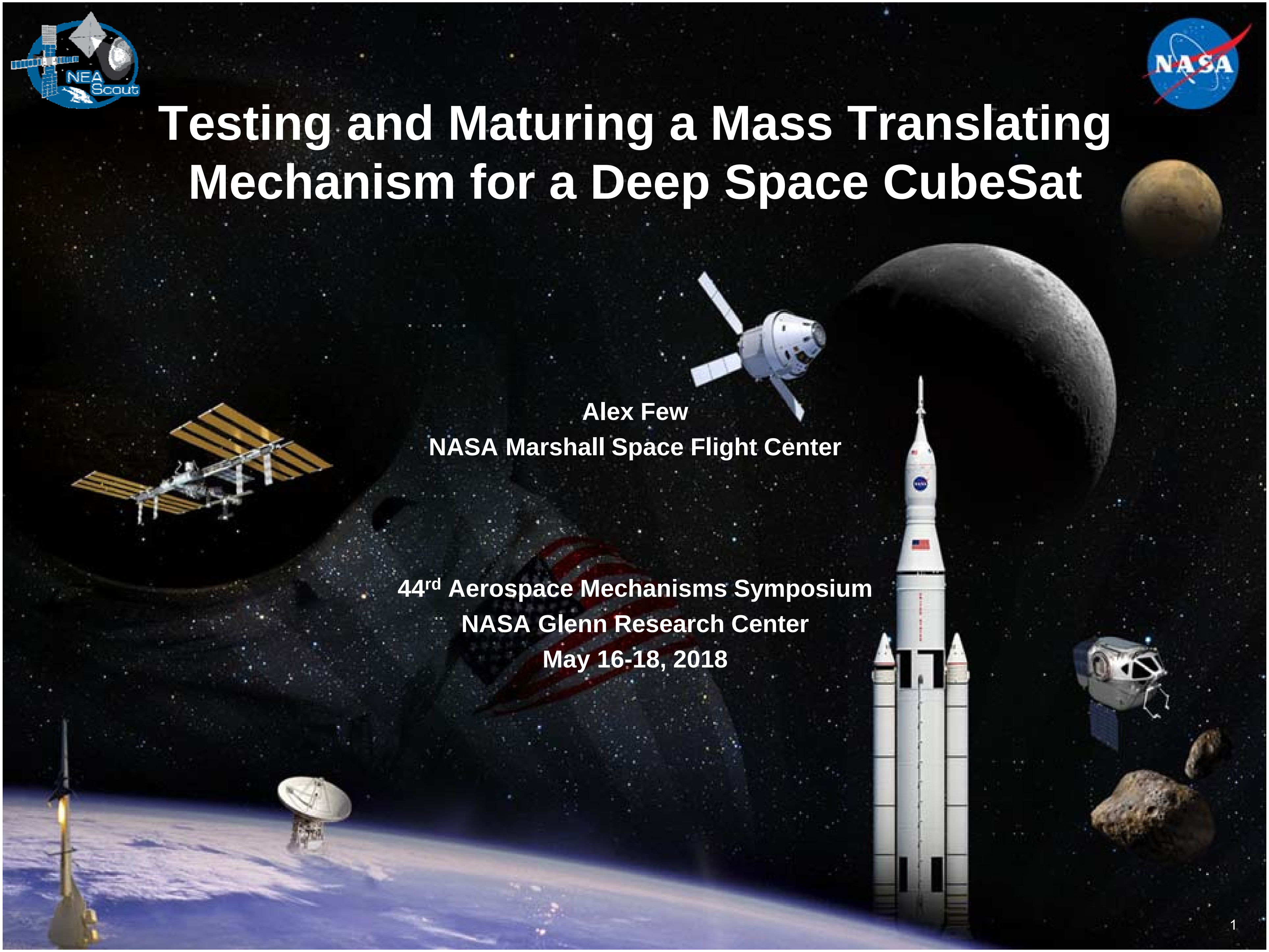
Testing and Maturing a Mass Translating Mechanism for a Deep Space CubeSat



Alex Few
NASA Marshall Space Flight Center

44rd Aerospace Mechanisms Symposium
NASA Glenn Research Center
May 16-18, 2018

Agenda

- **Near Earth Asteroid (NEA) Scout Overview**
  - Active Mass Translator (AMT) Overview
  - Current Design State
- **Thermal Design Challenges**
  - Discoveries during thermal vacuum testing
  - Design and motor contributions
  - Poor assumptions
- **Lessons Learned**
  - Observed mini motor primary failure modes in vacuum
  - How to remove heat from mini motors
  - Successful thermal interface design
  - How to monitor mini motor health during testing

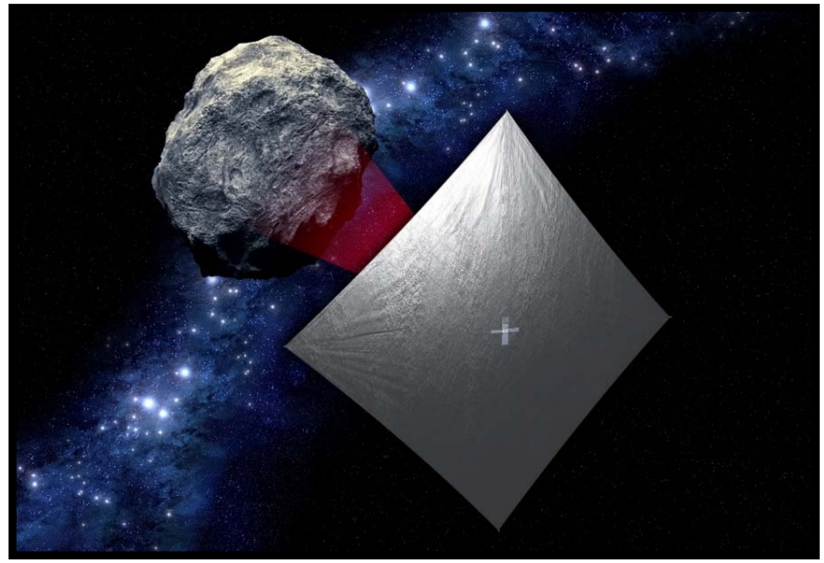
NEA Scout Overview

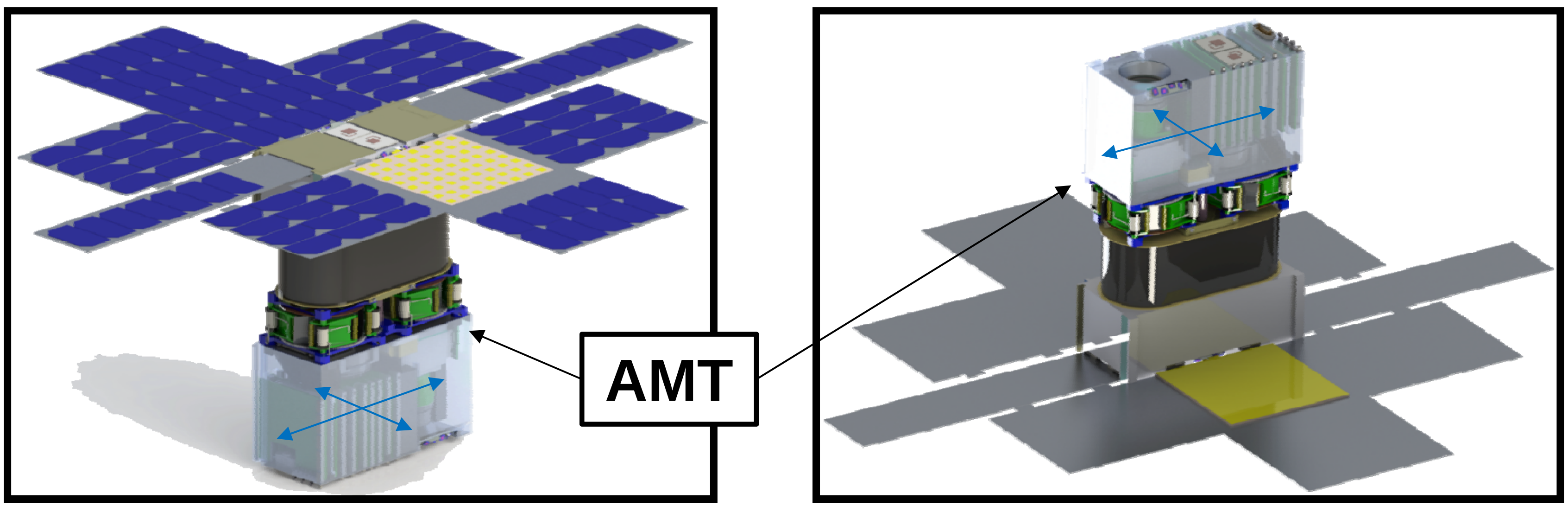
Goal:

