State-of-the-Art for Small Satellite Propulsion Systems

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Overview

✦ State-of-the-Art Overview
✦ Obstacles to System Development
✦ SmallSat Propulsion System Performance
✦ System in Flight
✦ Conclusion
State-of-the-Art Overview

• SmallSats enable low-cost access to space.
• Their uses and capabilities are growing to the point where a propulsion system is required.
• Current state-of-the-art for SmallSat propulsion systems is rapidly evolving. However, their technology readiness level (TRL) is still relatively low.

• Desired SmallSat propulsion system SoA:
  – Lowest cost possible
  – High performing
  – High reliability
  – Simplest design feasible

• Current SmallSat propulsion system SoA:
  – Low-cost, unreliable, and low performing, or
  – High-cost, reliable, and high performing
Obstacles to System Development

• Reliability
  – Low quality standards
  – Components not tested in harsh environments (radiation, thermal, vibration)

• Maturity

• Safety
  – Academia and hobbyists have low quality standards compared to government agencies and large private organizations.
  – Primary payloads and NASA/Johnson Space Center (NASA/JSC) (for ISS) will not allow additional hazards to be flown, e.g., high pressure systems (>100 psia) or hazardous propellants.

• Cost
  – Power Processing Unit (PPU) development is hindered by availability of space-flight qualified components (e.g., radiation hardened) at a low cost
  – Exceeding or well-documenting U.S. Range Safety compliance demonstrating that the system will not create undesirable risk.
SmallSat Propulsion Systems

• Chemical Propulsion Systems
  – Cold gas propulsion system propellants use primarily saturated liquids:
    • Refrigerants
      – R134a – used in air conditioning systems
      – R236fa – used in fire extinguishers
    • Sulfur Dioxide
    • Isobutane
  – High energy propulsion system development has primarily focused on green propellants (AF-M315E, LMP-103S). However, there are some hydrazine systems in development.

• Electric propulsion system
  – Electrospray (ionic liquids)
  – RF Ion (iodine or noble gases (xenon, krypton, etc.))
  – Electrothermal (refrigerants, ammonia, sulfur dioxide, isobutene)
  – Helicon Plasma (iodine or noble gases (xenon, krypton, etc.))
• The following are the performance metrics used to evaluate SmallSat propulsion system capability:
  – Change in Velocity, $\Delta v$ (m/s)
  – Specific Impulse, $I_{sp}$ (sec)
    • System’s fuel efficiency
  – Thrust, $F$ (N or lbf)
  – Power, $P$ (W)
  – Total Impulse, $I_t$ (N-sec)
    • Total momentum applied to a body
  – Volumetric Impulse, $I_t/V$ ((N-sec)/U or (N-sec)/L)
    • The amount of total impulse a system can impart to a body per unit volume
    • Volume in this case is based on a 1U CubeSat
    • An efficiency parameter (i.e., amount of performance per U)

• Technology Readiness Level, TRL, is a fundamental development metric used to evaluate technology maturation.
SmallSat Cold Gas Propulsion

**CubeSat MEMS Propulsion System (NanoSpace)**

- Propellant: Isobutane
- Wet Mass: 0.30 kg (Prop: 0.05 kg)
- Performance:
  - Thrust: 0.01 to 1 mN (x4 thrusters)
  - Specific Impulse: 110 sec
  - Vol. Imp.: 133.3 Ns/U
- Power Req: < 2.5 W
- TRL: 6
- Salient Features:
  - MEMS thruster chips contain flow components
  - Closed loop control

**3D Printed Cold Gas Propulsion System (UT-Austin)**

- Propellant: R-236fa
- Wet Mass: 0.38 kg (Prop: 0.09 kg)
- Performance:
  - Thrust: 40 mN (Bevo-2 model shown above)
  - Specific Impulse: 35 sec
  - Vol. Imp.: 146.5 Ns/U (Bevo-2 model shown above)
- Power Req: 1.5 W
- TRL: 6
- Salient Features:
  - Accura Bluestone resin
  - SLA provides flexible system architecture
SmallSat Green Propulsion

