Preliminary Design Review

May 7, 2002
Space System Product Development Class
Department of Aeronautics & Astronautics, MIT
Electro Magnetic Formation Flight Of Rotating Clustered Entities

Introduction
- Mission
- Background & Motivation
- Requirements Summary
- Approach
- PDR Purpose
- Overview

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Introduction

Geeta Gupta

EMFFORCE Mission

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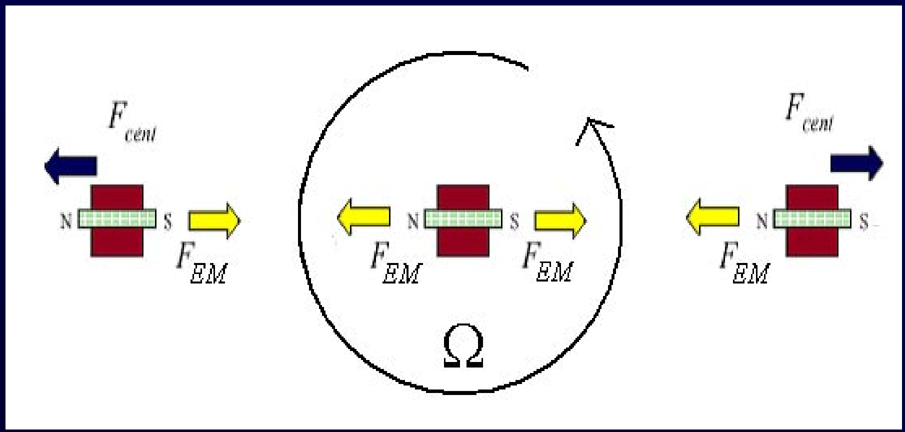
Demonstrate the feasibility of electromagnetic control for formation flying satellites.



Definition of Formation Flight

A cluster of cooperating satellites flying in a desired formation.

Applications of Formation Flight

- Large sensor apertures
  - Increased resolution
- Servicing
  - Can replace failed formation elements individually
- Upgrade and Maintenance
  - Can work on individual components without removing whole mission
- Change formation geometry
  - Evolving mission sensing requirements

Advantages of Formation Flight

- Large baselines to improve angular resolution
- Smaller vehicles
  - Ease of packaging, launch and deployment
- Redundancy
  - Mission does not fail if one satellite fails
- Reconfigurable
  - Replace individual space craft
  - Can integrate new technology during mission

Challenges of Formation Flight

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- Command and Control
  - Control multiple vehicles' absolute positions/motion vs.. relative positions/motion
- Propellant Drawbacks
  - Fuel limits lifetime
  - Exhaust particulates contaminate imaging instruments
  - Exhaust creates haze which limits imaging

Definition of Electromagnetic Control

- Implement electromagnetic dipoles to create forces and torques between the vehicles
- Dipoles can be controlled by varying the amount of current through the electromagnet coil.
  - Can provide steady forces and torques for maneuverability
  - Can provide disturbance rejection for more precise control

Advantages of EMFF

- No thrusters
  - Fewer consumables → Longer life
  - Zero pollution
    - → No contact contamination
    - → No radiative contamination
- Controls relative position/motion vs.. absolute position/motion

Challenges of EMFF

- Control Problem
  - Unstable – not unique to EMFF
  - Coupled control
    - Each vehicles' motion affects all other vehicles
- Electromagnet Drawbacks
  - Ferromagnetic material is heavy
  - Electromagnetic force is weak
    - Force in the far-field drops of as the 4th power of separation distance
  - Electromagnetic interference with other electronic subsystems

Customer Requirements

- Multiple Vehicles
- Representative Formation Flying Vehicles
- Control to replace thrusters
- Control three degrees of freedom (DOF), traceable to six DOF
- Robust controller
  - Disturbance rejection
  - Reposition vehicles

Constraints

- Schedule
- Budget
- Limited human resources to CDIO class and staff
- Testing facility
- No use of umbilical resources; power, air supply, communications
- Recorded test data
- Safety of people, facility, and system

System Functional Requirements

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Musts:

- Stability with at least three vehicles
- Control in each relative DOF

Shoulds:

- Representative 5 rotation maneuver
  - One rotation spin-up, 3 rotations steady state, and one rotation spin-down
- Operate in the far field
  - Separation distance at least 10x length of electro-magnet

System Operational Requirements

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- Test time 5 minutes
- Identical interchangeable vehicles
- Send/record test data
- Respond to other satellites
- Respond to user input
- Demonstrate autonomy
- Maintain safety

EMFFORCE Testbed Development Approach

- Conceive and Design EMFFORCE testbed → PDR May 7, 2002
- Implement testbed → CDR Nov., 2002
- Operate completed testbed → AR March, 2003
  - Operate at MIT
  - Operate at Lockheed Flat Floor Facility in Denver

PDR Purpose

- To review the preliminary design and identify and resolve high risk elements of the system.
- Have outside expert review of current progress.

Space System Product Development Class

<u>Actuation</u>

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<u>Formation Flight</u>

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- Sub-System design
  - Actuation
  - Formation Flight
  - Electronics
  - Structure/Power
- Operations
- Implementation
  - Resource Tracking
  - Budgets
  - Verification & Validation
  - Schedules
  - Action Items
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  - **Issues**
  - **Budget Estimates**
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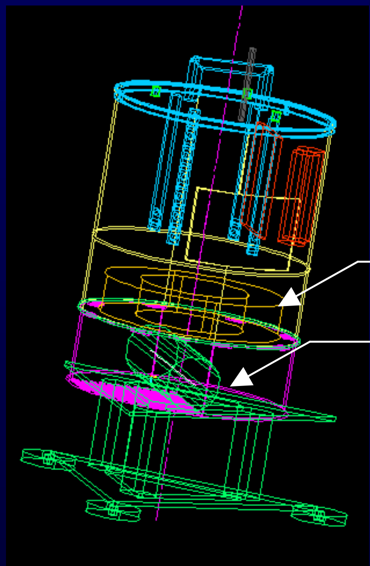
Actuation

Melanie Woo



Reaction Wheel

Electromagnet

Actuation

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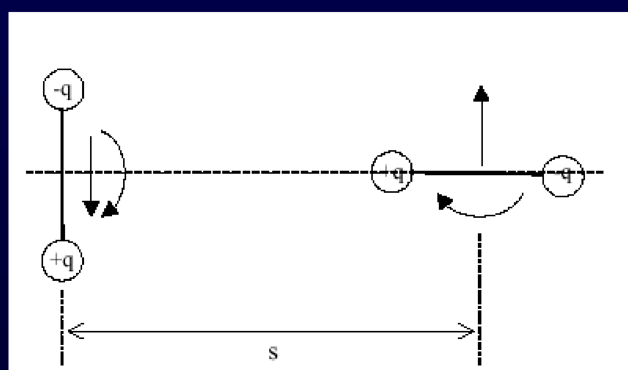
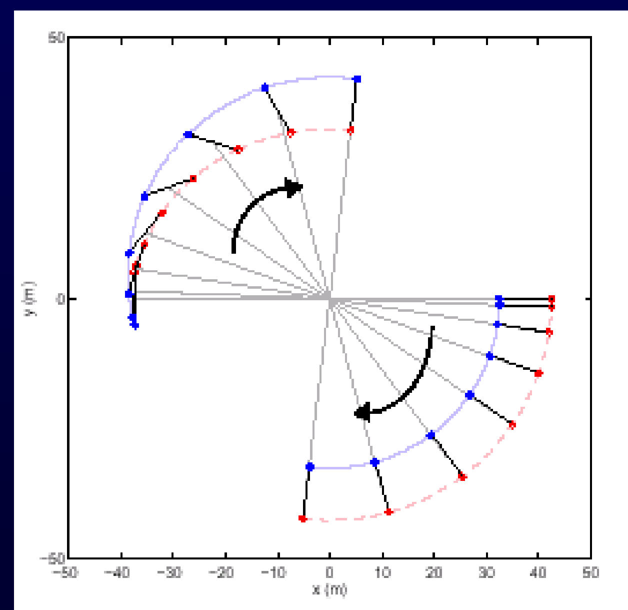
- EM force induces spin-up of cluster from initial perpendicular orientation
- RW provides counter torque to balance moments induced by electromagnets





Actuation Requirements

- Actuate control of vehicle cluster
- Magnets must be controllable in necessary DOF
- No thrusters may be used
  - Electromagnets provide force
  - Reaction wheel provides torque
- Minimize mass and power consumption