Characterize a NEA during flyby while demonstrating low cost reconnaissance capability (Solar Sail)

Vehicle and Mission Details:

- **6U CubeSat manifested on SLS Exploration Mission 1**
- **86m^2 solar sail propulsion**
- **2.5 year mission**
- **1.5 x10^8 km (1 AU) distance from Earth**

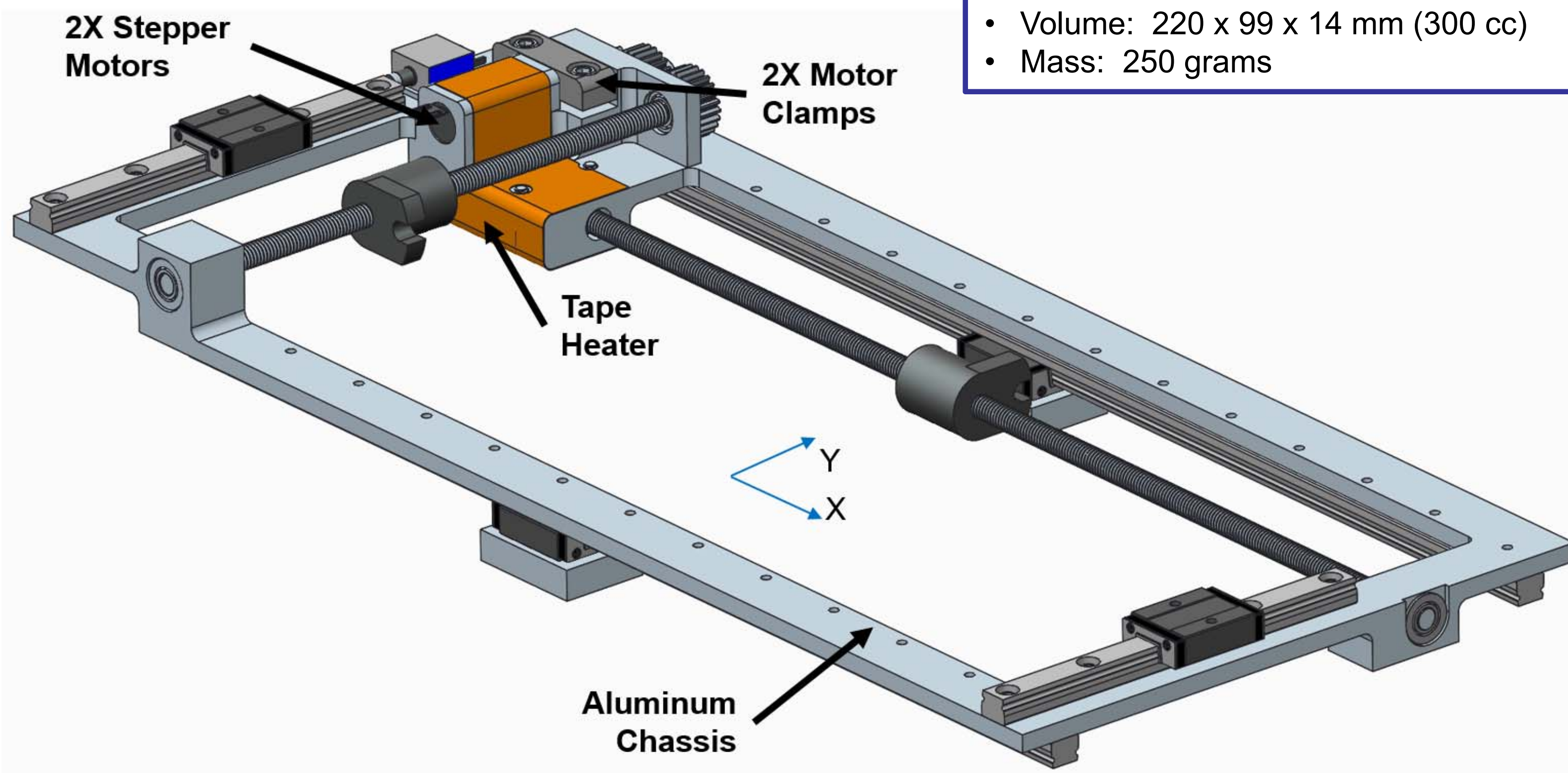




AMT Overview

CAPABILITIES

- Translation: 160 X 68 mm (X & Y respectively)
- Speed: 0.3 and 0.1 mm/s (X & Y respectively)
- Precision: 0.1 mm
- Volume: 220 x 99 x 14 mm (300 cc)
- Mass: 250 grams

