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In-Orbit Assembly of Modular Space Systems with Non-Contacting, Flux-Pinned Interfaces

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Overview

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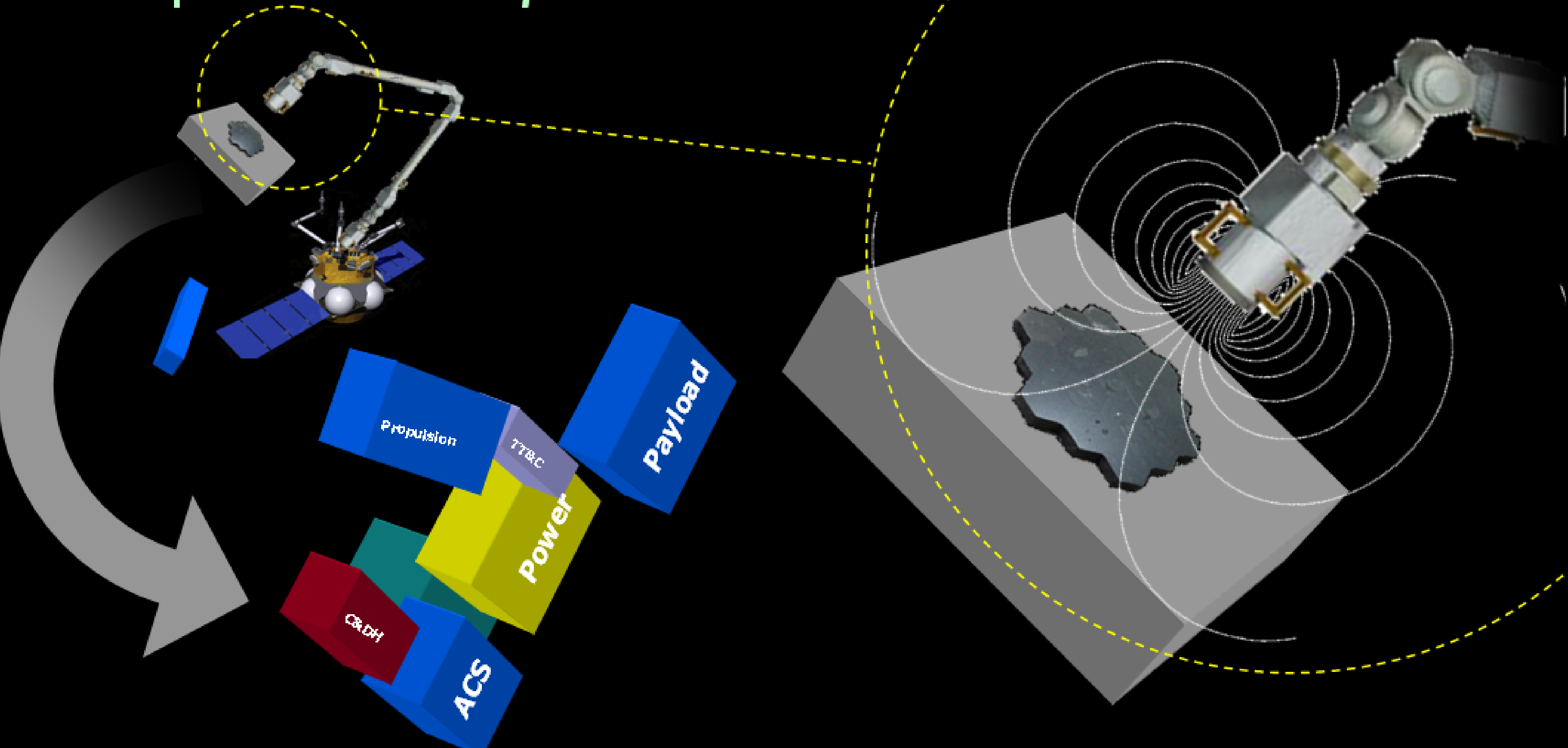
The Big Picture

Superconductors pin magnetic flux; use them to establish permanent, zero-contact mechanical fixity among space-system components *without power*.

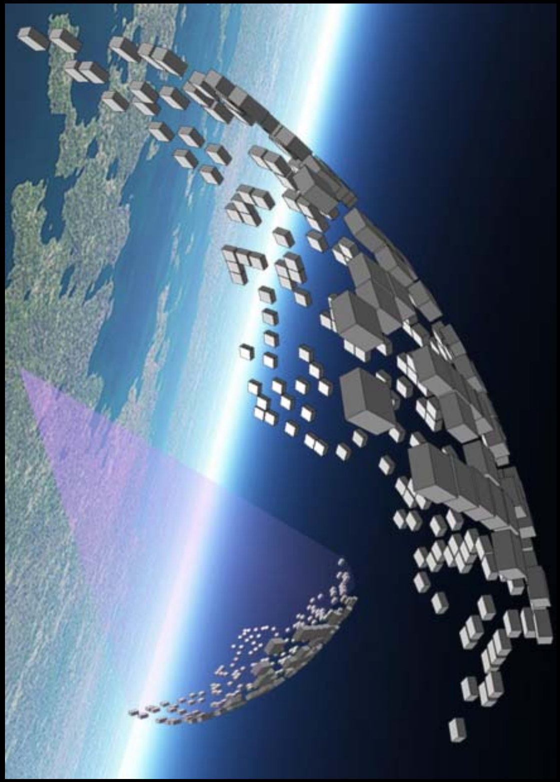


Why?

- Technological motivators
  - Very low power--space is cold
  - No active control for stabilization
  - Eliminate most environmental interactions normally associated with attitude control and propulsion.
    - No plume impingement
    - No momentum build-up
  - Improve and simplify control/structure interactions that plague large systems to be assembled in orbit, such as the ISS.
  - Electrostatic discharge upon contact is far less likely
  - The possibility of sticky or otherwise failed mechanical interfaces need not be accommodated
  - Special handling techniques for bolting together hardware in space are irrelevant.

