SpaceCube Technology Brief
Hybrid Data Processing System

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SpaceCube Overview

Heritage
• GOAL: close the gap with commercial processors while retaining reliability
• Started in 2006 at GSFC as R&D
• 38+ Xilinx device-years on orbit
• 22 Xilinxes in space by 2016
• 8 systems in space by 2016
• Various R&D efforts on hardware acceleration

Hybrid Data Processing
• Parallel data processing:
  • FPGA + DSP + Processor(s)
• SpaceCube can move 3,000x more data than a sequential processor per clock cycle

SpaceCube v2.0
• Currently TRL-7
• Leverages 10 years of design heritage and operation experience
• $10M+ of NRE
• Adopted by SSCO for all missions
• IPC 6012B Class 3/A PWB Reliability
• Modular: 9 Mission-Unique I/O cards
• Run-Time Reconfigurable

Xilinx Virtex-5 FPGA

SpaceCube v2.0

SpaceCube is a Mission-Enabling Technology
Commercial Processor Trend

“Fastest” consumer CPU in 2011
Space Processor Trend
Processor Trend Comparison
Processor Trend Comparison

- SCS750
- 8086
- RCA 1802
- 1750A
- RAD6000
- RAD750
- 386
- 1,000x Gap
- 16-Core SPARC T3
- Six-Core Core i7
- Six-Core Xeon 7400
- Dual-Core Itanium 2
- AMD K10
- POWER6
- Itanium 2 with 9MB cache
- AMD K10
- Six-Core Core i7 (Quad)
- Itanium 2
- AMD K8
- Barton
- Atom
- Pentium 4
- AMD K7
- AMD K6-III
- AMD K6
- Pentium III
- Pentium II
- AMD K5
- Pentium
- AMD K5
- 68000
- 8086
- 80286
- 80386
- 80486
- 80186
- 6800
- 8085
- Z80
- MOS 6502
- 4004
- RCA 1802
- 10-Core Xeon Westmere-EX
- 8-core POWER7
- Quad-core z196
- Quad-Core Itanium Tukwila
- 8-Core Xeon Nehalem-EX
- Core Opteron 2400
- (Quad)
Future Space Processing Requirement

Next Generation Mission Processing Requirements (Decadal Surveys)

Transistor count

1,000x Gap

SCS750

RAD6000

RAD750

8086

386

1750A

RCA 1802

SpaceCube Closes the Gap

Next Generation Mission Processing Requirements (Decadal Surveys)

1,000x Gap

SCS750

RAD750

RAD6000

1750A

RCA 1802

SpaceCube v2.0

SpaceCube v1.0

8086

RCA 1802

RAD6000

1750A

RCA 1802

RAD750

RAD6000

1750A

RCA 1802

RAD750

RAD6000

1750A

RCA 1802

RAD750

RAD6000

1750A

RCA 1802
SpaceCube Family Overview

v1.0
2009 STS-125
2009 MISSE-7
2013 STP-H4
2016 STP-H5
2018 STP-H6

v1.5
2012 SMART (ORS)

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

v2.0-FLT
2017 RRM3
2018 STP-H6 (NavCube)
2018 NEODaC
2020 Restore-L
Many NASA proposals

v2.0 Mini
2016 STP-H5
Many NASA proposals
Example SpaceCube Processing

- Real-Time Image Tracking of Hubble
- Fire Classification
- Gigabit Instrument Interfacing

- Xilinx ISS Radiation Data
- Spectrometer Data Reduction
- Image Compression
On-Board Image Processing

→ Successfully tracked Hubble position and orientation in real-time operations
→ FPGA Algorithm Acceleration was required to meet 3Hz loop requirement

<table>
<thead>
<tr>
<th>Rendezvous</th>
<th>Deploy (Docking Ring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Typical space flight processors are 25-100x too slow for this application</td>
<td></td>
</tr>
</tbody>
</table>
Processor Card

- 2x Xilinx Virtex-5 (QR) FX130T FPGAs
- 1x Aeroflex CCGA FPGA
  - Xilinx Configuration, Watchdog, Timers
  - Auxiliary Command/Telemetry port
- 1x 128Mb PROM, contains initial Xilinx configuration files
- 1x 16MB SRAM, rad-hard with auto EDAC/scrub feature
- 4x 512MB DDR SDRAM
- 2x 4GB NAND Flash
- 16-channel Analog/Digital circuit for system health
- Optional 10/100 Ethernet interface
- Gigabit interfaces: 4x external, 2x on backplane
- 12x Full-Duplex dedicated differential channels
- 88 GPIO/LVDS channels directly to Xilinx FPGAs
- Mechanical support for heat pipes and stiffener for Xilinx devices

Power Draw: 6-15W
Weight: 0.98-lbs
22 Layers, Via-in-Pad
IPC 6012B Class 3/A

2014 Global Award: Most innovative design worldwide in the Military/Aerospace sector
Example Mission-Unique I/O Cards

- Restore-L Video/Spacecraft Interface Card
- GPS RF Front-End Interface Card
- LIDAR Digitizer, Front-End, and Laser Card
Spinoff Technologies

GPS Receiver – L1/L2C Tracking

LIDAR Instrument – Configurable Resolution
Restore-L Satellite Servicing Mission

High Level Requirements:
• Interface with Spacecraft and Payload Busses
• Interface with vision sensors
• Host Relative Proximity Operations application
• Host Robotic Manipulation Control application

Restore-L will fly 21 Xilinx Virtex-5 FPGAs
What About Radiation Effects??