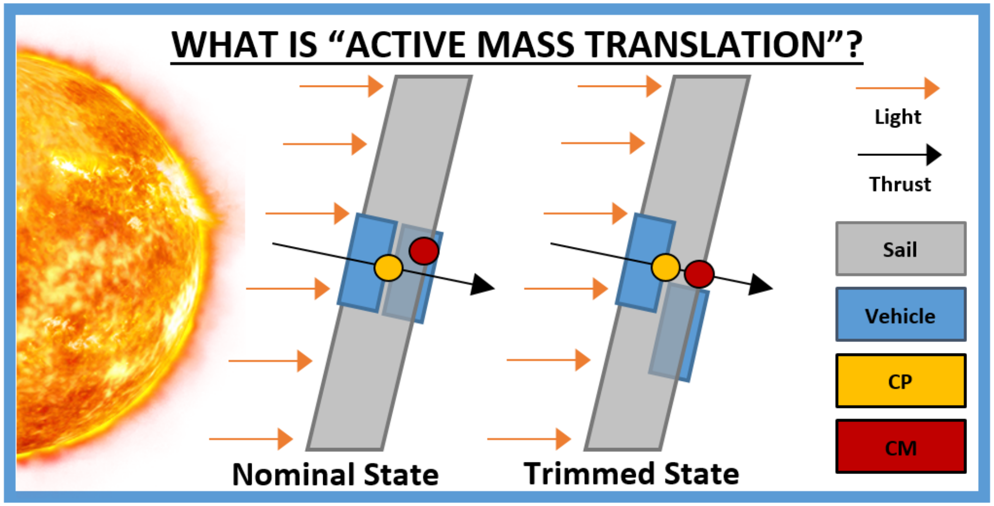


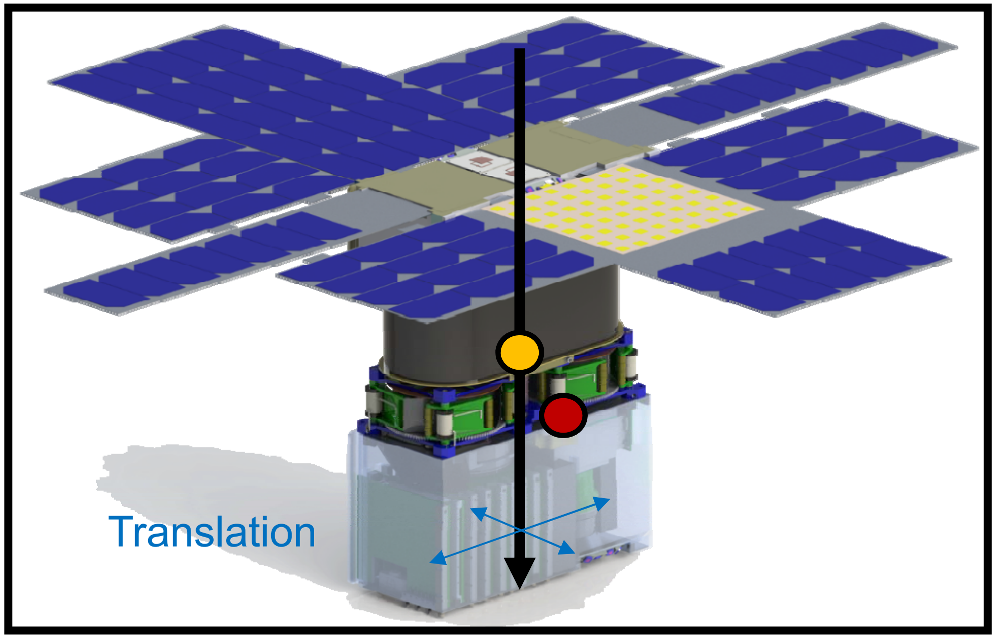
AMT Overview

Purpose: Alter the inertial properties of the vehicle while controlling the center of pressure (CP) and center of mass (CM) offsets

How: The AMT will move one portion of the NEA Scout relative to the other.

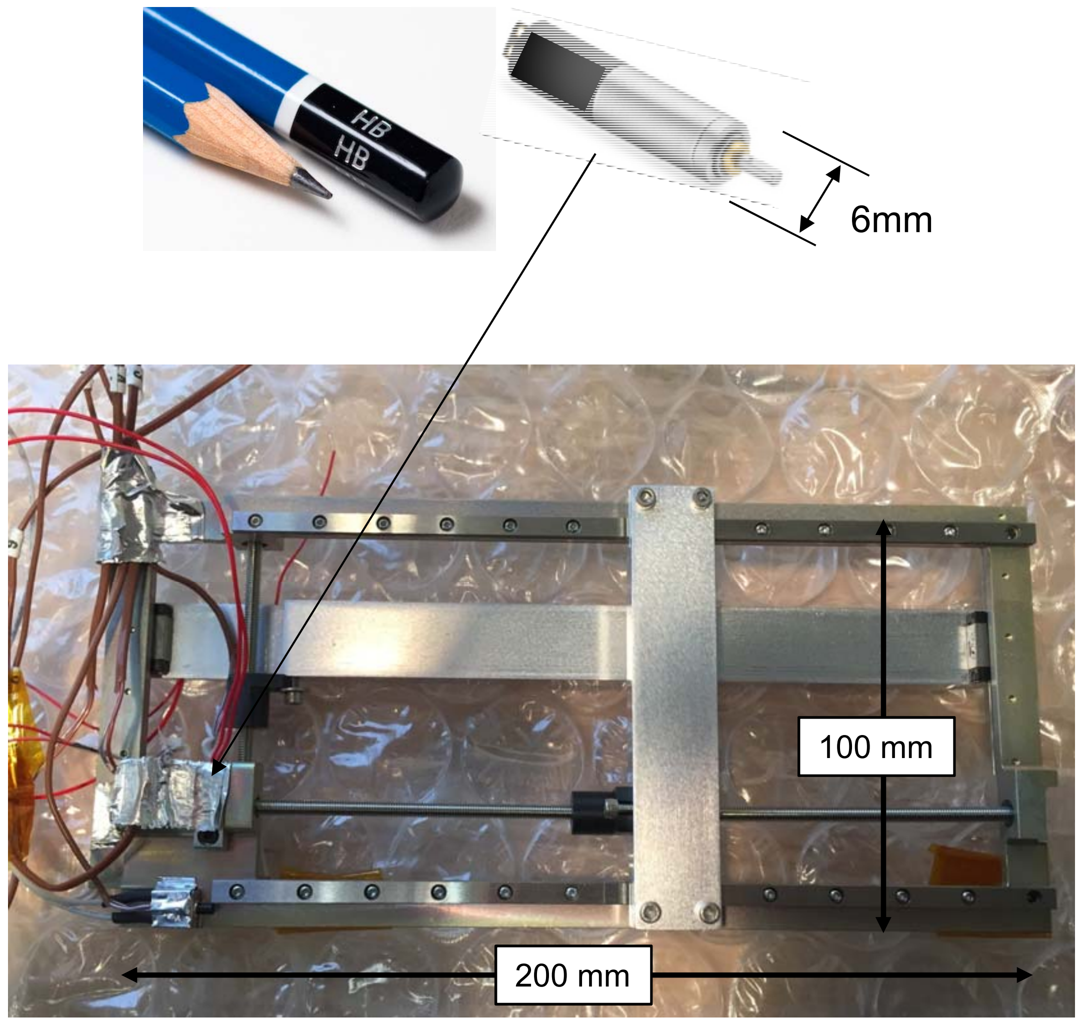
Why: A conventional control system (Reaction wheels or sail vanes) cannot accommodate the possible CP/CM offsets within the 6U volume





