SPACECUBE OVERVIEW AND USE OF COTS PARTS IN SPACE

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Embedded Processing Group

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https://spacecube.nasa.gov | Embedded Processing Group
Outline

I. Background

II. SpaceCube Introduction

III. SpaceCube Design Approach

IV. SpaceCube Flight History

V. Use of COTS Parts

VI. Conclusion
Embedded Processing Group (EPG)

EPG Group Specializes in Embedded Development
- Hardware acceleration of algorithms and applications
- Intelligence, autonomy, and novel architectures
- Flight software integration for development platforms
- Advanced architectures and research platforms

Advanced Platforms for Spaceflight
- SpaceCube v1.0
- SpaceCube v2.0 and v2.0 Mini
- SpaceCube v3.0 and v3.0 Mini
- SpaceCube Mini-Z and Mini-Z45

Key Tools and Skills
- **Flight Software**: cFE/cFS, driver integration, flight algorithms
- **GSE**: COSMOS, GMSEC, system testbeds
- **FPGA Design**: Hardware acceleration, fault-tolerant structures
- **Mission Support**: Supporting flight cards, algorithm development
- **On-board Autonomy and Analysis**: deep-learning and machine-learning frameworks, unique architectures
Background

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

Mission Enabling Science Algorithms & Applications

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

- On-Board Classification
- Real-time “Situational Awareness”
- “Intelligent Instrument”
  Data Selection / Compression
- Real-time Calibration / Correction
- Inter-platform Collaboration
Background (for context)

• SpaceCube’s first mission use was for the HST Servicing Mission 4....which came with the strict HST design and mission assurance mindset of:
  – Thou shalt fly only Level 1 parts → major screening/qual plan for Xilinx Virtex-4 FX60 FPGAs
  – Thou shalt fly only IPC 6012B Class 3/A circuit boards → much time wasted
  – Thou shalt mitigate ALL possibilities of SEUs → QMR was baseline mitigation....QMR!!!

• What happened: we nearly didn’t make it due to unneeded requirements
  – Schedule for screening started to slip and costs were sky-rocketing
    → terminated the effort
  – Cost/schedule growth for figuring out 6012 Class 3/A for a back-to-back 1mm-pitch FPGA
    → went with Class 2/3
  – Converging on a QMR voting structure for 4 PowerPC processors was more challenging than “sold”, risking not making the mission
    → single-string, simple watchdog, internal TMR’d self scrubbing

• Did I mention this was for an Autonomous docking tech demo that only had to operate for roughly 24 hours???
The General Mentality in 2007....maybe still?

Unless you have 6012 Class 3/A circuit boards and Level 1 or 2 parts, it will never fly and never work
Our Solution

SpaceCube

A family of NASA developed space processors that established a hybrid-processing approach combining radiation-hardened and commercial components while emphasizing a novel architecture harmonizing the best capabilities of CPUs, DSPs, and FPGAs.

High-performance reconfigurable science / mission data processor based on Xilinx FPGAs

- Hybrid processing - algorithm profiling and partitioning to CPU, DSP, and FPGA logic
- Integrated “radiation upset mitigation” techniques
- SpaceCube “core software” infrastructure (SCSDK) – Example (cFE/cFS and “SpaceCube Linux” with Xenomai)
- Small “critical function” manager/watchdog
- Standard high-speed (multi-Gbps) interfaces
Our Approach

01 The traditional path of developing radiation-hardened flight processor will not work ... they are always one or two generations behind

02 Use latest radiation-tolerant* processing elements to achieve massive improvement in computing performance per Watt (for reduced size/weight/power)

03 Accept that radiation-induced upsets may happen occasionally and just deal with them appropriately ... any level of reliability can be achieved via smart system design!

*Radiation tolerant – susceptible to radiation-induced upsets (bit flips) but not radiation-induced destructive failures
Device Comparisons

GOPS = Giga-Operations Per Second

BAE Systems RAD750  Cobham GR712RC  Cobham GR740  BAE Systems RAD5545  PowerPC 750FX (SCS750)  Freescale MPC8548E  Microsemi RTG4  Xilinx Virtex-5 QV FX130  Virtex-5 Q FX130T EF1738-1  Zynq MPSoC 7EG*  Kintex UltraScale KU060*

8-Bit Integer
16-Bit Integer
32-Bit Integer
Single-Precision Floating Point
Double-Precision Floating Point

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*UltraScale results are an estimate based off of existing data, new metrics are in progress but not currently available

