Responsive Flight Software Development & Verification Techniques for Small Satellites

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Overview

• Project Background

• System Architecture

• Software Process

• Single-Axis System Test
AeroCube Exploded View

Satellite is 10x10x10 cm and Weighs <1.5 kg
Satellite Electronics

- **Main Radio**
  - Freewave

- **Flight Computer μP**
  - FPCB

- **P-PCB μP x 6**
  - ICPCB

- **GPS μP**
  - GPS

- **ADV Radio μP**
  - Adv_Radio

- **Solar & Bat Board #1 μP**
  - SBPCB

- **Batteries 1 & 2**

- **Solar arrays**

- **Sun sensors**
  - X 2

- **Earth sensor suite**
  - X 1

- **Triax rotation, accelerations, magnetics**

- **Reaction Wheels (orthogonal)**
  - X 3

- **Torque coils (orthogonal)**
  - X 3

- **Visible cameras**
  - X 3

- **RAM sensor**
Satellite Electronics

• Attitude Control on a PIC Processor
  – 8-bit architecture
  – Unfolded 32-bit floating point math
  – No operating system
  – Timing through on-chip timers
Objectives

• Develop an enhanced attitude determination & control algorithm for an existing hardware architecture
  – Support both nadir-pointing and inertial tracking of ground uploaded profiles
  – Estimate gyro bias onboard to reduce attitude error when Earth or Sun data is not available

• Implement algorithm on an 8-bit PIC
• Deliver shipment code in 2-3 months, with an opportunity to patch on-orbit 6 months later
• Verify algorithm & code using both engineering & qualification model hardware via ground test
Software Development Process Flow

1. Algorithm Development: Embedded MATLAB in Simulink
2. Auto-generate C Code using the MATLAB Embedded Coder
3. Hand Coded Hardware Drivers / Interface in Assembly & C
4. Merge Auto-generated C code with Drivers & Interface
5. Test on Engineering Model Board using Pre-recorded Sensor Inputs from Simulink
6. Open Loop HIL System Test
7. Single-axis Closed-loop test on Qual Model using Artificial Light/Heat Sources to Stimulate Sensors

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Control Analysis Department
Control System Block Diagram
Flight Software Auto-Code Generation

- ACS Algorithms were developed in MATLAB
- The MATLAB Coder was used to auto-generate C code that was later merged with hand coded low level drivers and supporting command and data handling functions
Flight Software Integration

• Leveraged legacy AeroCube software as a starting point
  – *Low-level hardware drivers already in place*
  – *Mixed language architecture: C and Assembly*

• Implemented auto-code generated attitude control algorithm
  – *Memory map optimization (90% program memory utilization)*
  – *Added support for on-orbit reprogramming*

• Developed optimized telemetry storage system
  – *Multi-rate storage to reduce data size*

• Partitioned flash memory for algorithm inputs & telemetry storage
Open Loop HIL Testing

• Verified timing margin
• Identified & corrected underflow error in auto-generated code
  – *Embedded code generator used a hard coded double precision value for an epsilon in a library function instead of single precision*
  – *Feedback provided to The Mathworks*
• Identified & corrected interface bugs
• Identified hardware error with the real-time clock register roll-over
  – *Sampling issue in the real-time clock integrated circuit*
  – *Corrected with a software detection algorithm*
• Compared stored telemetry output to simulation predicts
System Testing

• Verified timing margin
• Identified & corrected sensor read no-response issues
  – Added timeouts based on expected sensor read times
• Identified hardware design flaw – reaction wheel vibrations at high
  rotation rates corrupting gyro sensor data
  – Demonstrated that reduced wheel speeds alleviated the problem
  – Changed reaction wheel mounting for follow-on mission
• Identified & corrected Sun sensor processing database constants
  – Improved gyro bias estimation performance
• Compared stored telemetry output to simulation predicts
Single-Axis System Test
Overview

• Test Setup

• Scenario Con-ops

• Simulation Comparison

• Gyro Bias Estimation Results
Test Setup

Overhead view

String Mount

Hot Plate (Earth Model)

~110 Degree Separation

AeroCube & Platform

Flood Light (Sun Model)

Spacecraft on hanging string fixture with Earth target visible

Low Cost System Test Identified Several Software and Hardware Issues
## Scenario Con-ops

<table>
<thead>
<tr>
<th>Simulation Event</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Earth acquisition</td>
<td>0</td>
</tr>
<tr>
<td>- Y-axis Earth search (about string axis)</td>
<td></td>
</tr>
<tr>
<td>Found Earth, pull-in</td>
<td>22</td>
</tr>
<tr>
<td>Start Z-axis Sun search (perpendicular to string)</td>
<td>32</td>
</tr>
<tr>
<td>Found Sun (already in field of view)</td>
<td>32</td>
</tr>
<tr>
<td>Attitude determination initialization</td>
<td>34</td>
</tr>
<tr>
<td>1. Switch to ephemeris based Nadir-Sun commanding</td>
<td></td>
</tr>
<tr>
<td>2. Start gyro bias estimation</td>
<td></td>
</tr>
<tr>
<td>Transition to inertial tracking mode</td>
<td>316</td>
</tr>
<tr>
<td>1. Maintain Nadir-Sun attitude</td>
<td></td>
</tr>
<tr>
<td>Begin inertial profile</td>
<td>388</td>
</tr>
<tr>
<td>180 Deg Y-axis slew maneuver (about string axis)</td>
<td>388</td>
</tr>
<tr>
<td>Gyro bias estimation halted – no sensor data</td>
<td>397</td>
</tr>
<tr>
<td>Return to Nadir-Sun attitude</td>
<td>588</td>
</tr>
<tr>
<td>End inertial profile &amp; test</td>
<td>788</td>
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</tbody>
</table>
Closed Loop Performance
Earth Acquisition

- Differences attributed to:
  - Larger inertia for hardware test due to under estimate of platform inertia
  - String disturbance torque in hardware test but not simulation
  - Earth sensor model mismatch at large off center angles
Closed Loop Performance

Inertial Tracking

- During Slew about +Y the controller’s integral term saturated due to string restoring torque
- Slew about -Y did not exhibit this problem because it was “unwinding” the string so the restoring torque wasn’t a big factor
- Attitude control error is in agreement with simulation predicts despite larger disturbance environment
Gyro Bias Estimation Results

- Simulation “True” bias selected based on mean value of test estimate during steady state for comparison purposes
- Note that test estimate is likely noisier in roll and pitch due to swinging of the test platform on the string (and resulting variations in the earth sensor readings)
- Results shown are for when both Earth and Sun data are being used for the estimate
- Behavior matches simulation predicts fairly well
- Verifies estimation algorithm, sensor alignments, database selections
Thank you