MSU Project Update: 4/26/13

“Radiation Tolerant Computing”

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Research Statement

Support the Computing Needs of Space Exploration & Science

- Computation (2,000 MIPs)
- Power Efficiency (200 MIPs/Watt)
- Mass ($100/lb by 2025)
- Reliability (99.99999% availability, instant recovery during critical operation)

Space Launch System (SLS)
MSU’s Approach

Use COTS FPGAs as the Computing Fabric
  • Take advantage of process trends for computation and power efficiency

Support Reconfigurable Computing
  • RC can increase computation through hardware optimization
  • RC can decrease power through hardware efficiency
  • RC can reduce mass through hardware reuse
  • RC enables novel fault mitigation architectures

Radiation Tolerance Through Underlying Architecture
  • Extend Triple Modular Redundancy (TMR) to include *spares*
  • Spatial Avoidance of faults to increase foreground availability
  • Continually *scrub* configuration memory in background

Radiation “Awareness” through an External Sensor
  • Provides potential fault awareness in unused regions (e.g., no TMR)
  • Direct scrubber location to decrease correction latency
Radiation Effects on Electronics

On Earth Our Computers are Protected
- Our magnetic field deflects the majority of the radiation
- Our atmosphere attenuates the radiation that gets through our magnetic field

Our Satellites Operate In Trapped Radiation in the Van Allen Belts
- High flux of trapped electrons and protons

In Deep Space, Nothing is Protected
- Radiation from our sun
- Radiation from other stars
- Particles & electromagnetic

We Care About Ionizing Radiation
- Unwanted charge injection effects semiconductors
- High energy protons, Heavy Ions
Radiation Effects on Electronics

There are two broad categories of radiation effects:

1) Total Ionizing Dose (TID)
   - Long term, cumulative damage due to lower energy proton and electrons
   - Charge trapping results in permanent damage to devices.

2) Single Event Effects (SEE)
   - By itself, does not cause permanent damage.
   - Electron/hole pair creation leads to current transients that can change the state of a logic circuit.
   - Permanent damage can result from secondary interactions (e.g., latch-up)
Radiation Effects on Electronics

TID Failure Mechanisms

1. Oxide Breakdown
   - Threshold shifts,
   - Gate leakage,
   - Timing changes
   - Actually gets better in modern processes

2. Leakage Currents
   - Hole trapping slowly “dopes” field oxides to become conductive
   - Dominant failure mechanism for commercial processes
Radiation Effects on Electronics

TID Mitigation Techniques

1. Radiation Hardened by Design (RHBD)
   - Special layout techniques in commercial process
   - Enclosed Transistors
   - Guard Rings

2. Radiation Hardened by Process (RHBP)
   - Special materials used (e.g., SOI)

3. Shielding
   - Effective for lower energy particles
   - Diminishing returns above 0.25” (Al)

MSU Approach Does Not Target TID

- Although modern COTS parts are less susceptible to TID than older parts.
- Spatial avoidance technique “could” avoid permanently damaged regions of IC
Radiation Effects on Electronics

SEE Fault Mechanisms

1. Single Event Transients (SET)
   - A pulse that can flip a gate
   - Glitches in combinational logic

2. Single Event Upset (SEU)
   - The glitch is captured by a storage device resulting in a state change

3. Single Event Functional IRQ (SEFI)
   - The system is put into a state that causes function failure that cannot be resolved through normal operation.
   - Requires reset, power cycling or reprogramming.

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MSU Project Update (4/26/13)
SEE Mitigation Techniques

1. Architecture: Triple Module Redundancy
   - Triplicate each circuit
   - Use a majority voter to produce output

2. Background Checking: Scrubbing
   - Compare contents of a memory device to a “Golden Copy”
   - Golden Copy is contained in a radiation immune technology
     (fuse-based memory, MROM, etc…)

Note: TMR+Scrubbing is the recommended mitigation approach for FPGA-based aerospace computers
Our Approach

Use COTS FPGAs

1. Increased Computation by Tracking Commercial Processes
2. Increased Power Efficiency by Tracking Commercial Processes
3. SRAM-based FPGAs support Reconfigurable Computing