Why?

- Visions
  - Toward a "materials science" of in-orbit assembled systems
  - Create arbitrarily large space systems
  - No longer are we required to distinguish among spacecraft subsystems, individual spacecraft, and constellations of spacecraft. Instead, the proposed concept blurs the distinction between modular spacecraft and formation flying, between spacecraft bus and payload, and to some extent between empty space and solid matter. Articulated payloads, reconfigurable space stations, and adaptable satellite architectures are possible without the mass and power typically associated with maintaining relative position and mechanically rebuilding structures.



Overview

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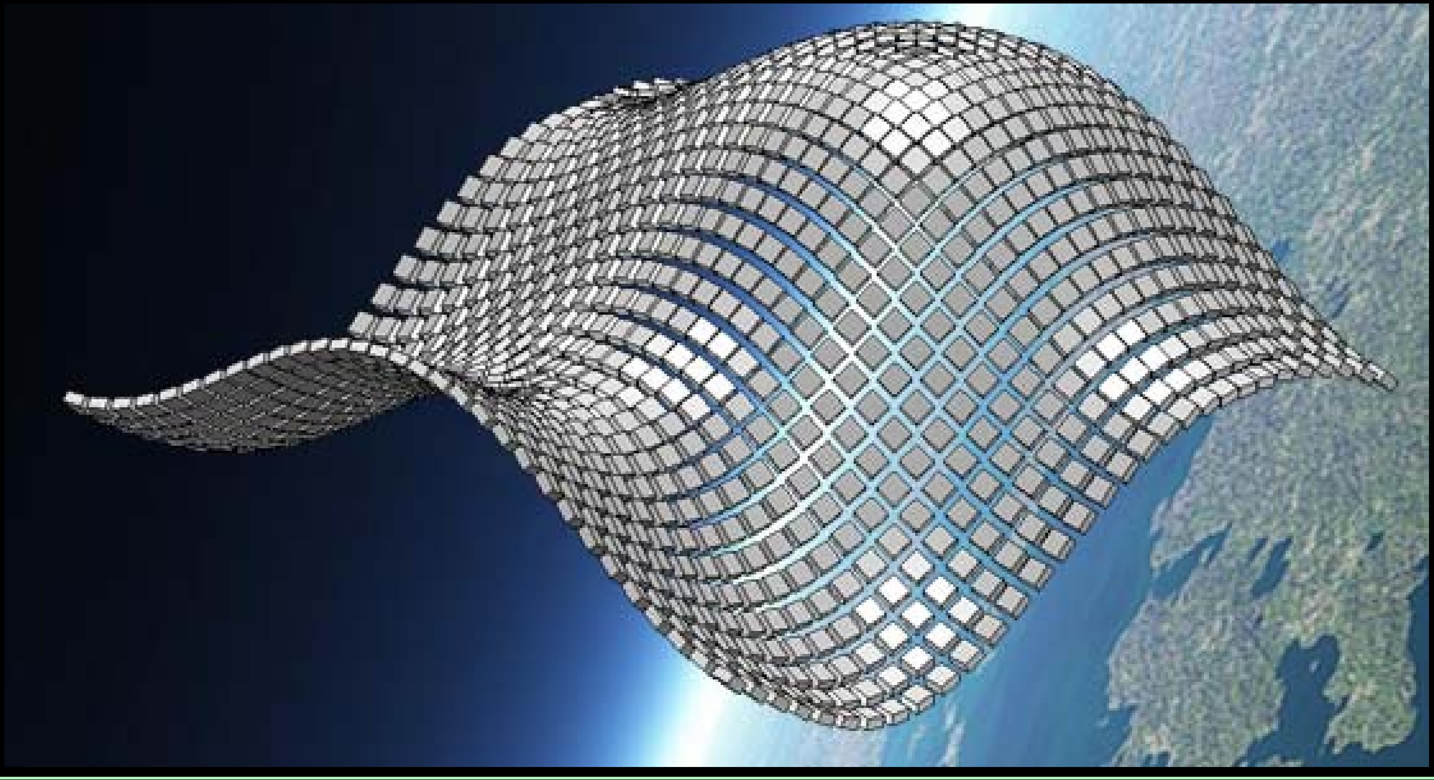
Phase I Objectives

Analytical and Experimental Results

– 6DOF Stiffness
– Extrapolation

Roadmap for the Next 40 Years



First, a Little Physics

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Earnshaw's Theorem

– **No passive arrangement of magnets is stable in all six rigid-body degrees of freedom.**
– **Magnetic bearings classically require active control.**

Options for Action at a Distance

– **Quantum effects, but quantum distance is not of useful scale.**
– **Feedback control, which moves the magnets (or temporally varies their fields)**
  - D. Miller's formation-flying approach.
  - Requires power
  - Can interacts detrimentally with spacecraft electronics
  - Induces unwanted, attitude-perturbing torques due to the environment (such as the geomagnetic field)
  - Introduces the very real risk that a temporary loss of power or a software failure may cause the assembly to lose structural integrity.

First, a Little Physics

Earnshaw's Theorem

- No passive arrangement of magnets is stable in all six rigid-body degrees of freedom.
- Magnetic bearings classically require active control.

Options for Action at a Distance

- Oscillating and moving magnets, whose quasi-passive, periodic motion creates relative equilibria (in the Hamiltonian sense:
  - Levitron
  - Bound angular momentum conflicts with spacecraft attitude-control design considerations.
  - Outside the relatively small stable region, the levitated magnet is unstable and exhibits unwelcome, energetic dynamics.

