SpaceCube: A Family Of Reconfigurable Hybrid On-Board Science Data Processors

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The Challenge

The next generation of NASA science missions will require “order of magnitude” improvements in on-board computing power

Mission Enabling Science Algorithms & Applications

- Real-time Wavefront Sensing and Control
- On-Board Data Volume Reduction
- Real-time Image Processing
- Autonomous Operations
- On-Board Product Generation
- Real-time Event / Feature Detection

- Real-time “Situational Awareness”
- Intelligent Data Compression
- Real-time Calibration / Correction
- On-Board Classification
- Inter-platform Collaboration
Our Approach

• The traditional path of developing radiation hardened flight processor will not work ... they are always one or two generations behind
• Science data does not need to be 100% perfect, 100% of the time ... occasional “blips” are OK, especially if you can collect 100x MORE DATA using radiation tolerant* processing components
• Accept that radiation induced upsets will happen occasionally ... and just deal with them
• Target 10x to 100x improvement in “MIPS/watt”

*Radiation tolerant – susceptible to radiation induced upsets (bit flips) but not radiation induced destructive failures (latch-up)
Our Solution

SpaceCube: a high performance reconfigurable science data processor based on Xilinx Virtex FPGAs

- Hybrid processing ... CPU, DSP and FPGA logic
- Integrated “radiation upset mitigation” techniques
- SpaceCube “core software” infrastructure
- Small “critical function” manager/watchdog
- Standard interfaces

Note: SpaceCube 2.0 and SpaceCube Mini can be populated with either commercial Virtex 5 FX130T parts or radiation hardened Virtex 5 QV parts ... offering system developers the option of trading computing performance for radiation performance
Commercial Processor Trend

- "Fastest" consumer CPU in 2011

Graph showing the trend of MIPS over time, starting from Intel 286 in 1975 to Intel Core i7 980 (Hex core) in 2011.
Space Processor Trend

- Shuttle
- Galileo
- HST
- Pathfinder
- ISS
- EOS Terra
- EOS Aqua
- New Horizons
- Mars Rovers
- MRO
- LRO
- DAWN
- SDO
- GPM
- Curiosity
Processor Trend Comparison

Processor: Intel Core i7 3960X (Hex core)

Processor: Intel Core i7 980 (Hex core)

Processor: Intel Core i7 920 (Quad core)

Processor: Intel Core 2 QX9770 (Quad core)

Processor: Intel Core 2 (Quad core)

Processor: AMD Athlon FX

Processor: AMD Athlon XP

Processor: Intel Pentium 4

Processor: Intel Pentium III

Processor: PowerPC 750

Processor: Intel Pentium Pro

Processor: Intel Pentium

Processor: Galileo

Processor: HST

Processor: ISS

Processor: EOS Terra

Processor: Mars Rovers

Processor: MRO

Processor: New Horizons

Processor: DAWN

Processor: LRO

Processor: SDO

Processor: Curiosity


MIPS: 0, 50,000, 100,000, 150,000, 200,000

1,000x
SpaceCube Closes the Gap

Next Generation Mission Processing Requirements (STMD, Decadal Surveys)

SpaceCube v2.0
SpaceCube v1.0

1,000x Gap

Space Processor Trend

Commercial Processor Trend

## Processor Comparison

<table>
<thead>
<tr>
<th>Processor</th>
<th>MIPS</th>
<th>Power</th>
<th>MIPS/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIL-STD-1750A</td>
<td>3</td>
<td>15W</td>
<td>0.2</td>
</tr>
<tr>
<td>RAD6000</td>
<td>35</td>
<td>15W</td>
<td>2.33</td>
</tr>
<tr>
<td>RAD750</td>
<td>300</td>
<td>15W</td>
<td>20</td>
</tr>
<tr>
<td>LEON 3FT</td>
<td>75</td>
<td>5W</td>
<td>15</td>
</tr>
<tr>
<td>LEON3FT Dual-Core</td>
<td>250</td>
<td>10W</td>
<td>25</td>
</tr>
<tr>
<td>BRE440 (PPC)</td>
<td>230</td>
<td>5W</td>
<td>46</td>
</tr>
<tr>
<td>Maxwell SCS750</td>
<td>1200</td>
<td>25W</td>
<td>48</td>
</tr>
<tr>
<td>SpaceCube 1.0</td>
<td>3000</td>
<td>7.5W</td>
<td>400</td>
</tr>
<tr>
<td>SpaceCube 2.0</td>
<td>6000</td>
<td>10W</td>
<td>600</td>
</tr>
<tr>
<td>SpaceCube Mini</td>
<td>3000</td>
<td>5W</td>
<td>600</td>
</tr>
</tbody>
</table>
## Algorithm Acceleration