Trades – EM Configuration

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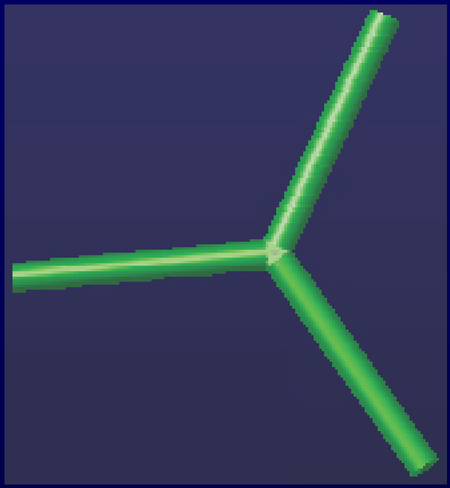
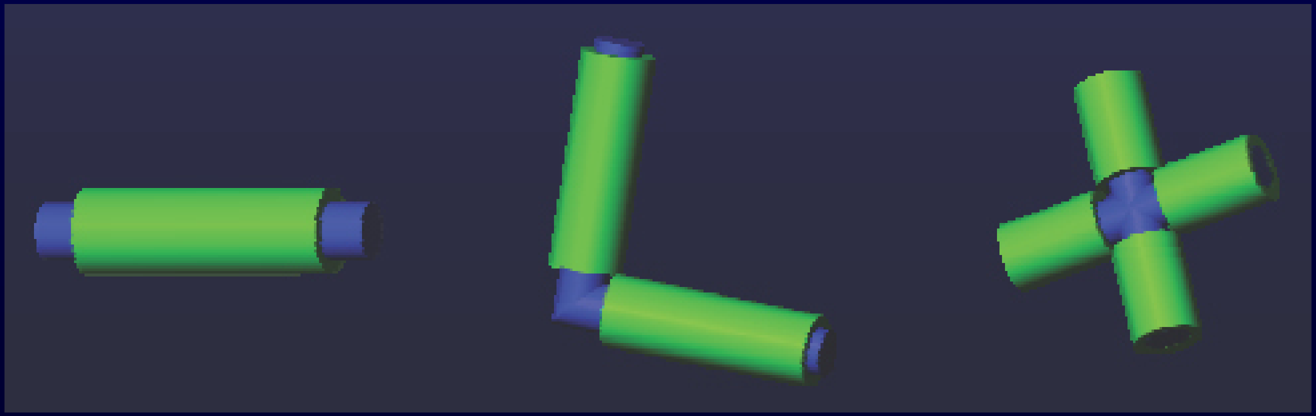
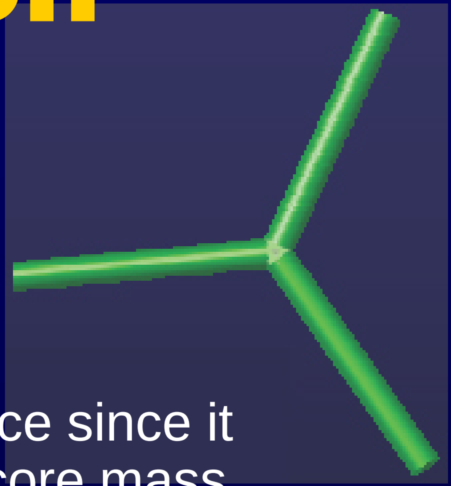


- Possible configurations:
  - Dipole, Y-pole, L-pole, X-pole
- Eliminate:
  - L-pole: center of mass problem
  - X-pole: mass distribution to 4 dipole legs



Trades – EM Configuration



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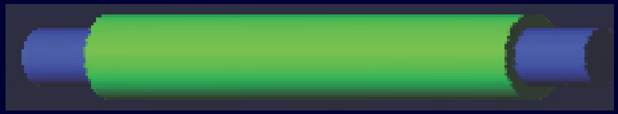
- Dipole vs.. Y-pole
- Considerations:
  - Mass distribution: Force
    - Dipole generates greater force since it energizes larger amount of core mass
    - Y-pole can vary direction of magnetic field without being rotated by reaction wheel
  - Torque
    - Y-pole generates additional torque to be countered by reaction wheel



Trades – EM Core Material

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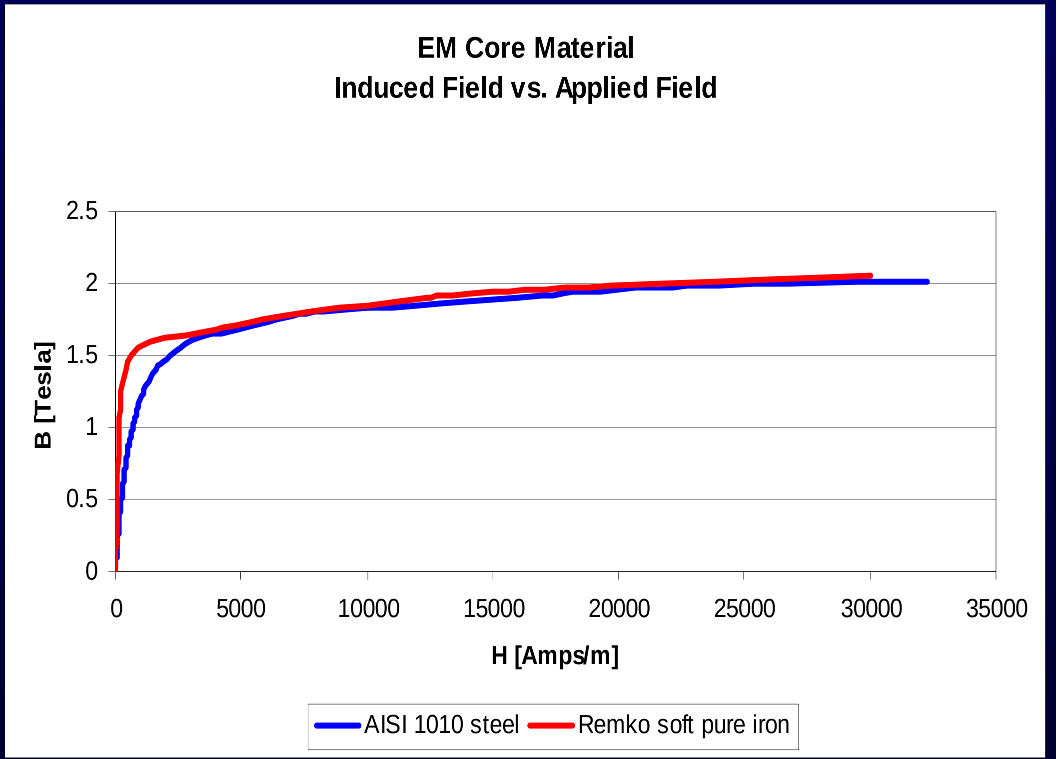
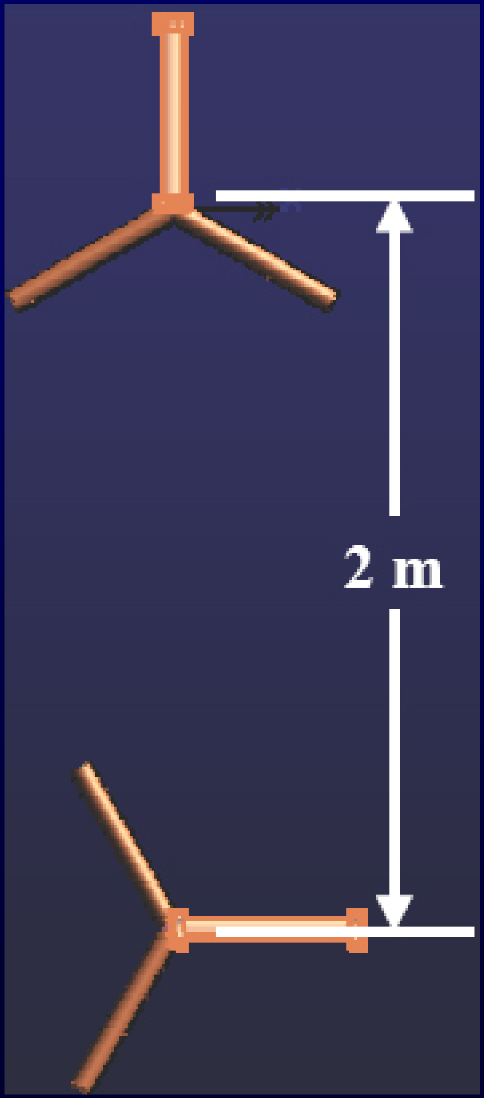
- Cost
- Availability
- Magnetic Properties
  - B-H curve
  - $B_{saturation}$
  - Permeability
- Steel vs.. Iron



Modeling

- EM Software: Infolytica MagNet
  - Input EM configuration and geometry to obtain forces and torques
- Example:
  - Y-pole configuration
  - Separation: 2 m
  - Core mass: 19.5 kg
  - Applied current: 10 Amps



