# Toils for Coils

## The MXL's First On-Orbit Active Control System

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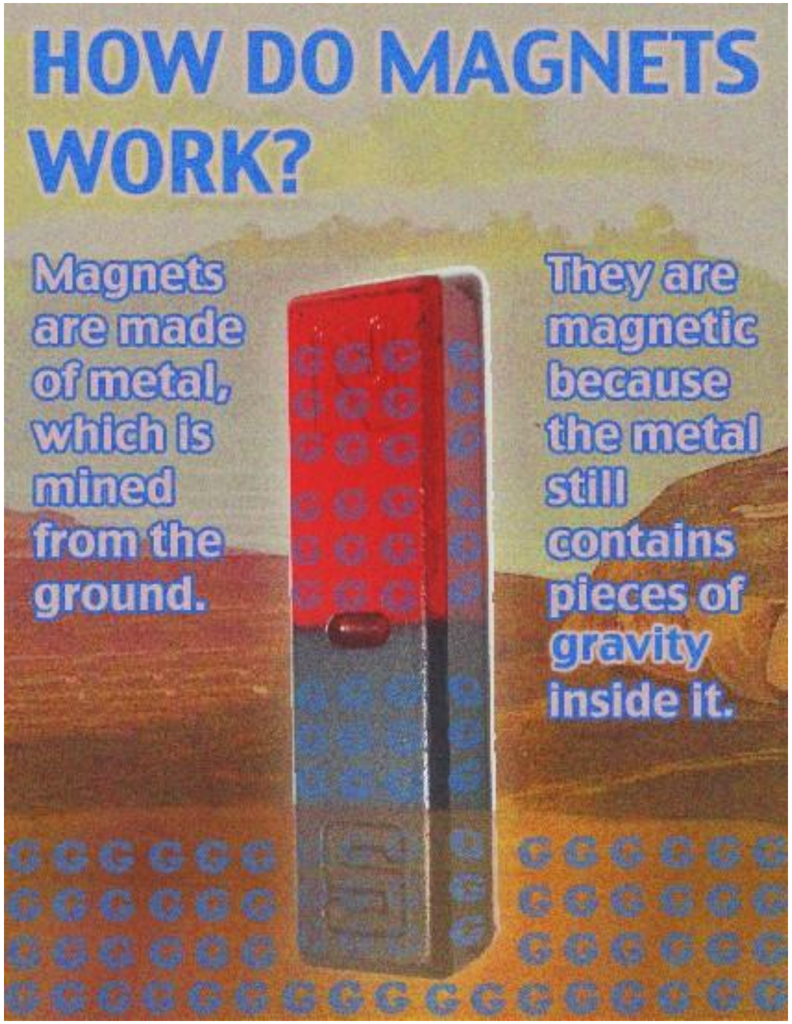
# Kind of Funny



# Quick Guide to Magnets

- *Magnetic Dipole*: strength of the specific magnet; determines torque on S/C; oscillation frequency about B-field lines increases with stronger dipoles

$$\vec{\tau} = \vec{m} \times \vec{B}$$

- *Hysteresis*: resistance to changing B-field (damps oscillations —"friction" ); greater the amount of material=greater amount of steady-state error
- *Remnance*: material property; higher remnance = smaller weight and size for a given dipole
- *Coercitivity*: resistance toward demagnitization (high T)
- *Relative permeability (core)*: formation of B-field within itself

$$\mu_r = \frac{\mu}{\mu_0}$$

# History of MXL Passive Control

- Common industry standards:
  - Magnets
    - AlNiCo-5: stable; requires length-diameter ratio of at least 4 (for magnetic stability)
    - Neodymium: Computer magnets; low Curie temperature (loses magnetism); very high remnance; l-d ratio less of a factor
  - Hysteresis:
    - HiMu80; Permalloy; Permenorm
    - Energy dissipation through heating
- RAX and RAX-2
  - 4 AlNiCo-5 magnets (custom notched from Storch Magnetics): 3 A-m$^2$ (magnetic moment decreased significantly after launch)
  - Hysteresis strips: HyMu80; 0.9g in each axis
- M-Cubed
  - 1 longer AlNiCo magnet: 1.415 A-m$^2$
  - Hysteresis strips: HyMu80; 0.9g in each axis

# M-Cubed-2 Permanent Magnet

- Permanent magnet: original baseline
- Flipped direction from Mcubed-1
  - Camera in +y direction
  - magnetic moment now in +z direction
  - Maximizes earth viewing from camera
- Hysteresis material –same as M-Cubed
- Neodymium ring magnets
  - Strong and small
  - But can it survive the high sunside temperatures without demagnetizing? (Yes)
  - Can we mount them efficiently? (Yes)