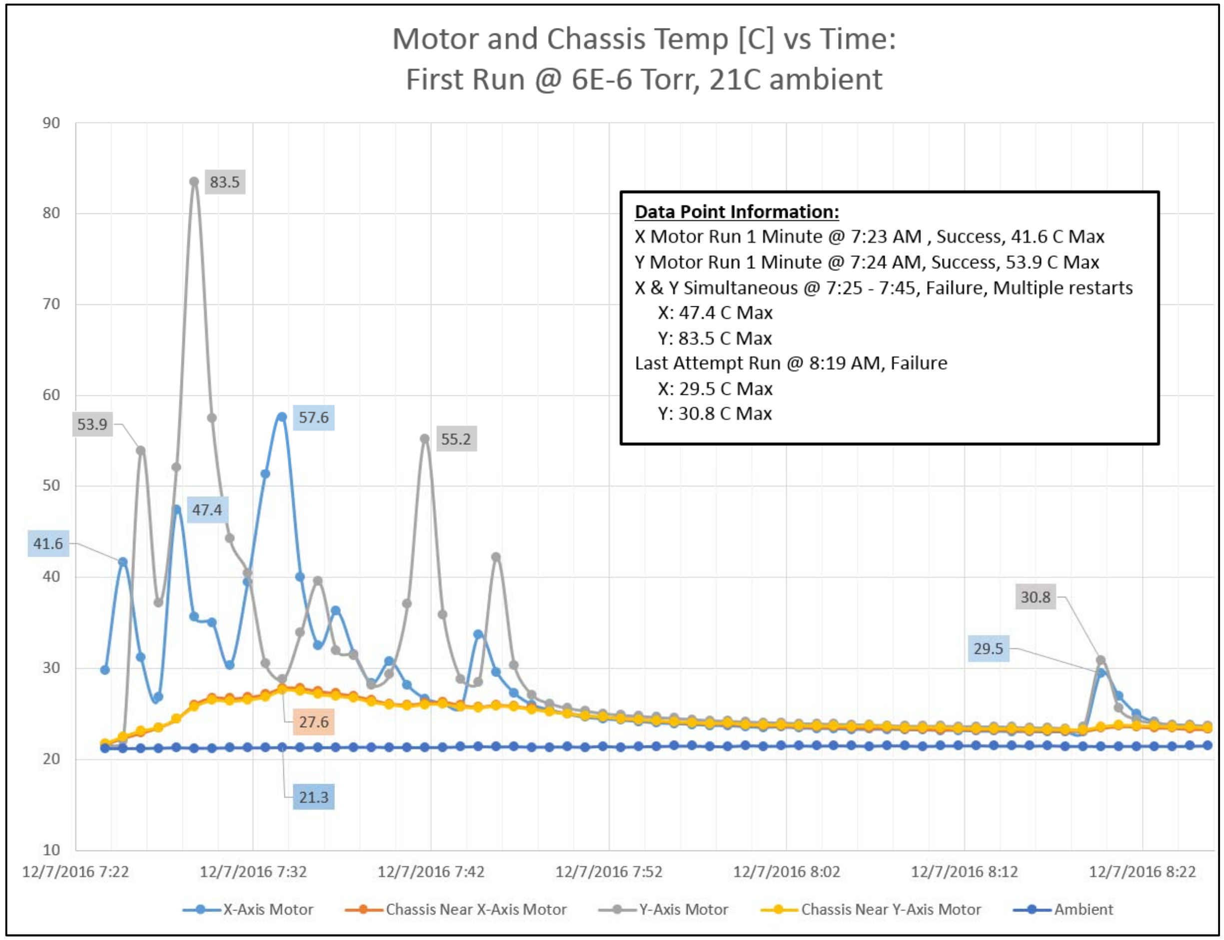
Thermal Design Challenges

- The mechanism is completely exposed to deep space environments, requires -70 to 70 C operational range
- Very low mass and surface area to conduct heat (this will cause problems later)
- Only viable motors are rated for -35 to 70 C but are *“space rated”*
- Motors are very low mass (1g) and draw 0.5 W
- Will spend vast majority of life shaded from sun
- Small area makes temperature monitoring very difficult during test



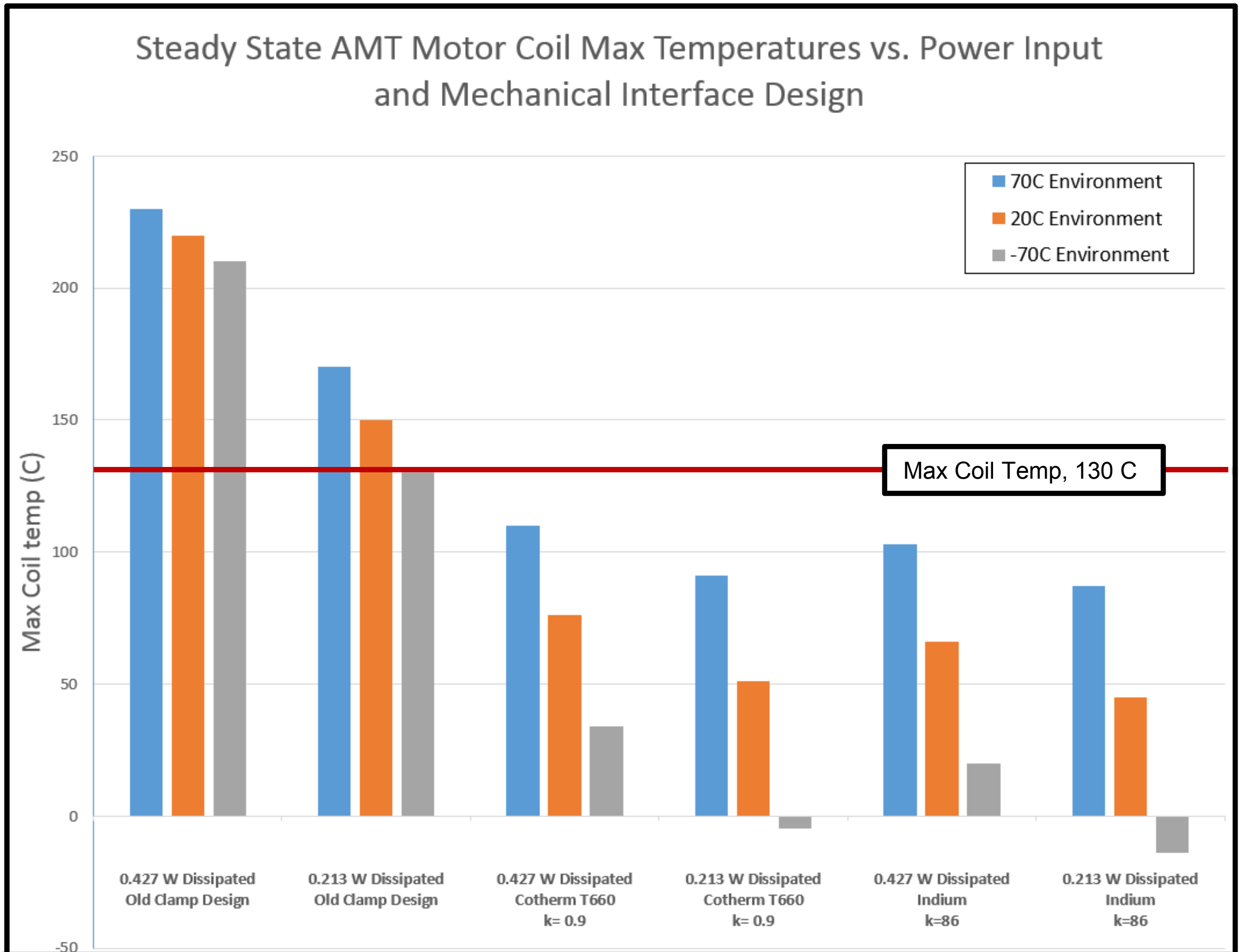
Discoveries During Thermal Vacuum Testing

- Moments into the first AMT thermal vacuum test, the mechanism failed.
- Context: AMT required operational life is about 1000 hours
- 3 month investigation determined that the motors were overheating
- How to design motor/chassis interface capable of conducting heat?
  - How to remove heat from such small areas?
  - Clamps design?
  - Epoxy, grease and heat spring material traded



Discoveries During Thermal Vacuum Testing

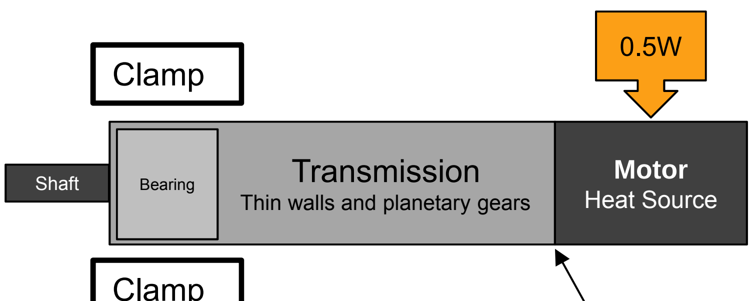
- After failure, thermal models were updated with more accurate motor internal and external conduction properties
- The first two columns reflect the old clamp design, showing clear design flaws
- Adding *any* material to the motor surface showed improvement
- Indium was chosen for ease of design and robustness

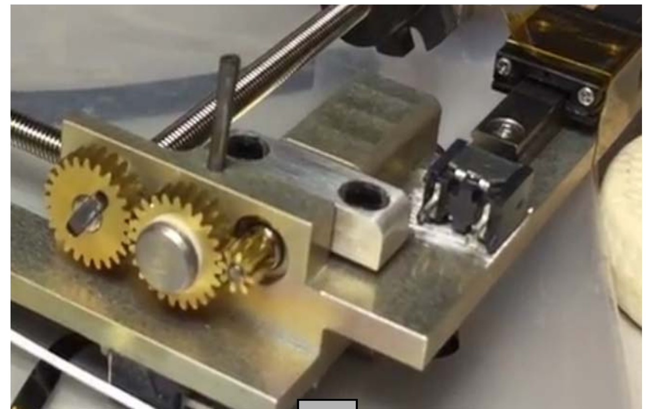


Motors analyzed at full and half power for old design, thermal grease and indium heat spring

