Hardware Design Diversity

Background
- Hardware redundancy techniques
  - Duplex
  - Triple Modular Redundancy (TMR)

Outline
- Background
- Motivation
- Metric
- Reliability
- Self-testing property
- Layout Diversity
- Experiment
- Summary

Background
- Classical TMR reliability
  $R_m^3 + 3R_m^2(1 - R_m)$
- Compensating faults

Background
- Reliability analysis of TMR systems
  - Siewiorek [Siewiorek 75]
  - York [York 85]
  - Stroud [Stroud 94]
- Faults in multiple copies
  - Multiple event upsets
  - Multiple errors from single event upset
- Common-mode faults [Lala 94]
  - Affects multiple copies simultaneously
  - Generally single cause
- Design Diversity
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Design Diversity
- Independent design [Avizienis 85]
- Software
  - N-version programming
- Hardware
  - Function and its dual [Tamir 84]
- No metric available

Motivation
- ROAR project
  - Reconfiguration capabilities
- High Reliability
  - Multiple failures
  - Common-mode failures
- Metric for design diversity

A Metric
- n input combinational logic function
- Two copies
- Fault f₁ in copy 1
- Fault f₂ in copy 2
- T(f₁) = set of vectors detect f₁

\[ r = 1 - q = \left( |T(f_1) \cap T(f_2)| \right) / 2^n \]

Significance of r
- System with redundancy
  - Fault f₁ in first copy
  - Fault f₂ in second copy
  - Probability of incorrect output
- Extendible to 3 copies
- Faults considered
  - Single stuck-at

Example
- n = 3, f₁ : D / 1, f₂ : E / 0
- T(f₁) = \{000, 010, 100\}
- T(f₂) = \{001, 011, 101, 111, 110\}
- T(f₁) \cap T(f₂) = \emptyset \text{ implies } r = 0

Design 1
- n = 3, f₁ : D / 0, f₂ : E / 0
- T(f₁) = \{110\}
- T(f₂) = \{001, 011, 101, 111, 110\}
- |T(f₁) \cap T(f₂)| = 1 \text{ implies } r = 1/8
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$r$ Spectrum

$r$ Histogram

Design 2

Example

Cumulative Graph

Observations

- Replication of Design 1
- Bad
- Design 2 or diverse?
- Calculate reliability
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Reliability
- Two components
  - \( f_1, f_2 \) appear simultaneously
  - \( f_1, f_2 \) do not appear simultaneously

Reliability - First Component
- \( f_1, f_2 \) appear simultaneously at instant \( i \)

\[
\begin{array}{cccccc}
0 & \bullet & \bullet & \bullet & i & \bullet \\
\end{array}
\]

Reliability - Second Component
- \( f_1 \) appears before \( f_2 \)
- \( f_1 \) appears at instant \( i \)
- \( f_2 \) appears at instant \( j \)

Self-Testing Property
- Fault \( f_1 \) in copy 1
- Fault \( f_2 \) in copy 2
- \( T(f_1) = \) set of vectors detect \( f_1 \)
- \( T(f_1) = T(f_2) \)
  - Not self-testing when \( f_1, f_2 \) present
  - Equivalent fault pairs
  - Minimize # such pairs

Example: Design 1
- Equivalence classes
  - \( S_1 = \{A/0, B/0, D/0\} \)
  - \( S_2 = \{C/1, D/1, E/1\} \)
  - \( S_3 = \{A/1\} \)
  - \( S_4 = \{B/1\} \)
  - \( S_5 = \{C/0\} \)
  - \( S_6 = \{E/0\} \)
- # equivalent fault pairs
  - \( 3 \times 3 + 3 \times 3 + 1 + 1 + 1 = 22 \)
  - 22% fault pairs not self-testing
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Example: Design2

- Equivalence classes
  - \( S_1 = \{A/1, D/1, F/1\} \)
  - \( S_2 = \{B/1, E/1, G/1\} \)
  - \( S_3 = \{C/1, H/1\} \)
  - \( S_4 = \{A/0, B/0\} \)
  - \( S_5 = \{D/0\} \)
  - \( S_6 = \{F/0, G/0, H/0\} \)
  - \( S_7 = \{E/0\} \)
  - \( S_8 = \{C/0\} \)
- \(14.84\% \) fault pairs not self-testing

Diverse Copies

- Copy 1: Design1
- Copy 2: Design2
- 21 out of 160 pairs equivalent
- \(13.1\% \) not self-testing

Layout Diversity

- Enhance reliability for local faults
- \( q \) used to guide placement
- Issues
  - Complex routing
  - Shorts

Example

- Lower \( r \)
  - More proximity

Experiment

- ISCAS \( c17 \) circuit
- ALU181 circuit
- Original Design
- Redesign using SIS
  - Two-level minimization
  - Multi-level transformations
  - Mapped to G10p library
- Calculate spectrum
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TMR Reliability - Output 1

TMR Reliability - Output 2

c17 Spectrum - Output 2

c17 - Self-Testing Properties

- Replicated copy
  - 96 of 1296 pairs (7.4%) not self-testing
- Diverse copy
  - 82 of 1584 pairs (5.1%) not self-testing

Summary

- Design diversity in redundant systems
- Metric
- Spectrum
  - No significant change
- Self-testing property
  - Improvement
- Layout diversity
  - Needs further investigation

References