<table>
<thead>
<tr>
<th>Application</th>
<th>Xilinx Device</th>
<th>Acceleration vs CPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR Altimeter</td>
<td>Virtex-4 FX60</td>
<td>79x vs PowerPC 405 (250MHz, 300 MIPS)</td>
</tr>
<tr>
<td>RNS GNFIR FPU, Edge</td>
<td>Virtex-4 FX60</td>
<td>25x vs PowerPC 405 (250MHz, 300 MIPS)</td>
</tr>
<tr>
<td>HHT EMD, Spline</td>
<td>Virtex-1 2000</td>
<td>3x vs Xeon Dual-Core (2.4GHz, 3000 MIPS)</td>
</tr>
<tr>
<td>Hyperspectral Data Compression</td>
<td>Virtex-1 1000</td>
<td>2x vs Xeon Dual-Core (2.4GHz, 3000 MIPS)</td>
</tr>
<tr>
<td>GOES-8 Ground System Sun correction</td>
<td>Virtex-1 300E</td>
<td>6x vs Xeon Dual-Core (2.4GHz, 3000 MIPS)</td>
</tr>
</tbody>
</table>

- All functions involve processing large data sets (1MB+)
- All timing includes moving data to/from FPGA
- **SpaceCube 2.0 is 4x to 20x more capable than these earlier systems**
Being Reconfigurable …

... equals BIG SAVINGS (both time and money)

During mission development and testing
- Design changes without PCB changes
- “Late” fixes without breaking integration

During mission operations
- On-orbit algorithm updates
- Adaptive processing modes

From mission to mission
- Avionics reconfigured for new mission
Past Research / Missions

2006 - 2012
On-Board Data Reduction

Accomplishments

SAR Nadir Altimetry Results (FY07)

On-board processing yields lossless 6:1 data volume reduction

Difference < 0.1%
On-Board Data Reduction (cont.)

Accomplishments

SAR Mapping Results (FY09)

Original Matlab Output

On-board product generation yields factor of 165x data volume reduction

SpaceCube Output

Difference < 1%
On-Board Product Generation

• Classification
• Product Generation
• Event Detection
• Atmospheric Correction
SpaceCube Family Overview

v1.0
- 2009: STS-125
- 2009: MISSE-7
- 2013: STP-H4
- 2016: STP-H5

v1.5
- 2012: SMART

v2.0-EM
- 2013: STP-H4
- 2016: STP-H5

v2.0-FLT
- 2015: GPS Demo
  - Robotic Servicing
  - Numerous proposals for Earth/Space/Helio
“First Generation” Systems

SpaceCube 1.0a

Prototype

SpaceCube 1.5

SpaceCube 1.0b
On-Board Image Processing

Long Range Camera on Rendezvous

Short Range Camera on Deploy

Flight Image

RNS Tracking Solution

Flight Image

RNS Tracking Solution

HST-SM4

GSFC SpaceCube 1.0a - Hubble SM 4 (May 2009):
• Autonomous Rendezvous and Docking Experiment
• Hosted camera AGC and two Pose algorithms

STS-125 Payload Bay
MISSE7/8 SpaceCube
SpaceCube Upset Mitigation

“First” to reprogram an FPGA in space!