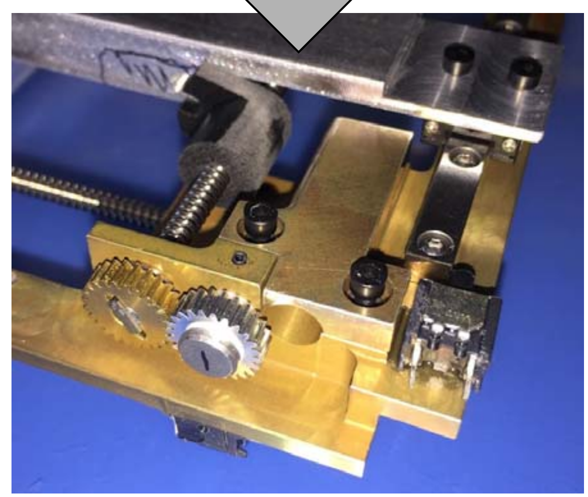
Design and Motor Contributions

- Design space required smallest motors on the market
- Motors did not have surface mounting or threaded interfaces
  - Vendor gave suggested clamping configurations, but this configuration was crippled thermally
  - Thin wall cannot take high clamp loads
  - Clamp location was far from heat source
- Insufficient internal and external conductive and radiative areas
- Only 1 gram on thermal mass in motors → time to thermal-induced failure ≈ seconds



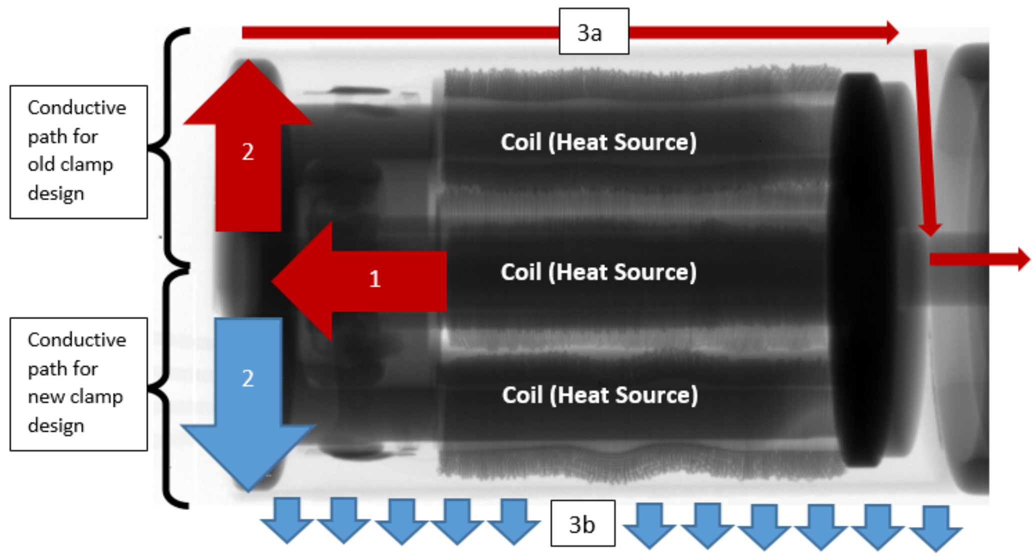


Matured to…



Poor Assumptions

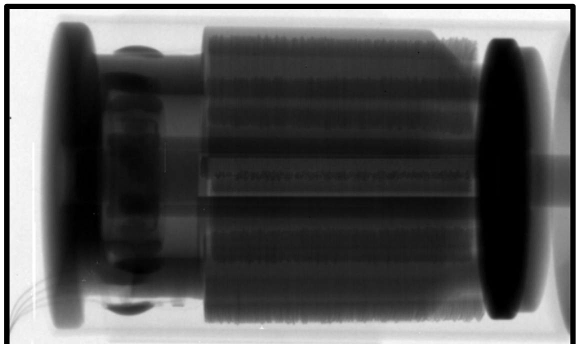
- **We thought…**
  - “Space-rated”
  - Internal conductive path was substantial between motor and transmission
  - 0.5 W could be dissipated through radiation and conduction
- **In fact…**
  - Space-rated only in theory. Larger models have flown, but none this small
  - Negligible internal conductive path
  - Convection dominated bench top testing



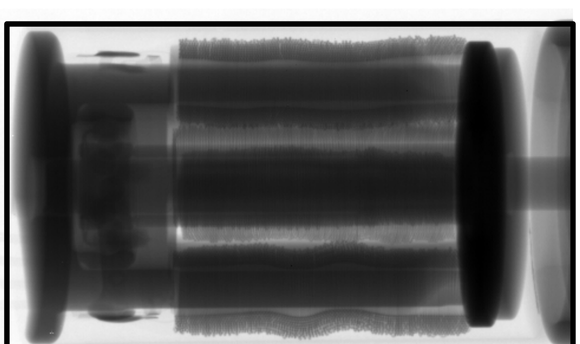
1:	Coil residual heat conducts through stator into rear cover.
2a:	Heat conducts to outer cover through sub-mm thick rear cover interface.
3a:	Heat conducts though motor cover, into threaded interface at rear of gearbox
3b:	Heat conducts out of motor cover into indium interface material

Lessons Learned

- **Observed mini motor primary failure mode for low-load, low speed application in vacuum environment**
  - Motor overheats causing the windings to short
  - Very little warning. We suggest to constantly measure motor coil resistance throughout testing.
  - Coils' resistance would decrease (Example: 120Ω to 100 Ω to 60 Ω to 0 Ω) over consecutive operations
  - Motor windings may not degrade at same rate, perhaps caused by variation in windings and/or insulating layer
  - Motor torque output decreases as coil resistance decreases until motion stops
  - Larger currents increase rate of degradation



Healthy Coils

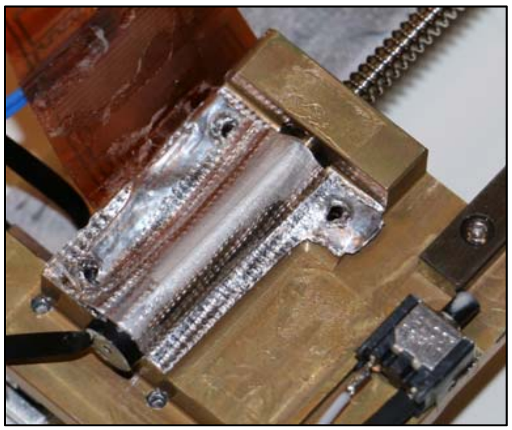
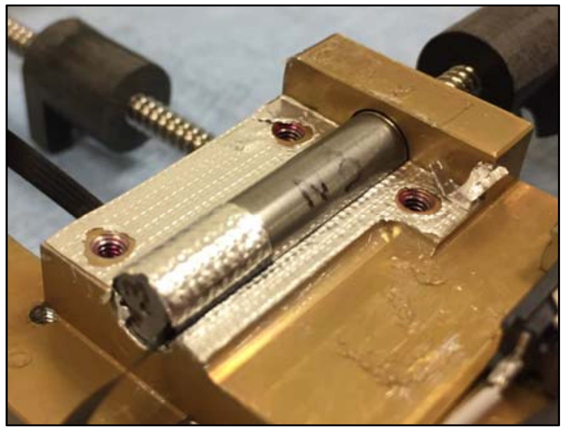
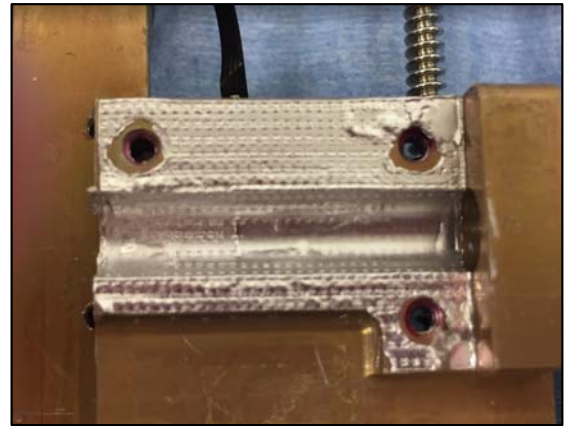
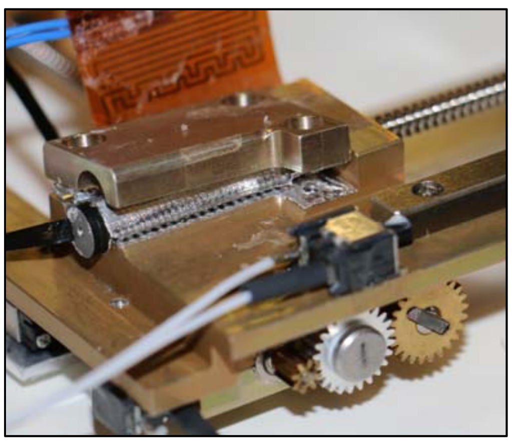
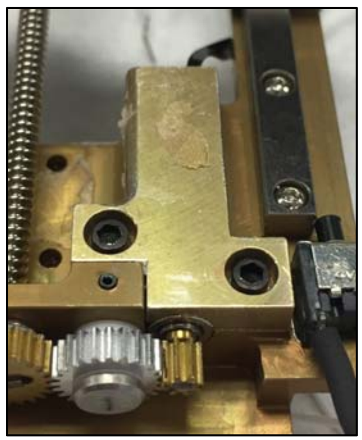