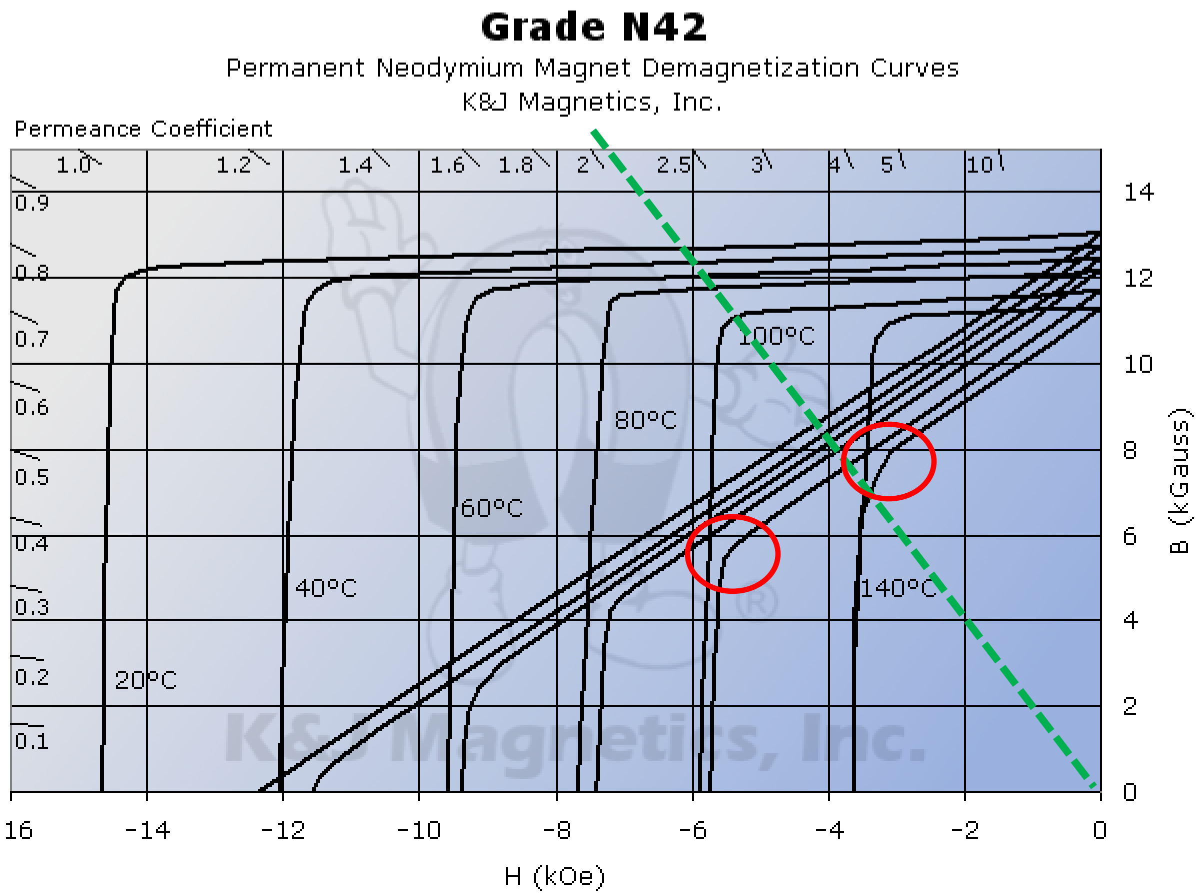
# B-H Curves

- Permeance coefficient of R422: 2.21

1. Draw load line
2. It's above the 100 degree 'knee,' below the 140 degree knee.
3. Below knee= irreversibly demagnetized
4. Max estimated operating temperature: **130 C**

Note: high T neodymium is available but required custom order from K&J

R422 magnet: R=ring, 42=Grade N42 neodymium




Examples: http://www.kjmagnetics.com/blog.asp?p=temperature-and-neodymium-magnets
Calculator: http://www.kjmagnetics.com/calculator.asp?calcType=ring

# Process for Selecting M-Cubed Magnet

1. RMS sum of expected torques magnitudes on orbit (4e-7 N-m)
   - Residual dipole (dominates), solar pressure, aerodynamic toque, grav. grad **with contingency**
   - Solve for order of magnitude magnetic strength (~0.2 A-m$^2$)

$$\vec{\tau} = \vec{m} \times \vec{B}$$

2. Literature review of documented CubeSats using permanent magnets (15 specs found)
   - Corroborate with dipole trends from review (✓)
   - Corroborate with Alex's/Young's simulations (✓)
3. Find N42 ring magnets to meet size and strength requirements
   - **"Magnetic dipole" not a given parameter of sold magnets**
     - **Used B-field measurements (from K&J online calculator or magnetometer testing) at a known axial distance to back out dipole strength**

$$B_{\text{axial}} = \frac{\mu_0}{4\pi} \frac{2mr}{(r^2 - l^2)^2}$$

length$=2l$
magnetic moment$=m$
axial distance $= r$

   - Stacking two R22 magnets on top of each other: superposition doubles dipole and only adds to thermal stability; the exact size not sold

