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Magnetically Coupled Solar Sails

US Space & Rocket Center Huntsville, Alabama

Solar Sail Propulsion

- **The pressure exercised by sunlight on a sail is constant and inexhaustible but small (P = 9.13 μN m^{-2} at 1 AU).**
- **Since a = f / m, we want a large f and a small m, hence a sail with large area and light structure.**
- **Sail propulsion for useful missions requires large sail sizes (L > 100 meter side) with minimum structure and mechanisms.**

Solar Sail Propulsion

Potential Mission Applications
- Earth Pole Observation
- Heliophysics
- NEO rendezvous and reconnaissance
- Interstellar Precursors

~80-m space demo planned (L'Garde)

Deploytech (Surrey)

20-m ground demo (2005)

3.5-m NanoSail-D (2010)

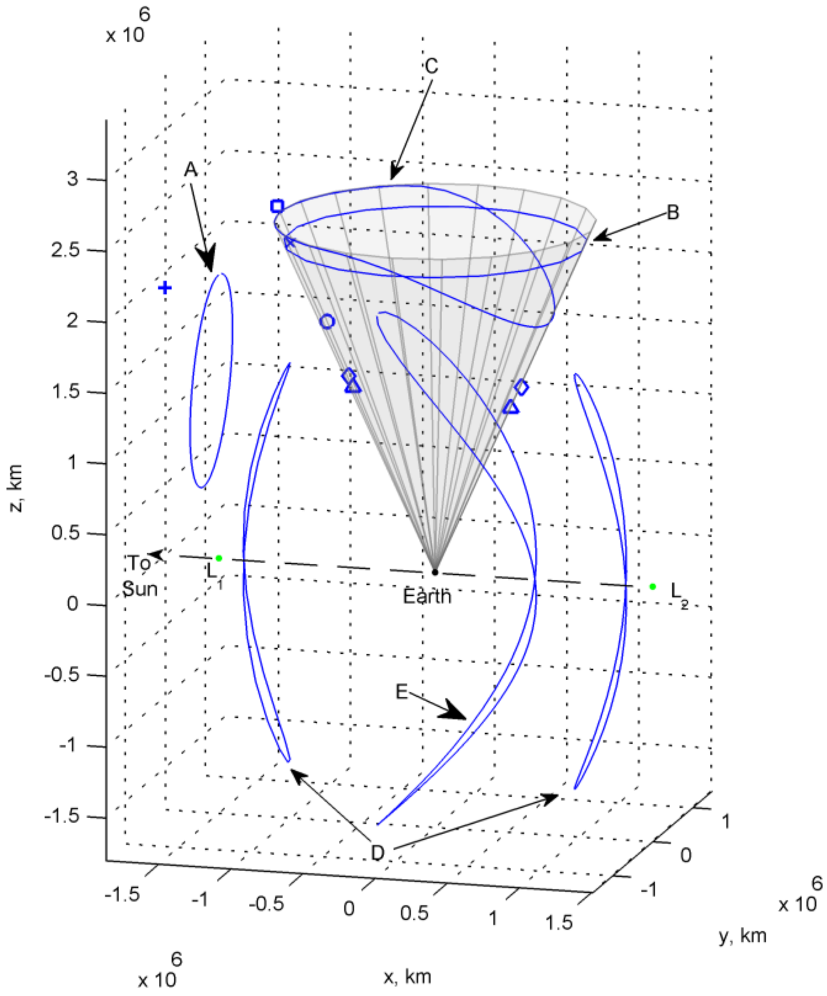
Potential Mission Applications
- Orbital Debris Mitigation
- Small Satellite Propulsion

Potential Missions

Mission	Effective Sail dimension	Orbital/Trajectory parameters	Primary Science Objective
Solar Polar Imager	150 – 180 m on a side	Heliocentric with semi-major axis of 0.48 AU at inclination of 75 degrees	Convective flows in polar regions and the deep solar interior
Heliostorm	100m x 100m	Sun-centered orbit at artificial Lagrange point (0.967 AU from Sun)	Advanced Early Warning of Geo-effective solar events
GeoSail	41.2m x 41.2m	Earth Orbit: 11R_E Perigee, 23 R_E Apogee; Period of 4.5 days	Extended presence in Earth's magnetotail using sail to precess inertial orbit
Multiple Near-Earth Object (NEO) Rendezvous	80m X 80m	Earth Escape to rendezvous with each NEO	Precursor exploration prior to human visits
Interstellar Probe	~400m diameter	Solar swing by (0.25 AU) then radial trajectory at ~15AU/yr (sail jettisoned at 5 AU)	Measurements of the nearby interstellar medium

Hybrid Sail-SEP Missions

- Combination of sail and Solar Electric Propulsion (SEP) can enable new Earth-Sun missions focused on Earth observations and telecommunication with lifetimes of the order of 5 - 8 years.
- SEP propulsion thrust is used for stationkeeping and to counteract perturbations.
- Long mission duration is possible because as the on-board mass of fuel decreases the sail contribution increases.



