High-Temperature Superconductors (HTSs) as Electromagnetic Deployment and Support Structures in Spacecraft

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**Mission Statement:** Using comprehensive mission analysis, identify key enabling technologies and mature them through terrestrial and on-orbit testing.
Electromagnetic Formation Flight (EMFF)

• Subject of 2002 NIAC study

• Basic Concept
  • Provide actuation in relative degrees of freedom for formation flight systems using electromagnetic forces/torques and reaction wheels

• Motivation
  • Station-keeping for distributed satellite systems
  • Replacement of consumables (thrusters)
  • Eliminate thruster plumes
  • Enable high ΔV formation flying missions

• Implementation
  • Create a steerable electromagnetic dipole using three orthogonal electromagnetic coils made of superconducting wire.
  • De-couple torques by using reaction wheels
  • Demonstrated in 3DOF in lab, using cryogenic heat pipe
  • **Next step: ISS demonstration (RINGS)**

Credit: Sedwick (UMD)
Background

- Many space structures have performance benefits at larger sizes.
- However, spacecraft size is limited by a number of factors, including but not limited to:
  - Dimensions of launch vehicle fairing
  - Max takeoff weight of launch vehicle
  - Cost budget available

- Larger primary telescope mirrors can observe objects farther away.
- Larger solar sail can provide more thrust.
- Larger solar panels generate more power.
- Larger parabolic antennas have higher gain.
- Larger sunshields can keep more or bigger equipment cold.
Structures: Massive and Costly

Top 4 Most Massive Subsystems Avg, from SME-SMAD [25] Tbl A-1:

<table>
<thead>
<tr>
<th>Subsystem (% of Dry Mass)</th>
<th>No Prop (%)</th>
<th>LEO Prop (%)</th>
<th>High Earth (%)</th>
<th>Planetary (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>41%</td>
<td>31%</td>
<td>32%</td>
<td>15%</td>
</tr>
<tr>
<td>Struct/Mech</td>
<td>20%</td>
<td>27%</td>
<td>24%</td>
<td>25%</td>
</tr>
<tr>
<td>Power</td>
<td>19%</td>
<td>21%</td>
<td>17%</td>
<td>21%</td>
</tr>
<tr>
<td>Attitude D&amp;C</td>
<td>8%</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Structural components are 2nd largest avg. fraction of spacecraft dry mass - translates to greater launch vehicle costs.

Reduction of structural mass is a worthwhile investment applicable to all spacecraft, especially those leaving Earth’s orbit.

But we still want the performance benefits of large structures!

Electromagnetic forces could support larger structures for less mass...

Credit: Bearden (2001) [2]
Superconductors and NIAC

- Previous NIAC studies have touched on space applications of superconductors and magnetic fields, including:

<table>
<thead>
<tr>
<th>Principal Investigator</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller/Sedwick (2002)</td>
<td>Electromagnetic formation flight</td>
</tr>
<tr>
<td>Zubrin (1999)</td>
<td>Magnetically tensioned solar sails (”magsails”)</td>
</tr>
<tr>
<td>Hoffman (2004), Westover (2011)</td>
<td>Radiation protection for astronauts</td>
</tr>
</tbody>
</table>

- Powell (2005) Conceptual studies of magnetically-expanded high-temperature superconductor (HTS) cables for applications like:
  - LEO propulsion using Earth’s mag. field
  - Energy storage for lunar bases
  - Large telescopes w/ perimeter tensioning
1. Can we use electromagnetic forces generated by and acting between high-temperature superconductor (HTS) current-carrying coils to move, unfold, and support parts of a spacecraft from its stowed position?

2. For what operations does this technology represent an improvement over existing or in-development options?

3. What new mission capabilities does this technology enable?
**Vision: Next Next Generation Telescope**

Many potential functions and advantages of electromagnets on spacecraft, including:

<table>
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<tr>
<th>Function</th>
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<tbody>
<tr>
<td>Wireless power and data transfer</td>
</tr>
<tr>
<td>Electromagnetic formation flight and positioning</td>
</tr>
<tr>
<td>No obscuration from 2nd mirror assembly</td>
</tr>
<tr>
<td>Unfolding from stowed position</td>
</tr>
<tr>
<td>Staged deployment and element upgrades/replacement</td>
</tr>
<tr>
<td>Magnetic stiffening and tensioning</td>
</tr>
<tr>
<td>Reduced # of deployments</td>
</tr>
<tr>
<td>Attitude control &amp; momentum trading</td>
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<tr>
<td>Dynamic and thermal isolation</td>
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<td>Membrane mirror shaping</td>
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**Example:**