*M-Cubed total permanent dipole: 0.168 A-m$^2$*

# Active Control

- As opposed to passive (magnets, grav grad, solar pressure, residual dipole, aerodynamic drag)
- Motivation: used to point and slew for optical systems, sun tracking, science (WINCS)
- 1axis, 2axis, 3axis
- Limited history on CubeSats

# Magnetorquers

***Advantages***

- Suitable for restricted volumes due to custom design possibility
- No moving elements; no propellant
- High reliability

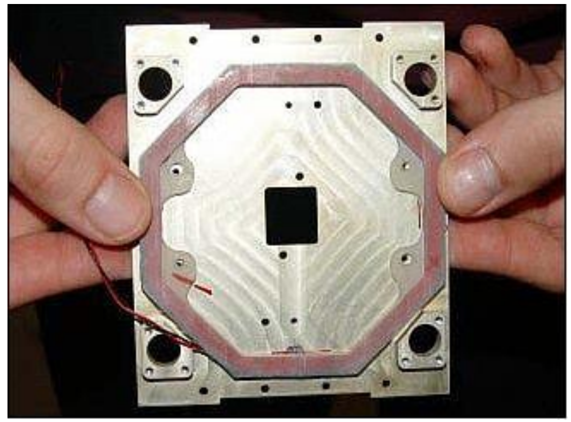
***Disadvantages***

- Low torque (~$10^{-7}$nNm); no torque along Earth's B-field vector
- B-field uncertainties/errors can lead to unstable control
- No use beyond low Earth orbit

***Designs***

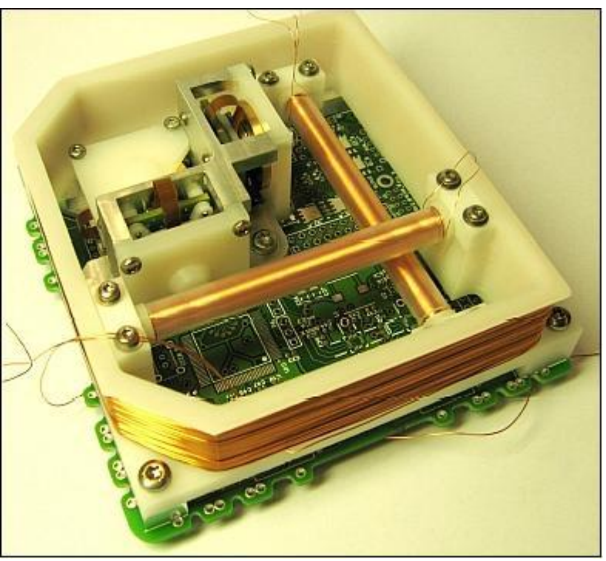
- Air core
  - Bigger area footprint
  - No hysteresis in control; negligible transients
  - Requires hysteresis rods to detumble and dampen oscillations
- Ferrous core
  - Iron rods with high relative permeabilities increase the dipole moment of the solenoid
  - Cores have nonlinear hysteresis effect on control and dampening

