Electromagnetic Formation Flight

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Outline

• Motivation/Conceptual Picture

• Applications

• Challenges
  – Modeling
  – Stability
  – Trajectory Planning
  – Angular Momentum Management
  – Space Hardware Design

• Phase II Objectives

• Conclusions
Motivation

- Traditional propulsion uses propellant as a reaction mass

- Advantages
  - Ability to move center of mass of spacecraft
    (Momentum conserved when propellant is included)
  - Independent (and complete) control of individual spacecraft

- Disadvantages
  - Propellant is a limited resource
  - Momentum conservation requires that propellant mass increase exponentially with the velocity increment (\(\Delta V\))
  - Some propellants can be a surface contaminant to precision optics and solar arrays
  - Lingering propellant clouds can obscure or blind infrared telescopes

- Is there an alternative??
A Candidate Solution

• Yes… inter-spacecraft forces can be used…
  – …provided it is not necessary to alter the center of mass motion of the system

• What forces must be transmitted between satellites to allow for all relative degrees of freedom to be controlled?
  – In 2 dimensions, $N$ spacecraft have $3N$ DOFs, but we are at most able to control $3N-2$ (no translation of the center of mass)
  – For 2 spacecraft, that’s a total of 4:

• DOFs 1-3 can be controlled with inter-spacecraft axial forces and on-board torques, but 4 requires a transverse force

• Electrostatic monopoles cannot provide this type of force, but Electromagnetic and electrostatic dipoles can!
- In the Far Field, the dipole field structure for electrostatic and electromagnetic dipoles are the same

- The electrostatic analogy is useful in getting a physical feel for how the transverse force is applied

- Explanation …
• In the Far Field, Dipoles add as vectors

• Each vehicle will have 3 orthogonal electromagnetic coils
  – These will act as dipole vector components, and allow the magnetic dipole to be created in any direction

• Steering the dipoles electronically will decouple them from the spacecraft rotational dynamics

• A reaction wheel assembly with 3 orthogonal wheels provides counter torques to maintain attitude
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EMFF Applications in 10-20 Years

Terrestrial Planet Finder

Cluster Reconfiguring

EMFF Secondary Mirrors

Rendezvous and Docking
Reconfigurable Arrays & Staged Deployment

Planet Imager

Image from 1999 TPF Book

Non-Keplerian Orbits
Linear Formation Spin-Up

- Electromagnets exert forces/torques on each other
  - Equal and opposite “shearing” forces
  - Torques in the same direction

- Reaction wheels counteract EM torques
  - Resultant is shearing force
  - Angular momentum conserved by spin of the system

- There are many possible combinations of EM strength and dipole orientation, causing different distributions of angular momentum storage.
Spin-up of formations are not restricted to linear arrays.

Configurations of any shape can be spun-up.

Shown here is a SPECS configuration of 3 satellites in an equilateral triangle.
We also have the ability to solve for complex 3D motion of satellites.
Writing the force in terms of the coil radius ($R$), separation distance ($s$) and total loop current ($I_T$), the force scales as

$$F \sim \frac{3\pi}{2} \mu_0 I_T^2 \left( \frac{R}{s} \right)^4$$

We see that for a given coil current, the system scales ‘photographically’, meaning that two systems with the same loop current that are simply scaled versions of one another will have the same force.

For design, it is of interest to re-write in terms of coil mass and radius, and physical constants:

$$F \sim \frac{3\pi}{2} \mu_0 \left( \frac{M_C I_C}{2\pi R} \right)^2 \left( \frac{R}{s} \right)^4 = \frac{3}{2} \left( 10^{-7} \right) \left( \frac{I_C}{\rho} \right)^2 (M_C R_C)^2 \frac{1}{s^4}$$

The current state-of-the-art HTS wire has a value of $\left( \frac{I_C}{\rho} \right) = 14,444 \text{ A} \cdot \text{m/kg}$}

And the product of coil mass and radius becomes the design parameter.
With further simplification:

\[ F \sim 31.2 \left( M_C R_C \right)^2 \frac{1}{s^4} \]