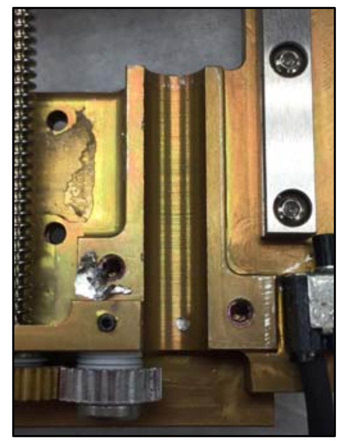
Overheated Coils

Vs.

Lessons Learned

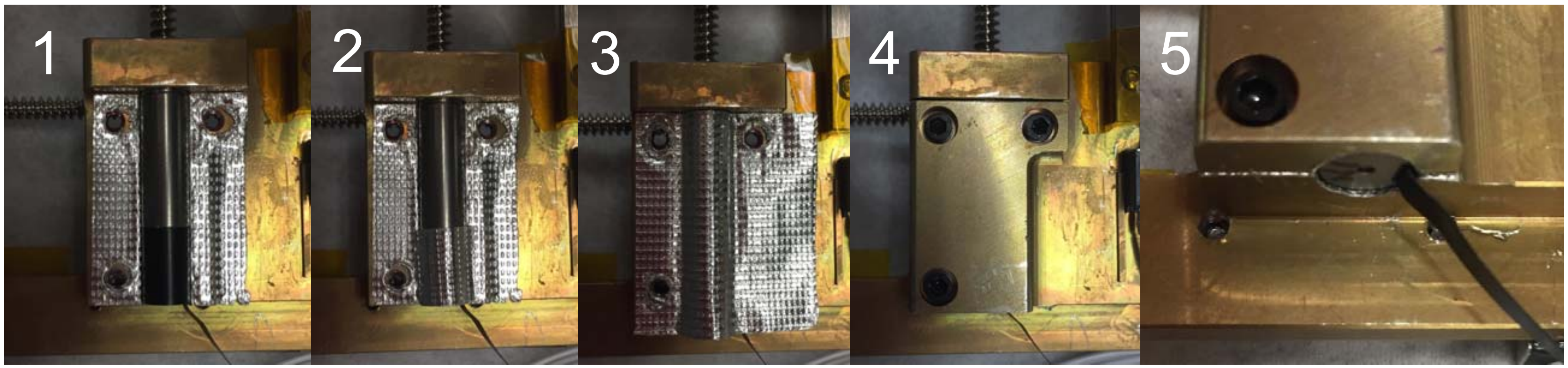
- **How to remove heat from mini-motors**
  - Clamshell design with indium heat spring
  - Because heat doesn't conduct into transmission, clamp is required over all motor surfaces

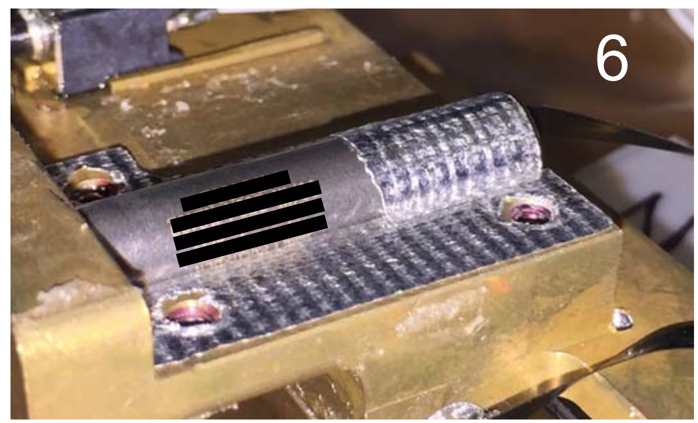


Lessons Learned

- **Mechanical-thermal interface design for small DC motors in vacuum**



1. Cover base clamshell surfaces with indium
2. Completely wrap motor surfaces (black) with indium
3. Cover motor and top clamshell with indium
4. Fasten top clamshell to bottom, pre and post tightened heights to verify indium compression
5. Trim excess indium
6. Verify indium compression when deconstructed



Lessons Learned

- **How to monitor mini motor health during testing**
  - ***If you cannot*** access motor surfaces or internals with thermocouples
  - ***And cannot*** view motor surfaces with thermal imaging
  - ***You can*** measure motor coil resistance immediately after operation to determine coil temp
  - Increased resistance = temperature increase from T_0
  - Decreased resistance = temperature decrease from T_0
  - Use system known characteristics to create correlation b/w resistance and coil temperature

