Brane Craft: Phase 1 Results

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Brane Craft for Orbital Debris Removal

- Start from an ISS orbit
- Move to target’s orbit
  - Major Thrusting
- Rendezvous with target
  - Minor thrusting
- Wrap around target
  - Shape change
- Lower altitude to ~200km
  - Major thrusting

If propellant is still available:
- Open up
  - Shape change
- Release target object
- Boost to higher altitude
  - Major thrusting
- Go after another target

A Brane Craft has enough delta-V (ability to change velocity) to deorbit multiple space debris objects in different orbits.

(Graphic: Joseph Hidalgo, The Aerospace Corporation)
Brane Craft: Removing Orbital Debris on a Budget

• **Funding:**
  – Phase I concept study funded from June 2016 to Feb 2017 at $100,000
  – Phase II technology development funded from May 2017 through April 2019 at $500,000

• **Innovation**
  – Ultra-thin (~50 microns) spacecraft with 10-micron thick Kapton® sheets as the main structure
  – Thin-film solar cells, electronics, sensors, actuators, and electrospray thrusters
  – 82 gram mass vs. multi-kilogram mass for conventional approaches
  – Max acceleration: 0.1 m/s² *(Huge for electric propulsion!)*
  – Shape-changing ability *(required!)*
  – Can remove thousands of debris objects in LEO up to several kg in mass
  – Can also perturb the orbits of large debris objects for collision avoidance, inspect asteroids, and explore our solar system

*This is a radically new way to build and fly spacecraft*
The Growth of Orbital Debris:

These are just the tracked objects. The population of objects smaller than \(\sim10\) cm is much greater. Note satellite collision.

Impact Energy:

- Aluminum sphere
- 10 km/s impact

<table>
<thead>
<tr>
<th>Debris Diameter</th>
<th>Mass (grams)</th>
<th>Kinetic Energy</th>
<th>Explosive Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 cm</td>
<td>0.177 grams</td>
<td>8.84 kJ</td>
<td>1/113 sticks</td>
</tr>
<tr>
<td>1 cm</td>
<td>1.41 grams</td>
<td>70.7 kJ</td>
<td>1/14 stick</td>
</tr>
<tr>
<td>3 cm</td>
<td>38.2 grams</td>
<td>1.91 MJ</td>
<td>1.9 sticks</td>
</tr>
<tr>
<td>5 cm</td>
<td>177 grams</td>
<td>8.84 MJ</td>
<td>8.8 sticks</td>
</tr>
<tr>
<td>10 cm</td>
<td>1.41 kg</td>
<td>70.7 MJ</td>
<td>71 sticks</td>
</tr>
</tbody>
</table>

Even a tiny, 0.5-cm diameter object could degrade satellite operation. 10 kJ is the energy released by dropping a golf ball 72 feet above a target, in a vacuum. There are hundreds of thousands of this size or larger objects in LEO.
Cost of Removing 5,000 1-kg-class Debris Objects from LEO:

- **Cost using conventional tech:**
  - ~$2 billion U.S.

- **Cost using Brane Craft:**
  - ~$30 million U.S. + R&D costs

- You can spend $1.5 billion US on R&D and still save money

*The non-recurring R&D up to $1.5 billion would be wisely spent*
A Brane Craft uses distributed micro/nanostructured electrospray thruster modules. The propellant tank is the space between Kapton® layers. Ionic liquids have virtually no vapor pressure.

Brane Craft $\Delta V = 9.8 \times 4000 \ln \left( \frac{1}{0.67} \right) = 15.7$ km/s

(1/3 wet mass is propellant)
Brane Craft Design at End of Phase I:

~25 million, 5-micron minimum feature size, thin film carbon nanotube transistors required

~25 million, 30-micron minimum feature size, thin film silicon transistors on glass for a 4K screen

The Brane Craft cross section is similar to that of a modern high-resolution display. It’s much thinner, flexible, and designed for a much harder radiation environment. Delta-V is still 15.7 km/s.
The difference in orbit inclination between the starting orbit and the debris object orbit is a strong driver of the required delta-V for the outbound maneuver. 5 or 6 km/s may be required to reach the target orbit.
Brane Craft Analysis: Outbound Transfer Time

Constraints:
- Maximum eclipse fraction
- Symmetric thrusting about the Earth-Sun line to minimize growth of orbit eccentricity

A maximum of 5 days are required to go from the ISS starting orbit to any orbit from 0° inclination to sun-synchronous within LEO.
Brane Craft Analysis: Orbit Rephasing Time

Constraints:

- Maximum eclipse fraction

The orbit rephasing maneuver reduces the true anomaly difference between the tracker and target body, starting in the same orbit, to zero. Orbit altitude is temporarily changed to make the orbit periods different, thus enabling matching of the “clock” hands at a later time for rendezvous.

Worst-case orbit rephasing times (180° rephasing) can be 3 to 8 days in LEO. Delta-V values of less than 20 m/s are required.
Brane Craft Analysis: How Much Mass Can it Drag Down?