(from: Ceriotti, et al. Acta Astronautica)

Sail-craft Design Elements

- **Spacecraft elements are connected to the sails with booms and lines**
- **Sails attitude (and hence thrust direction) is controlled by:**
  - Warping the sail, control vanes (similar to ailerons), or
  - Shifting the center of mass in relation to the sail center of pressure
  - Changing the reflectance of selected portions of the sail (demonstrated by JAXA on IKAROS)
- **Instruments, antennas, and solar arrays need gimbals to maintain a pointing that is independent on the one of the sail GN&C**
- **Large sails connected to a bus held by a central hub require sturdy masts**

Sail-craft Design Optimization

The fabrication of light solar sail material is approaching technological maturity.

Optimal systems for sail deployment, sail support, element attachment and control still need to be developed and tested.

In order to optimize sail performance:

Either deploy very large sails or to assemble several modular sails in orbit to achieve large area.

Minimize complexity, power, and mass penalties associated with mechanisms for sail steering, gimbals for pointing, payloads, antennas, and solar arrays.

New Sail-craft Technologies

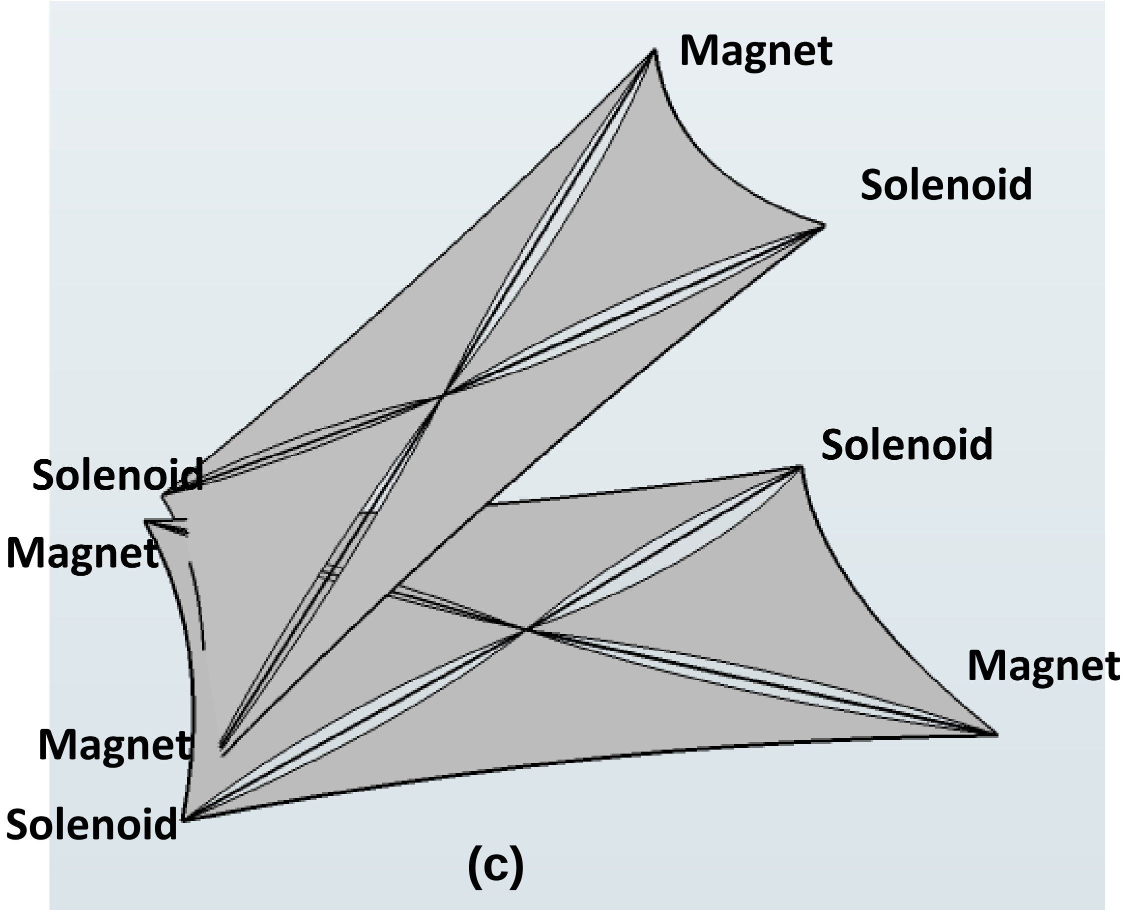
Electromagnetic Contactless Motion Controllers and Gimbals (CMC&G) can help with both:

CMC&G uses a combination of solenoids under software control, and permanent magnets to attract and repel spacecraft elements and thereby move them relative to one another.

- **CMC&G can be used to assemble a single large sail from several independently deployed sails.**
- **CMC&G can be used to attach spacecraft elements to the sail without physical booms or structs.**

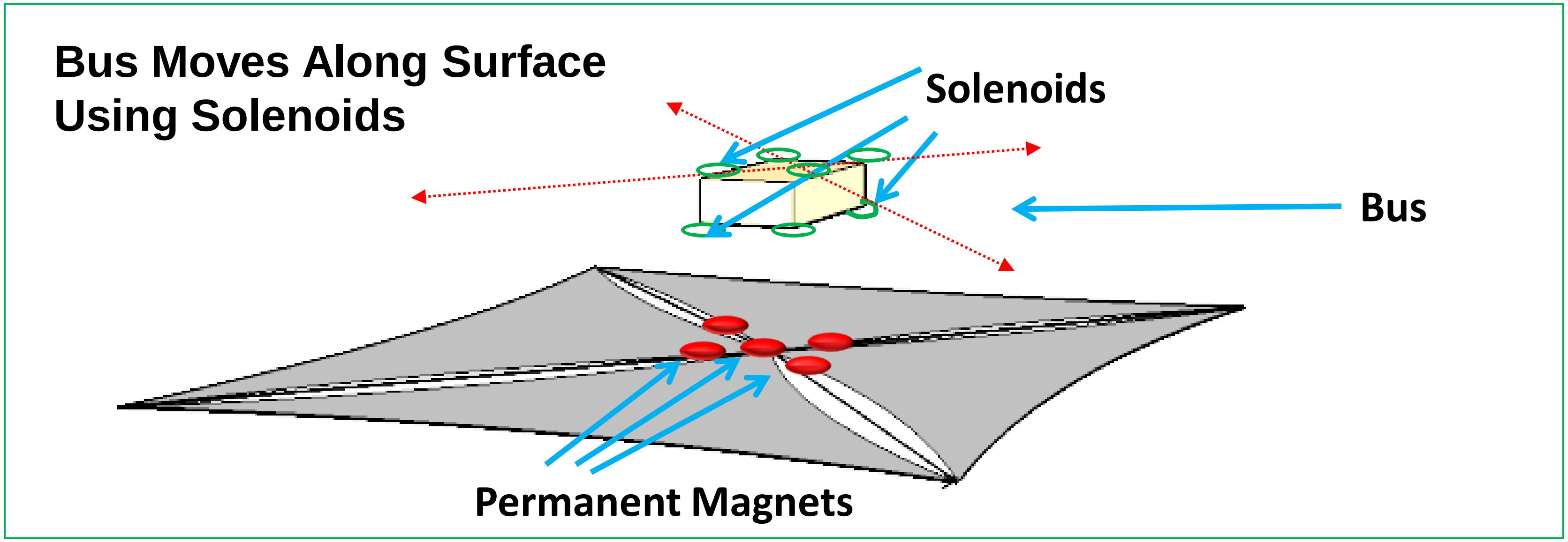
CMC&G – Fitting Sail Together

- Sails that are delivered and unfurled separately in space can be assembled by magnets and coils placed on alternating corners of the sails
- For some of the missions, the time period available for assembling can be very long (e.g. L1 orbit insertion can require ~ 10^6 sec - 6 months)