SpaceCube Family provides more power efficient processing
Reconfigurability

**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 hybrid algorithm updates
- Adaptive processing modes
  - hi-reliability vs. high-performance
  - intelligently adapt to current environment

**From mission to mission**
- Same avionics reconfigured for new mission
Reliability Analysis (SpaceCube v2.0)

SpaceCube is rooted on solid design, analysis and test practices

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts Stress and De-rating</td>
<td>Complete</td>
</tr>
<tr>
<td>Signal/Power Integrity</td>
<td>Complete</td>
</tr>
<tr>
<td>Reliability Block Diagram</td>
<td>Complete (specific to Restore-L use)</td>
</tr>
<tr>
<td>Worst Case Circuit Analysis</td>
<td>Complete</td>
</tr>
<tr>
<td>FMECA</td>
<td>Complete (specific to Restore-L use)</td>
</tr>
<tr>
<td>Radiation TID Analysis</td>
<td>Complete</td>
</tr>
<tr>
<td>Radiation SEE Rate Estimation</td>
<td>Complete for Polar, ISS, Mars</td>
</tr>
<tr>
<td>Back-to-Back CGA Solder Joint Fatigue</td>
<td>Complete</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWB Coupon Tests</td>
<td>Complete – All PASS IPC 6012B 3/A</td>
</tr>
<tr>
<td>Qual TVAC/Vibe per GEVS</td>
<td>Complete - PASS</td>
</tr>
<tr>
<td>RRM3/NavCube SpaceCube TVAC/Vibe/EMI</td>
<td>Complete - PASS</td>
</tr>
<tr>
<td>“Quick-Look” EMI/EMC</td>
<td>Complete - PASS</td>
</tr>
<tr>
<td>4x CGA Life Test Articles (-55/+100C)</td>
<td>Complete - 5x MoS factor achieved</td>
</tr>
</tbody>
</table>
Reliability Spectrum (It’s your choice)

- **Box redundancy**
- **Card redundancy**
- **Internal redundancy**
- **Higher Part levels (COTS, 3→2→1)**
- **Single string**
- **Solid Robust Design Base**

**Full TMR/NMR**
- Selective mitigation
- DDR ECC
- Fault-Tolerant processor
- Xilinx device type
- BRAM Mitigation
- Flash ECC
- Configuration Scrubbing
- SEL Monitors
- No Mitigation

The systems trades: Computing Performance vs. Radiation Performance (adding levels of radiation tolerance requires some level of resources)

Mission Examples (low end to high end, in order of increasing cost):
- **Tech Demo (Do no harm):** ISS, Single string, “EDU” parts, Config scrubbing, Flash ECC, Defense-grade Xilinx
- **Class D:** COTs, Level 3 parts, selective mitigation and redundancy, FT processing
- **Class C:** Level 3 parts, some redundancy, DDR ECC, FT processor for critical tasks, selective mitigation
- **Class A/B critical function:** Level 1/2 parts, Box redundancy, FT processor, memory EDAC, possibly full TMR

**COTS:** Use-as-is from vendor, derated, most parts have “space” equivalent which gives some sense of radiation performance, radiation assessment as needed. In some cases, DigiKey, Avnet, Mouser (as-is), “commercial” or “engineering model” versions of “flight” parts
Flight History

Closing the gap with commercial processors while retaining high reliability

- **66+ Xilinx device-years on orbit**
- **26 Xilinx FPGAs in space to date (2020)**
- **11 systems in space to date (2020)**

**SpaceCube is Mission Enabling...**

- **SpaceCube v1.0**
  - STS-125, MISSE-7, STP-H4, STP-H5, STP-H6

- **SpaceCube v1.5**
  - SMART (ORS)

- **SpaceCube v2.0-EM**
  - STP-H4, STP-H5

- **SpaceCube v2.0-FLT**
  - RRM3, STP-H6 (NavCube), NEODAC, Restore-L (Lidar)

- **SpaceCube v2.0 Mini**
  - STP-H5, UVSC-GEO

(all industry/commercial/defense grade, no additional screening)
Flight Heritage

SpaceCube on the ISS
(Past and Present)

Image Credit: DoD Space Test Program  Do Not Distribute
SpaceCube Family Flight Mission Timeline

- **SpaceCube v1.0**
- **SpaceCube v1.5**
- **SpaceCube v2.0 Mini**
- **SpaceCube v2.0-EM**
- **SpaceCube v2.0-FLT**