The graph to the right shows a family of curves for various products of \( M_C \) and \( R_C \):

\[
\frac{3}{2} \left( \frac{1}{10^7} \right) \left( \frac{1}{\rho} \right)^2 = 312 \, \frac{m^3}{kg \cdot s^2}
\]

Example:
- 300 kg satellite, 2 m across, needs 10 mN of thrust, want \( M_C < 30 \) kg
- EMFF effective up to 40 meters
Case Study: TPF Retrofit

- **PPTs**
  - Higher efficiency system but still requires significant propellant over a 10 year mission lifetime

- **FEEP s**
  - Ideal for very short mission lifetime systems (less than 6 yrs)
  - Must consider contamination issue

- **EM coil (R = 4 m) (M_{tot} = 4198 kg)**
  - Less ideal option when compared to FEEP s even for long mission lifetime

- **EM Super Conducting Coil (R = 2 m) (M_{tot} = 3089 kg)**
  - Best option if mission lifetime of greater than 6.2 years is desired
  - No additional mass is required to increase mission lifetime

- **Cold Gas and Colloids**
  - Low $I_{sp}$ systems translate to high propellant requirements
  - Not viable options
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Dipole-Dipole Interaction

• Just as an idealized electric charge in an external electric field can be assigned a scalar potential, so can an idealized magnetic dipole in a static external magnetic field, by taking the inner product of the two

\[ U = -\vec{\mu}_2 \cdot \vec{B} \]

• Continuing the analogy, the force on the dipole is simply found by taking the negative potential gradient with respect to position coordinates

\[ F = -\nabla_r U = \nabla_r (\vec{\mu}_2 \cdot \vec{B}) = \vec{\mu}_2 \cdot \nabla_r \vec{B} \]

• In a similar manner, taking the gradient with respect to angle will give the torque experienced by the dipole

\[ T = -\nabla_\theta U = \vec{\mu}_2 \times \vec{B} \]

• Since the Force results from taking a gradient with respect to position, and the Torque does not, the scaling laws for the two are given as

\[ |F| \sim \frac{3}{2\pi} \mu_0 \frac{\mu_1 \mu_2}{s^4} \quad |T| \sim \frac{3}{4\pi} \mu_0 \frac{\mu_1 \mu_2}{s^3} \]
The far field model does not work in the near field
- (Separation/Distance)>10 to be within 10%
  - Some configurations are more accurate
A better model is needed for near-field motion since most mission applications will work in or near the edge of the near field
  - For TPF, (s/d) ~ 3 - 6

\[\beta = 0^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\]
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3-D Dynamics

- Two-spacecraft array
  - Each has **three** orthogonal electromagnets
    - EM pointing toward other spacecraft carries bulk of centripetal load; others assist in disturbance rejection
  - Each has **three** orthogonal reaction wheels, used for system angular momentum storage and as attitude actuators

- State vector:

\[
x = \begin{bmatrix} r \phi \Psi \alpha_1 \alpha_2 \alpha_3 \beta_1 \beta_2 \beta_3 \end{bmatrix}^T
\]
EMFF Stability

- Full-state system \((n=18)\) has eigenvalues:
  \[
  \lambda_{1, 2, 3, 4, 5, 6} = 0 \quad \lambda_{7, 8} = \pm \dot{\phi}_0
  \]
  \[
  \lambda_{9, 10} = \pm i \dot{\phi}_0 \quad \lambda_{11, 12} = \pm i \frac{r_0 \ddot{\phi}_0}{(I_{rr, s} + I_{rr, w})} \sqrt{m \left( m r_0^2 + \frac{I_{rr, s} + I_{rr, w}}{3} \right)}
  \]
  \[
  \lambda_{13, 14} = \pm i \frac{r_0 \ddot{\phi}_0}{(I_{rr, s} + I_{rr, w})} \sqrt{m \left( m r_0^2 + I_{rr, s} + I_{rr, w} \right)}
  \]
  \[
  \lambda_{15, 16} = \pm i r_0 \ddot{\phi}_0 \sqrt{\frac{m}{3 I_{zz, s}}}
  \]
  \[
  \lambda_{17, 18} = \pm i r_0 \ddot{\phi}_0 \sqrt{\frac{m}{I_{zz, s}}}
  \]