# Creative Design Space (1)

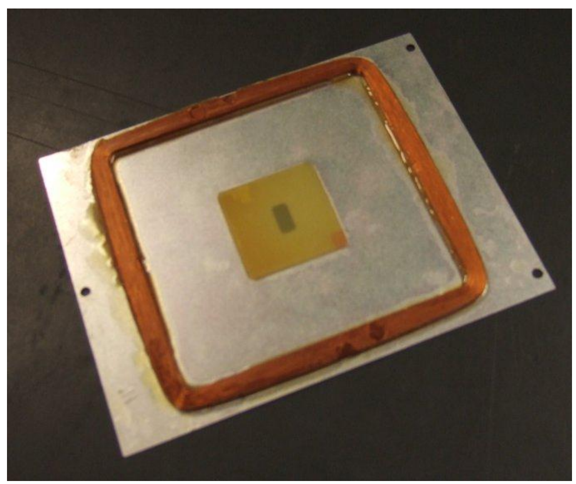


DTU-Sat 2

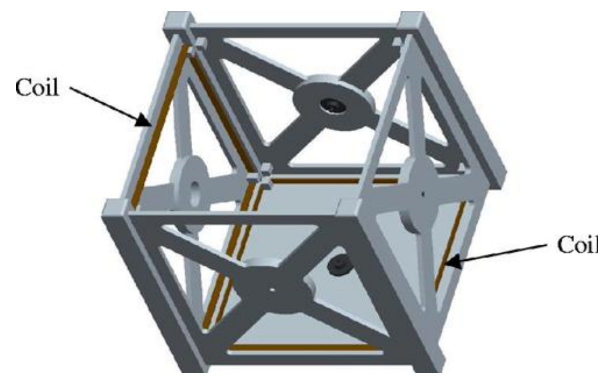

ZACube 1



Delfi n3Xt

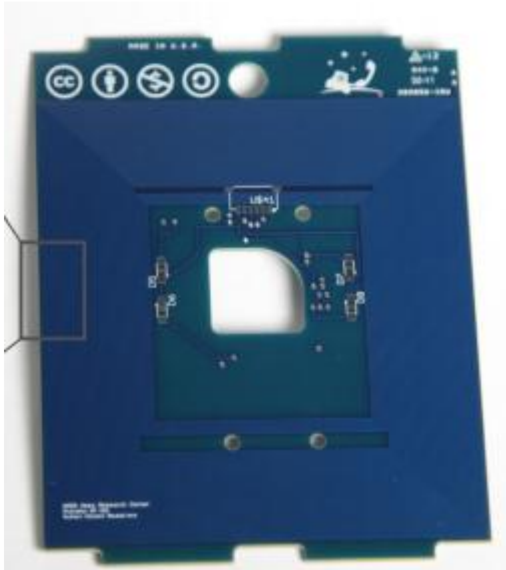


AAUSat II

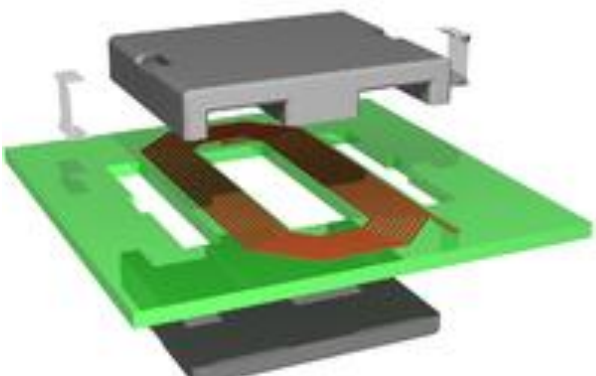


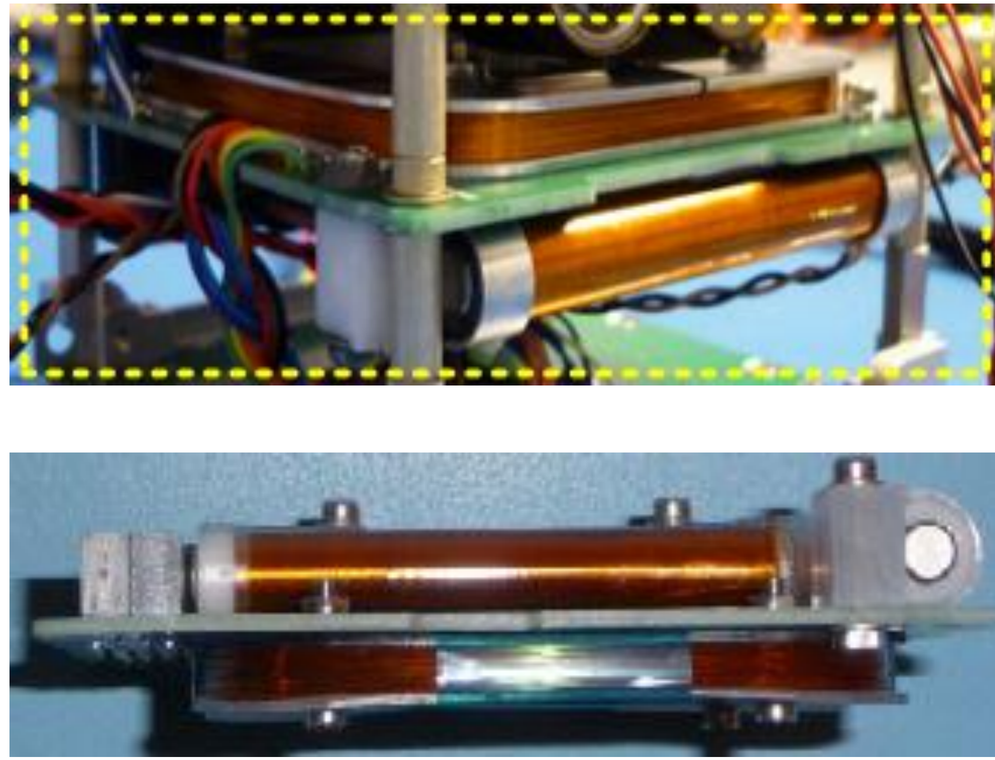

St. Louis University

# Creative Design Space (2)



Ames/CalPoly





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# Building Magnetorquers in House