- Remaining delta-V is a function of debris orbit altitude and inclination
- No inclination change required for deorbit
- 0.9 kg can be removed under worst-case condition (debris in 2000-km sun-sync orbit)
- 2.2 kg can be removed from a 900-km sun-sync orbit

Remaining ΔV for empty Brane Craft:
(15.7 km/s minus value from Chart 9)
Brane Craft Analysis: Inbound Orbit Simulation

- **Initial 900-km, sun-synchronous debris object orbit**
- **Maximum debris object mass of 2.2 kg for this orbit**
- **Thrusting only during sunlit periods with real eclipses**
- **Orbit eccentricity allowed to grow**

In this case, 6 days are required to go from the debris object orbit to a burnup orbit. Maximum time for maximum mass in any LEO orbit is 10 days.
Brane Craft Analysis: Radiation Environment at 700-km sun-sync

- 700-km sun-synchronous orbit
- Yearly dose rate in silicon
- Commercial, off-the-shelf, (COTS) silicon electronics can tolerate 1 to 10 kilorads of total dose
- A mm or more of aluminum shielding is required to guarantee a 1-year lifetime for conventional spacecraft
- There is almost no radiation shielding for a Brane Craft

For a 700-km altitude, sun-synchronous circular orbit, at least one millimeter of aluminum shielding is required to reach a 1-year lifetime using silicon COTS electronics. Data from the European Space Agency’s SPENVIS program.
Brane Craft Analysis: General Radiation Environment

• Circular orbits
• Yearly dose rate in silicon
• 10-microns of Kapton® shielding on top, 30 microns below
• Most debris objects orbit at inclinations greater than 60°.
• Maximum deorbit time in LEO:
  - 5 days to reach orbit
  - 8 days for orbit rephasing
  - 2 days for rendezvous and wrapping
  - 10 days to deorbit

Brane Craft will need electronics with a total dose limit of at least 5 Megarads for a worst-case 1-month mission in LEO.
Brane Craft Analysis: Micrometeoroid Environment

- 1,200-km altitude circular orbit
- Grün model is for natural objects
- MASTER model includes man-made debris
- 10-microns of Kapton® shielding on top, 30 microns below
- Most debris objects orbit at inclinations greater than 60°.

*The on-orbit flux of micron-scale micrometeoroids is surprisingly high. Data from the European Space Agency’s SPENVIS program.*
### Brane Craft Analysis: Micrometeoroid Environment

- **MASTER model includes man-made debris**
- **4.1-micron diameter micrometeoroids can penetrate the top, 10-micron-thick Kapton® sheet at 10 km/s relative velocity**

<table>
<thead>
<tr>
<th>( V ) (km/s)</th>
<th>( D_c ) for 10( \mu ) Kapton(^*) (( \mu ))</th>
<th>( D_c ) for 20( \mu ) thick Kapton(^*) (( \mu ))</th>
<th>Penetrating Yearly Impacts for 10( \mu ) Kapton(^*)</th>
<th>Penetrating Yearly Impacts for 20( \mu ) Kapton(^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>7</td>
<td>14</td>
<td>480</td>
<td>230</td>
</tr>
<tr>
<td>10</td>
<td>4.1</td>
<td>8.2</td>
<td>970</td>
<td>400</td>
</tr>
<tr>
<td>14</td>
<td>3.1</td>
<td>6.2</td>
<td>1000</td>
<td>500</td>
</tr>
<tr>
<td>20</td>
<td>2.4</td>
<td>4.8</td>
<td>600</td>
<td>270</td>
</tr>
</tbody>
</table>

*About 40 penetrations per month, through a 10-micron-thick Kapton\(^*\) structural layer, can be expected. A Brane Craft has to literally be bullet-proof.*
Thermal Environment

• **Almost no thermal mass**
  - Kapton specific heat: 1.09 J/gram-K
  - EMI-BF4 specific heat: 1.9 J/gram-K
  - 1350 W thermal input in full sun
  - 200 W max in eclipse
  - Temp range: 206 to 342 K
    (-67 °C to +69 °C)

• **Propellant freezing**
  - Standard propellant, EMI-BF4, freezes at 15 °C (298 K)
  - Need to find other propellants with lower freezing point, or
  - Live with fixed shape during eclipse

  EMI-BF4 = 1-Ethyl-3-methylimidazolium tetrafluoroborate

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Thermal control is a big issue. May need to leave the Brane Craft frozen during eclipse; no power for thrusting anyway.
Brane Craft Challenges: Attitude Determination, Attitude Control, Navigation, and Shape Control:

• **Attitude Determination:**
  - *Micro sun sensors:* easy; 0.5° accuracy
  - *Earth sensing:* easy, 0.5° accuracy, distributed thermal sensors
  - *GPS attitude:* difficult, 0.2° accuracy using distributed antennas

• **Attitude Control:**
  - *Distributed thruster arrays:* moderate
  - *Magnetic torque generation:* moderate, planar currents across surface using positive/negative ion emitters
  - *Aerodynamic:* easy, but only works below ~500-km altitude

• **Navigation:**
  - *Thin film GPS receivers:* difficult

• **Shape Control:**
  - *Distributed electroactive polymer ribs,* moderate

*It’s challenging, but not impossible, to implement these systems as thin film systems.*
Summary:

- A Brane Craft is an ultra-thin spacecraft (~55 microns)
- It weighs about 80 grams, yet can deorbit up to 2 kg
- It may be mass-produced
- Potential ~100X decrease in orbit cleanup costs
- Many other potential uses:
  - Asteroid inspectors
  - Asteroid re-directors (multiple per asteroid, dock or high speed impact)
  - Planetary and lunar orbiters
- Significant technology development is required in Phase II
- Thank you NIAC (NASA Innovative Advanced Concepts) group!!!!