Advanced Monoprop Application for CubeSats (Busek)

- Propellant: AF-M315E
- Wet Mass: 1.49 (Prop: 0.29)
- Performance:
  - Thrust: 425 mN
  - Specific Impulse: 220 sec
  - Vol. Imp.: 565.0 Ns/U
- Power Req: 20 W
- TRL: 5
- Salient Features:
  - Developed 500 mN thruster & catalyst
  - Post-launch Pressurization System (PLPS)

<table>
<thead>
<tr>
<th>Component</th>
<th>ID#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Processing Unit (PPU)</td>
<td>1</td>
</tr>
<tr>
<td>Bellows Propellant Tank</td>
<td>2</td>
</tr>
<tr>
<td>Pressure Transducer x2</td>
<td>3</td>
</tr>
<tr>
<td>High-Pressure Burst Disc</td>
<td>4</td>
</tr>
<tr>
<td>Piezo-Actuated Thruster Valve</td>
<td>5</td>
</tr>
<tr>
<td>0.5N Thruster BGT-X5 with Thermal Shield</td>
<td>6</td>
</tr>
<tr>
<td>Post-Launch Pressurization System (PLPS) Cell</td>
<td>7</td>
</tr>
<tr>
<td>Tank Manifold &amp; Component Mounting Plate</td>
<td>8</td>
</tr>
</tbody>
</table>
SmallSat Electric Propulsion

Scaleable ion Electrospray Propulsion System (MIT/Accion Systems)

- System Type: Electrospray
- Propellant: Ionic Liquid
- Wet Mass: 0.028 kg (Prop: 0.01 kg)
- Performance:
  - Thrust: 0.075 mN
  - Specific Impulse: 1000 sec
  - Vol. Imp.: 260.6 Ns/U
- Power Req: 1.5 W
- TRL: 5
- Salient Features:
  - Low power usage
  - Useful for fine maneuvering
SmallSat Electric Propulsion

BIT-3 (Busek)
- System Type: RF Ion
- Propellant: Iodine
- Wet Mass: 3 kg (Prop: 1.5 kg)
- Performance:
  - Thrust: 1.15 mN
  - Specific Impulse: 2100 sec
  - Vol. Imp.: 15,451 Ns/U
- Power Req: 45 W
- TRL: 5
- Salient Features:
  - First system that will use iodine in flight
SmallSat Electric Propulsion

**Propulsion Unit for CubeSats** *(CU Aerospace/VACCO/AFRL)*
- System Type: Electrothermal
- Propellant: R-134a, R-236fa, SO$_2$
- Wet Mass: 0.72 kg (Prop: 0.27 kg)
- Performance (R-236fa/Warm Gas):
  - Thrust: 5.4 mN
  - Specific Impulse: 72 sec
  - Vol. Imp.: 514.5 Ns/U
- Power Req: 15 W
- TRL: 6
- Salient Features:
  - Compact

**CubeSat High Impulse Propulsion System** *(CU Aerospace/VACCO/AFRL)*
- System Type: Electrothermal
- Propellant: R-134a, R-236fa, SO$_2$
- Wet Mass: 1.2 kg (Prop: 0.7 kg)
- Performance (R-236fa/Warm Gas):
  - Thrust: 30 mN
  - Specific Impulse: 82 sec
  - Vol. Imp.: 526.2 Ns/U
- Power Req: 30 W
- TRL: 5
- Salient Features:
  - Integrated battery pack
  - Cold Gas ACS thrusters
SmallSat Electric Propulsion

*CubeSat Ambipolar Thruster*
(Univ. Of Mich./Phase Four/NASA-ARC)

- System Type: Helicon Plasma
- Propellant: Xenon & Argon (as tested)
- Wet Mass: 1.5 kg (Prop: 0.5 kg)
- Performance (as tested w/ Xenon):
  - Thrust: 1.0 mN
  - Specific Impulse: 800 sec
  - Vol. Imp.: 936.7
- Power Req: 5 W
- TRL: 5