First, a Little Physics

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Earnshaw's Theorem

- No passive arrangement of magnets is stable in all six rigid-body degrees of freedom.
- Magnetic bearings classically require active control.

Options for Action at a Distance

- Diamagnetism
  - Several high-temperature superconductors (Type I and many of Type II) and some room-temperature solids such as pyrolytic graphite can be used.
  - They magnetize in the direction opposite to a magnetic field in which they are placed.
  - Separation distances are too small and stiffnesses too low for any of the many advantages a non-contacting interface ought to offer.

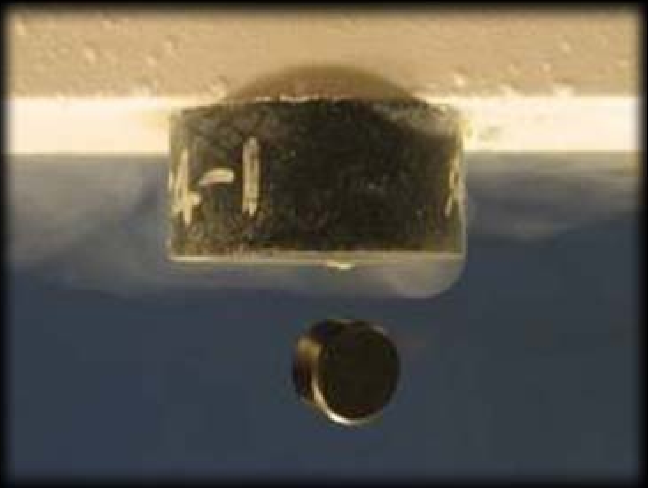
First, a Little Physics

Earnshaw's Theorem

– **No passive arrangement of magnets is stable in all six rigid-body degrees of freedom.**
– **Magnetic bearings classically require active control.**

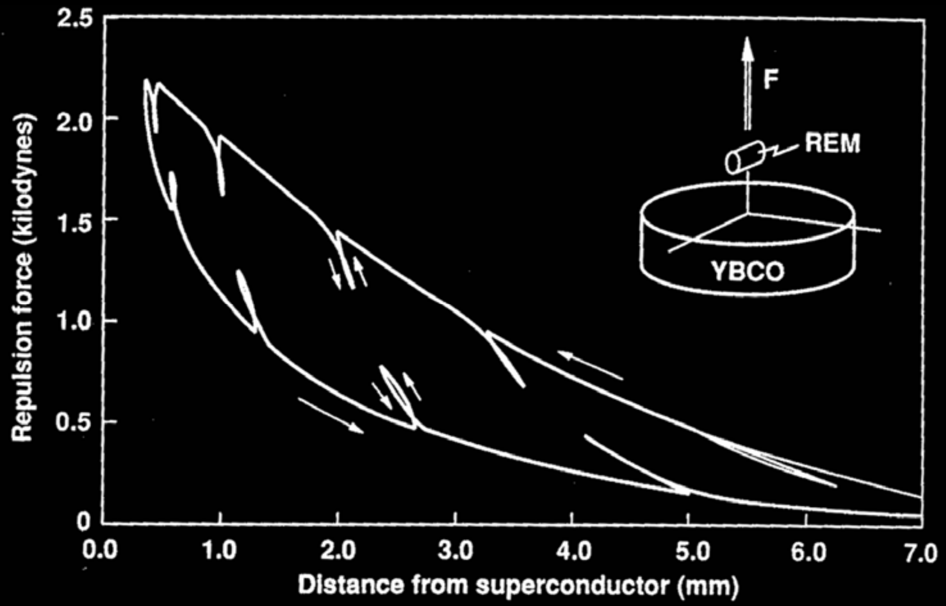
Options for Action at a Distance

– **Flux pinning, another property of Type II superconductors, notably YBCO.**
  - Vortex-like supercurrent structures in the material create paths for the flux lines.
  - When the external sources of these flux lines move, these supercurrent vortices resist motion or are “pinned” in the superconducting material.
  - Hysteresis-related behavior offers very high structural damping.
  - Thaw & refreeze to establish new equilibria: variable-morphology spacecraft.



Neodymium permanent magnet pinned in 5DOF by YBCO and suspended stably in gravity

First, a Little Physics



Exponential, Hysteretic Force Model for a YBCO Superconductor and Rare-Earth Magnet (REM) Configuration (F. Moon, Cornell University)

YBCO Superconductor Flux-Pinning Demo
(Space Systems Design Studio, Cornell University, 2007)
Video:
http://www.mae.cornell.edu/mpeck/SSDS/NCMRS/video1.avi