Modeling

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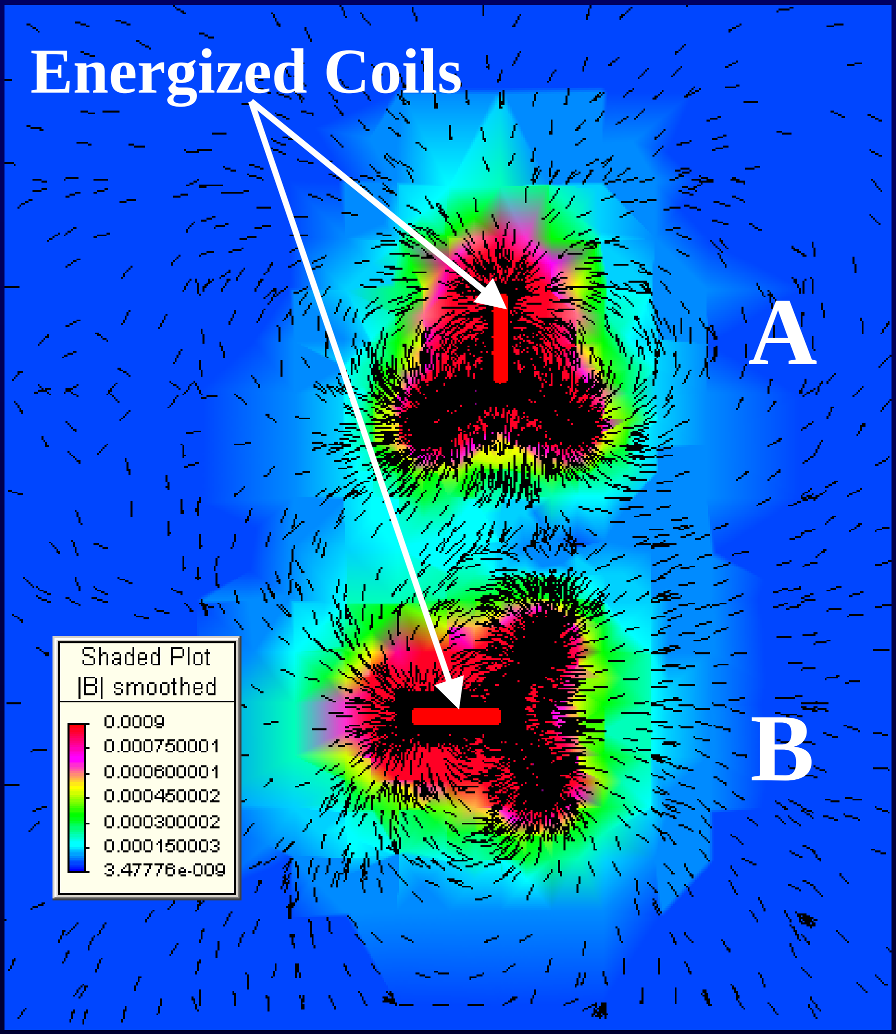
- Results:
  - Force on A and B equal
    - Magnitude: 0.42 N
  - Torque greater on B than A
    - A: 0.052 N-m
    - B: 0.848 N-m



Test Run Video

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EM Design

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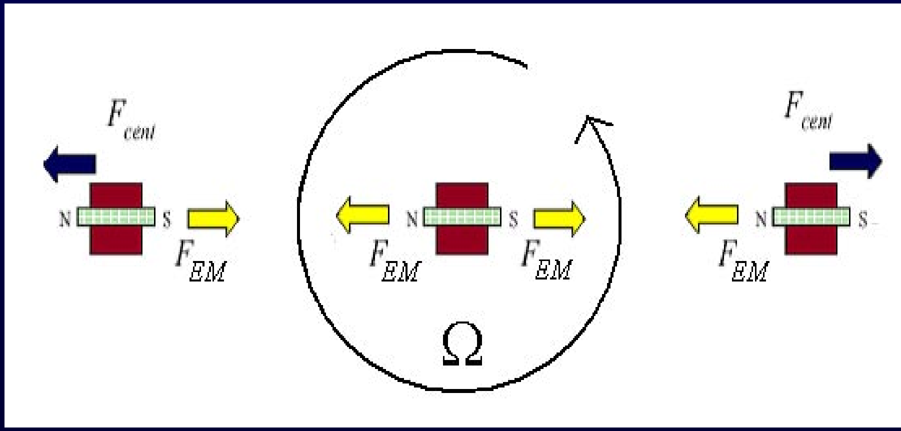
Operational Setup

- Separation: 3m
- Spin Rate: 1 RPM



EM Design

- Magnetic Force for Three Vehicles

$$F_{mag} = \frac{3\mu_o \mu_A \mu_B}{2\pi (\frac{s}{2})^4} + \frac{3\mu_o \mu_A \mu_C}{2\pi (s)^4}$$

- Set equal to centripetal force

$$F_{cent} = \Omega^2 (\frac{s}{2}) m_{tot}$$

EM Design

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- Substituting in the following relations

$$\mu_A = \mu_B = \mu_C = \frac{BV_{core}}{\mu_o} = \frac{Bm_{core}}{\mu_o \rho_{core}}$$

- And solving for m_{core}

$$m_{core} = \frac{\Omega \rho_{core}}{B} \sqrt{\frac{m_{tot} \pi \mu_o s^5}{51}}$$

EM Design

- Substituting

$$m_{tot} = m_{core} + m_{coil} + m_o$$

$$m_{coil} = \frac{\rho_{coil}\pi}{C_o\alpha}\left(\frac{4m_{core}\alpha^2}{\rho_{core}\pi}\right)^{\frac{2}{3}} H$$

- Where

$$\alpha = \frac{L_{core}}{2r_{core}} \quad C_0 = \frac{i_{max}}{\pi r_{coil}^2} \quad m_0 = 7kg$$

EM Design

- Substituting
  - B = 2 Tesla
  - α = 10
  - H = 20000
- Solving numerically for m_{core} yields
  - m_{core} = 6.5 kg
- Solving for core dimensions
  - L_{core} = .47m
  - r_{core} = .02m

EM Design

- The applied field is set by the number of amp-turns in the coil

$$Ni = HL_{core}$$

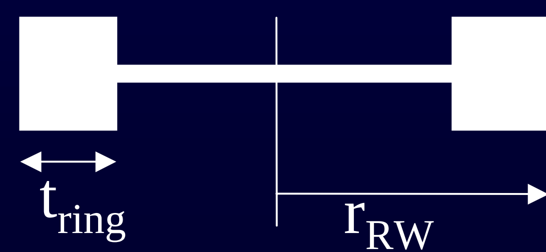
- Current limited by the wire gauge
- Number of turns sets coil length and voltage requirements
- Coil mass proportional to Ni
- More analysis needs to be done to optimize number of turns

RW Trades

- Build vs.. Buy
  - Will build RW to specifications
    - Cheaper
    - Commercial RWs are spacecraft sized
- Material: Steel vs.. Aluminum vs.. Plastic
  - Use Aluminum
    - Doesn't interfere with magnetic field
    - Higher density than plastics – RW will not have to be as large

System Assumptions for RW Analysis

- Cluster contains two vehicles
- Vehicles are modeled as uniform density cylinders
- Max Ω_{RW} = 2000 rpm ~ 210 rad/s
- RW is modeled as a ring with a thin plate in the center
- Ring has square cross section with diameter t_{ring}



System Dynamics

- RWs provides counter torque to balance system: $2H_{RW} = -H_{cluster}$
- Cluster angular momentum ($H_{cluster}$): $H_{cluster} = I\Omega$
- Cluster moment of inertia (I):

$$I = 2\left(I_0 + m_{tot}\left(\frac{s}{2}\right)^2 \right)$$

RW Dynamics

- Moment of inertia of RW (I_{RW}):

$$I_{RW} = m_{RW} r_{RW}^{2} + \frac{1}{2} m_{RW} \left(r_{RW} - t_{ring}\right)^{2}$$

- RW angular momentum (H_{RW}):

$$H_{RW} = \left(m_{RW} r_{RW}^{2} + \frac{1}{2} m_{RW} \left(r_{RW} - t_{ring}\right)^{2} \right) \Omega_{RW}$$

- RW mass (m_{RW}):

$$m_{RW} = t_{ring}^{2} 2\pi r_{RW} \rho_{Al}$$

RW Mass vs.. RW Radius

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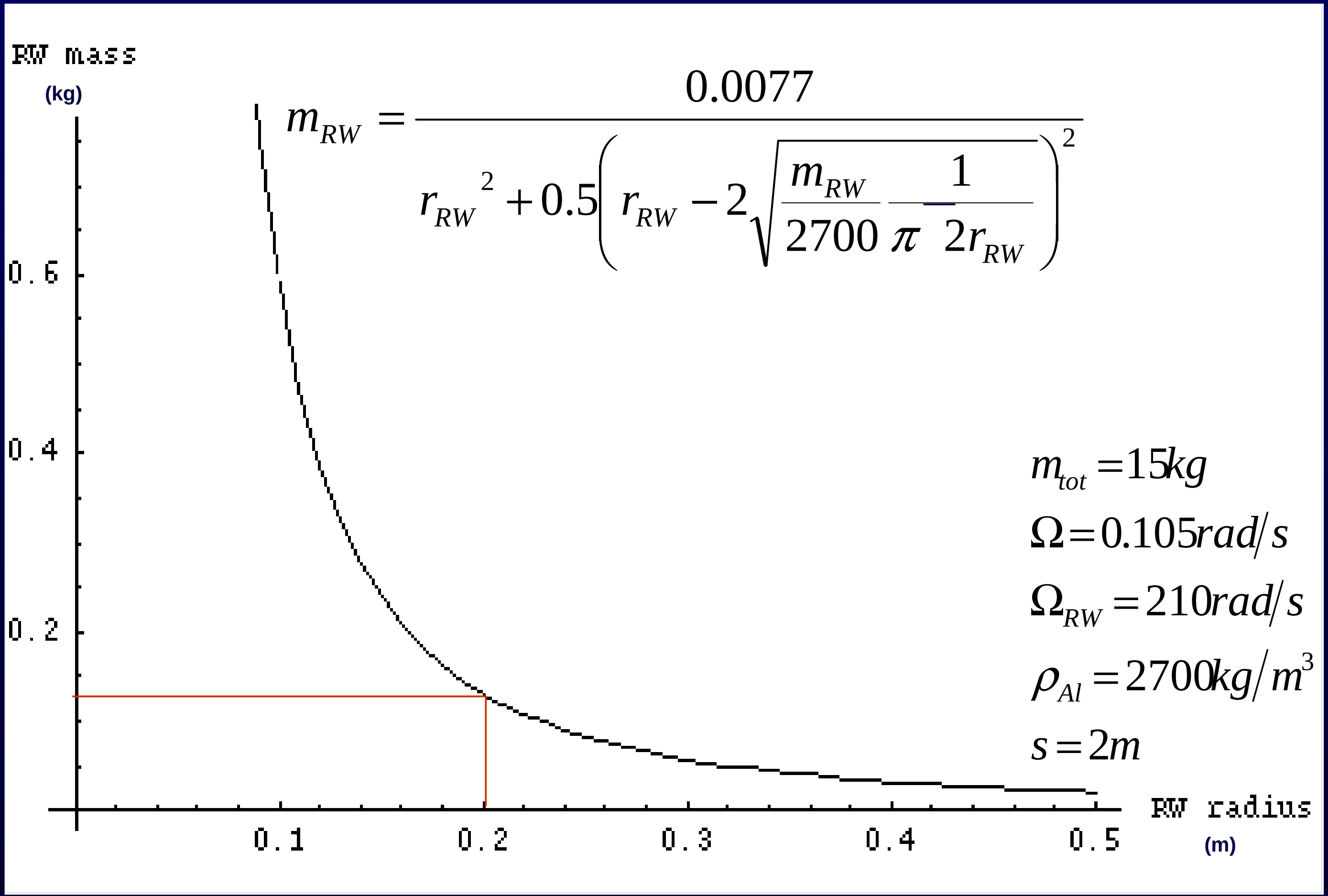

