Program-level Soft Error Derating in a Brake-by-Wire System

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Motivation

Current automotive electronic systems are used to assist the driver
- Anti-lock braking system (ABS)
- Electronic stability program (ESP)
- Adaptive cruise controller (ACC)

Safe shutdown is a viable approach to handling failures in these systems

Future electronic systems will include
- Advanced active safety system (e.g. collision mitigation)
- Brake-by-wire
- Steer-by-wire

Reliability and safety requirements of automotive electronic systems will become strict because
- Advanced active safety systems take full control of vehicle
  => Failures may have more severe consequence than in today’s systems
- Brake-by-wire and steer-by-wire cannot be shut down while driving.
Brake-by-wire and Collision Mitigation System

- Full authority system - Takes control of the vehicle in emergencies
- False activations are potentially very dangerous
- Main challenge - Systems must be low cost and extremely reliable
Architectural Trade-Offs

Node replication
- Single nodes – cost-effective, but may not achieve adequate partitioning coverage
- Double nodes – provide effective physical partitioning, but costly
- Triple nodes – high degree of fault tolerance, but may be too costly

Node design
- Internally fault-tolerant – can become cost-effective with systems-on-chip solutions
- **Self-checking – minimum requirement**
- No error handling (probably not an option)

Network design
- Redundant wired network
  - Bus topology, Star topology, etc.
- Non-redundant wired network with wireless backup
Multi-layer fault-tolerance
Outline

- Objectives, assumptions and research questions
- Causes of soft errors
- Impact of soft errors in the IBM Power6 microprocessor
- Our experimental setup
- Results – impact of soft errors
- Conclusions and ongoing work
Research Objectives

- Investigate the impact of soft errors on the wheel control loop of a brake-by-wire system

- Assess the feasibility of using a microcontroller with non-prefect coverage of soft errors for the wheel control
Assumptions

- Future microcontrollers will be manufactured in circuit technologies (e.g. 90 nm or 65 nm CMOS) that are sensitive to cosmic ray induced high energy neutrons.

- These microcontrollers will be equipped with error detection and error correction mechanisms that can detect, mask, and recover from a majority of the soft errors.

- However, these mechanisms will not have prefect error coverage.

- Hence, some soft errors will propagate to the architected state (CPU registers and main memory).
Causes of soft errors

- Terrestrial cosmic rays
  - Primarily neutrons, but also protons and some pions
  - Generated when cosmic particles interact with atomic nuclei in the atmosphere

- Alpha particles
  - Typically emitted from trace amounts of Uranium and Thorium found in production and packing material

- Thermal neutrons (< 0.4 eV) captured by $^{10}$B
  $$ n + ^{10}\text{B} \rightarrow ^7\text{Li} (0.84 \text{ MeV}) + ^4\text{He} (1.47 \text{ MeV}) + \text{gamma} (0.48 \text{ MeV}) $$

- Cross-talk

- Aging faults
  - Negative Bias Temperature Instability (NBTI)
  - ....
Flux of cosmic ray-induced high-energy neutrons

- The neutron flux is influenced by latitude, longitude, altitude, atmospheric pressure, and solar activity.
- Reference point: New York City, sea-level, medium solar activity.
  - Total flux at NYC is **12.9 cm\(^{-2}\) h\(^{-1}\)** for neutron energies > 10 MeV.
  - Roughly 10 times higher at an altitude of 3000 meters.
- The neutron flux at a specific location can be calculated at http://www.seutest.com.
- More information can be found in the JEDEC Standard:
  
  JESD89A - Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices (October, 2006)
## Variations in cosmic ray neutron flux at selected locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation (m)</th>
<th>Atm depth (g/cm²)</th>
<th>Relative neutron flux compared to NYC, sea-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangkok</td>
<td>20</td>
<td>1031</td>
<td>0.52</td>
</tr>
<tr>
<td>London</td>
<td>10</td>
<td>1032</td>
<td>0.98</td>
</tr>
<tr>
<td>Johannesburg</td>
<td>1770</td>
<td>834</td>
<td>3.13</td>
</tr>
<tr>
<td>Stockholm</td>
<td>30</td>
<td>1030</td>
<td>1.04</td>
</tr>
<tr>
<td>Los Alamos</td>
<td>2250</td>
<td>786</td>
<td>5.60</td>
</tr>
<tr>
<td>South Pole Station</td>
<td>2820</td>
<td>731</td>
<td>9.81</td>
</tr>
</tbody>
</table>
Indicative Figures for the Sensitivity of CMOS circuits

- The **raw** soft error rate due to terrestrial high energy neutrons is in the order of 0.001 FIT/latch for sensitive latches in bulk CMOS.

- SOI is 2 to 8 times less sensitive than bulk.

Source: Panel presentations at SELSE-2 available at http://www.selse.org
Research Questions

- Will soft errors that reach the architected state (CPU register and main memory) cause catastrophic failures in a brake-by-wire system?

- Can we reduce the probability of such catastrophic failures to a tolerable level by software implemented error detection?
Layout of IBM Power 6 Microprocessor

Please see presentation mentioned below

From presentation at SELSE-3 by Kellington et al., *IBM POWER6 Processor Soft Error Tolerance Analysis Using Proton Radiation*, available at www.selse.org
Overall Derating of BZIP2 running on a POWER6 Processor

Please see presentation mentioned below

From presentation at SELSE-3 by Kellington et al., *IBM POWER6 Processor Soft Error Tolerance Analysis Using Proton Radiation*, available at www.selse.org
Brake-by-wire evaluation
Experimental setup

Brake system emulator
- Two single board computers based on the MPC565 from Freescale
- Brake controller
- Environment simulation model

Error injection:
- GOOFI tool
- Pre-injection analysis – injection in live data
- Single bit-flips in registers and data memory
Program derating in brake-by-wire control loop
Maximum deceleration

- 40% No impact
- 33% Detected by HW exception
- 24% Silent Data Corruption
- 3% Systems Hangs

Critical failures:
- Wheel locked for more than 0.03 s
- No brake force applied for 0.03s

Benign failure:
- 85%

Critical failure:
- 15%

Program derating $\frac{1}{(0.24 \times 0.15)} = 13.9X$
Brake-by-wire evaluation
Classification of error impact

- About 30% (1754 of 5802) of the bit-flips caused silent data corruptions
- Memory errors are more likely to cause silent data corruptions
Brake-by-wire evaluation

Critical failures

About 15% (268 of 1754) of the errors that propagated to the output resulted in a critical failure

- Wheel being locked (41% of the critical failures)
- Loss of braking (59% of the critical failures)
Brake-by-wire evaluation

Critical failures

A majority of the critical failures were caused by
- Errors injected into the stack pointer
- Errors affecting the scheduler
- Errors affecting the brake controller state
Brake-by-wire evaluation
Program-level error masking

- About 47% of the injected errors were non-effective even though errors were injected into live data

- Memory errors were masked more often than register bit-flips
  - 51% of the memory bit-flips were masked
  - 40% of the register bit-flips were masked
Conclusions

- High degree of program-level error masking
  - 47% of the injected errors did not have an effect on the produced brake command even though the bit-flips were injected into live data

- 4.6% of all injected errors resulted in critical failures
- 30% of the injected errors passed undetected
  - About 15% of these errors resulted in critical failures
- Paper available at [www.selse.org](http://www.selse.org)

- On-going work
  - Implementation of software-based error detection mechanisms
  - Evaluate error coverage (program derating) of these mechanisms
Questions?