Phase I Objectives

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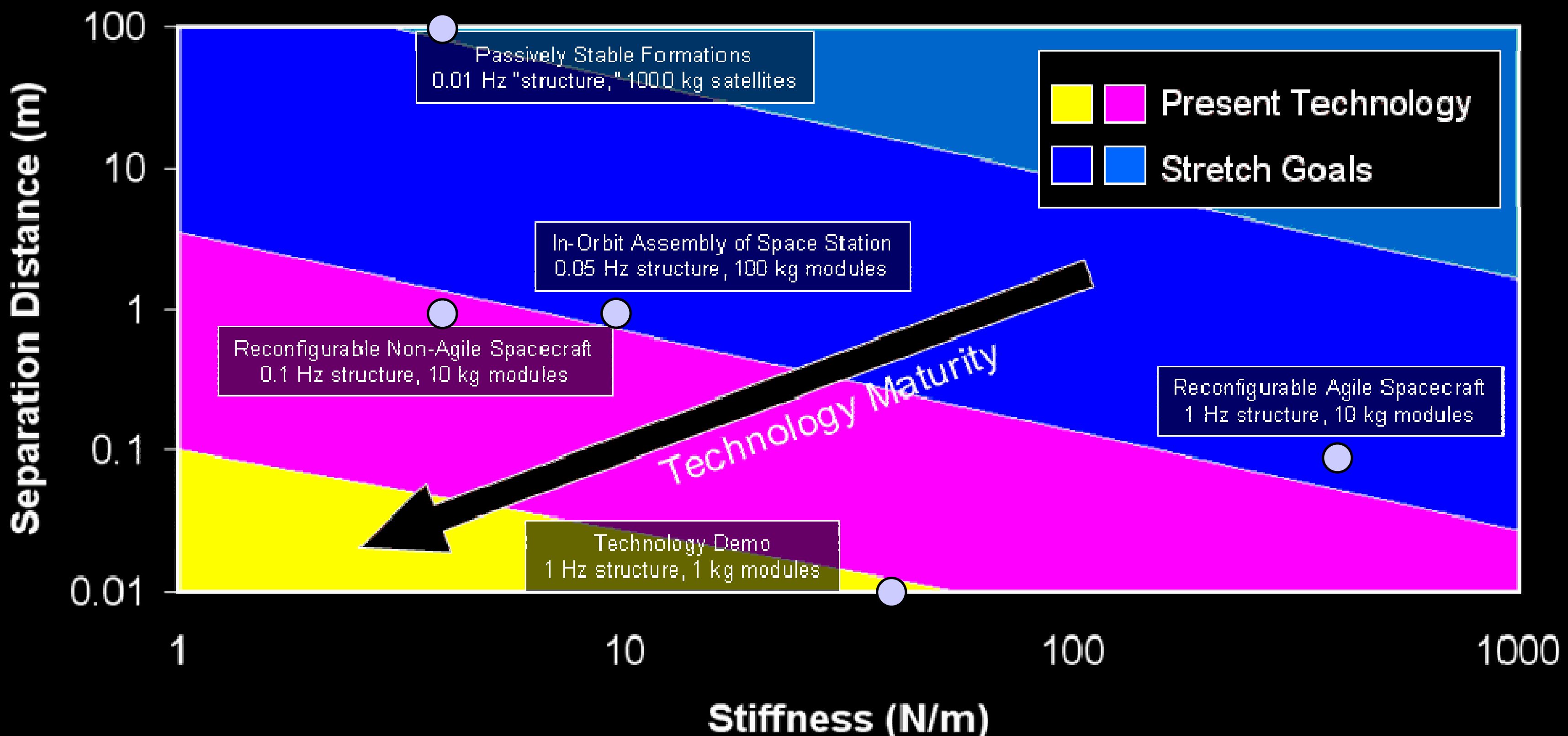
What performance will the state of the art support in 40 years?

- How stiff?
- How far apart?
- How cold?

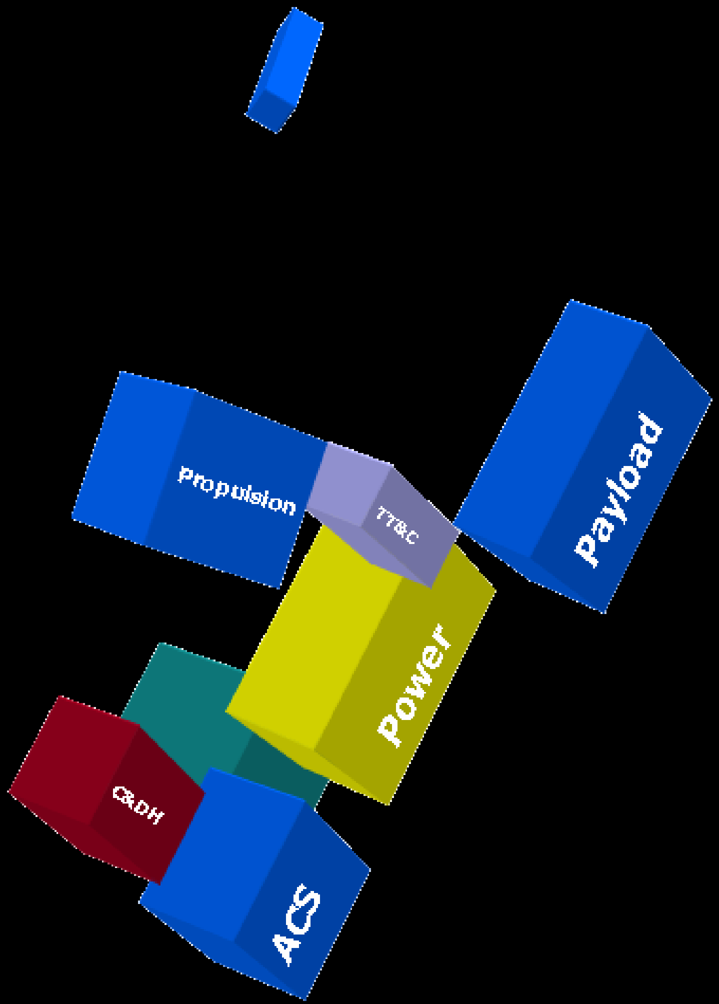


Phase I Objectives

What can we accomplish?

Autonomous construction

- An *a priori* requirement for the in-orbit assembled space systems envisioned here is that the mechanical stiffness of the non-contacting interface be highly reliable.
- The space system shall exhibit long-term, failure-tolerant operation (e.g. 24 hours without power)
- The flux-pinned interface shall be stiff with a large basin of attraction.



Concept of operations

- Simply maneuvering the components into coarse proximity with one another will result in forming a mechanical configuration without the need for power, without active control, and without environmental interactions normally associated with attitude control and propulsion.
- The components find one another and join together.

