Make Your Cubesat Overnight and Put it in Any Orbit (Well... almost)

Jim White, Colorado Satellite Services, LLC
Walter Holemans, Planetary Systems Inc.
Dr. Adam Huang, University of Arkansas
Build overnight and any orbit
Main Components

- Printed-in torsion spring-hinge of solar panel
- Printed AA Battery Holder
- Printed bus and card cage, (covers removed)
- Printed wiring boards
- Printed Propulsion System (shown translucent)
- Nozzle
- Wire guide, 4 x
- Fill Valve

Build overnight and any orbit

Colorado Satellite Services, LLC
The Promise of Cubesats

- Do very cool experiments, very inexpensively, in short time windows

- To fulfill that promise we need to
  - Get them built quickly and inexpensively
    - Faster and cheaper
  - Be in orbit long enough to do something useful
    - Match orbit life to mission life

- However
  - Often take nearly as long to build as microsats
  - Often get very low orbits with a short life and are stuck in that orbit (more so more recently)
Two developments are changing the game

• 3D printing for production
  – The ability to make mechanical pieces by creating a CAD drawing, feeding it into a machine, and have a part a few hours later

• Capable propulsion
  – Simple, safe, effective warm gas propulsion with enough capability to change the orbit in useful ways
3D Printing for Flight - Real Results

- RAMPART Cubesat out of printed parts (SLS Windform XT)
The Current Design
Printed Material and Method

- Used on Rampart Solar panels, card cage, battery and propulsion unit
- Printing Process: Selective Laser Sintering (SLS) by CRP
- Material: Windform XT
  - Nylon with Carbon microfibers
- Surface Finish: Nickel Plate, 0.001 thick, best commercial practices
- Meets Outgassing Requirements
  - TML [%] <1.0%, CVCM [%] <0.10

CRP Technologies

<table>
<thead>
<tr>
<th>Properties Windform® XT</th>
<th>Test Method</th>
<th>SI Unit</th>
<th>Windform® XT</th>
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</thead>
<tbody>
<tr>
<td><strong>General Properties</strong></td>
<td></td>
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</tr>
<tr>
<td>Density [20°C]</td>
<td>g/cm³</td>
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<tr>
<td>Colour</td>
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<tr>
<td><strong>Thermal Properties</strong></td>
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<tr>
<td>Melting Point</td>
<td>ASTM D 3418</td>
<td>°C</td>
<td>173.33</td>
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<tr>
<td>HDT, 1.82 Mpa</td>
<td>ASTM D 648</td>
<td>°C</td>
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<tr>
<td>Vicat, 1°N</td>
<td>ASTM D 1252</td>
<td>°C</td>
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<td><strong>Mechanical Properties</strong></td>
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<tr>
<td>Tensile Strength</td>
<td>UNI EN ISO 527-1:1997</td>
<td>Mpa</td>
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<tr>
<td>Tensile Modulus</td>
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<td>Elongation at break</td>
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<td>Flexural Strength</td>
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<td>Impact Strength - Charpy Unnotched [22°C]</td>
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<td>KJ/m²</td>
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<tr>
<td>Impact Strength - Charpy Notched [23°C]</td>
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<td>KJ/m²</td>
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<td><strong>Surface Finish</strong></td>
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<td></td>
<td></td>
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<tr>
<td>After SLS Process</td>
<td>Ra μm</td>
<td>6.0</td>
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</tr>
<tr>
<td>After finishing</td>
<td>Ra μm</td>
<td>1.0</td>
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<tr>
<td><strong>Properties per Density Unit</strong></td>
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<tr>
<td>UTS per density unit</td>
<td>Mpa g/cm³</td>
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<tr>
<td>Tensile modulus per density unit</td>
<td>Mpa g/cm³</td>
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</table>

Note: These are all indicative values, data were generated from the testing of parts produced with the Windform® XT materials under optimal processing conditions.