- Start with z-axis air core for mcubed
  - 1) Design the hardware (optimization)
    - Required accuracy, power consumption, footprint, mass
  - 2) Design the electronic schematics
    - Hbridge, controller (MSP430/STAMP), bus components
  - 3) Test and characterize
    - Actual power consumed, transient effects on integrated satellite
- CADRE 3axis control
  - Same process. New Variables

# Process for Selecting M-Cubed Torquer

1. [Same as magnet] RMS sum of expected torques magnitudes on orbit (4e-7 N-m)

$$\vec{\tau} = \vec{m} \times \vec{B}$$

2. Literature review of documented CubeSats using active magnetic control (13 specs found)
3. Optimize the (air core) coil in Matlab

$$\vec{m} = \mu N i \vec{A}$$

   – Unknown variables: number of turns (n), wire gauge (aw), enclosed area, length of the wire, wire resistance, mass, power, filter(?)
      • Buckingham ∏ theorem reduces to 3 independent unknown variables. Choose: turns, mass, power at a set wire gage
   – Requirements: magnetic moment must be >= permanent magnet to undock (attack, etc)
4. Two matlab codes
   – msize: brute force—ie. grid the design space
      • Trends are intuitive but wire gauge is discrete not continuous; more difficult to pick out optimizer than originally thought
   – msize2: graph variables and propose a variety of feasible designs. Choose one.