Phase I Objectives

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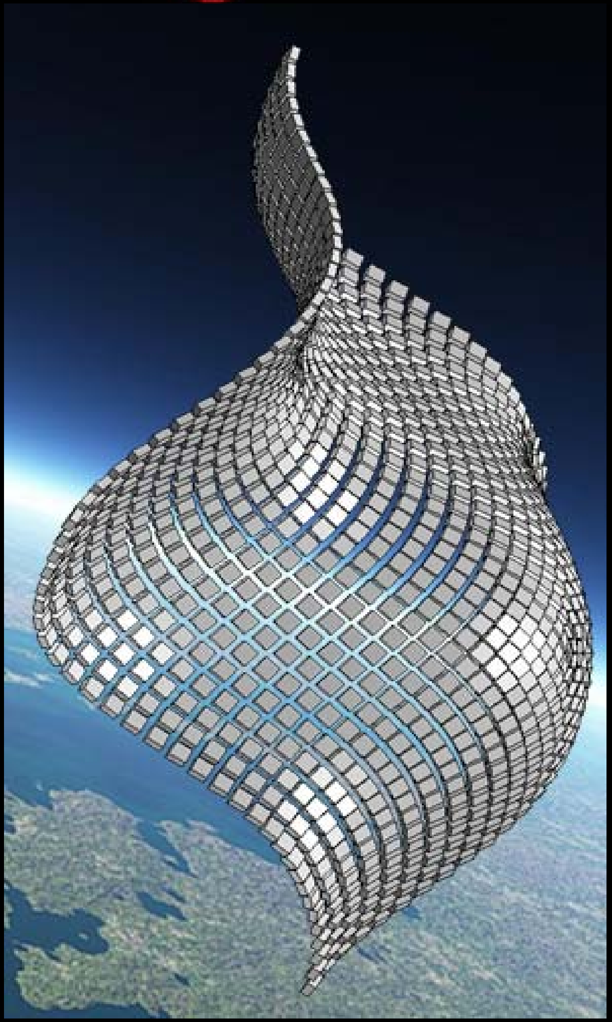
What can we accomplish?

Articulated Spacecraft

- Generalize the idea of re-shapable spacecraft
- Alter the flux-pinned equilibrium by traveling along hysteresis lines or by thawing/freezing cycle.

Concept of Operations

- Launch a densely packed set of elements or launch elements on multiple vehicles
- Allow modules to establish a baseline equilibrium configuration through passive attraction & pinning.
- Electromagnetic control can be used to alter the shape as part of the mission, perhaps coupled to thermal control of the YBCO.



Articulated Spacecraft with Reconfigurable Structure; Many Payloads and Subsystems in Multiple Simultaneous Orientations

Phase I Objectives

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What can we accomplish?

Modular, Reconfigurable Spacecraft

- Reshape a spacecraft, particularly its payload.
- Reconfigure a spacecraft
  - Move around or even replace components
  - Respond to quickly changing mission objectives

Concept of Operations

- Rather than launching a new spacecraft to meet newly defined mission objectives, which may take years, an in-orbit asset may be reconfigured (really, rebuilt) with the help of non-contacting modules.
- Modules may be single components, e.g. optical elements, batteries, sensors, or actuators; but they may also comprise entire subsystems, modular packages for attitude control, thermal control, structure, propulsion, power, telemetry and command, and payload.

Phase I Objectives

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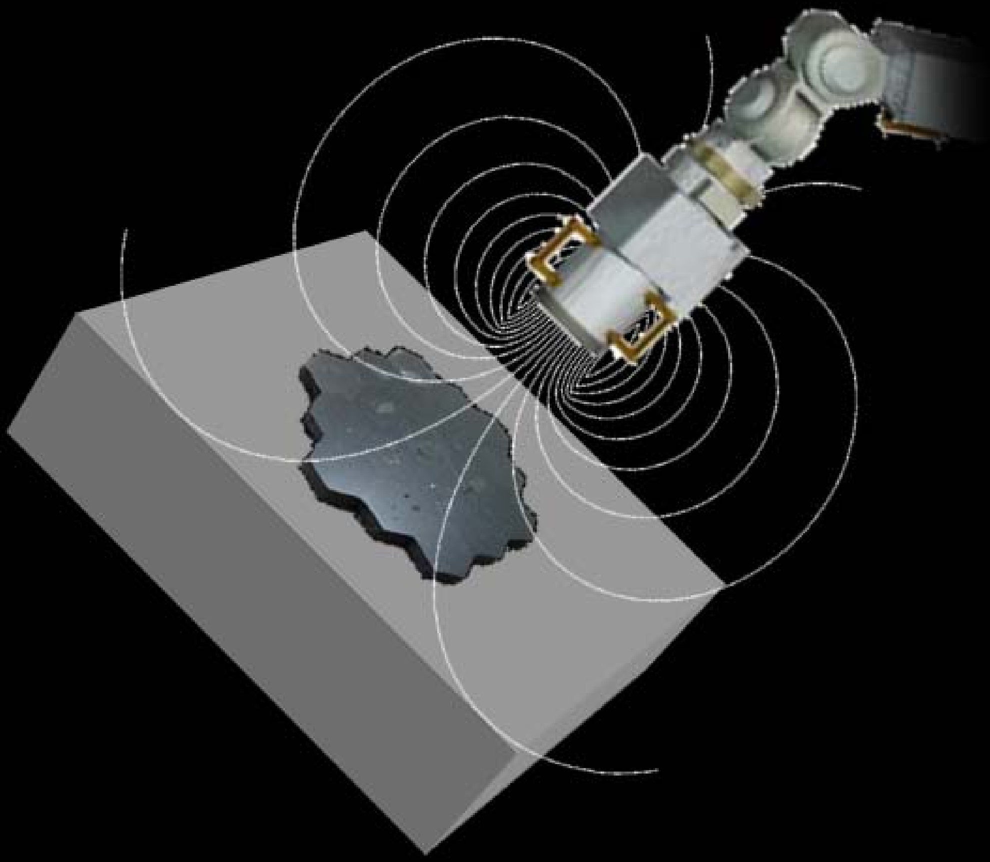
What can we accomplish?