However, FPGA’s are Uniquely Susceptible

1. Single Event Effects
   o SETs/SEUs in the logic blocks
   o SETs in the routing
   o SEUs in the configuration memory for the logic blocks (SEFI)
   o SEUs in the configuration memory for the routing (SEFI)

A Comprehensive, Radiation Tolerant Architecture Is Needed…

Radiation Strikes in the Circuit Fabric (Logic + Routing)
Radiation Strikes in the Configuration Memory (Logic + Routing)
Our Approach

Fault Tolerance Through Abundant Spares

1. TMR + Spares
   • 3 Tiles run in TMR with the rest reserved as spares

2. Spatial Avoidance and Background Repair
   • If TMR detects a fault, the damaged tile is replaced with a spare and foreground operation continues
   • The tile is “repaired” in the background via PR

3. Scrubbing
   • Blind scrubbing continually runs through tiles (fast)
   • Readback scrubbing periodically runs through rest of fabric (slower)

4. External Radiation Sensor
   • An external spatial radiation sensor provides awareness of potential strike

Precedent: Shuttle Flight Computer (TMR + Spare)
Our Approach

Why do it this way?

*With Spares, it basically becomes a flow-problem:*

- If the repair rate is faster than the incoming fault rate, you're safe.
- If the repair rate is slightly slower than the incoming fault rate, spares give you additional time.
- The additional time can accommodate varying flux rates.
- Abundant resources on an FPGA enable dynamic scaling of the number of spares. (e.g., build a bigger tub in real time)
Our Approach

Practical Reason’s for Doing It this Way

• Bringing up a spare tile is faster than PR (us vs. ms). This means foreground availability can be increased if repair (e.g., PR of damaged tile) is conducted in the background.

• Performing PR of the entire tile is much simpler than trying to track at a finer granularity (e.g., a specific CLB). Partial bit streams generated by the tool contain all the necessary information about a tile configuration.

• PR of a tile also takes care of both SEUs in the circuit fabric & configuration SRAM so the system doesn’t care which one occurred.

• The “spares” are held in reset to reduce power. This is as opposed to running in N-MR with every tile voting.

• The sensor is faster at detecting faults that aren’t detected by active circuitry (e.g., a spare not in TMR) and the scrubber can be intelligently directed.
Our Approach

Modeling: Is this an improvement to TMR+Srubbing?

- We use a Markov Model to predict *Mean-Time-Before-Failure*
  - 16 tile MicroBlaze system on Virtex-6 (3+13)
  - \( \lambda \) is fault rate
  - \( \mu \) is repair rate
Our Approach

Modeling: Fault & Repair Rates

Fault Rate ($\lambda$)
- Derived from CREME96 tool for 4 different orbits
- Used LET fault data from V4

<table>
<thead>
<tr>
<th>ORBITAL FAULT RATES FROM CREME96, IN FAULTS/DEVICE/SECOND</th>
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<tbody>
<tr>
<td>Average</td>
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<tr>
<td>ISS</td>
</tr>
<tr>
<td>HEO</td>
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<tr>
<td>E1P</td>
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<tr>
<td>GEO</td>
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</table>

Repair Rate ($\mu$)
- Measured empirically in lab on V6 system

<table>
<thead>
<tr>
<th>MEASURED SCRUBBING RATES, IN SECONDS</th>
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<tbody>
<tr>
<td>Clock Rate</td>
</tr>
<tr>
<td>------------</td>
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<tr>
<td>25 MHz</td>
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### Our Approach

#### Modeling Our Approach: Results

<table>
<thead>
<tr>
<th>Baseline System (TMR+scrubbing)</th>
<th>MTBF for Baseline TMR+Scrubbing System (in Seconds)</th>
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<tr>
<td></td>
<td>Average</td>
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<td>GEO</td>
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<table>
<thead>
<tr>
<th>Our System (TMR+scrubbing+spares)</th>
<th>MTBF for TMR+Scrubbing+Spares System (in Seconds)</th>
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<tbody>
<tr>
<td></td>
<td>Average</td>
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<td>盲</td>
<td>ISS</td>
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<td>GEO</td>
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#### Improvement

