Enabling Collaborative Behavior Among CubeSats

SSC11-VI-9

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- Dr. Carlee Bishop
- Dr. Mick West
- Dr. Rich Vuduc
• Summary
• Motivation and Application
• Software Development
• Final Algorithms
• Simulations and Results
• Conclusion and Future Work
• Select balanced force model for on-board propagation of s/c teammates
• Implement on-board orbit determination algorithm
• Develop algorithm for maintaining shared state knowledge of team
• Identify/Define ISL framework for CubeSat platform
• Demonstrate power savings
Motivation and Application
Motivation and Application

- Format flying / Distributed systems
- CubeSat platform
- Cost, Versatility, and Robustness
- Time from Concept to Launch
- Science / Data Value
- Distributed Sensor Gathering
CubeSat Platform Power Constraint

• 0.06m² PV area ➞ 15W max power
  • Assuming 3U body-fixed panels
• RF transmission ~4W
• Microcontroller active ~0.825mW / MIPS
• 1 sec RF = 20 min of 4MIPS μc
• Reducing communication provides power for data collection or other tasks

http://em.avnet.com/img_shared/fea/df2df2usa/Feat-TI-MSP430AFE221.gif
Orbit Propagation
• Two sets of orbit “truth”
  • a.i. solution’s FreeFlyer
  • JPL HORIZONs
• Propagation Technique
  • Cartesian ECIF
  • Orbit Elements (Var. of Parameters)
  • Relative Motion (simplest, CWH)
Propagation Development

- Force Model
  - Non-spherical
  - Drag and SRP
  - 3\textsuperscript{rd}-Bodies

- Integration Routine
  - RK Family (4\textsuperscript{th} – 8\textsuperscript{th} order)
    - Fixed and Variable step
  - Future work: Gauss-Jackson
Force Models – *FreeFlyer* Comparison

![Graph showing position and velocity error over orbit number for different models: J₂, J₂ + Drag, J₂ + SRP, J₂ + 3rd-Body, and Final Model.](image)
Integration Routines – Time Steps w/ Eclipse

The diagram illustrates the step times for two integration routines, `ode45` and `ode113`, over several orbits. The step times are shown for each orbit, with `ode45` represented in blue and `ode113` in red.

- **ode45**: Blue line, labeled as 'In Eclipse'.
- **ode113**: Red line, labeled as 'ode113'.

The x-axis represents the orbit number, ranging from 0 to 10, while the y-axis represents the step time in seconds, ranging from 0 to 4 seconds for steps. The graph shows how the step times vary during each orbit, particularly highlighting the impact of 'In Eclipse' conditions on the step times.
Integration Routines – Execution Time
Sensor Options

- Radar: Range and Range Rate
- GPS: Position and option of Velocity

On-board vs. Ground Station Update
Orbit Determination – Tuned Filter
Orbit Determination – Tuned Filter

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[Graphs showing data plots such as ΔH_{Earth}, ΔJ_2, ΔCphi, ΔCphi, ΔH_{Moon}, and ΔH_{Sun} over orbit number.]
Orbit Determination – Tuned Filter

The graph shows the error in position (top) and velocity (bottom) over orbit number. The blue line represents the EKF (Extended Kalman Filter) performance, while the red crosses indicate noisy GPS measurements (position only). The error decreases significantly with the EKF, demonstrating its effectiveness in filtering out noise and improving accuracy.
Inter-Satellite Communication
• 29-byte Wrapper/Preface
  • Appended to Ephemeris Update
  • Available for Sensor Data Messages

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• 160-byte ephemeris message
## ISL – Protocol, Frequency, Hardware