Versatile Robotic Gripping

- Contact-free manipulation
- Low-temperature environments (assembly of large spaceborne mirrors)

Concept of Operations

- Mount an arrangement of permanent magnets and/or an electromagnets on the payload or the robot's end effector.
- Grab, place, and disengage (thermally?), preventing ESD, contamination, and mechanical damage



Experimental & Analytical Results

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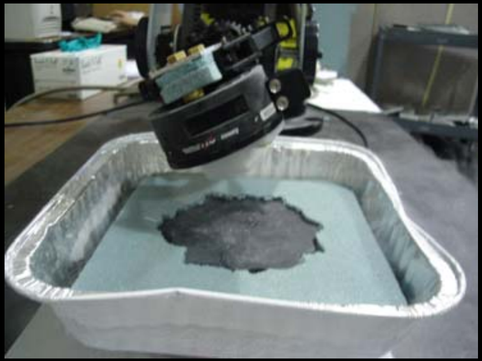
Methods

- **6DOF stiffness measurements**
  - 5DOF robotic manipulation to fit 6DOF stiffness matrix
  - Dynamic system ID

$$\underset{6\times1}{\begin{bmatrix} F \\ \tau \end{bmatrix}} = -\underset{6\times6}{\begin{bmatrix} K_{rr} & K_{r\theta} \\ K_{\theta r} & K_{\theta\theta} \end{bmatrix}} \underset{6\times1}{\begin{bmatrix} r \\ \theta \end{bmatrix}}$$

22.406	-0.467	-0.324	-0.007	0.015	-0.005
-0.467	51.391	-0.109	0.006	0.002	0.004
-0.324	-0.109	98.556	-0.132	-0.081	-0.045
-0.007	0.006	-0.132	0.142	0.000	0.000
0.015	0.002	-0.081	0.000	0.121	0.000
-0.005	0.004	-0.045	0.000	0.000	0.000

6DOF Stiffness: N/m, N, Nm/rad
10 g Neodymium Magnet, YBCO 80 K
1 cm separation
Jan 2007



Experimental & Analytical Results

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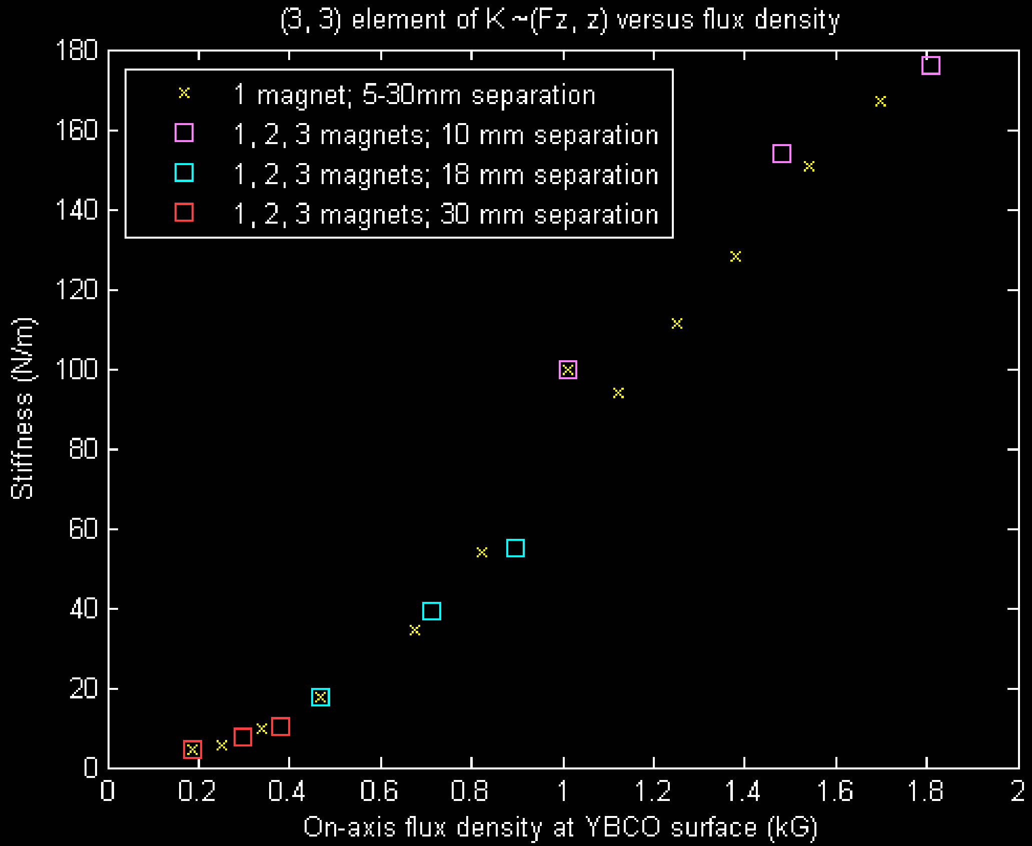
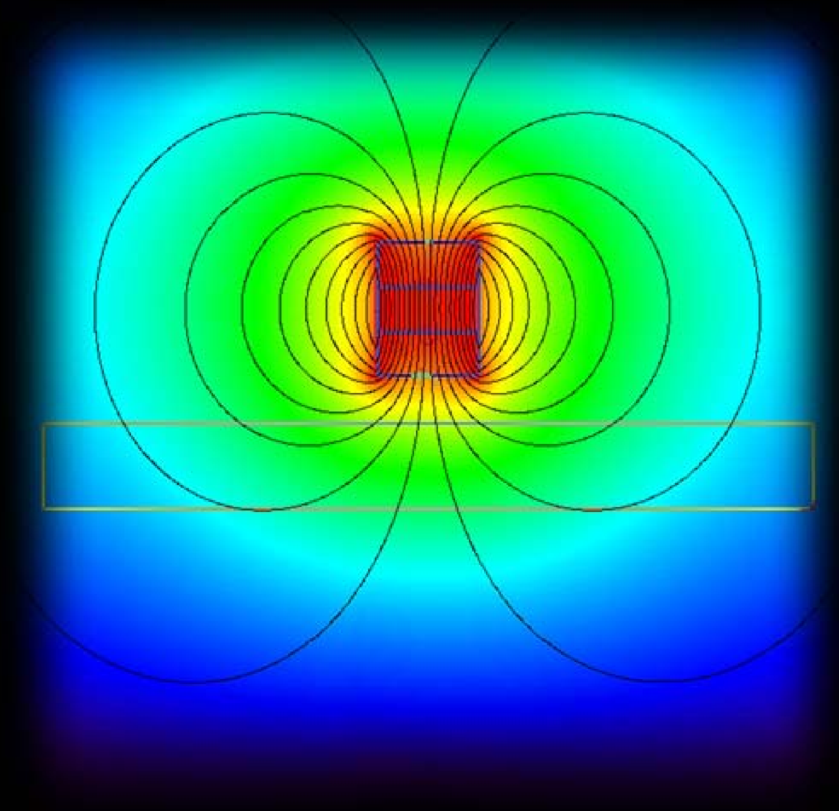
Stiffness Results