**Salient Features:**
- No Cathode necessary
- Magnetic Nozzle
SmallSat Propulsion Performance

6U (12kg) CubeSat Propulsion Systems -
Volumetric Impulse & TRL

Cold Gas
- NanoSpace - MEMS +
- 3D - Bevo-2
- Busek - AMAC
- Accion - S-iEPS

Green
- Busek - BIT-3
- CU - PUC
- CU - CHIPS

Electric
- Phase Four - CAT
- 936.7

VOL. IMP. [(Ns)/U]

10000.0
10000.0
1000.0
100.0
10.0
1.0

133.3 146.5
565.0
260.6
15,450.8
514.5
526.2
936.7

TRL

6U (12kg) CubeSat Propulsion Systems -
Volumetric Impulse & TRL

Vol. Imp. (Ns/U) TRL

NanoSpace - MEMS +
3D - Bevo-2
Busek - AMAC
Accion - S-iEPS
Busek - BIT-3
CU - PUC
CU - CHIPS
Phase Four - CAT

+ International Company

Vol. Imp. (Ns/U) TRL
SmallSat Propulsion Performance

3U (4kg) CubeSat Propulsion Systems - Power

<table>
<thead>
<tr>
<th>System</th>
<th>Power [W]</th>
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<tbody>
<tr>
<td>NanoSpace - MEMS+</td>
<td>2.5</td>
</tr>
<tr>
<td>3D - Bevo-2</td>
<td>1.5</td>
</tr>
<tr>
<td>Busek - AMAC</td>
<td>20.0</td>
</tr>
<tr>
<td>Accion - S-iEPS</td>
<td>1.5</td>
</tr>
<tr>
<td>Busek - BIT-3</td>
<td>45.0</td>
</tr>
<tr>
<td>CU - PUC</td>
<td>15.0</td>
</tr>
<tr>
<td>CU - CHIPS</td>
<td>30.0</td>
</tr>
<tr>
<td>Phase Four - CAT</td>
<td>5.0</td>
</tr>
</tbody>
</table>
SmallSat Propulsion Performance

6U (12kg) CubeSat Chemical Propulsion Systems - Thrust & Specific Impulse

Thrust (mN) vs. Specific Impulse (sec) for NanoSpace-MEMS+, 3D-Bevo-2, and Busek-AMAC. The graph shows the performance of different propulsion systems in terms of thrust and specific impulse.
6U (12kg) CubeSat Electrical Propulsion Systems - Thrust & Specific Impulse

<table>
<thead>
<tr>
<th>Company</th>
<th>Thrust (mN)</th>
<th>Isp (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accion - S-iEPS</td>
<td>1800.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Busek - BIT-3</td>
<td>2100.0</td>
<td>4.5</td>
</tr>
<tr>
<td>CU - PUC</td>
<td>70.0</td>
<td>2.8</td>
</tr>
<tr>
<td>CU - CHIPS</td>
<td>82.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Phase Four - CAT</td>
<td>800.0</td>
<td>2100.0</td>
</tr>
</tbody>
</table>

+ International Company
System Flight Opportunities

• MEMS CubeSat Propulsion Module (NanoSpace)
  – Mission: Tianwang-1 (China)
  – Launch: Late Sept. 2015
  – S/C Bus Size: 3U (Tianwang-1C)

• 3D Printed Cold Gas Propulsion Module (UT-Austin)
  – Mission: LONESTAR/Bevo-2 (Texas A&M & UT-Austin)
  – Launch: Late Jan. 2016
  – S/C Bus Size: 3U (Bevo-2)

• BIT-3 (Busek)
  – Mission: Lunar IceCube (Morehead St.)
  – Launch: 2018
  – S/C Bus Size: 6U
Conclusion

• SmallSats are a low cost access to space with an increasing need for propulsion systems.

• NASA, and other organizations, will be using SmallSats that require propulsion systems to
  – Conduct high quality near and far reaching on-orbit research
  – Perform technology demonstrations

• Increasing call for high reliability and high performing for SmallSat components

• Many SmallSat propulsion technologies are currently under development
  – Systems at various levels of maturity
  – Wide variety of systems for many mission applications