# Matlab Sizing Script 2

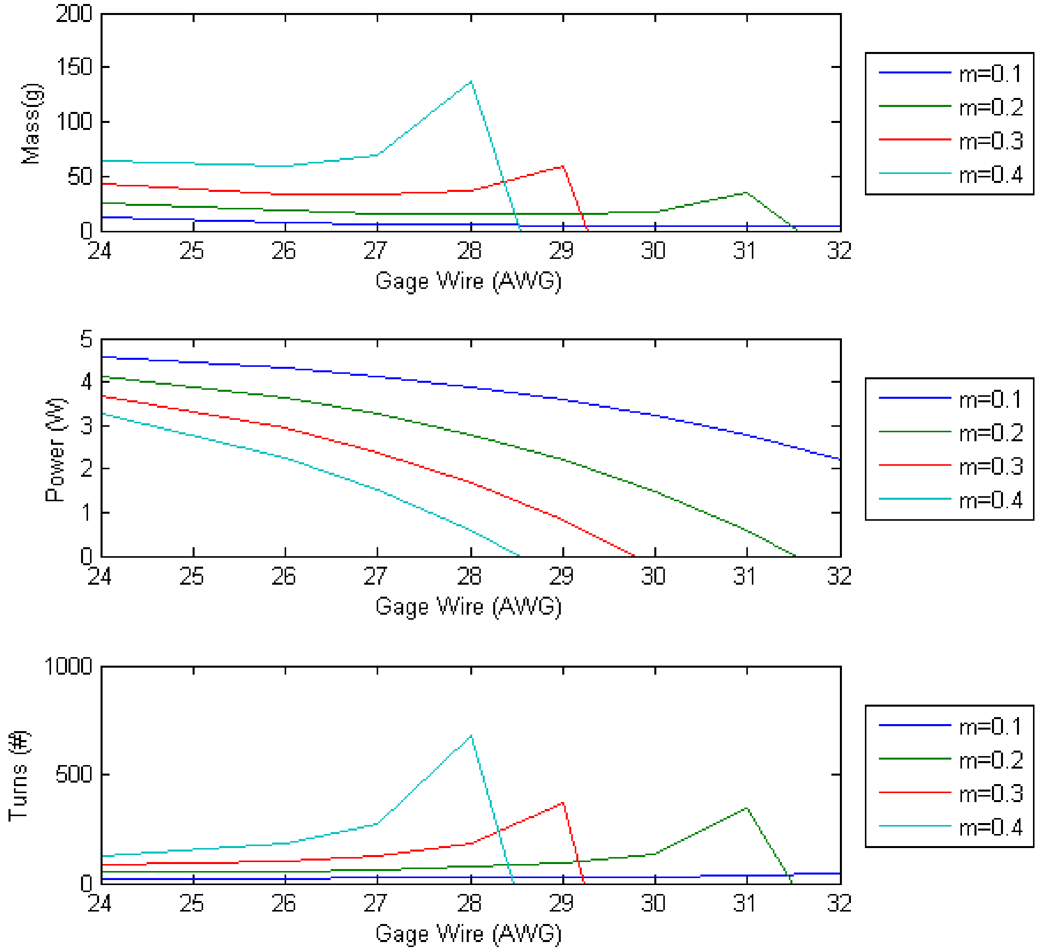
*Trends*

- Increasing wire gauge (smaller area) reduces the power (higher resistance)
- Low power tradeoff is a higher mass

*More complex that it seems*

- For the same magnetic moment, smaller wire gauge requires more turns→ increases length→ increases resistance → decreases current → requires more turns→→

Turn count/mass reach infinity/ infeasible range=no solution

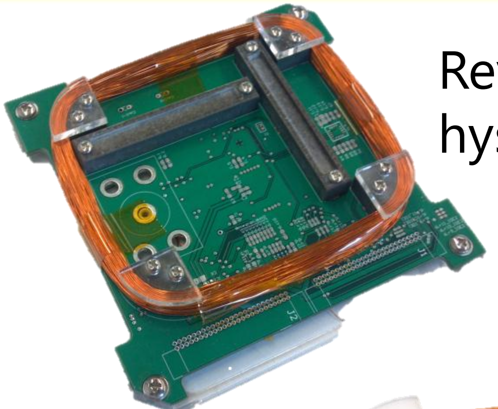



Graph is representative.

# The Hardware

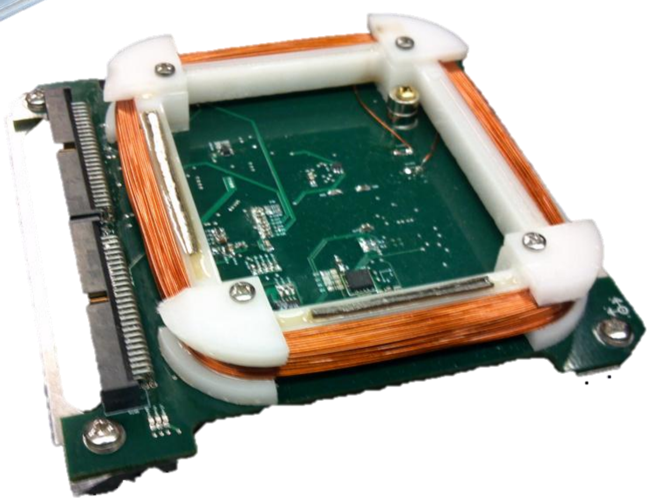
- Copper wire
  - Polythermaleze coating (space rated, low outgassing, low deterioration)
  - SPRL has even wire gages
    - Greater than >2 years old (NASA standard)
    - Tested in the lab for cracks (wind/unwind)
- Mount
  - Lasercut from White Delrin Acetal Resin
  - Made in layers
- Scotchcast 280
  - Increases dielectric (only important for HV)
  - Rigidly locks wires in place (doesn't unwind)
  - Seals wire to mount (less risk of vibration modes)