– Combine models to scale from test data
– Performance metric of interest: magnet's flux density at YBCO surface





Experimental & Analytical Results

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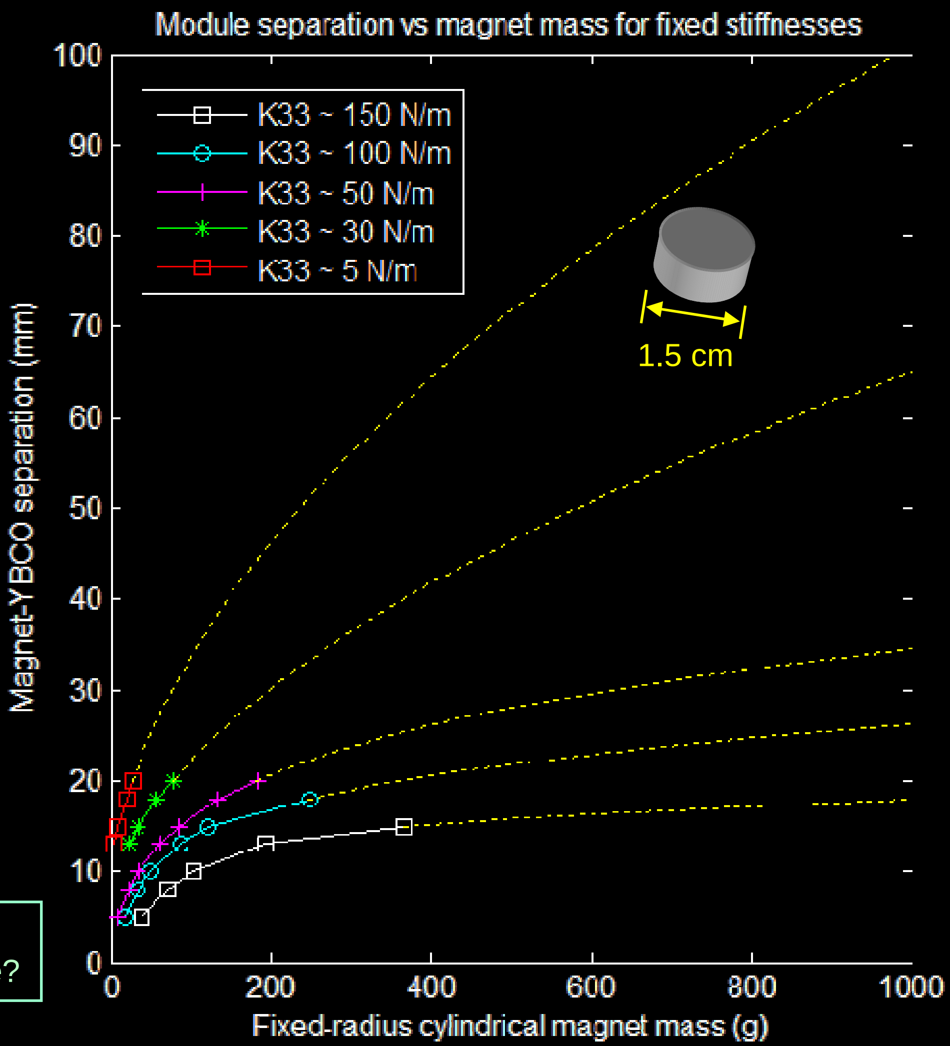
Extraplation of Results

- Intensify magnetic fields with rod-shaped magnets
- Extrapolated from test data
- NdFeB permanent magnets



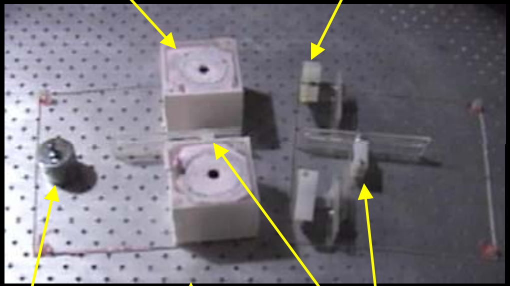
How does the basin of attraction and stiffness among non-contacting components scale with spacecraft size?