GSFC SpaceCube 1.0b (Nov 2009):
• “Radiation Hardened by Software” Experiment (RHBS)
• Autonomous Landing Application
• Collaboration with NRL and the DoD Space Test Program (STP)

MISSE7/8

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>ISS</td>
</tr>
<tr>
<td>Days in orbit</td>
<td>1800+</td>
</tr>
<tr>
<td>Total SEUs detected &amp; corrected</td>
<td>200+</td>
</tr>
<tr>
<td>Total SEU-induced resets</td>
<td>6</td>
</tr>
<tr>
<td>Total SEU-induced reset downtime</td>
<td>30 min</td>
</tr>
<tr>
<td>Total processor availability</td>
<td>99.99%</td>
</tr>
</tbody>
</table>
On-Orbit Upset Locations
On-Orbit Upset Locations
SMART Sounding Rocket Experiment

SpaceCube 1.5 on the SMART sounding rocket payload (SubTec-5, launched June 2011):
- Multi-function avionics
- Collaboration with ORS
SMART Video

SpaceCube 1.5 - SMART GigE Camera Clip
NASA Wallops Flight Facility - June 10, 2011
GSFC Satellite Servicing Lab

Testing with simulated 6-DOF motion of Argon and Target

- Rotopod and FANUC motion platforms simulate target-sensor dynamics
- Up to 13 m separation possible

Testing conducted at GSFC in January-February 2012

- Motion includes closed-loop approach and non-cooperative “tumble”
- Open loop testing to characterize sensor/algorithm performance
- Closed-loop tests - evaluate end-to-end system (sensors, algorithms, control law) in real time
Current Research / Missions

2013 - 2014
ISS SpaceCube Experiment 2.0

FireStation

SpaceCube 2.0

Camera Box

CIB

FireStation Antenna

Image Credit: DoD Space Test Program
STP-H4 / ISE 2.0 Location & FOV

- SpaceCube 1.0b
- ELC-2
- ELC-3
- Columbus-EPF
- JEM-EF
- MISSE-7 & MISSE-8

ISS Flying Towards You

STP-H4/ISE 2.0
ELC-1
Launched Aug 2013
Nadir/Ram/Outboard ExPA Location

Image Credit: DoD Space Test Program
Camera 1 – SpaceCube Earth View, 8° FOV (35mm lens, ~40m/pixel)
Manta G-125, 1280 x 960 px, up to 30 fps
Camera 2 – SpaceCube Earth View, 32° FOV (8.5mm lens, ~175m/pixel)
Manta G-125, 1280 x 960 px, up to 30 fps
Camera 3 – SpaceCube Earth View, 53° FOV (6mm lens, ~300m/pixel)
Manta G-125, 1280 x 960 px, up to 30 fps
ISE 2.0 on ISS – August 2013

ISS SpaceCube Experiment 2.0 (ISE 2.0) on STP-H4

Camera Box
FireStation
SpaceCube 2.0
EHD Plate
SpaceCube 1.0
STP-H5 On-Orbit Location
ISS SpaceCube Experiment – Mini (ISEM)

MISSE-8
ELC-2

STP-H4
ELC-1

STP-H5
ELC-1

Image Credit: DoD Space Test Program
STP-H5 Location on ELC1

STP-H5 to be installed at this location

Image Credit: DoD Space Test Program
STP-H5 Pallet Layout

Image Credit: DoD Space Test Program
STP-H5 Configuration Overview

ISS/ELC

SpaceCube CIB (1.0)

ISEM Raven (2.0)

ISEM Stack (Mini & CSP)

DoD Exp 1

DoD Exp N
ISEM Experiment Overview

- Electro-Hydro Dynamic (EHD) thermal fluid pump experiment
- Fabry-Perot Spectrometer (FPS) for atmospheric methane
- SpaceCube Mini (Virtex 5) science data processor
- CHREC* Space Processor (CSP) and visible camera (Zynq)

*CHREC – National Science Foundation Center for High-performance Reconfigurable Computing (www.chrec.org)
ISEM Stack Components

- SpaceCube Mini
- Power Modules
- FPS
- EHD
- CSP
ISEM FPS Science

Fabry-perot Spectrometer Measures Absorption By Atmospheric Gases In Sunlight Reflected Off The Earth
Raven is a technology development experiment to the ISS with the objective to

- Demonstrate cooperative and non-cooperative rendezvous can be accomplished with similar hardware suite
- Provide an orbital testbed for servicing-related relative navigation algorithms and software
- Demonstrate an independent visiting vehicle (VV) monitoring capability