RW Mass Estimate

- RW has a mass of 0.16 kg given a radius of 0.2 m
- RW Assembly will not exceed 1 kg - includes motor

RW Power Analysis

- RW uses power mainly when applying torque – during spin up

$$P_{RW} = \tau_{mag} \Omega_{RW}$$

- Torque induced by dipole (τ_{mag}):

$$\tau_{mag} = \mu_A \times B$$

- Relationship for B-field:

$$B = \frac{\mu_0}{2\pi} \frac{\mu_B}{x^3}$$

RW Power Estimate

- Magnetic moment (μ_A):

$$\mu_A = \frac{BV_{core}}{\mu_0}$$

- Power required by RW (P_{RW}):

$$P_{RW} = \frac{\mu_0}{2\pi}\frac{\mu_A \mu_B}{x^3}\Omega_{RW}$$

- RW power estimate:

$$P_{RW} \cong 13W$$

$$x = 1m$$
$$L_{core} = 0.5m$$
$$r_{core} = 0.02\,m$$
$$V_{core} = 6.3 \times 10^{-4}\,m^3$$
$$\Omega_{RW} = 2000\ rpm = 210\ rad/s$$

Actuation Issues

- System may not be able to operate in the far field
- Total mass is large (~15 kg)
  - Magnet core mass increases rapidly with vehicle mass
- Magnet temperature must be monitored during operation

Budgets Estimates

Part	Cost ($US)	Mass (kg)	Power (W)
Iron Core	100	6.5	>120
Copper Wire	50	1.5	
RW Assembly	1000	1	13
Total (vehicle)	**1150**	**9**	**133**

Control

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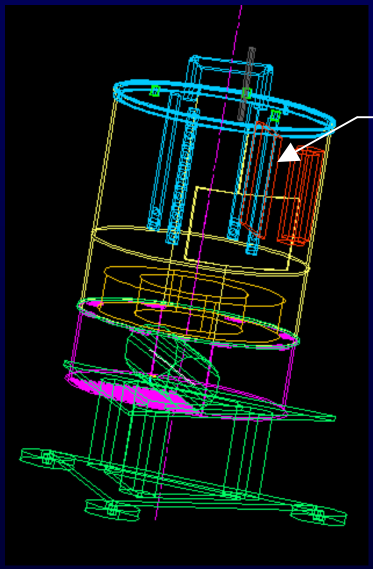
Will Fournier



Control

Requirements

- Counteract disturbances
- Reposition satellites to perform maneuvers
  - One rotation spin-up
  - Three rotations steady state
  - One rotation spin-down
- Control tolerance to 1/10 separation distance

Design

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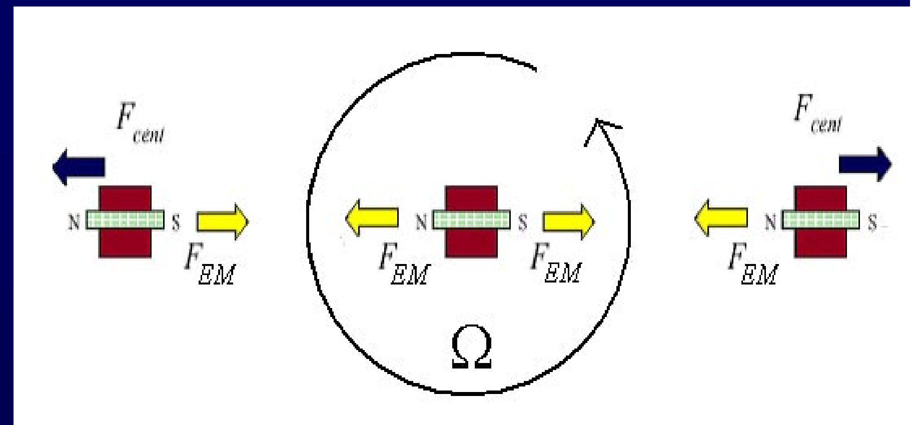
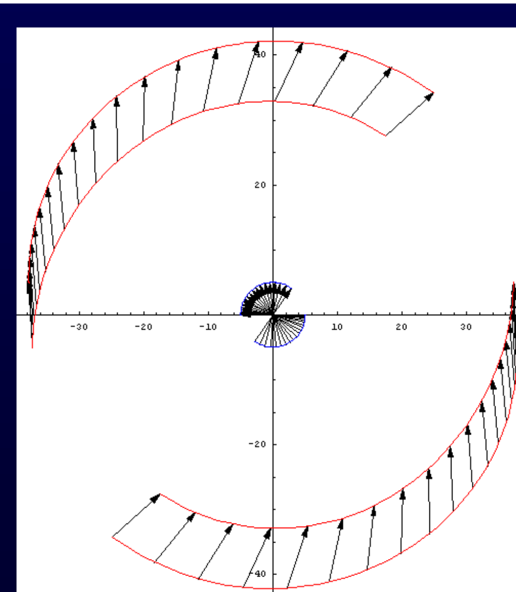
Two modes:

- Steady state



- Spin-up/De-Spin



Steady State

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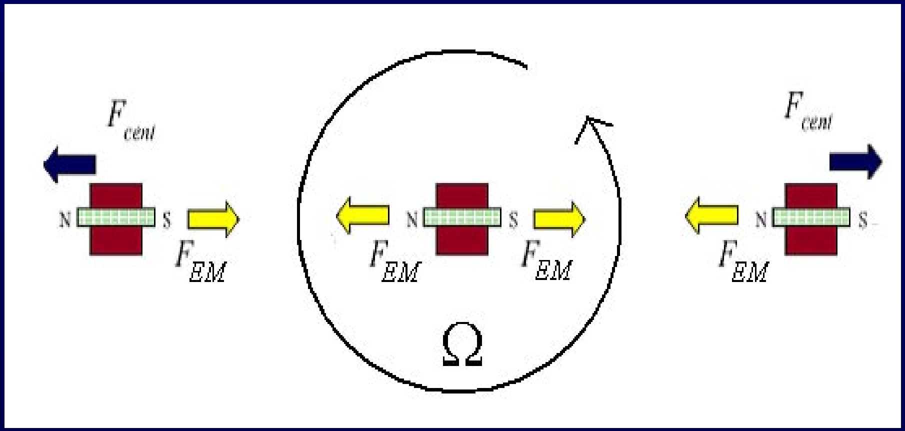


Must model axial dynamics

Steady State Derivation of Poles for Three Vehicles

- Force Balance

$$F_{cent.} = \frac{mv^2}{s} = m\Omega^2 s = \frac{mh^2}{s^3} \qquad F_{EM} = \frac{c_{0avg}}{s^4} + \frac{c_0\mu_{avg}^2}{(2s)^4}$$

- Perturbation Analysis

$$m\ddot{s} = \frac{c_0\mu_{avg}^{\ 2}}{s^4} + \frac{c_0\mu_{avg}^{\ 2}}{(2s)^4} - m\Omega^2 s$$

$$c_0 = \frac{3\mu_0}{2\pi}$$

$$\mu_A = \mu_B = \mu_C = \mu_{avg}$$

$$m(\ddot{s}_0 + \delta\ddot{s}) = \frac{17c_0(\mu_{avg}+\delta\mu_{avg})^2}{16(s_0+\delta s)^4} + \frac{mh^2}{(s_0+\delta s)^3}$$

$$m\delta\ddot{s} - \frac{mh^2}{s_0^{\ 4}}\delta s = -\frac{c_0\mu_{avg}}{4s_0^{\ 4}}\delta\mu_{avg}$$

Yields poles at $\pm\frac{h}{s_0^{\ 2}} = \pm\Omega$

State Space Analysis

$$\begin{bmatrix} \frac{\delta\dot{s}}{s_0} \\ \frac{\delta\ddot{s}}{s_0} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \Omega^2 & 0 \end{bmatrix} \begin{bmatrix} \frac{\delta s}{s_0} \\ \frac{\delta\dot{s}}{s_0} \end{bmatrix} + \begin{bmatrix} 0 \\ 2\Omega^2 \end{bmatrix} \frac{\delta\mu_{avg}}{\mu_{avg}} \qquad \dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u}$$

- Using the Cost Function: $J = \int_0^\infty \left[\mathbf{x}^T R_{xx}\mathbf{x} + \mathbf{u}^T R_{uu}\mathbf{u}\right] dt$
- And knowing that cost, J, is minimized when

$$0 = R_{xx} + PA + A^T P - PBR_{uu}^{-1} B^T P$$

$$\mathbf{u} = -R_{uu}^{-1} B^T P\mathbf{x} = -F\mathbf{x}$$

- Where Rxx describes what states the controller penalizes. Ruu describes the “cost” of actuation.