- Several poles on the imaginary axis and one unstable pole
- \(\lambda_{7, 8}\) at +/- array spin-rate
- Poles move away from origin as \(\dot{\phi}_0\) increases
Steady-State Spin

- Steady-state spin
  - Constant spin rate for data collection
  - Relative position and orientation maintenance
  - Disturbance rejection
  - Linearized dynamics about nominal spin
- Optimal control design
  - Choose ratio of penalties on state and control (\(\frac{\lambda}{\rho}\))
  - Can stabilize dynamics and reject disturbances \(\rho\)
- Experimental validation on linear air track
  - Similar unstable dynamics
  - Stabilized using optimal control

Unstable poles:
\[ s_{1,2} = \pm \Omega \]
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\[ \vec{F}_A = \frac{3\mu_0}{4\pi} \left( -\frac{\vec{\mu}_A \cdot \vec{\mu}_B}{r^5} \vec{r} - \frac{\vec{\mu}_A \cdot \vec{r}}{r^5} \vec{\mu}_B - \frac{\vec{\mu}_B \cdot \vec{r}}{r^5} \vec{\mu}_A + 5 \frac{(\vec{\mu}_A \cdot \vec{r})(\vec{\mu}_B \cdot \vec{r})}{r^7} \vec{r} \right) \]

- For a given instantaneous force profile, there are (3N-3) constraints (EOM), and 3N variables (Dipole strengths).
  - This allows us to arbitrarily specify one vehicle’s dipole
  - Allows the user the freedom to control other aspects of the formation especially angular momentum distribution
  - For a specific choice of dipole, there are multiple solutions due to the non-linearity of the constraints

- To determine the required magnetic dipole strengths
  - Pick the magnetic dipole strengths for one vehicle
  - Set the first equation equal to the desired instantaneous force and solve for the remaining magnetic dipole strengths.
  - There will be multiple solutions. Pick the solution that is most favorable
Torque Analysis

- Shear forces are produced when the dipole axes are not aligned.
- Torques are also produced when the shear forces are produced (Cosv. of angular mom.)
- The torques on each dipole is not usually equal
  - For the figure to the right \( \frac{\tau_A}{\tau_B} = \frac{1}{2} \)
- Even for pure shear forces, \( (F_x = 0) \) one can arbitrarily pick one of the dipole angles.

\[
\alpha = \pm \cos^{-1} \left( \pm \frac{\sqrt{2} \sin \beta}{\sqrt{5 + 3 \cos(2\beta)}} \right)
\]
Multiple Solutions

Satellite 1 - X Component

Satellite 1 - Y Component

Satellite 1 - Z Component

Satellite 2 - X Component

Satellite 2 - Y Component

Satellite 2 - Z Component

Satellite 3 - X Component

Satellite 3 - Y Component

Satellite 3 - Z Component
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The Earth’s Magnetic field produces an insignificant disturbance force, but a very significant disturbance torque, due to the scaling of force and torque.

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Another Sat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu)</td>
<td>(8 \times 10^{22}) Am(^2)</td>
<td>(5 \times 10^5) Am(^2)</td>
</tr>
<tr>
<td>(d)</td>
<td>&gt; 6,378,000 m</td>
<td>2-100 m</td>
</tr>
<tr>
<td>(F \sim \mu_0 (\mu_1 \mu_2) / r^4)</td>
<td>(~1 \times 10^{-5}) N</td>
<td>(~1 \times 10^4-2 \times 10^{-3}) N</td>
</tr>
<tr>
<td>(T \sim \mu_0 (\mu_1 \mu_2) / r^3)</td>
<td>(~2 \times 10^1) Nm</td>
<td>(~3 \times 10^4-3 \times 10^{-2}) Nm</td>
</tr>
</tbody>
</table>
Satellites are undergoing a specific forcing profile in the presence of the Earth’s magnetic field
  - This way the satellites that are not dumping momentum are still being disturbed by the Earth’s magnetic field.

