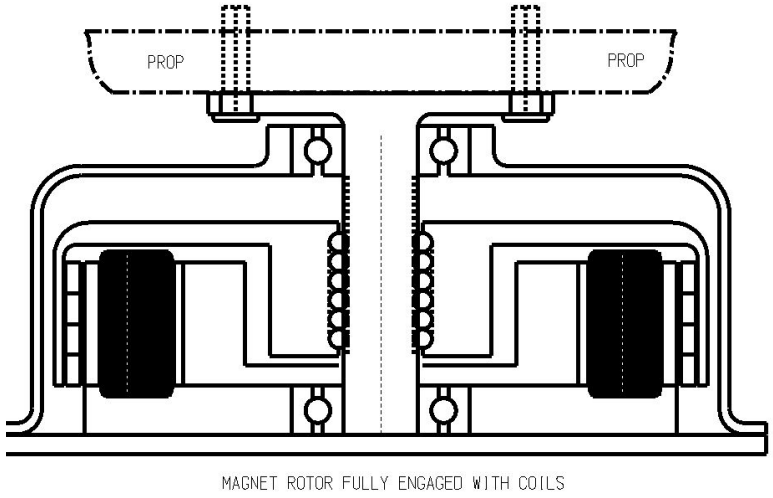
= Same stator, magnets and hover performance
+ Add spline between shaft and rotor
+ Add prop on shaft hub
+ Add shift actuator

Comparison: Rotors Fully Engaged

Conventional



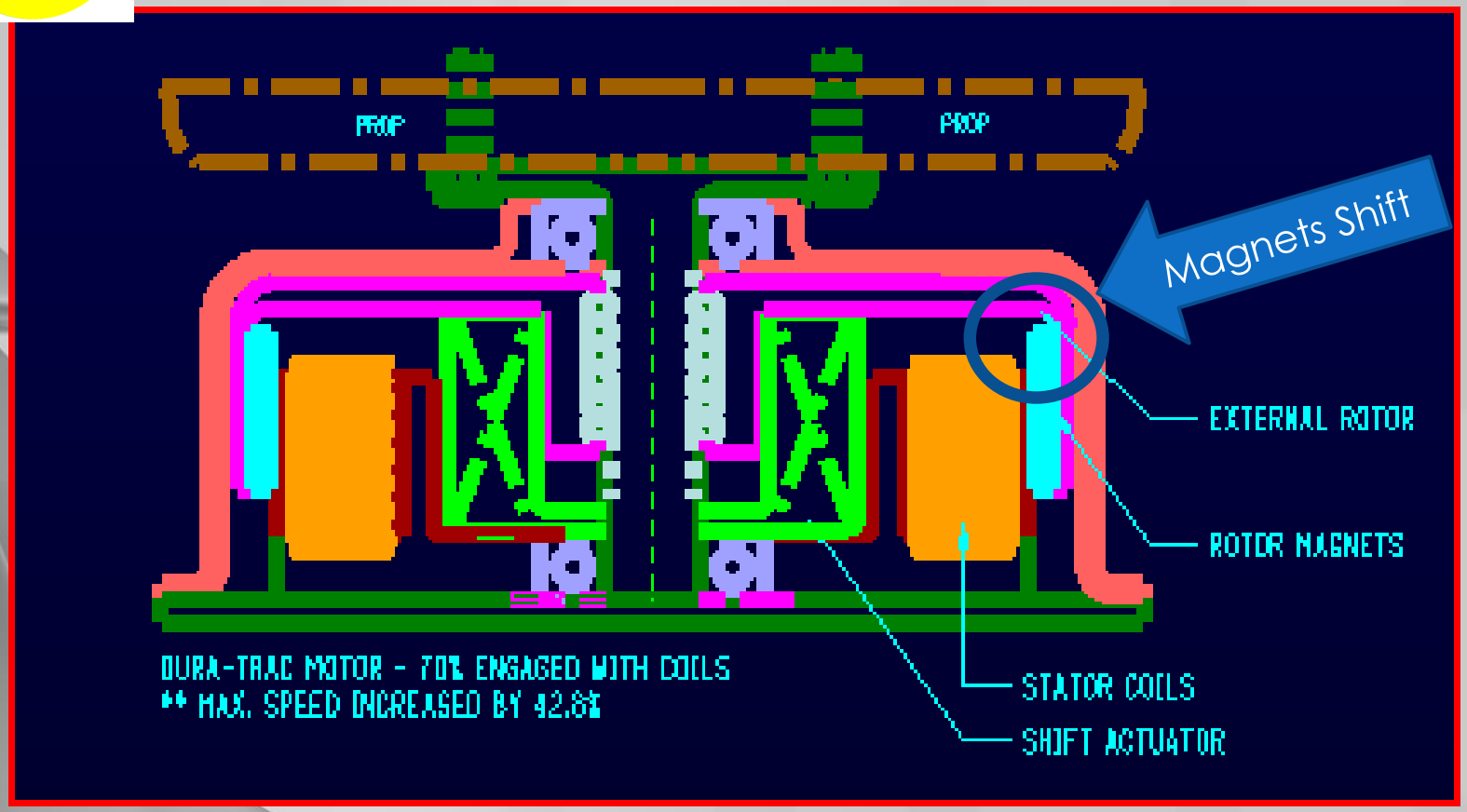
Dura-Trac – Fully Engaged Rotor



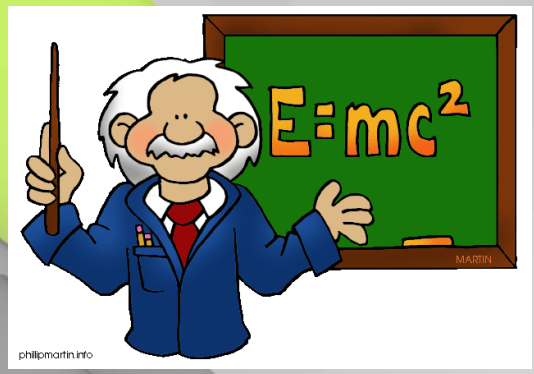
= Same hover performance
= Same relative size, torque and efficiency
= Same stator dia., magnets and air gap
+ DuraTrac offers extended cruise speed

External Rotor Shifted 30%

Benefit: **40%** increased cruise speed and range



Physics (and Math) of Field Weakening



- PM motors linear between field and rpm
- Formula for extended speed =

  (1/decimal engagement) X Base speed
- Example – Base speed (max) = 1,310 rpm
  - 75% rotor = (1/.75) x 1,310 = 1,746 RPM
- Effect:
  - ⇑ Speed
  - ⇓ Torque
  - Why? A: Only part of the magnets are working
- More info in the handout

Safety, Efficiency, Reliability Concerns with Electronic Field Weakening

- Electronic field weakening:
  - Motor runs faster but…
  - Consumes more energy
- IF electronic hiccup and motor control shuts down
  - Sudden dynamic braking
  - Possible voltage spike
  - Potentially affecting all controllers in the vehicle
  - Possible catastrophic failure

- **DuraTrac:** fail safe and retains high efficiency

Conclusions and Summary

DuraTrac Benefits to eVTOL Craft

- ✓Greater speed (up to 40%)
- ✓Extended range
- ✓Works with existing motor designs
- ✓Durable – torture-tested by Cummins
- ✓Fail safe

Thanks for Your Interest and Attention!

Questions, Please

- For more information, please contact me at:
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