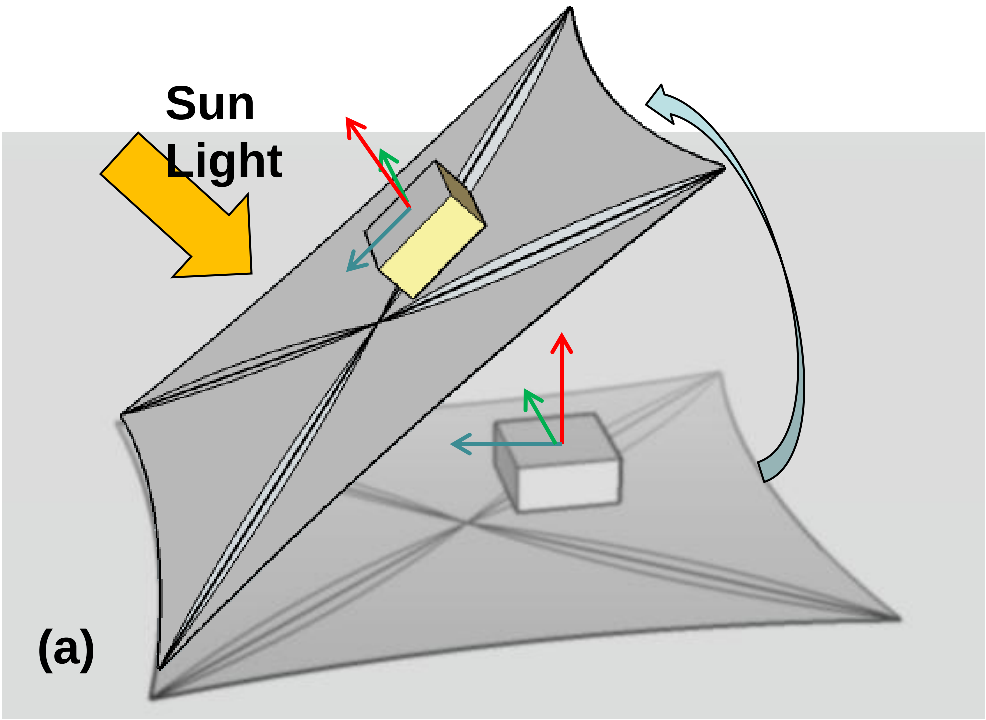
CMC&G – Translational Shift

Spacecraft bus and instruments can be coupled magnetically to the Solar Sail propulsion system and they can move in relation to the sail by changing the relative field strength of CMC&G's on the sail and the bus.



Sailcraft Guidance and Navigation

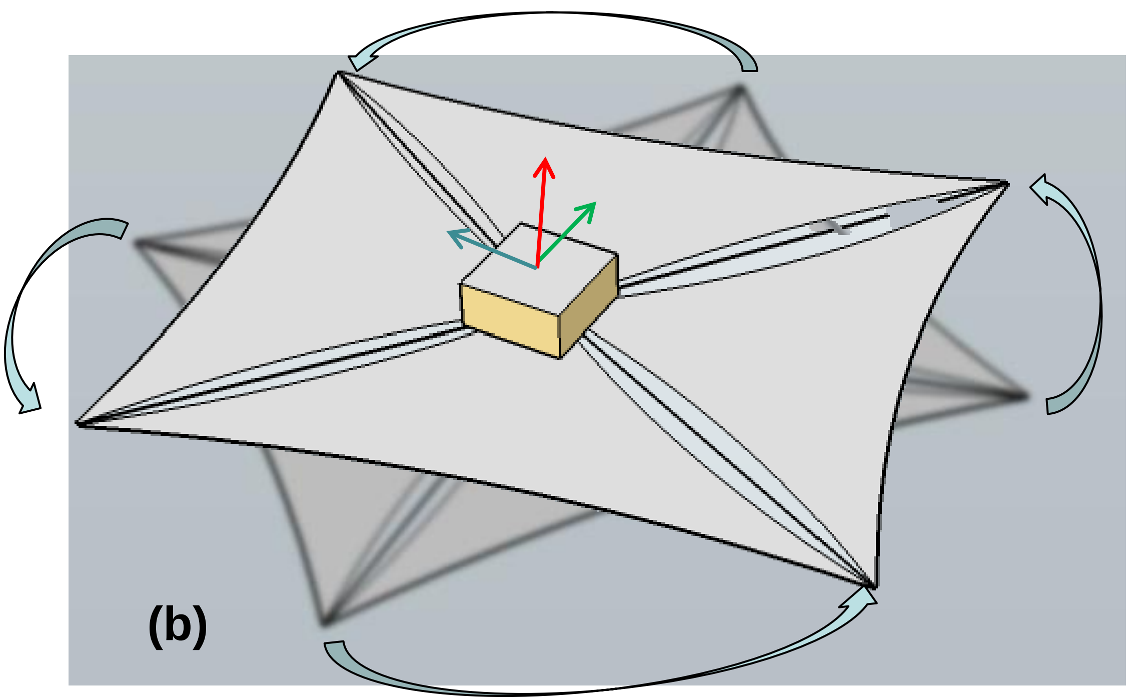
Any shift in the center of gravity (CG) of the craft relative to the center of pressure (CP) on a sail effectively changes the direction of flight.