Raven utilizes a complex, but compact, complement of hardware to accomplish these goals:

- Two-axis gimbal provides sensor pointing
- Relative navigation sensors provide tracking in three bands—visible, SWIR, and LWIR
- High-performance SpaceCube avionics provide efficient, reliable, and reconfigurable computing environment
- State-of-the-art pose and navigation algorithms provide non-cooperative operations

Raven tracking representative visiting vehicle
Raven Movie
More SpaceCube Applications

- Navigator GPS
- Goddard Reconfigurable Solid-state Scanning LiDAR (GRSSLi)

SpaceCube Navigator GPS (sounding rocket flight August 2015)

GRSSLi LIDAR High-Speed Digitizer Card

GRSSLi SpaceCube and Front End Box
Future Research / Missions?

2014 – 20??
SpaceCube 2.0 Flight Unit

SpaceCube 2.0 Flight Processor

Four Card Flight Unit
- Dimensions: 5 x 7 x 9 inches
- Weight: 5.8 kg
- Power: 20 watts (typical)
Robotic Satellite Servicing

- Autonomous rendezvous & docking
- Robotic servicing

- Inspect
- Refuel
- Repair
- Replace
- Relocate
Imaging Spectrometers

- Direct broadcast
- Real-time products
- Data volume reduction
- Adaptive processing
- Sensor webs

Image Credit: HyspIRI Mission Concept Team

Evaporative Stress Index
1 month composite ending September 5, 2012

Standardized ET/PET anomalies

-2σ < -1σ 0 +1σ > +2σ
**Terrain Relative Navigation (TRN)**

- Works by taking images during parachute descent and matching them to an onboard map
  - Uses a dedicated compute element and camera
  - Yields a position solution
- Performs terrain relative navigation while the spacecraft is priming the descent engines
- Executed by the Lander Vision System (LVS)

**Multi-Point Divert**

- Uses position solution and list of safe landing locations to select a landing target
- Augments original MSL backshell avoidance divert (requires slightly higher backshell separation altitude)
- Lives within MSL fuel and control authority constraints

Credit: JPL Mars EDL Team
Mars Sample Caching
High Priority Sites

- TRN Enables Landing at NE Syrtis and E Margaritifer
- MSL could not land at these sites

East Margaritafer Terra

| East Margaritafer Terra | 2.2%  | 9.2% |

Northeast Syrtis

| Northeast Syrtis | 2.9% | 8.7% |

End of mission hazard
Not end of mission, but hard to drive
Landing hazards, but OK to land on
No landing hazards

Credit: JPL Mars EDL Team
Real-time Mars Terrain Analysis

Figure by Garvin for MSL Science team: MARDI-based DEM derived from sidewalk video imaging mode data collection on the 22 m drive to “Book Cliffs” illustrating the power of fixed-nadir video imaging for terrain analysis of Mars in support of engineering (geotechnical) assessments.

* NOTE: DEM made from 26 overlapping MARDI video frames (nadir viewing)
More Rover Applications?

Fast traverse
Terrain mapping (while driving)
Background science (while driving)
Entry/Descent/Landing documentation (video)
  - Landing
  - Parachute release
  - Sky Crane

On-board processing for efficient use of downlink

Image Credit: JPL / MSSS MARDI Team
SpaceCube “Next”

• Xilinx Zynq?
• Multi-core / Many-core?
• GPU?
• Other devices (Altera, etc.)?
Future Collaborations?

- NASA Centers
- DoD Space Test Program
- CHREC (Florida, BYU)
- CubeSats
- Commercialization
- Universities / Industry
- You?
Conclusions

SpaceCube is a MISSION ENABLING technology

• Delivers 10x to 100x on-board computing power
• Cross-cutting (Earth/Space/Planetary/Exploration)
• Being reconfigurable equals BIG SAVINGS
• Past research / missions have proven viability
• Ready for infusion into operational missions
The SpaceCube Team
Thanks you! Questions?

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Special thanks to our sponsors: NASA/GSFC IR&D, NASA Satellite Servicing Capabilities Office (SSCO), NASA Earth Science Technology Office (ESTO), DoD Space Test Program (STP), DoD Operationally Responsive Space (ORS)