State Space Analysis Continued

- Choosing:

$$R_{xx} = \begin{bmatrix} \alpha & 0 \\ 0 & 0 \end{bmatrix} \qquad R_{uu} = \rho$$

- And using:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix}$$

- Feedback is then:

$$F = R_{uu}^{-1} B^T P = \frac{1}{\rho} \begin{bmatrix} 0 & 2\Omega^2 \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix} = \frac{2\Omega^2}{\rho} \begin{bmatrix} P_{12} & P_{22} \end{bmatrix}$$

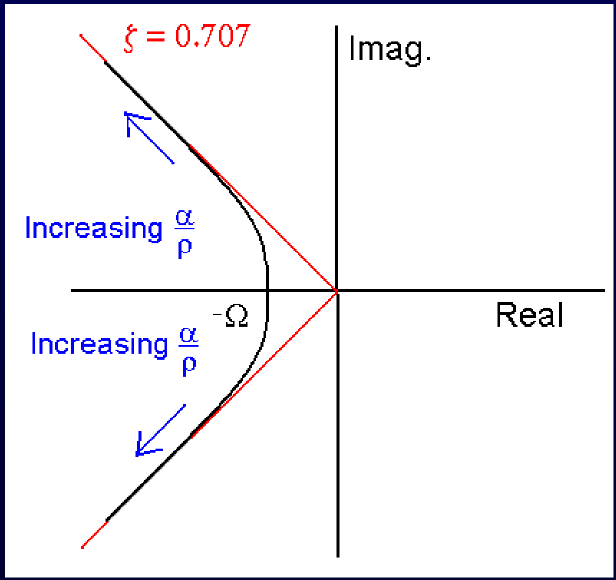
State Space Analysis Continued

- Now solve for the closed loop matrix where $\mathbf{u} = -F\mathbf{x}$

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u} = [A - BF]\mathbf{x} = A_{CL}\mathbf{x}$$

- Evaluate as $\frac{\alpha}{\rho}$ increases from 0 → ∞

- Therefore the closed loop poles for the most efficient controller lie along this curve



Steady State Stable Test Setup

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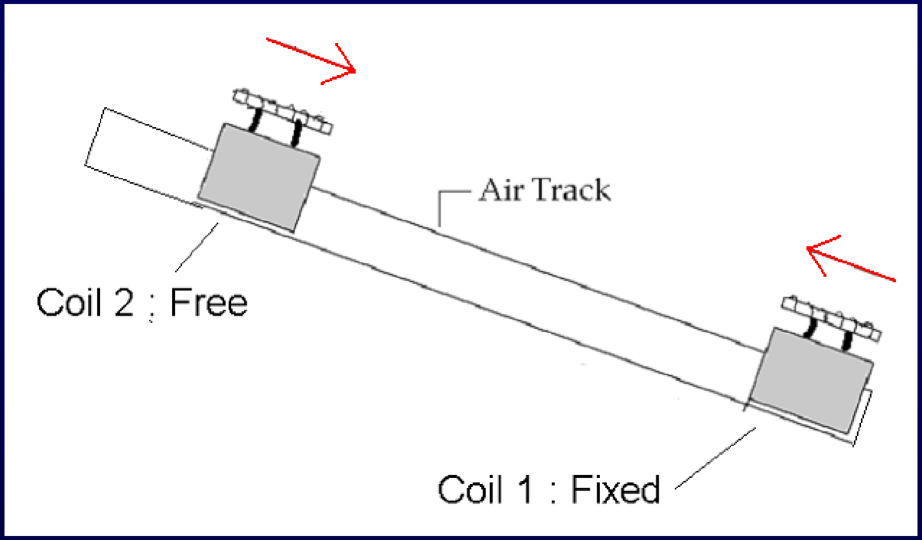
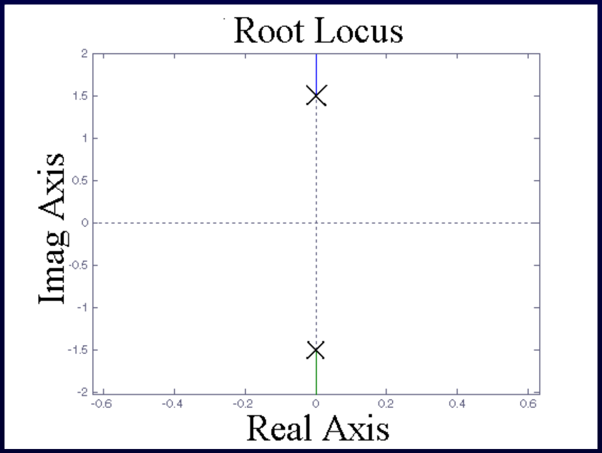


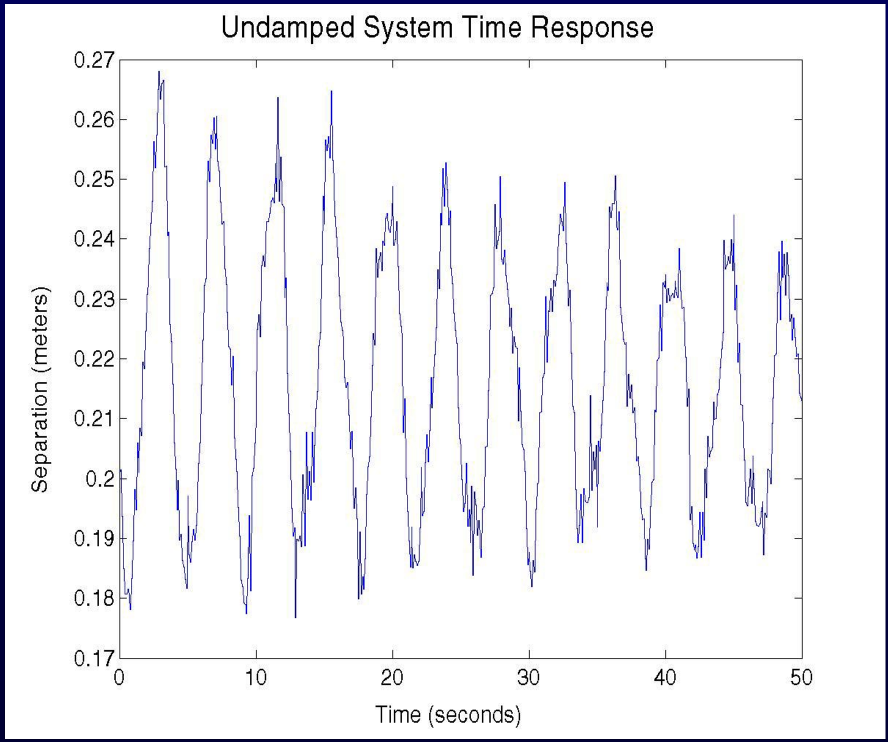
Stable mode poles at:

$$\pm\sqrt{\frac{6\mu_0\mu_{avg}^2}{\pi x_0 m}}\,i$$



16.62X Uncontrolled System

- Step response of plant
- Negligible damping



16.62x Controlled System

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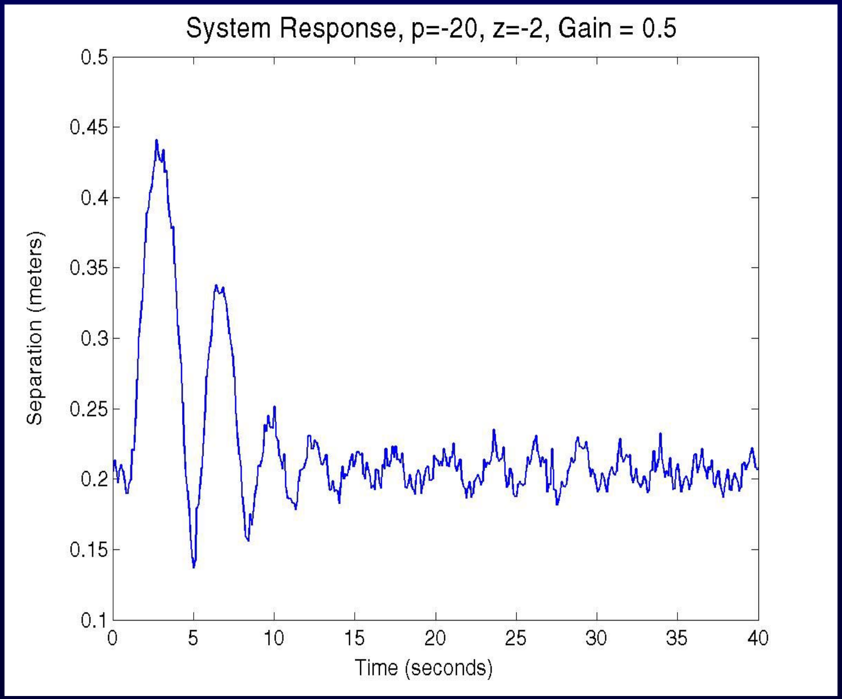
- Phase lead controller
- Damping ratio: 0.11 ± 0.01
- Error caused by distance sensor noise