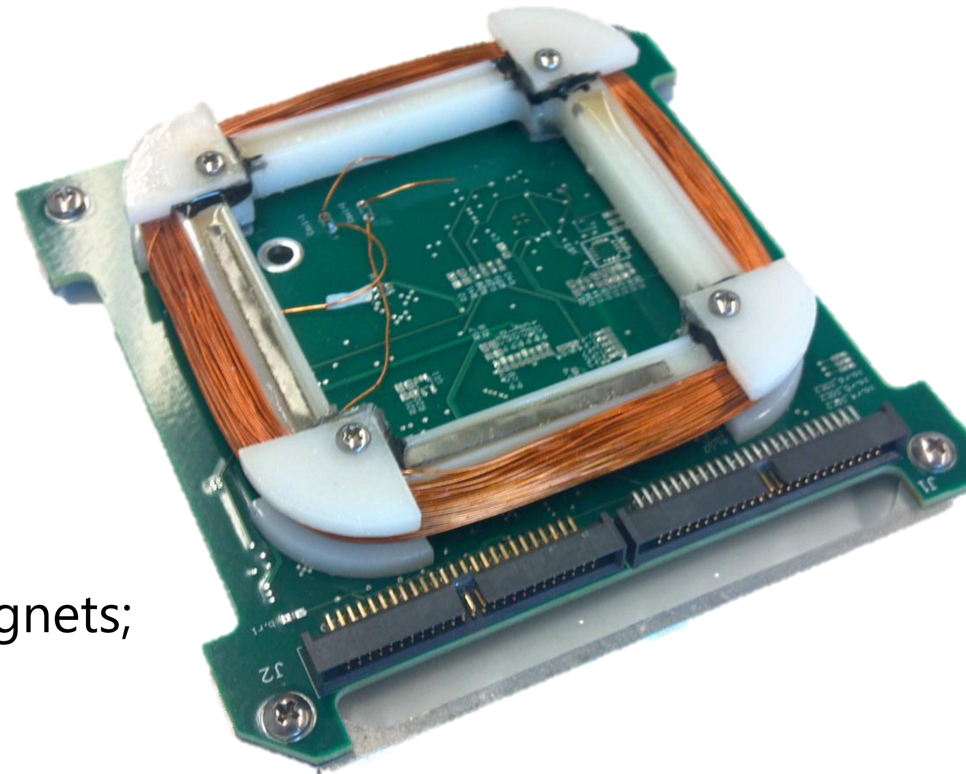
# Design Iterations



Rev1: Coil wound directly on board; 4 AlNiCo-5 magnets; hysteresis mounts

Rev3/4: Square coil (slightly smaller)





Rev2: Removable coil; neodymium magnets; integrated hysteresis

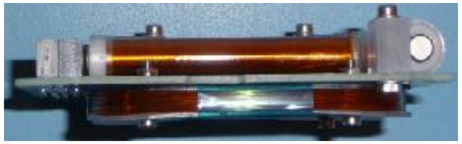
# Flight Hardware Specifications

- Turns: 193
- Length of wire: 54.04 m
- Gage: 30 AWG
- Designed Area: 6.5 cm x 6.5 cm
- Effective Area: 45.87 $cm^2$
- Designed magnetic moment: 0.36 A-m^2 at 8.2 Vbatt
- Resistance: 15.64 Ohm
- Inductance: 5.0923 mH (tested at 1kH, Q value of 2.045)
- Power when running: 0.4 A so about ~3W
- Mass: 47.92g

*Operations:*

- Bang-bang control=short intervals in operation
- Secondary to COVE mission—ACB only powered on after primary mission completed.
- Raises TRL of MXL technology (coil fab, gyros) and a good exercise in attitude estimation (gyros) and one axis control

# Process for Designing CADRE Coils



- Two ferrite cored; z-axis air core
- Optimization using fmincon
- New unknown variables: core length, core radius

Objective function

$$f(x) = \vec{m} = \frac{rV_{bus}}{2W_{res}}\left(1 + \frac{\mu_r - 1}{1 + (\mu_r - 1)N_d}\right) \rightarrow max$$

Where:

$$N_d = \frac{4[\ln l/r - 1]}{(l/r)^2 - 4\ln l/r}$$

rod length $= l$
rod radius $= r$
wire resistance $(\Omega/\mathrm{m}) = W_{res}$

Subject to constraints (design parameters of previously selected ISIS torquer)

*Mass<50g*
*Power<200mW*
*Reasonable turn count*
*Feasible region*

$$\begin{cases} h_1(x) = \rho_{core}\pi r^2 l + a_w l_w \rho_{Cu} - 0.05 \leq 0 \\ h_2(x) = \frac{V_{bus}^2}{R} - 0.2 \leq 0 \\ h_3(x) = n - 10,000 \leq 0 \\ h_4(x) = r - l \leq 0 \end{cases}$$

# Notes

- Figures of merit much different than M-Cubed-2:
  - Required moment only 0.05 A-$m^2$ decided from Alex Fox's simulations
  - Active almost every orbit→ necessitates low power
- Limits on wire gage area: >40AWG is uncommon and riskier (easier to break during winding, more variation in wire area)

# Proposed X-Y Designs

| CONSTRAINTS | | | RESULTS | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Power** | **Mass** | **Length (cm)** | **DIPOLE** | **Mass** | **Power** | **Turns** | **Radius (mm)** | **Length (cm)** | |
| 200mW | 30g | 5cm | 0.217 | 30g | 200mW | 7.66k | 3.59mm | 5cm | |
| 100mW | 30g | 5cm | NO Solution | | | | | | |
| 100mW | 50g | 5cm | No Solution | | | | | | |
| 150mW | 50g | 5cm | 0.193 | 50g | 150mW | 7.416k | 4.9mm | 5cm | |
| 100mW | 50g | 3cm | 0.107 | 49g | 100mW | 9.9k | 5.5mm | 3cm | |
| 300mW | 50g | 2cm | 0.1064 | 32g | 298mW | 2.94k | 6.3mm | 2.2cm | (no active constraints) |
| 200mW | 30g | 2cm | 0.0707 | 18.2g | 200mW | 8.404k | 3.3mm | 2cm | |