Year Timeline:
- 2009: STS-125/HST/RNS
- 2010: MISSE-7
- 2011: SMART
- 2012: STP-H4
- 2013: STP-H4
- 2014: STP-H5
- 2015: STP-H5
- 2016: STP-H5
- 2017: RRMI3
- 2018: XCOM/NAVCUBE
- 2019: STP-H6

Current missions:
- UVSC

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SpaceCube v2.0 Processor Card

Overview

• TRL9 flight-proven processing system with unique Virtex back-to-back installed design methodology
• 3U cPCI (190 x 100mm) size
• Typical power draw: 8-10W
• 22-layer, via-in-pad, board design
• IPC 6012B Class 3/A PWB design

Key Features

• 2x Xilinx Virtex-5 (QR) FX130T FPGAs (FX200T Compatible)
• 1x Aeroflex CCGA FPGA
  • Xilinx Configuration, Watchdog, Timers
  • Auxiliary Command/Telemetry port
• 4x 512 MB DDR SDRAM
• 2x 4GB NAND Flash
• 1x 128Mb PROM, contains initial Xilinx configuration files
• 1x 16MB SRAM, rad-hard with auto EDAC/scrub feature
• 16-channel Analog/Digital circuit for system health
• Mechanical support for heat pipes and stiffener for Xilinx devices

• External Interfaces
  • Gigabit interfaces: 4x external, 2x on backplane
  • 12x Full-Duplex dedicated differential channels
  • 88 GPIO/LVDS channels directly to Xilinx FPGAs

• Debug Interfaces
  • Optional 10/100 Ethernet interface

US Patents:
9,705,320
9,549,467
9,851,763
SpaceCube v1.0

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

1% COTS Parts

2% COTS Parts

STS-125 Shuttle Payload Bay

MISSE-7/8 ISS Payload
On-Board Image Processing

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

Typical space flight processors are 25-100x too slow for this application
STP-H4 ISS Payload

Goddard Space Flight Center

2 years of operation. 3x Virtex-5 XC5VFX130T: 1 SEU/FPGA/Week
Successful on-orbit file upload and reconfiguration

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

Camera Box
FireStation
SpaceCube 2.0
EHD Plate
SpaceCube 1.0

99% COTS Parts
1% COTS Parts

COTS HD Cameras
COTS Ethernet Switch

99% COTS Parts
1% COTS Parts
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.

2/2017 - Current
Raven Payload

**Objective:**
To advance the state-of-the-art in rendezvous and proximity operations (RPO) hardware and software by:
- Providing an orbital testbed for servicing-related relative navigation algorithms and software
- Demonstrating relative navigation to several visiting vehicles:
  - Progress
  - Soyuz
  - Cygnus
  - HTV
  - Dragon
- Demonstrating that both cooperative and non-cooperative rendezvous can be accomplished with a single similar sensor suite

**SpaceCube v2.0**
- $20M+ payload reliant on confidence in the SpaceCube computer, which in this case was pre-populated with 99% COTS Parts, and then thoroughly tested.

**Raven**
- Deployed Configuration
- Stowed Configuration
- Visible Camera
- Infrared Camera
- LIDAR

Raven installed on STP-H5 (Stowed Configuration)
Raven is currently generating valuable science that is setting the groundwork for future NASA missions that require rendezvous and proximity operations systems.

Raven demonstrated successful on-board vehicle tracking of all vehicles docking with ISS.
STP-H6 Payload

99% COTS Parts

SpaceCube v2.0 NavCube

1% COTS Parts

SpaceCube v1.0 CIB
Infusion: NavCube on X-ray Communication Experiment (XCOM)

**NavCube**: Union of Navigator GPS and SpaceCube technology
- NavCube drives electronics for Modulated X-ray Source on Space Test Program-H6 (STP-H6) as part of X-ray Communications Experiment (XCOM)
- 2016 Goddard Innovation of the Year

**Flexible SpaceCube design enabled low-cost, rapid mission development**
- Delivered Command and Data Handling FSW
- Supports inflight updates of FPGA and software
- Allowed significant software reuse leveraging key components from previous SpaceCube Missions
  - RRM3: Core FSW component
  - CeREs: AOS processing as part of cFS library
  - STP-H: Packet processing for CCSDS and STP protocols

99% COTS Parts
Accomplishments and Key Highlights: RRM3

Overview

Robotic Refueling Mission 3 (RRM3)
- Technology demonstration experiment to highlight innovative methods to store and replenish cryogenic fluid in space