Standard Technical Details for Accuracy versus Tolerance:
For parts up to 6" (150 mm) the standard tolerance is +/- 0.012 inch (0.3 mm)
For parts more than 6" (150 mm) the standard tolerance is +/- 0.005 inch per inch (0.05 mm per 25 mm)
Manufacturing Current State

• Printing
  – 6 weeks, could have been 1 week

• Plating
  – 3 weeks, could have been 1 week

Note:
  – Printed parts and plating donated on RAMPART
    » Our schedule was not a priority
  – Estimated total cost to print and plate a 2U satellite ~$3,000
**Precision of Printed Parts (SLS Windform XT)**

- Printed parts have errors about 5 times greater than machined parts
  - Machined part typically has an error less than 0.005 inches on an 8.0 inch feature size
  - Greatest error on solar panels was 0.023 inches on an 8.49 inch feature size

### Example: Printed Solar Panel Inspection

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Feature Size [inch]</th>
<th>Mass [g]</th>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>1</td>
<td>2.994</td>
<td>8.468</td>
</tr>
<tr>
<td>2</td>
<td>2.992</td>
<td>8.476</td>
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<tr>
<td>3</td>
<td>2.987</td>
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<tr>
<td>4</td>
<td>2.990</td>
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<tr>
<td>8</td>
<td>2.996</td>
<td>8.474</td>
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</table>

<table>
<thead>
<tr>
<th>Should be</th>
<th>Feature Size [inch]</th>
<th>Mass [g]</th>
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</thead>
<tbody>
<tr>
<td>2.986</td>
<td>8.490</td>
<td>0.147</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Greatest error</th>
<th>Feature Size [inch]</th>
<th>Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.011</td>
<td>0.023</td>
<td>0.007</td>
</tr>
</tbody>
</table>

| Mean Error [%] | 0.239 | -0.209 | -4.762 | 0.332 | -0.342 | 0.953 |
| 3 x Stdev error [%] | 0.341 | 0.135 | 0.000 | 0.347 | 2.906 | 2.426 |
| Greatest error [%] | 0.368 | 0.271 | 4.762 | 0.500 | 2.740 | 1.695 |
Advantage of SLS Windform XT

- Made quickly and cheaply
- Unlike machined parts:
  - Quantity of unique features does not influence cost
  - Designers need not consider how machining is completed or features created
    » Printed parts are to mechanical engineers what printed wiring boards are to electrical
    » Features can be inexpensively added
- Card Cage incorporates many features in one part
  - Load Cell
  - Hysteresis rods
  - Six cards
  - Five Antennas
  - Solar cell experiment
  - Snap in solar panel and covers
  - Wire guides
Disadvantages of Current Printing Methods

- Printed parts have dimensional errors about 5 times greater than machined parts
- SLS Resolution limits makes features smaller than 0.03 inches difficult to achieve
- Threading cannot be printed-in
  - Tapped threads are tight leading to high running torque on fasteners
- Nickel plating is rough like 280 grit sandpaper
- Mechanisms made from printed parts (deployable solar panels) require sanding, filing or a tuning feature
  - Integral mechanism are possible to avoid this issue
- Printed Plastic is weaker than metal and has much higher Coefficient of thermal expansion (CTE)
- Aspect ratios $\frac{D}{d} > 30$ can warp by 100% of $d$
  - Ribs are needed to decrease aspect ratio
Mission Assurance and Printed Parts

- Thermal vacuum
  - Pressure: <10-5 torr
  - Temperature: -34 to +70 C
  - Cycles: 27
  - Solar array deployment after 27th cycle at temperature extreme

- Random vibration
  - 14.1 Grms, 3 minutes/axis
  - Solar array deployment after excitation

- Load cell to monitor the strain of a preloaded cylinder on orbit
  - Thermal cycling, and radiation may cause degradation of material properties and creep
  - May be compared to terrestrial measurements

![Image of load cell and cylinder setup]
Development Advantages

• Short build cycles allowed rapid change and integration of new ideas
  – Three different solar panel release system tested
Future Performance

• More features to accommodate wiring harness
• Receive assembly-ready parts two weeks after order
• Complete mechanical assembly in 1 day
Second Enabler - Propulsion

- RAMPART warm gas printed propulsion
  - Construction
  - 3D printed performance

- Orbit change capability
  - In plane maneuvers
  - Out of plan maneuvers
**RAMPART Propulsion System**

- **Dimension:** 10cm x 10cm x 11.35cm (4.47”)
- **Empty Weight:** 450 grams
- **Fueled Weight:** 1100 grams (with R-134a propellant)
- **Nominal Propellant Volume:** 500 cm$^2$
- **Design Mission ΔV:** 300m/s
- **Design Performance:** 90s Isp, 0.5N 30 second pulse duration