This equation with these knowns…

$$R(T) = R_0(1 + \alpha(T_c - T_0))$$

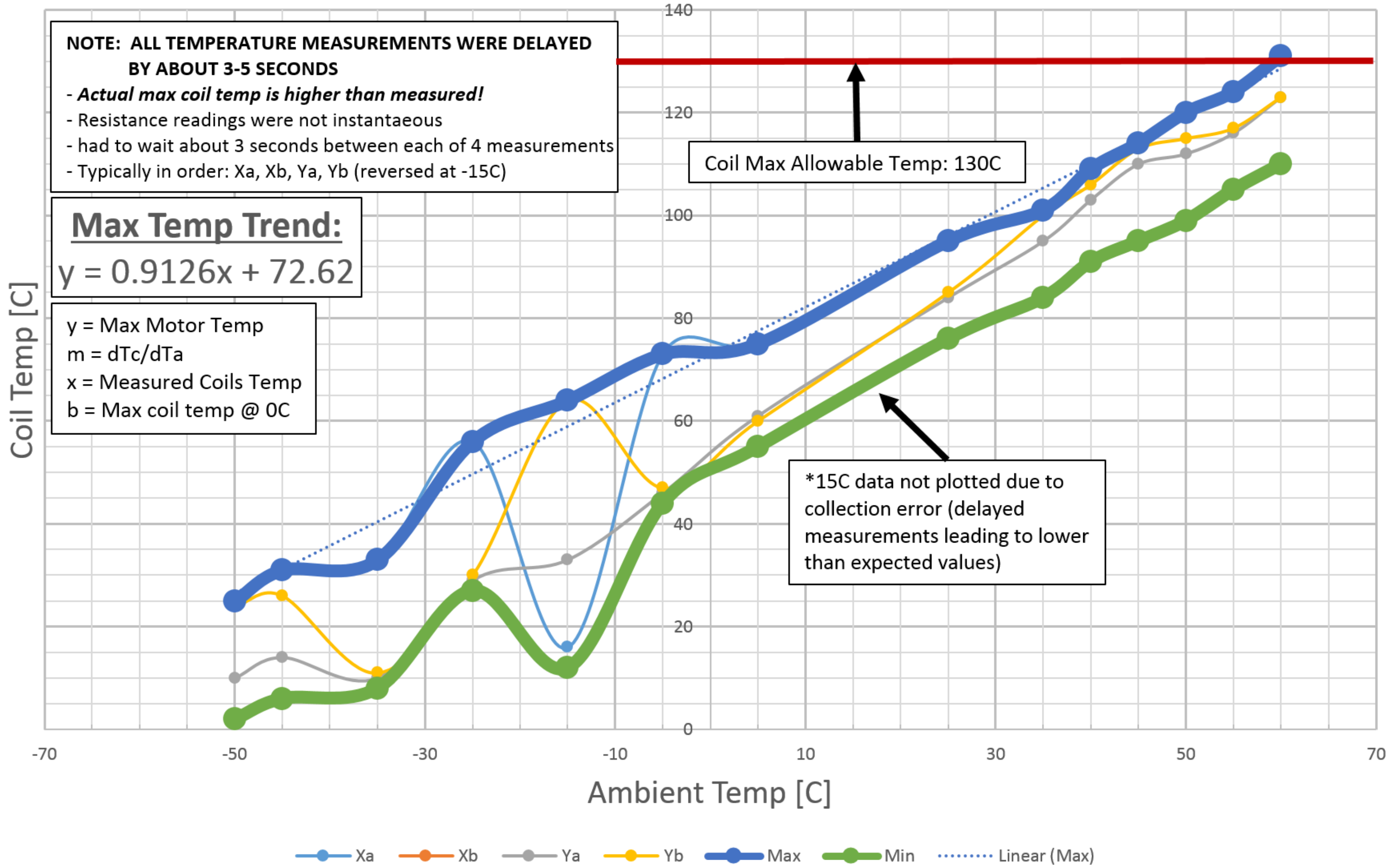
$R(T) = coil\ impedance\ at\ test\ environment\ temperature$
$R_0 = coil\ impedance\ at\ room\ temperature\ (120\ \Omega)$
$\alpha = coefficient\ of\ thermal\ resistance\ for\ coil\ material\ (copper = 0.0039\ {}^{\Omega}/_{\circ C})$
$T_c = coil\ temperature\ at\ test\ environment\ temperature$
$T_0 = room\ temperature\ (20\ °C)$

produced our system's simple equation…

$$\boxed{T_c = \mathbf{2.14 * R(T) - 236.4}}$$

Lessons Learned

… and determined the motors' operational range in vacuum environment

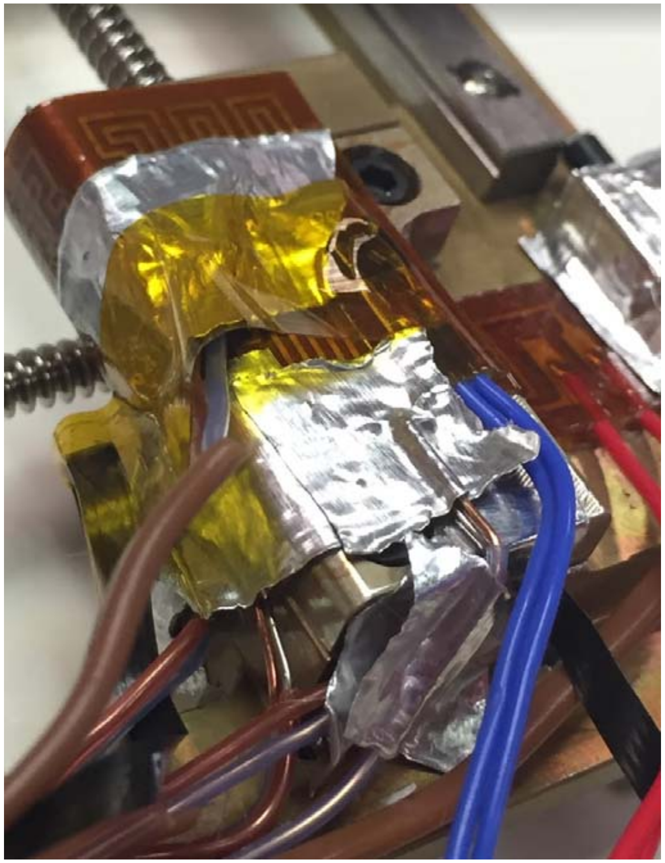


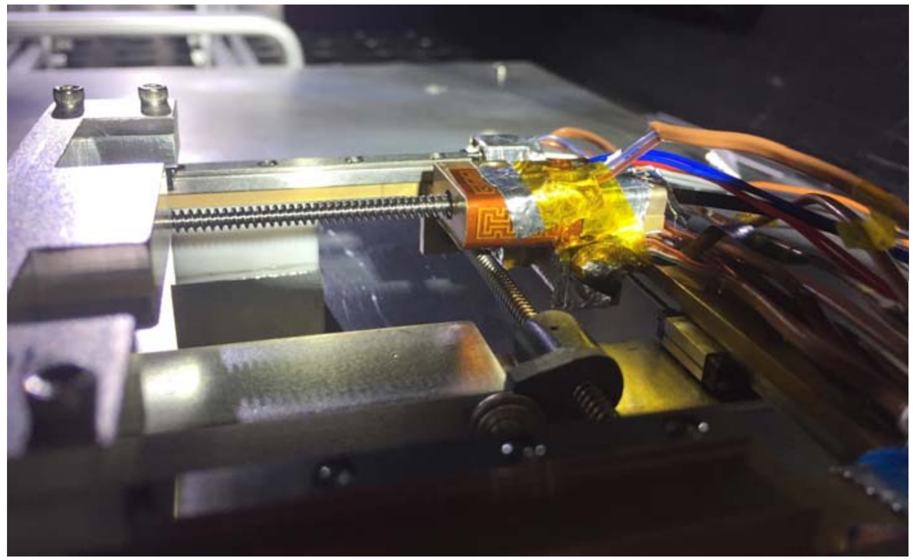
In Conclusion

- **Indium is suitable for thermal interfaces with DC minimotors**
  - Coil temps decreased from 230 C to 90 C at comparable temperatures
  - Inexpensive, predictable method produced significant results
  - Simple disassembly, avoids epoxies, greases or oils
- **Use motor coils as thermistor if internals are not understood**
  - Produce a simple method to characterize motor health over temperature range
  - Recognize limitations: data delays after operation lessen actual maxima
- **Use test data to determine operational ranges if vendor data is incomplete or unavailable**
  - Able to accommodate COTS motor for space environments with limited procurement costs (< $1k per motor)
  - CubeSat form factor and budget did not allow more qualified vendor
- **CubeSat philosophies that need to be adopted or amended**
  - Allocate schedule and resources to procure engineering development units (EDUs)
  - Perform as many low-fidelity tests as possible (simple vacuum tests, vibe tests)
  - Arduinos accelerated development but were used for too long, transition to flight board EDUs as soon as possible