Restore-L SpaceCube Data Processing Architecture

If Spare is “Cold”, then worst case error probability: $P_e(sys) = [8 \times P_e(Xilinx) + 16 \times P_e(DDR)]$
Establishing SEE Error Rates

**Assessment Process**

- Radiation Environment
- Establish Device WCA
- Establish System WCA
- Establish Application WCA
- ID Functional Independence
- Selective FPGA Mitigation

**NASA Risk Assessment**

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Safety</th>
<th>Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Very High</td>
<td>$P_{SE} &gt; 10^{-1}$</td>
<td>$P_T &gt; 50%$</td>
</tr>
<tr>
<td>4 High</td>
<td>$10^{-2} &lt; P_{SE} \leq 10^{-1}$</td>
<td>$25% &lt; P_T \leq 50%$</td>
</tr>
<tr>
<td>3 Moderate</td>
<td>$10^{-3} &lt; P_{SE} \leq 10^{-2}$</td>
<td>$15% &lt; P_T \leq 25%$</td>
</tr>
<tr>
<td>2 Low</td>
<td>$10^{-5} &lt; P_{SE} \leq 10^{-3}$</td>
<td>$2% &lt; P_T \leq 15%$</td>
</tr>
<tr>
<td>1 Very Low</td>
<td>$10^{-6} &lt; P_{SE} \leq 10^{-5}$</td>
<td>$0.1% &lt; P_T \leq 2%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time (s)</th>
<th>Device WCA</th>
<th>PCC WCA</th>
<th>RPO PCC</th>
<th>RSW PCC</th>
<th>RPO + RSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>one orbit (96 minutes)</td>
<td>5760</td>
<td>0.484%</td>
<td>1.934%</td>
<td>1.074%</td>
<td>0.222%</td>
<td>1.296%</td>
</tr>
<tr>
<td>Rendezvous (30 min)</td>
<td>1800</td>
<td>0.151%</td>
<td>0.604%</td>
<td>0.336%</td>
<td>0.069%</td>
<td>0.405%</td>
</tr>
<tr>
<td>Capture (77 sec)</td>
<td>77</td>
<td>0.006%</td>
<td>0.026%</td>
<td>0.014%</td>
<td>0.003%</td>
<td>0.017%</td>
</tr>
</tbody>
</table>

Note: assumes BRAM Mitigation

Note: Actual utilization for RPO and RSW PCCs as of 4/18/2016
Note: assumes RPO & RSW PCCs must be error-free for full operation
Robotic Refueling Mission SpaceCube

High Level Requirements:
• Interface with ISS and RRM3 instruments:
  • Cameras, thermal imager, motors
• Monitor/Control cryocooler and fuel transfer
• Stream video data
• Motor control of robotic tools
• Host Wireless Access Point

1553/Ethernet/Digital Card

Analog Card
NEODaC Instrument Development

8x 3K x 3K detectors

- Detect and Characterize NEOs
- Working with “Partner” organization on complex detector instrument
- SpaceCube FPGAs being used to solve very challenging avionics requirements and host on-board data processing applications and compression
- Successful Detector readout with SpaceCube completed
- March 2018 Delivery

Xilinx Driver: 1.6Gbps, 1300mV, 17%

HSCSI Link Test Results

<table>
<thead>
<tr>
<th>Transmitter Swing (mV)</th>
<th>Transmitter % Pre-emphasis</th>
<th>Test Duration</th>
<th>Bit Error Count</th>
<th>BER (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0</td>
<td>6hr</td>
<td>32</td>
<td>9.2E-13</td>
</tr>
<tr>
<td>500</td>
<td>8</td>
<td>18hr</td>
<td>0</td>
<td>9.6E-15</td>
</tr>
<tr>
<td>800</td>
<td>0</td>
<td>4hr</td>
<td>4</td>
<td>1.7E-13</td>
</tr>
<tr>
<td>800</td>
<td>25</td>
<td>20hr</td>
<td>0</td>
<td>8.7E-15</td>
</tr>
<tr>
<td>1300</td>
<td>17</td>
<td>20hr</td>
<td>0</td>
<td>8.7E-15</td>
</tr>
<tr>
<td>1300</td>
<td>0</td>
<td>19hr</td>
<td>52</td>
<td>4.7E-13</td>
</tr>
</tbody>
</table>

*Note: BER calculation assumes at least 1 error
• 58-hours of error-free transmission
SpaceCube on the ISS

ISS Flying Towards You

Image Credit: DoD Space Test Program
SpaceCube v1.0

MISSE-7/8 ISS Payload

- STS-125 Shuttle Payload Bay

- 7 years of operation
- 4x Virtex-4 XC4VFX60: 0.1 SEU/FPGA/Week
- 2x on-orbit file uploads and reconfiguration
STP-H4 ISS Payload

2 years of operation. 3x Virtex-5 XC5VFX130T: 1 SEU/FPGA/Week
Successful on-orbit file upload and reconfiguration
The Space Test Program-H5 (STP-H5) external payload, a complement of 13 unique experiments from seven government agencies, is integrated and flown under the management and direction of the Department of Defense’s Space Test Program.

SpaceX Launch Scheduled November 11, 2016
Questions?