Steady State Unstable Test Setup

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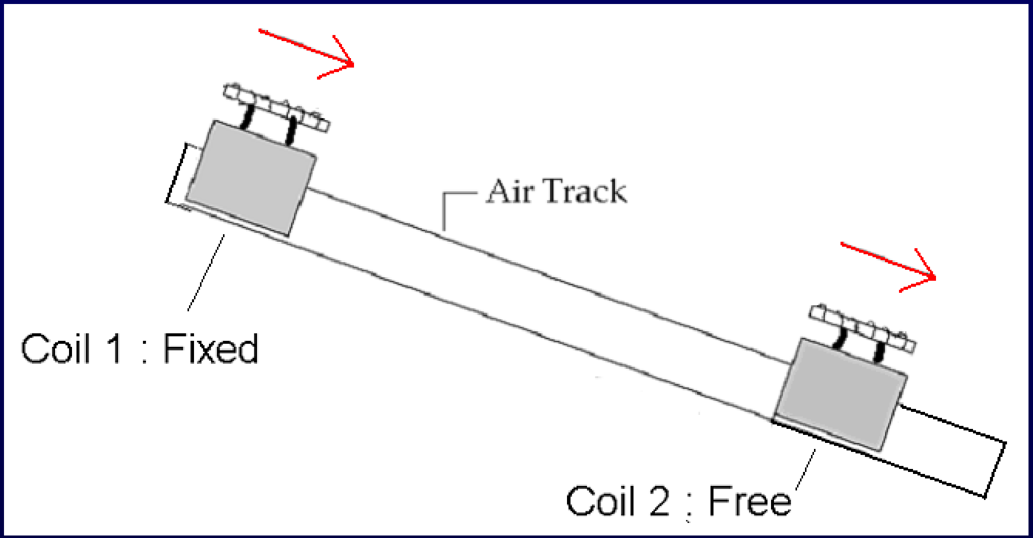
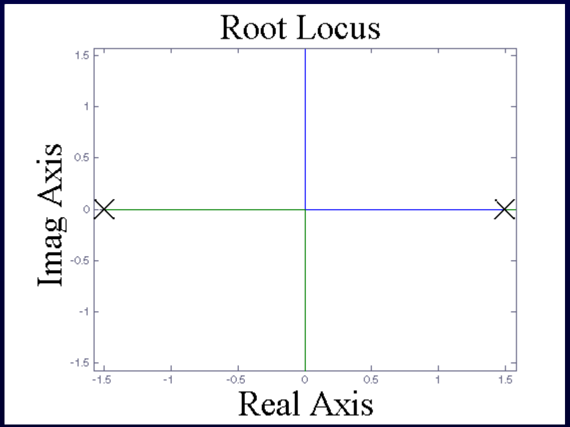


Unstable mode poles at:

$$\pm\sqrt{\frac{6\mu_0\mu_{avg}^2}{\pi x_0 m}}$$



Controller for Unstable Test Setup

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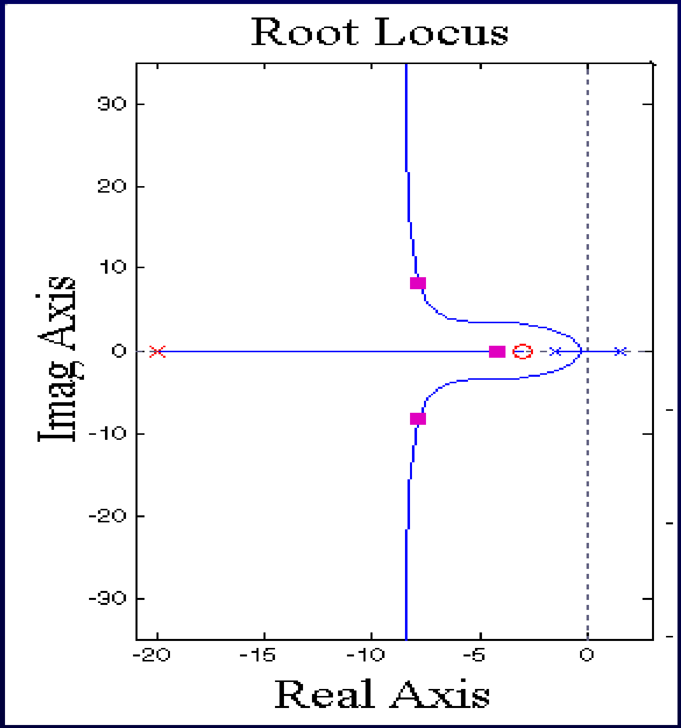
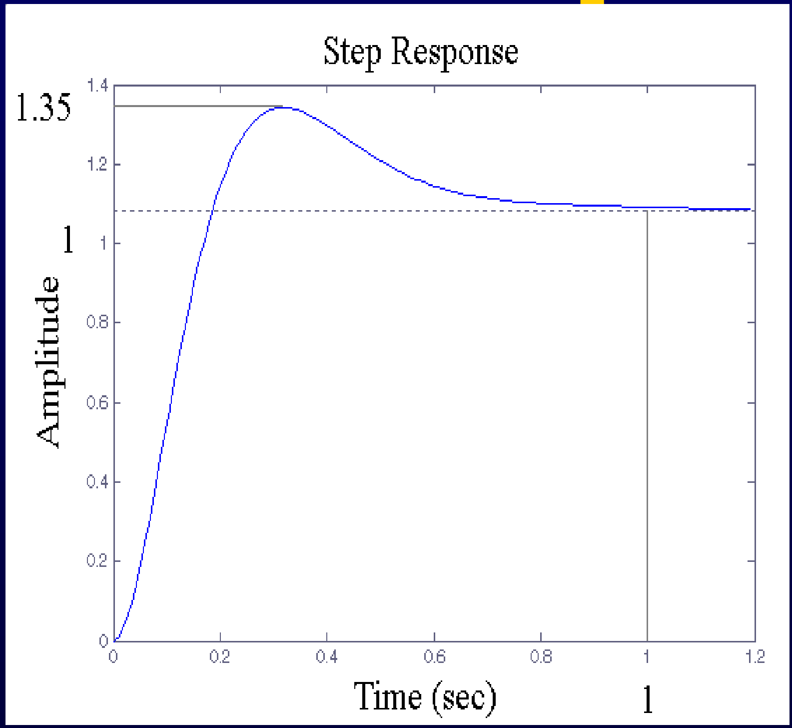