<table>
<thead>
<tr>
<th>Increase in MTBF after Addition of Spares (%)</th>
<th>Average</th>
<th>Worst Week</th>
<th>Peak 5 Min.</th>
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<tbody>
<tr>
<td>Blind</td>
<td></td>
<td></td>
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<tr>
<td>ISS</td>
<td>3.31E+35%</td>
<td>2356.07%</td>
<td>1067.45%</td>
</tr>
<tr>
<td>HEO</td>
<td>2.12E+08%</td>
<td>1051.79%</td>
<td>1021.88%</td>
</tr>
<tr>
<td>E1P</td>
<td>4.10E+23%</td>
<td>1127.98%</td>
<td>1031.20%</td>
</tr>
<tr>
<td>GEO</td>
<td>1.78E+37%</td>
<td>1047.86%</td>
<td>1024.00%</td>
</tr>
</tbody>
</table>

| RB                                          |         |            |             |
| ISS                                         | 1.38E+34% | 1912.98% | 1058.51% |
| HEO                                         | 2.05E+07% | 1046.32% | 1021.88% |
| E1P                                         | 1.78E+22% | 1103.77% | 1028.80% |
| GEO                                         | 7.40E+35% | 1042.38% | 1024.00% |

Ok, it looks promising…
Our Approach (2007-2010)

Let’s Build and Test…

• Initial computer architecture tested on Xilinx Virtex-5 evaluation board (2007-2010).

• Initial sensor was fabricated as a 1-sided fabrication sequence, implemented on a breadboard.

• Funded through a variety of senior design projects from NASA and research start-up funds from Montana Space Grant.

• Bench top testing

Clint Gauer (MSEE, 2010) giving demo at MSFC in 2010

“3+61 pBlaze Many Core”

“3+13 pBlaze Many Core w PR”

“Spatial Radiation Sensor”
Our Approach (2007-2010)

Let’s Build and Test…

Clint Gauer (MSU) giving Andrew Keys (NASA) Dynamic Recovery IO System Demonstration

Brock LaMeres (MSU) giving Mike Watson (NASA) the Spatial Radiation Sensor Demo
Our Approach (2011)

Build and Test Cont…

• Funding from NASA EPSCoR allows increasing TRL.

EPSCoR Project Objectives
- Increase many-tile system to TRL-5
- Fabricate spatial radiation sensor
- Integrated Sensor with many-tile system
- Test full system in cyclotron

• Functional testing still on bench top.

Todd Buerkle (MSEE, 2011) and Jenny Hane (MSEE, 2011) giving demonstrations at MSFC (2011)

“Many-Tile Integrated with Custom Sensor”
Our Approach (2011)

Build and Test Cont…

• Funding from NASA Education Office allows local balloon flights of system.

• Tests allow more sophisticated payload form-factor to be pursued.
Our Approach (2012)

Build and Test Cont…

- Cyclotron testing of sensor commences.

- Accepted into & completed NASA/LSU HASP Balloon program (130,000 ft for 10 hours)

- Grad students sent to “Rock-On” program to learn how to develop sounding rocket payloads.

- Final Payload Form Factor Pursued (e.g., cube-sat.)
Our Approach (2012)

Build and Test Cont...

- Funded by OCT-Game Changing Technology Program for sub-orbital flight demonstration (2013-2014…)

2012 News Article, Bozeman Chronicle
Our Approach (2013)

Build and Test Cont…

• Full Cube Fabrication Complete
  o Virtex-6, 9 processor many-tile system.
  o Relocation & Repair
  o Background scrubbing (blind & readback)
  o Support for 2 stacked sensors
  o Powered by single voltage (battery or provided)

Many-Tile

• Full System Test at Cyclotron

Texas A&M Cyclotron Testing

Ray Weber Assembling Stack

Justin Hogan Assembling Translation Stage

Stack Ready For Beam

MSU Stack in Beam
Our Approach (2013)

Upcoming Testing....

• Local Balloon Flights summer of 2013

• Will Fly on HASP again in September 2013

• Sounding Rocket Flight Late 2013 or early 2014
Our Approach (2014+)

What Research Has Been Uncovered?

• Faults in Routing – On-chip network could help

• Multiple Bit Upsets – Solutions for Single-Point of Failure

• New Applications of the Sensor
  • Thin, pixilated sensors to identify location AND species
  • Flexible sensing fabric for more accurate detection of ionizing radiation.
  • Dual sensor + solar cell technology

Where we want to go….

• More test data, more flights, cube-sat…
Demo