Next Next Generation Space Telescope

A conceptual display of some of the numerous purposes for which electromagnetic coils can be implemented on a spacecraft.
Previous Contributions to Vision

Many potential functions and advantages of electromagnets on spacecraft, including:

<table>
<thead>
<tr>
<th>Wireless power and data transfer</th>
<th><strong>Work by:</strong> Fisher, Soljačić (WiTricity) [9], Sedwick (RINGS) [20]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic formation flight and positioning</td>
<td><strong>Work by:</strong> Kwon [11,12], Kong [8], Schweighart [18], Miller, Sedwick (EMFF), Sakaguchi (μEMFF) [17], Peck (flux pinning) [22], Sedwick (RINGS) [20]</td>
</tr>
<tr>
<td>No obscuration from 2nd mirror assembly</td>
<td><strong>Work by:</strong> Zubrin (Magsail) [26], Powell (MIC Structures) [15], Benford (Microwave spin) [4]</td>
</tr>
<tr>
<td>Unfolding from stowed position</td>
<td><strong>Work by:</strong> Pedreiro (Disturbance Free Payload) [21]</td>
</tr>
<tr>
<td>Staged deployment and element upgrades/replacement</td>
<td><strong>Work by:</strong> Palisoc (holographic) [13], Ritter (photonic) [16], Bekey (scanning electron/shape memory) [3], Patrick [14], Stamper [23]</td>
</tr>
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Motivation

**TECH PUSH**
- High-temperature superconductor performance improvements
- Electromagnetic formation flight demonstrated
  - Many structural functions exist that can be performed magnetically

**MISSION PULL**
Large flagship spacecraft like JWST need structures that are:
- Light
- Simple
- Large
- Thermally isolated
- Vibration isolated
- Reparable w/out servicing

Credit: NASA

**Electromagnetic Structures and Mechanisms**
## Study Objectives/Progress

### TECHNOLOGY
- **Define** magnetically performable functions & design vector
- **Develop** usable model of coil physics
- **Design** example structures

### SYSTEMS
- **Derive** quantitative & qualitative impacts of HTS structures
- **Discuss** architecture trade
- **Describe** emergent capabilities
Study Objectives/Progress

**TECHNOLOGY**

- **Define** magnetically performable functions & design vector
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**HTS DESIGN VECTOR**

- Power req’d per duty type (W)
- Type of thermal control
- Current (A)
- AC or DC current?
- Resistance of circuitry (Ω)
- Magnetic field strength (G)
- Deployment time (s)
- Deployment steps (#)
- Type of physical constraints
- Type of HTS
- Quantity of coils (#)
- Quantity of turns (#)
- Length of HTS cable used (m)
- Size ratio (stowed/deployed)
- Change in separation (m)

- Involve one or more coils repelling or attracting one another
- Depend upon boundary conditions to differentiate the performed functions
- Design vector identifies design variables that will eventually factor into trades
Study Objectives/Progress

TECHNOLOGY

- Define magnetically performable functions & design vector

- **Develop** usable model of coil physics

- Design example structures

- Numerical appx of Biot-Savart Law
- One coil modeled as flexible but non-elastic, with mass
- Two coils modeled with mass, matches far-field analytical sol’n (valid at >10x coil diameter separation)
- Still need to incorporate:
  - Elasticity
  - Bending stiffness
Study Objectives/Progress

TECHNOLOGY

Define magnetically performable functions & design vector

Develop usable model of coil physics

Design example structures

Example structures take the defined deployment and support configuration models and apply

constraints (boundary conditions) and additional mass

to better simulate actual structure deployment
## Study Objectives/Methods

<table>
<thead>
<tr>
<th>Subsystem or process</th>
<th>Example impacts of HTS structure choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avionics/Comm</td>
<td>Potential electromagnetic interference</td>
</tr>
<tr>
<td>Thermal</td>
<td>Additional thermal control required, little or no conduction</td>
</tr>
<tr>
<td>ADCS</td>
<td>Current regulation needed, Earth’s magnetic field, additional momentum trading possible</td>
</tr>
<tr>
<td>Optical Path</td>
<td>Risks to position accuracy and disturbance control</td>
</tr>
<tr>
<td>Structures</td>
<td>Reduction of mass, vibration isolation, increased compaction ratio, enables reconfiguration</td>
</tr>
<tr>
<td>Propulsion (if EMFF)</td>
<td>No propellant required, eliminates thruster plumes</td>
</tr>
<tr>
<td>Power</td>
<td>Additional power draw</td>
</tr>
<tr>
<td>Testing</td>
<td>Difficult in 1g</td>
</tr>
</tbody>
</table>