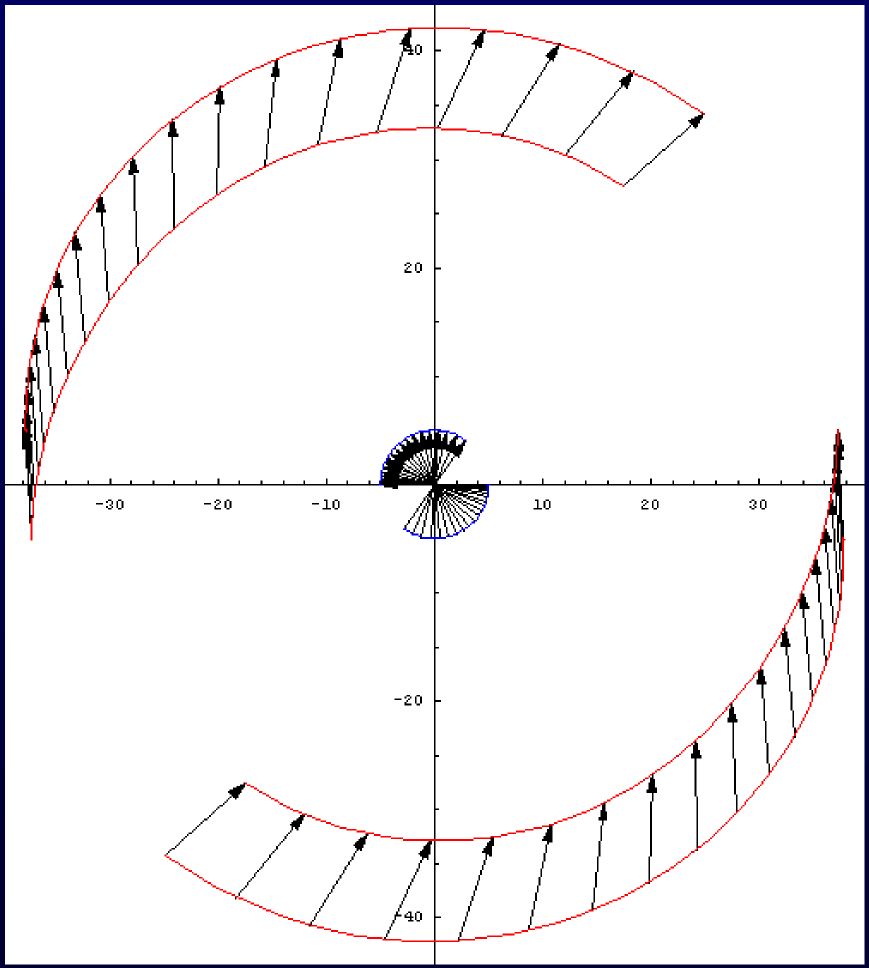
Phase Lead Controller

p = -20, z = -3, k = 30

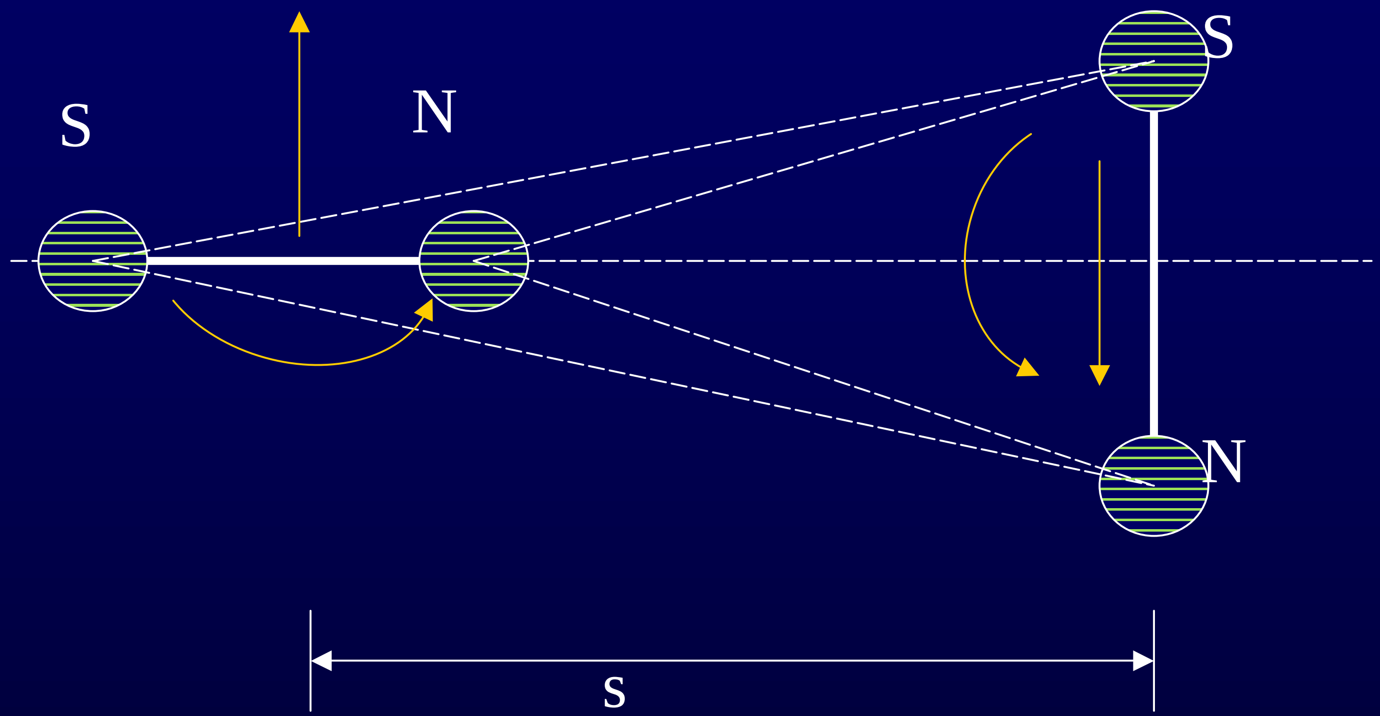
Damping = 0.68

Spin-up/De-spin Modes

- More complex
- Need to model translational forces and torques



Initial Spin-up Forces

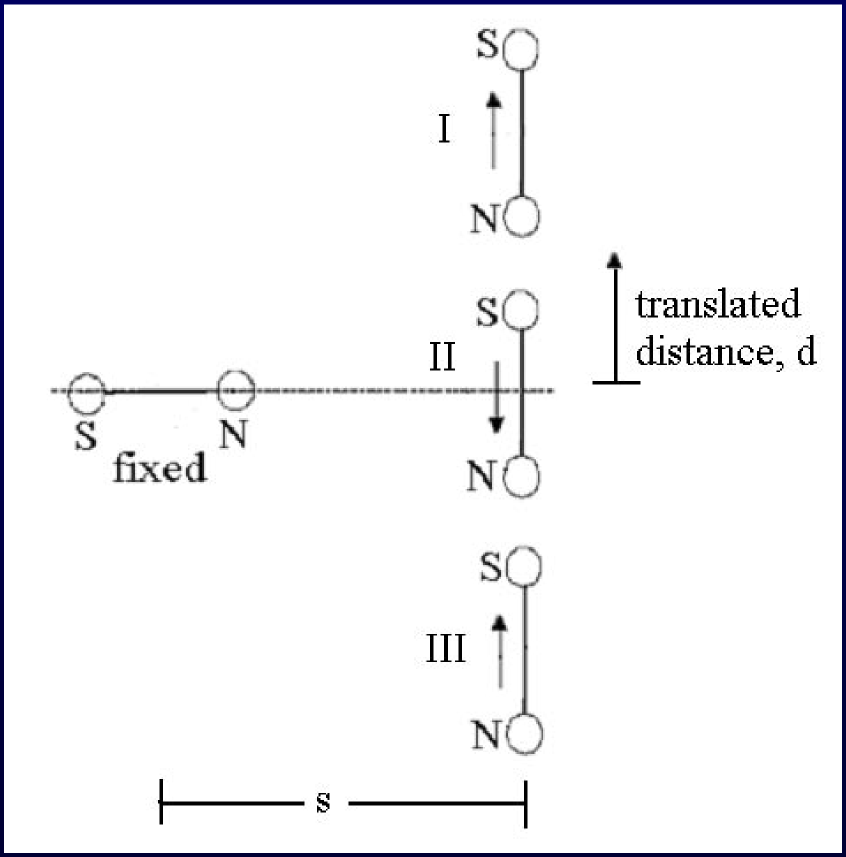


Results in a force and a torque on each magnet

Response to Translational Forces

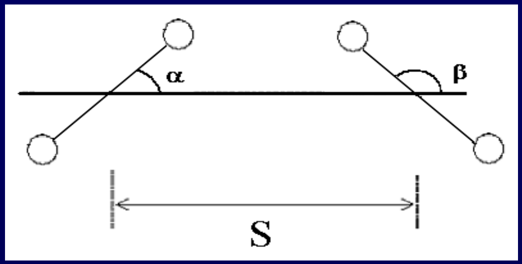
Three regimes of motion

Two equilibrium points

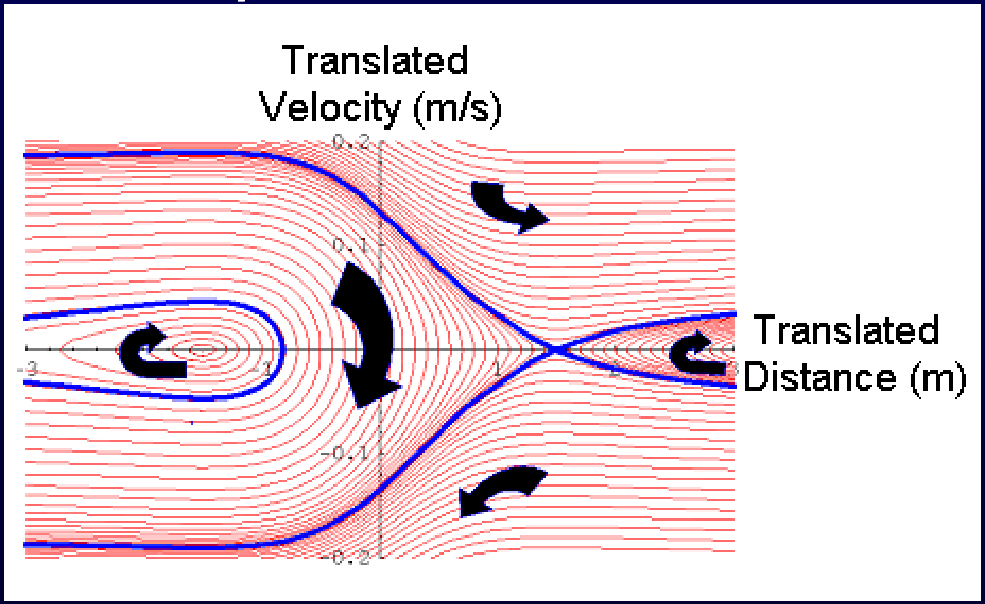


Response to Translational Forces

$$F_{trans} = \frac{3\mu_0 \mu_{avg}^2}{4\pi s^4}[Sin(\alpha + \beta)]$$

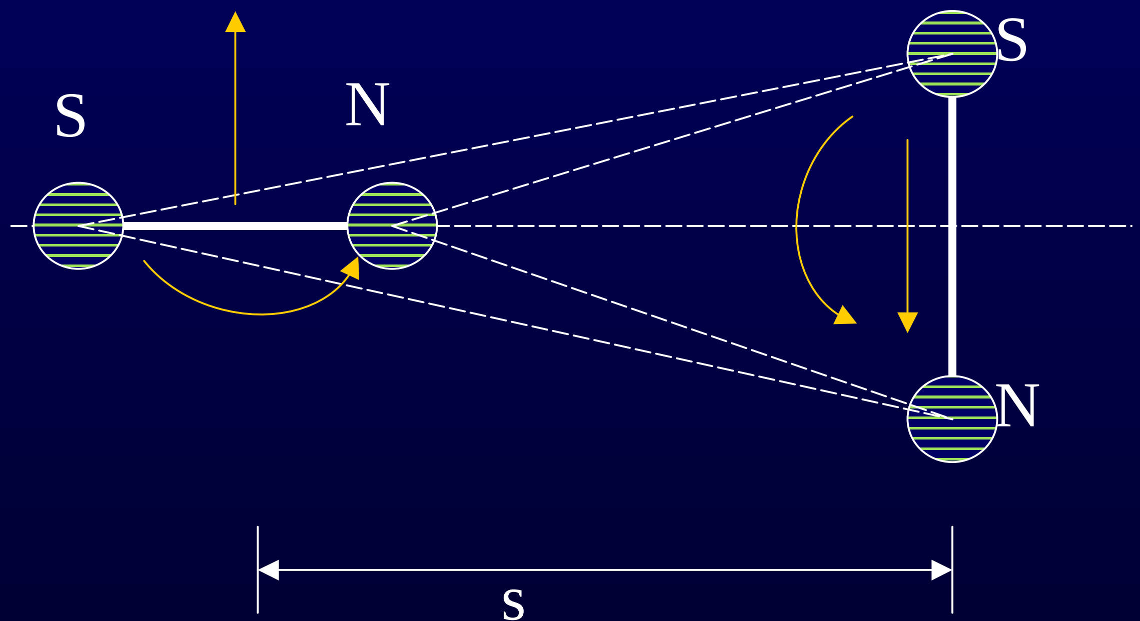


Due to the configuration, $F_{trans} = 0$ when $\alpha + \beta = 0$, thus when $d = \pm s$



Spin-up Configuration Trade

A closer look at the resultant forces on the two dipole configuration



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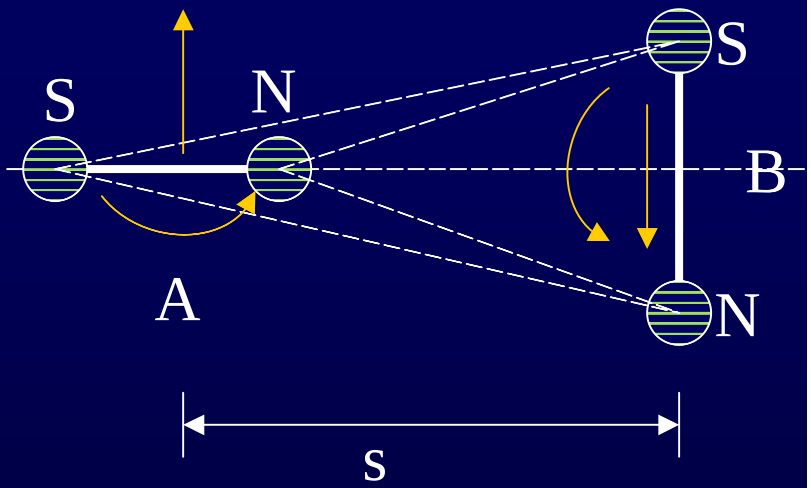
α=0, β=90

$$\tau_A = \frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\alpha - \beta) + 3(\alpha + \beta)\right]$$

$$\tau_B = \frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\beta - \alpha) + 3(\beta + \alpha)\right]$$