**Rule of Thumb—Every 100km Holmann transfer at LEO requires 50-60m/s ΔV**
Passive Heating (via Surface Coating)

Active Heating Zone

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Printed/Non-Printed Parts

Red: Printed Windform XT Propellant Tank
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**RAMPART Delta-V Performance**

DeltaV Available

DeltaV available [m/s] vs. Propellant mass [kg]

RAMPART total mass = 2 kg
RAMPART Drag Make-Up (Propellant Life)

• RAMPART with maximum frontal cross-section (panels deployed; 1.35kg; \( C_D = 2.5 \))

DeltaV required per orbit [m/s]

Total atmospheric density [kg/m³]
Propellant Life versus Atmospheric Density

- RAMPART total weight with propellant = 2.0 kg
- Δ = 0.05 kg

- Propellant = 0.65 kg
- Propellant = 0.05 kg

Total atmospheric density [kg/m³]

- Propellant Life [yr]

- RAMPART Drag Make-Up (Delta-V Available)
In-Plane Orbit Performance

Hohmann Transfer

Delta-V (km/s)

Altitude (Km)

Starting Altitude

RAMPART Limit at ΔV=350 m/s

• RAMPART total weight with propellant=2.0 kg

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Out-of-plane Performance

• RAMPART total weight with propellant = 2.0kg, 450km circular orbit
Propulsion Capability Summary

- The hard part to machine – the tank – is dead easy with 3D printing
- The Windform XT material is at least 3X stronger than needed for this tank
- With this simple warm gas system, using about 1U, a 2U orbit can be
  - Raised from 350 to (up to) 1000 circular
  - Raised from 800 to (up to) 1500 circular
  - Raised from 450 to (up to) 1200 elliptical, then the perigee lowered to reduce orbit life
  - Change the plane up to 2.5 degrees to ‘tune’ the orbit
  - Lower apogee at any time to reduce orbit life (de-orbit on demand)

- Limitations
  - Same tolerance limits as with the card cage
    » Must design the mounts for the end plate, valves, etc. to be tolerant of those dimension errors or do light post-printing machining
Status of that Promise

- Do very cool experiments, very inexpensively, in short time windows

- To fulfill that promise we need to
  - Get them built quickly and inexpensively
    - Make (Print) trial and test structures and mechanisms literally overnight out of plastic and similar materials
      - Can do that over and over again for a few 10’s of dollars per print
    - Can do the entire flight structure including complex internal parts in 2 weeks from drawings to completed pieces
    - Final assembly in less than a week including deployed panels and similar features
    - Include complex and multiple features at essentially no extra cost
    - Include external plating for a conductive RF ‘skin’
    - Can design to handle the tolerance issues
    - Easily change things like putting pockets in side to mount other items and test overnight

Start to finish in about 1 month now, perhaps 1 week in not too distant future
Status of that Promise

- Be in orbit long enough to do something useful
  - Can move the typical low altitude cubesat orbit to anything up to about 1200 elliptical then reduce orbit life to a few weeks at end of mission
  - Can move that same initial orbit up to about 800 circular and still reduce orbit life to < 20 years at end of mission
  - Warm gas using R134-A is safe and should gain more and more acceptance
    - Pressures are low, propellant volume is small, tank safety factors are large
  - Prop tank structure very easily modified for things like
    - Changing size
    - Points to mount external items
    - Change connection to remainder of spacecraft
    - Accommodate integral antennas
    - Scaled up for use on a 6U
    - Made pretty much any other size or shape for other applications

Can, with safe and cheap propulsion, be in orbit long enough to do useful work, and de-orbit or shorten life when done
Missions Made Possible

• What kinds of missions to these two capabilities enable
  – Rapid response: Build and be ready for launch in a few weeks
  – Long duration exposure to space environment
  – Exposure to radiation effects (may be less expensive than a full set of rad tests on the ground)
  – Wide area communications from higher orbit
  – Spread within orbit plane from a single launch
  – Station keeping
  – Orbit maintenance in highly elliptical with low perigee – for a ‘close look’ but long orbit life
  – Orbit maintenance in low orbit for longer durations
  – Iterate a mechanical design, launch and test, iterate again
  – Precise drag measurements with releasable spheres into an elliptical orbit – then spread out in that orbit
  – Rapid and cheap production of dozens (hundreds) of structures and mechanisms for swarms – could even be modified for different capabilities
  – Do a mission in one orbit, change the orbit and do a different mission
Questions