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

RRM3 SpaceCube

1553/Ethernet/Digital Card

Analog Card

99% COTS Parts
Accomplishments and Key Highlights: SpaceCube Mini-Z

Overview of SpaceCube Mini-Z
- Collaborative development with NSF CHREC at University of Florida for Zynq-based 1U Board
  - Selective population scheme between commercial and rad-hard components
  - Rapid deployment prototyping
  - Convenient pre-built software packages with cFS
- Re-Envisioned to support quality-of-life upgrades and enable specific NASA mission needs

Missions and Heritage
- Launched Feb 2017 to ISS on STP-H5/CSP featuring 2 CSPv1 cards performing image processing
- Launched May 2019 to ISS on STP-H6/SSIVP featuring 5 CSPv1 for massive parallel computing
- Featured on many more...
### Time-on-orbit

<table>
<thead>
<tr>
<th>Project</th>
<th>Version</th>
<th>Part Req</th>
<th>BOM Count</th>
<th>COTS %</th>
<th>COTS Months</th>
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<tr>
<td>RNS</td>
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<td>2+</td>
<td>3700</td>
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<td>MISSE-7</td>
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<td>N/A</td>
<td>3100</td>
<td>2%</td>
<td>22320</td>
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<td>SMART</td>
<td>v1.5</td>
<td>N/A</td>
<td>1000</td>
<td>95%</td>
<td>32</td>
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<td>N/A</td>
<td>1500</td>
<td>1%</td>
<td>900</td>
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<tr>
<td>STP-H4 ISE2.0</td>
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<td>N/A</td>
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<td>99%</td>
<td>111375</td>
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<td>1%</td>
<td>1101</td>
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<td>STP-H5 Raven</td>
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<tr>
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<td>STP-H6 GPS</td>
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<td>Restore-L Lidar</td>
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<tr>
<td>STPSat6</td>
<td>v2.0 Mini</td>
<td>N/A</td>
<td>1500</td>
<td>98%</td>
<td>N/A</td>
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**Totals**

<table>
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<tr>
<th>Units Flown</th>
<th>Xilinx FPGAs</th>
<th>Xilinx Device-Years</th>
<th>Part Years</th>
<th>COTS Part Years</th>
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<tr>
<td>11</td>
<td>26</td>
<td>66.64</td>
<td>141575</td>
<td>31050</td>
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</table>

All Xilinxes flown have been unscreened.

Failures:
- Commercial Ethernet Hub on ISE2.0, 1-yr into mission
- No known EEE part failures in orbit

Also to note: We flew many COTS components on some of these projects:
- ISE2.0, SMART, and ISEM all flew COTS cameras that were ruggedized. SMART flew COTS SATA drives.
- Raven flew a $5 USB interface card to an IR sensor
- STP-H5 and -H6 have CHREC Space Processors (CSPs) that were 95% COTS components. See references for more info on CSP results (no failures to date)
- RRM3 suffered a failure that may be related to a specific COTS part, but the part was used in a stressing condition that any grade part would eventually fail.
- NavCube Commercial vendor populated PWBs
• The likelihood of other issues is much greater than a part issue
  – Workmanship, solder shorts, thermal design, cold solder joint, design deficiency, incompatible connectors, improper derating, worst case analysis deficiency, etc.
  – Lots of “parts issues” that truly were not parts issues

• Do not need to satisfy long-standing practices or views

• Robust design and test philosophy injects more confidence in end-product than what parts levels are inside the box. Part tolerance issues are flushed out of a good design and test program.

• High number of EDUs increases the sample size, and the likelihood of finding a design/part issue
**Conclusion**

*SpaceCube is a **MISSION ENABLING** technology*

- Delivers exceptional computing power in number of form factors
- Cross-cutting technology for Comm/Nav, Earth and Space Science, Planetary, and Exploration missions
- Being reconfigurable equals **BIG SAVINGS**
- Past research / missions have proven viability
- Designs support AI applications for autonomy and analysis onboard
- Successful technology transfer to industry through commercialization

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SpaceCube Publications


- T. Flatley, “Keynote 2 — SpaceCube — A family of reconfigurable hybrid on-board science data processors,” International Conference on ReConFigurable Computing and FPGAs (ReConFig14), Cancun, Mexico, Dec 8-10, 2014.


SmallSat / CubeSat Publications