$$\frac{\tau_A}{\tau_B} = \frac{\frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\alpha - \beta) + 3(\alpha + \beta)\right]}{\frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\beta - \alpha) + 3(\beta + \alpha)\right]} = \frac{2}{4} = \frac{1}{2}$$

Spin-up Configuration Trade

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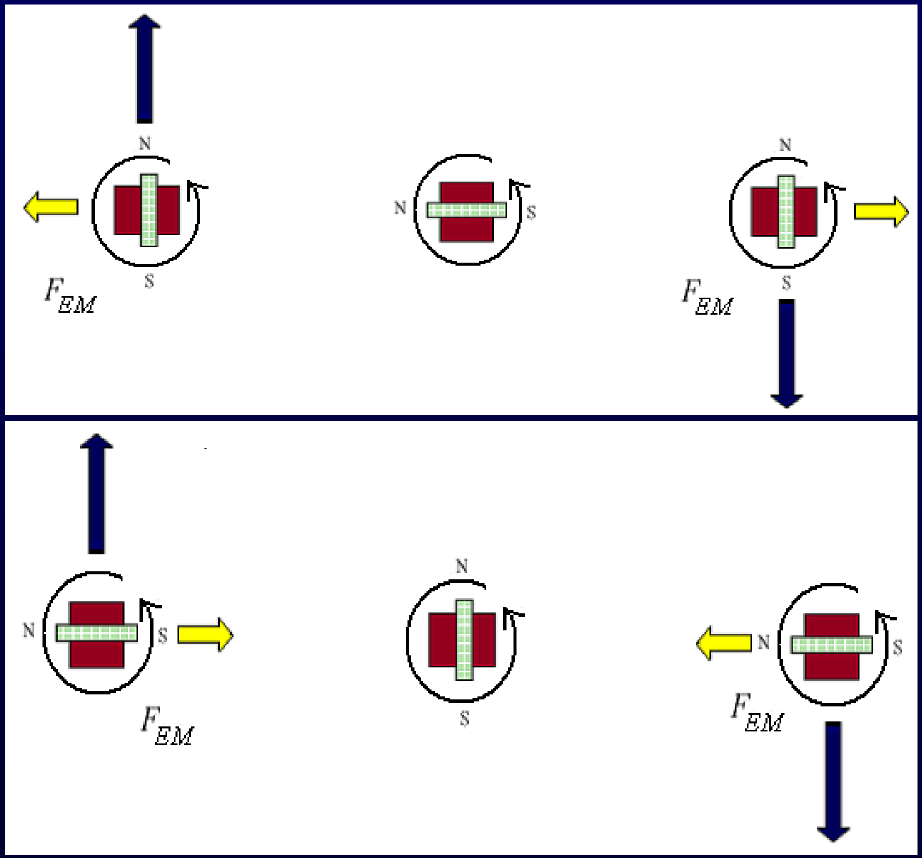
Configuration options:



- Favors equally sized vehicles

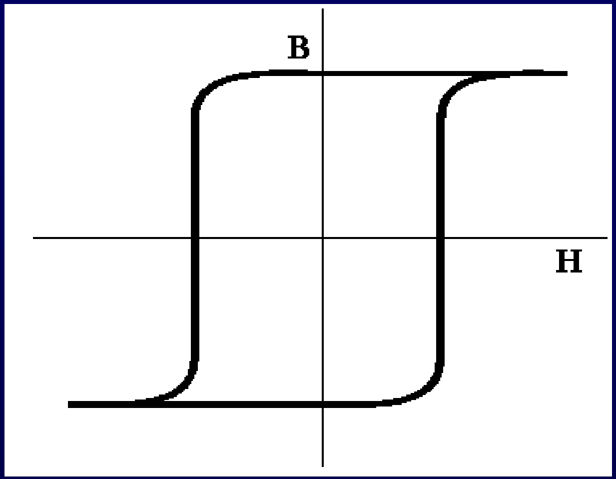
- Favors a larger center vehicle

Control Location Trade

- Centralized
  - All information communicated to a hub which calculates a control solution
- Independent Control
  - Vehicles collect and process their own information and derive a control solution for their own vehicle
- Hybrid control
  - Certain systems are controlled independently while other systems are controlled by the hub's control solution

Hysteresis and Saturation

- Hysteresis
  - Experimental data for curve



- Saturation of electromagnets and torque wheels

Budget Estimates

- No mass
- No power
- Cost for maintenance of lab equipment

Metrology

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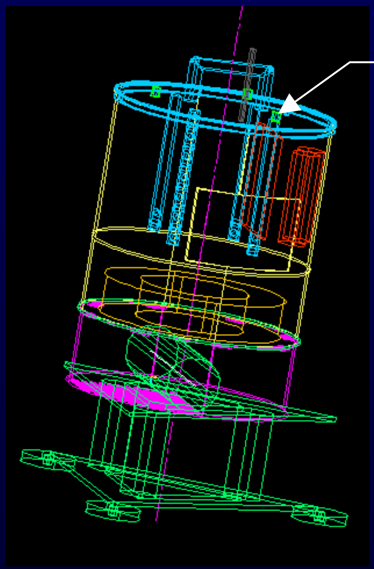
Oscar Murillo



Metrology