Video:
http://www.mae.cornell.edu/mpeck/SSDS/NCMRS/video2.mpg

Experimental & Analytical Results

Analytical and Experimental Results

– Rotational stiffness for a single magnet is not useful.
– Use multiple magnet/YBCO pairs for rotational stiffness instead.



Video:
http://www.mae.cornell.edu/mpeck/SSDS/NCMRS/video1.wmv

Experimental & Analytical Results

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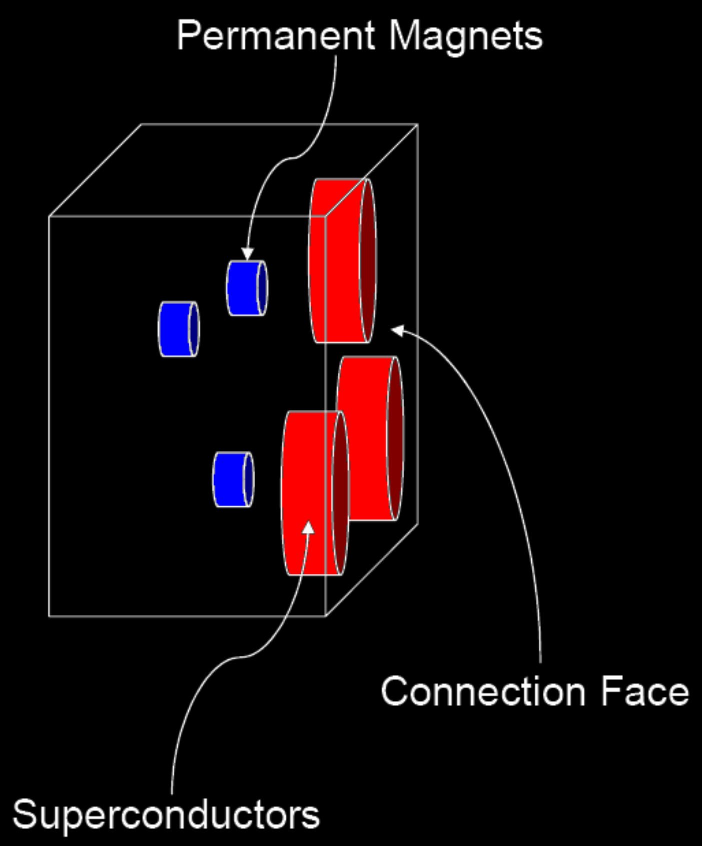
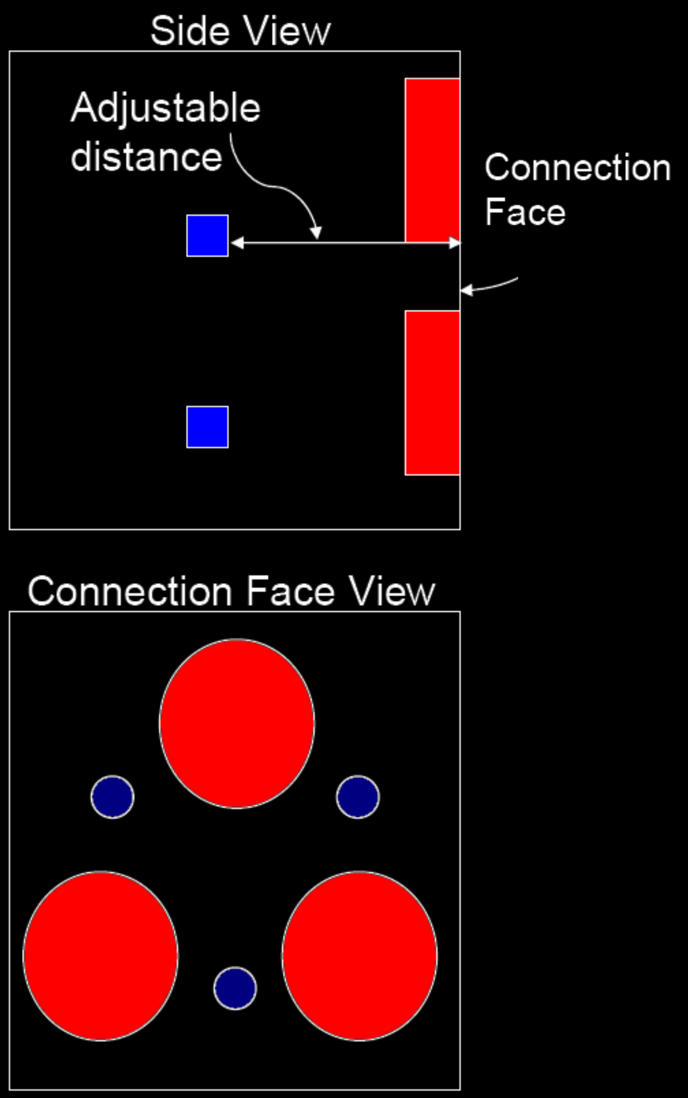
First Steps in Architecture

- **Non-contacting wireless communications (high TRL)**
- **Wireless power transfer**
  - Many possibilities
  - Air-core transformers performed poorly
  - IR lasers / LEDs seem most promising
- **Testbed components**
  in an ad-hoc enclosure:

Experimental & Analytical Results

Extension to 6DOF





Roadmap for the Next 40 Years

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What's Needed?

- Light, high-flux magnets
- Higher-temperature
- Microgravity test with active control at the end of Phase II