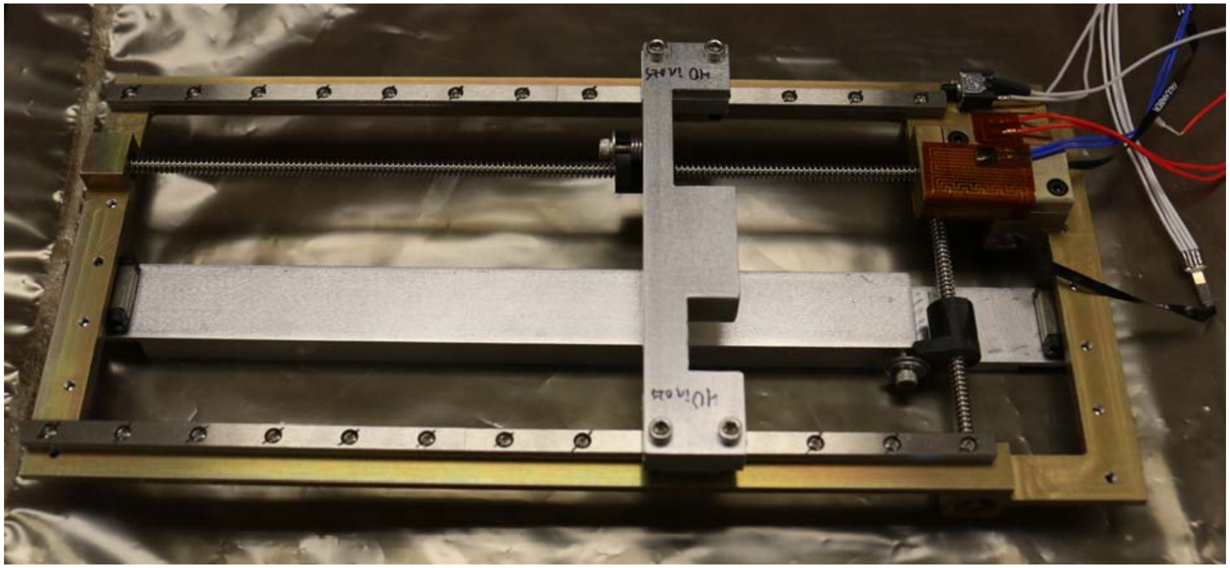
Questions

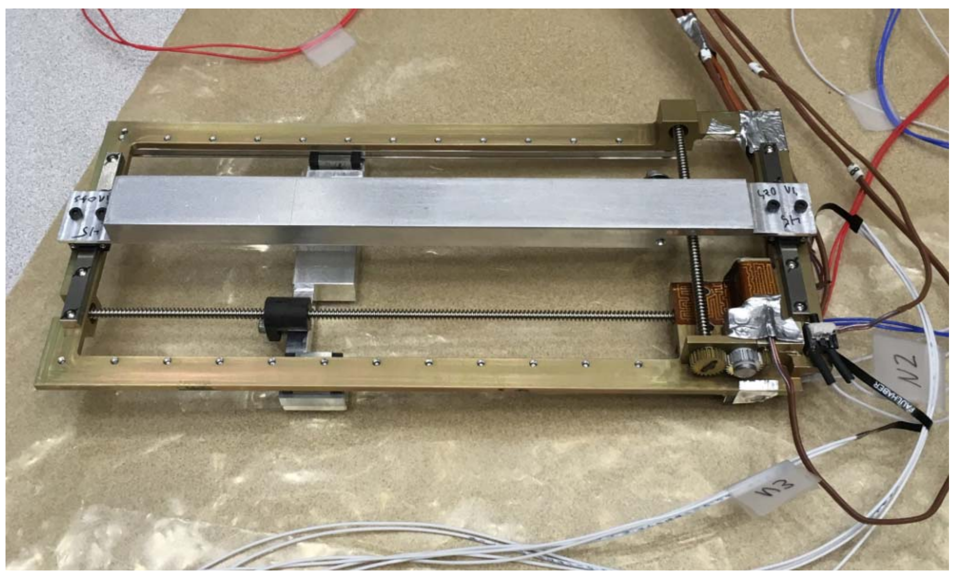
TVAC Test Instrumentation, Limitations



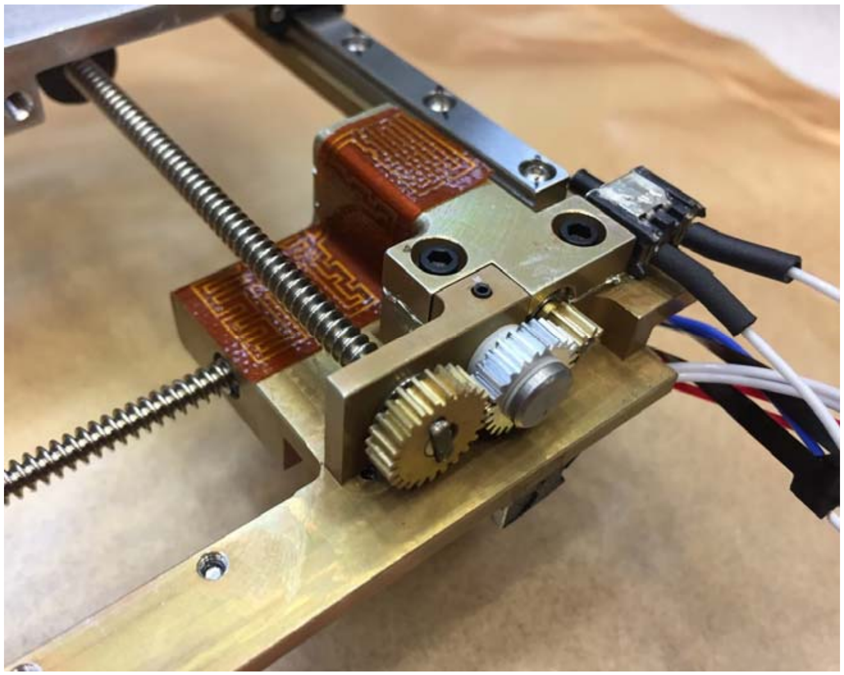


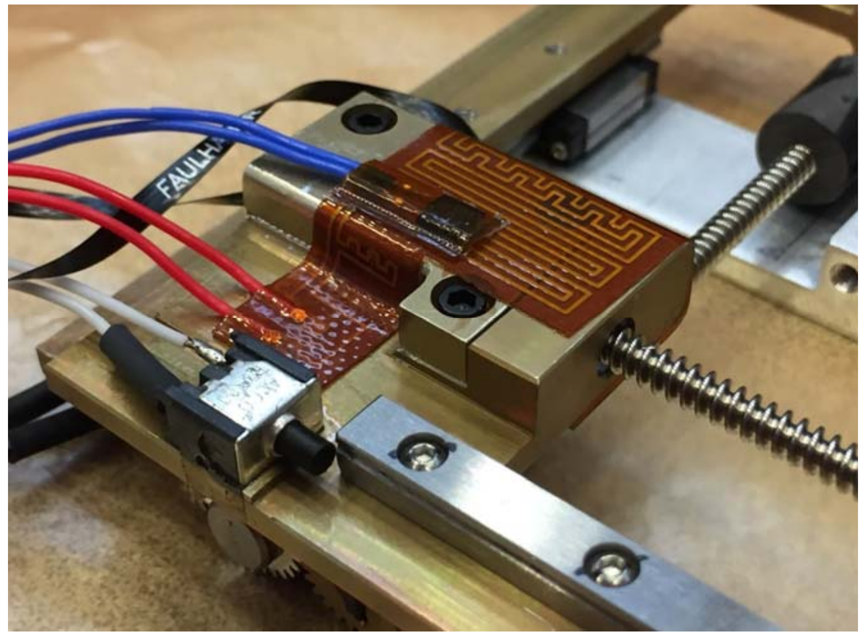
AMT Design with Simulated Interfaces (aluminum beams)





Completed Clamp Design, X and Y Axes





Used Indium

Pre/Post Design Change, Thermal Data Comparison