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<tr>
<th>Protocol</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>802.11</strong></td>
<td>• Ample COTS components &lt;br&gt;• Sufficient data rate for small messages &lt;br&gt;• Can be modified to increase range (slightly) and max power</td>
<td>• Need rad hard COTS &lt;br&gt;• Current range on the order of 100s meters (some research has pointed towards increasing this limit)</td>
</tr>
<tr>
<td><strong>802.16</strong></td>
<td>• Range up to 30 miles &lt;br&gt;• High data rates, if needed</td>
<td>• COTS not as common &lt;br&gt;• COTS available not rad hard</td>
</tr>
<tr>
<td><strong>AX.25</strong></td>
<td>• Extensive use on CubeSat missions &lt;br&gt;• GTRI gaining experience through other CubeSat project &lt;br&gt;• Flexible framework</td>
<td>• Open protocol, so needs modifications if secure data transfer required &lt;br&gt;• Packet handling is manual</td>
</tr>
<tr>
<td><strong>Microhard Inc. (MHX2420)</strong></td>
<td>• Flight experience &lt;br&gt;• Plug-and-Play for CubeSat &lt;br&gt;• 50+ km range &lt;br&gt;• 128-AES encryption available</td>
<td>• Closed protocol &lt;br&gt;• Limited hardware selection</td>
</tr>
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## Frequency Bands

### UHF vs. S-Band

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<tr>
<th>Band</th>
<th>Advantages</th>
<th>Disadvantages</th>
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</table>
| UHF    | • Very common among CubeSats  
        | • Lots of proven COTS hardware  
        | • Sufficient data rate for small messages  
        | • Sufficient range given W        | • Likely not preferred for defense applications  
        |                                                                                     | • For data-heavy applications, may be insufficient bandwidth                  |
| S-Band | • Has been indicated to be preference of defense projects  
        | • Higher data rates, if needed  
        | • Sufficient range given W        | • Less components to chose from, however COTS still avail.  
        |                                                                                     | • Lower TRL than UHF, but still has CubeSat flight experience                  |
• Variable broadcast power (0.1 – 1.0 W)
• Previous model flew on NASA GeneSat
• 19.2 – 230.4 kbps extended sensitivity
Final Algorithms & Simulation Results
Rx Data from S/C (temporarily store in buffer)

ICs of Self & S/C Team

Propagate S/C Team Forward in time $T$ seconds

Select Discrete Date to Reference

4D Tensor of S/C States

Select Discrete Date to Reference

Extended Kalman Filter

Compare Error with Tol

Fails

Broadcast New IC of Self to Team

Passes

Update S/C ICs

Rx ACK

Check Buffer for Messages

Output from GPS Receiver in ECIF Frame

(temporarily store in buffer)
Simulations – 10m Tolerance (10m, -m/s)
STM already available for “free” from extended Kalman filter

- Replaces numerical integration with matrix multiplication (much cheaper)

- Track $dx_0$ instead of $x_0$ for each s/c

$$d\hat{x}_f = \Phi(t_f, t_0) \, d\hat{x}_o$$

$$\Phi(t_2, t_0) = \Phi(t_2, t_1) \Phi(t_1, t_0)$$
Simulations – State Transition Matrix
Simulations – OpenMP Propagation Only
Simulations – OpenMP Propagation Only

![Graph showing normalized execution time vs. number of s/c and cores](image)
Simulations – OpenMP Full Algorithm
Simulations – OpenMP Full Algorithm

A graph showing the normalized execution time for different numbers of cores and sub-cores. The graph compares the OpenMP (OMP) performance against an ideal performance model. The trend indicates that as the number of sub-cores increases, the execution time also increases, deviating from the ideal line.
Conclusions & Future Work
Conclusions

- Relatively simple model represents LEO CubeSat environment

- On-board propagation with EKF realizes power savings by eliminating >1 broadcast for every 10 orbits
  - Results indicate 30+ less bcst per orbit

- Use of multi-core processor could further reduce power via throttling
Future Work

• Implement algorithms on multi-core μc
  • Utilize core throttling and variable core supply voltage for further power savings

• Explore higher-order STMs for propagation

• Iterate on ISL framework/standard

• Technology demonstration mission
Thank you.
Questions?