When bus shifts the center of mass of the system it changes the angle of exposure to sunlight, thus the electromagnetic systems effectively controls the navigation.

CMC&G – Rotation

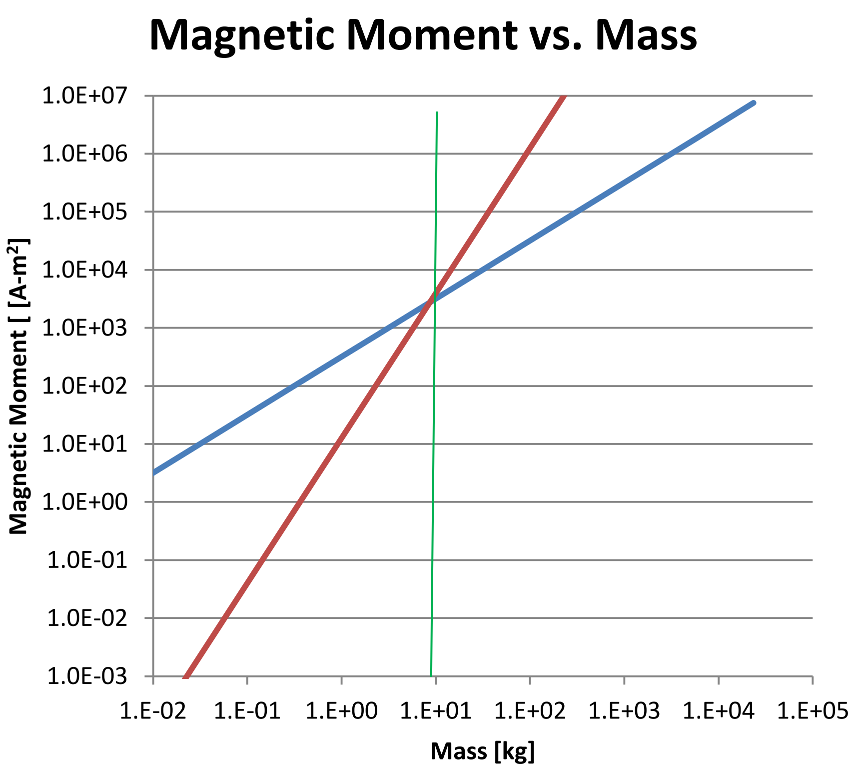
Because the instrumentation and the bus are connected to the Sail via CMC&G, they can be pointed in any direction independently on the sail orientation.



Bus can maintain its orientation even if the sail is turning or spinning.

Magnets vs. Superconductors

Flux Pinning (FP) and Electromagnetic Formation Flying (EMFF) were investigated for contactless assembling in space of subsystems at distances of several meters. They both required superconductors and associated cooling systems.



- **Superconducting wires are more effective than rare earth magnets when the total mass exceed about 10 kg.**
- **Active control systems demonstrated that stable positioning, pointing, and safe mode configurations of magnets and coils can be reliably acquired and maintained using common electronics.**

Mass comparison of the magnetic moments generated by commercially available rare earth magnets one centimeter thick (blue) and superconductors (red).

Conclusions

Advantages of CMC&G:

- **Simple Design: Because solar sail accelerations and forces are small, conventional coils and magnets can replace the booms and gimbals connecting sails and buses, significantly reducing system mass.**
- **Low Power: Attractive/Repulsive forces of ~10^{-4} N may be generated using power < 1W / per solenoid at distance of 10 cm.**
- **Flexible Architecture: Similar design approach can be used for CMC&G for deployment, formation flying, sail control, and instruments or antennas pointing.**
- **Low risk: electromagnetic components and dynamic magnetic control electronics are well characterized and space qualified.**