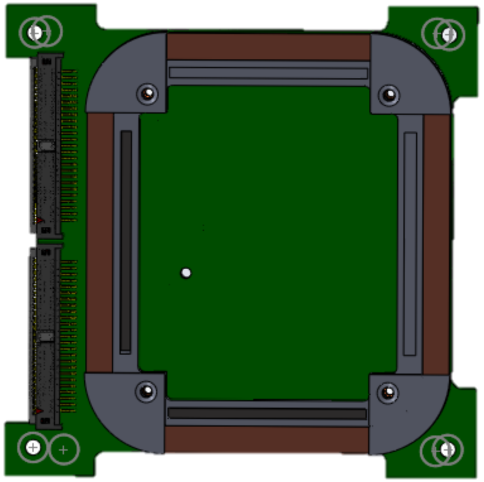
*Comments* (same similar trends as M-Cubed-2 coil design):

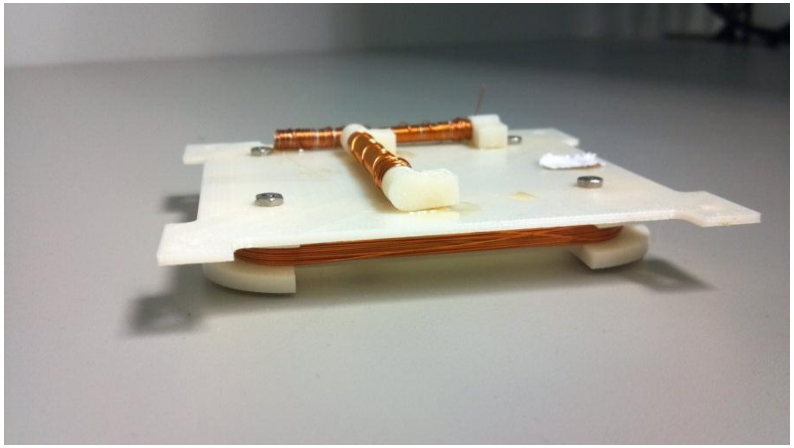
- Most of the torquer mass comes from core/mount, not extra wire
- Smaller magnetic dipoles doesn't really save us on mass (or much on power)!
- There are some constraints that have no solution
  - It's not a matter of just decreasing the magnetic dipole!
- Not actually doing us favor with smaller torque. See trends

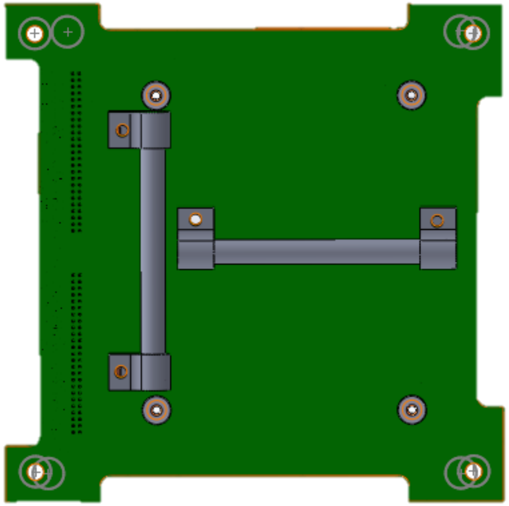
*Ideas:*

- Replace iron core with delrin core or hollow tube for smaller magnetic moment
- A series resistor can limit the current without smaller/longer wire (in order to achieve a smaller magnetic moment), but wastes power as heat and doesn't' save mass since the core is unchanged.
- Proposed sizing dipole of 0.22 A-m$^2$ is able to minimally control CADRE in the case of a wheel failure

# Torquer Control Board (TCB)







All three coils are being designed to mount to a single board, the Torquer Control Board (TCB), which may also function as a connector hub in the ADCS bay.

All control is intended to be over GPIO from the ADCS motherboard

# Future Work

- Ground testing of M-Cubed-2 integrated coil while we can
  - Re-confirm the magnetic moment with gaussmeter
  - Map out B-field? Effects on magnetometers?
- Fly M-Cubed-2 and test controllability on orbit
  - Use gyros for state estimation
  - Raises TRL of algorithms and hardware
- Torquer Control Board development
  - Finish the z-axis coil design
  - Prototype board with ferrite core magnetorquers and H-bridges (mechanical integration and demonstration). Fabrication of cores with Scotchcast dunk etc
- Algorithm simulations finished in Matlab, converting to C++
- Continued documentation in fabrication and design

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# *FIN*

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