### SYSTEMS

- **Derive** quantitative & qualitative impacts of HTS structures
- **Discuss** architecture trade
- **Describe** emergent capabilities

- Selection of HTS structural design impacts every subsystem
- Extent to which (and whether the impact is net positive or net negative) is determined by the priorities of the program
- **Overarching HTS effects are:**
  - Good for structures
  - Not so good for power and thermal
Study Objectives/Methods

MISSION PRIORITIES
- Mission destination (LEO/GEO/Lagrange pt?)
- Need for reconfigurability
- Orbital parameters (Sun-sync? Eclipse time?)

TECHNOLOGY (HTSs VERSUS...)
- Inflatable structures
- Tensegrity structures
- Pyrotechnic fasteners
- Piezoelectric actuators or motors
- Spring-loaded booms and hinges
- Traditional motorized actuation

PERFORMANCE (WITHIN HTSs)

EXAMPLES

EXAMPLE OBJECTIVE VECTOR
- min(total mass)
- min(power req’d)
- min(deployment time)
- min(thermal mass)
- min(mass/length or area)
- min(deployment steps)
- max(size ratio)
- min(current switching)

SYSTEMS
- Derive quantitative & qualitative impacts of HTS structures
- Discuss architecture trade
- Describe emergent capabilities

1. Min(total mass)
2. Min(power req’d)
3. Min(deployment time)
4. Min(thermal mass)
5. Min(mass/length or area)
6. Min(deployment steps)
7. Max(size ratio)
8. Min(current switching)

EXAMPLE OBJECTIVE VECTOR
- More turns in coil (Magnetic field ↑, Power/mass ratio ↓)
- Less turns in coil (Magnetic field ↓, Power/mass ratio ↑)

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PERFORMANCE (WITHIN HTSs)

EXAMPLE OBJECTIVE VECTOR
- More turns in coil (Magnetic field ↑, Power/mass ratio ↓)
- Less turns in coil (Magnetic field ↓, Power/mass ratio ↑)
Study Objectives/Progress

**Emergent capabilities:**
Functions that are not feasible or not possible with other technologies

- Deforming/reconfiguring
- Refocusing (future)
- In-space assembly
- Staged deployment

**SYSTEMS**

- **Derive** quantitative & qualitative impacts of HTS structures
- **Discuss** architecture trade
- **Describe** emergent capabilities
Final Remarks

**TECHNOLOGY CURRENT STATUS:**
- Mostly functional models of flexible single and double coil unconstrained systems
- Investigating validity of lack of oscillations in model
- Next step: implementing constraints

**SYSTEMS CURRENT STATUS:**
- High-level qualitative impacts and trades described
- More will emerge with quantitative analysis
- Next step: quantify trades with completed coil models

- Current progress consistent with hypothesis of feasibility
  - Breadth of applicability yet to be shown

- HTS structures not only present potential improvements over existing technologies, but enable previously infeasible functions
  - Staged deployment/in-space assembly and repair using EMFF
  - Isolation of sensitive payloads from vibration and heat
## Final Remarks

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physically possible?</td>
<td>Yes, fundamental physics support basic concept</td>
</tr>
<tr>
<td>Technologically achievable?</td>
<td>Yes, but how broad will the applications be?</td>
</tr>
<tr>
<td></td>
<td>EMFF demonstrated</td>
</tr>
<tr>
<td>Economically reasonable?</td>
<td>On par with other expensive and unique mission technology development</td>
</tr>
<tr>
<td></td>
<td>One goal is to make HTS technology generally applicable to reduce</td>
</tr>
<tr>
<td></td>
<td>development costs across multiple programs</td>
</tr>
<tr>
<td>Desirable compared to other options?</td>
<td>Planned research contribution</td>
</tr>
</tbody>
</table>
Questions?
Referenced Sources