Each satellite starts off with excess angular momentum

The satellite with the most excess momentum is selected for angular momentum dumping

The formation is then maintained to have $H<100$
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Cryogenic Containment

- Significant research concerning maintaining cryogenic temperatures in space
  - Space Telescope Instrumentation
  - Cryogenic propellant storage
- Spacecraft out of Earth orbit can use a sunshield that is always sun-pointing to reflect radiant energy away
- For Earth orbit operation, this won’t work, since even Earth albedo will heat the ‘cold’ side of the spacecraft
- Instead place each coil in a toroidal enclosure, with high reflectivity and emissivity, and insulate coils using aerogel or vacuum gap
- Preliminary analyses indicate ~10 Watts of heat extraction is necessary, which would require about 150 W of power to operate cryo-cooler
Efficient High Current Supplies

- The existing controllers are based on pulse width modulation for use with R/C cars and planes.

- An H-bridge is used to alternate applied potential to the coil, with the net current delivered dependent on the amount of time the voltage is applied in a given direction.

- Drawback is that current is always flowing through the batteries, providing both a power sink.

- One solution is to incorporate very high Farad capacitor instead of a battery, to reduce the internal resistance.

- Alternatively, a method of ‘side-stepping’ the storage device altogether may be employed, allowing the current to free-wheel during periods of low fluctuation.

- Estimated that ~100 Watt operation is achievable.
Shielding Considerations

- Attenuation of a DC magnetic field resulting from an enclosure scales approximately as

\[ A = \frac{\mu \Delta}{2R} \]

- Where \( \mu \) is the permeability, \( \Delta \) is the thickness of the material, and \( R \) is the characteristic radius of enclosure.

- Some high permeability materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (lbs/cu-in)</th>
<th>Permeability</th>
<th>Saturation (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amumetal</td>
<td>0.316</td>
<td>400000</td>
<td>8000</td>
</tr>
<tr>
<td>Amunickel</td>
<td>0.294</td>
<td>150000</td>
<td>15000</td>
</tr>
<tr>
<td>ULCS</td>
<td>0.0283</td>
<td>4000</td>
<td>22000</td>
</tr>
</tbody>
</table>

- Reducing a 600 G (0.06 T) field to ambient (0.3 G) requires an attenuation of \( 2 \times 10^3 \), or a minimum \( \Delta/R \) of 0.01.

- This is 1 mm thickness for each 10 cm of radius enclosed.
Shielding with Auxiliary Coils

• In addition to high permeability materials, shielding can be achieved locally using Helmholtz coils

• An external field can be nullified with an arrangement of coils close to the region of interest

• The small coil size requires proportionally smaller amp-turns to achieve nulling of the field
  – Will not significantly affect the main field externally
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• Conduct more in-depth systems trades using various NASA missions
  – Terrestrial Planet Finder
  – Life Finder
  – Constellation-X
• Assess issues associated with various subsystems
  – Tolerance of avionics
  – Maintenance of cryogenic temperatures
  – High current control with low power consumption
• Formulate general n-body dynamics to analyze control complexity growth with n
  – Real time optimal trajectory updating
    • Maintain bounded angular momentum in R/W of each spacecraft
  – Assess limit of linear control in maintaining stability
• Develop simulation of n-body dynamics
  – Validate analytic near field approximations
  – Evaluate linear and non-linear control performance
• Work in parallel with undergraduate testbed project to test 2D stability and control
  – Coordinate with undergraduate design-build class
  – Provides opportunity for undergraduate participation
Conclusions

- There are many types of missions that can benefit from propellantless relative control between satellites
  - Provides longer lifetime (even for highly aggressive maneuvers)
  - Reduces contamination and degradation
- Angular momentum management is an important issue, and methods are being developed to de-saturate the reaction wheels without using thrusters
- Preliminary experimental results indicate that we are able to perform disturbance rejection in steady state spin dynamics for multiple satellites
- Optimal system configurations and trajectory designs and have been determined for relatively small satellite arrays
  - Currently larger formations are being investigated
- Flight hardware challenges appear to be within reasonable limits
  - Power requirements on the order of 100’s of Watts