Application of the UVA Dependability Assessment Methodology to Digital Reactor Protection Systems

June 22, 2010

For ORNL

Presented by:

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Overview of the Methodology

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Current Situation: Digital I&C

- Issues
  - New digital technologies and more complex applications are being introduced into the nuclear industry
  - The new technologies can provide both operational improvement and increased reliability and safety, if implemented properly
- The advantages this new technology comes at a price.
- Significant challenges
  - Increased complexity → Impedes understanding
  - Potentially new failure modes→ How do we Know them
  - Fundamentally different behavior from analog system→ Continuous vs Discrete.
- Ever-increasing use of these new digital technologies and complex applications requires effective, objective, and repeatable review processes.
  - Tools and methodologies needed for independently evaluating new applications.

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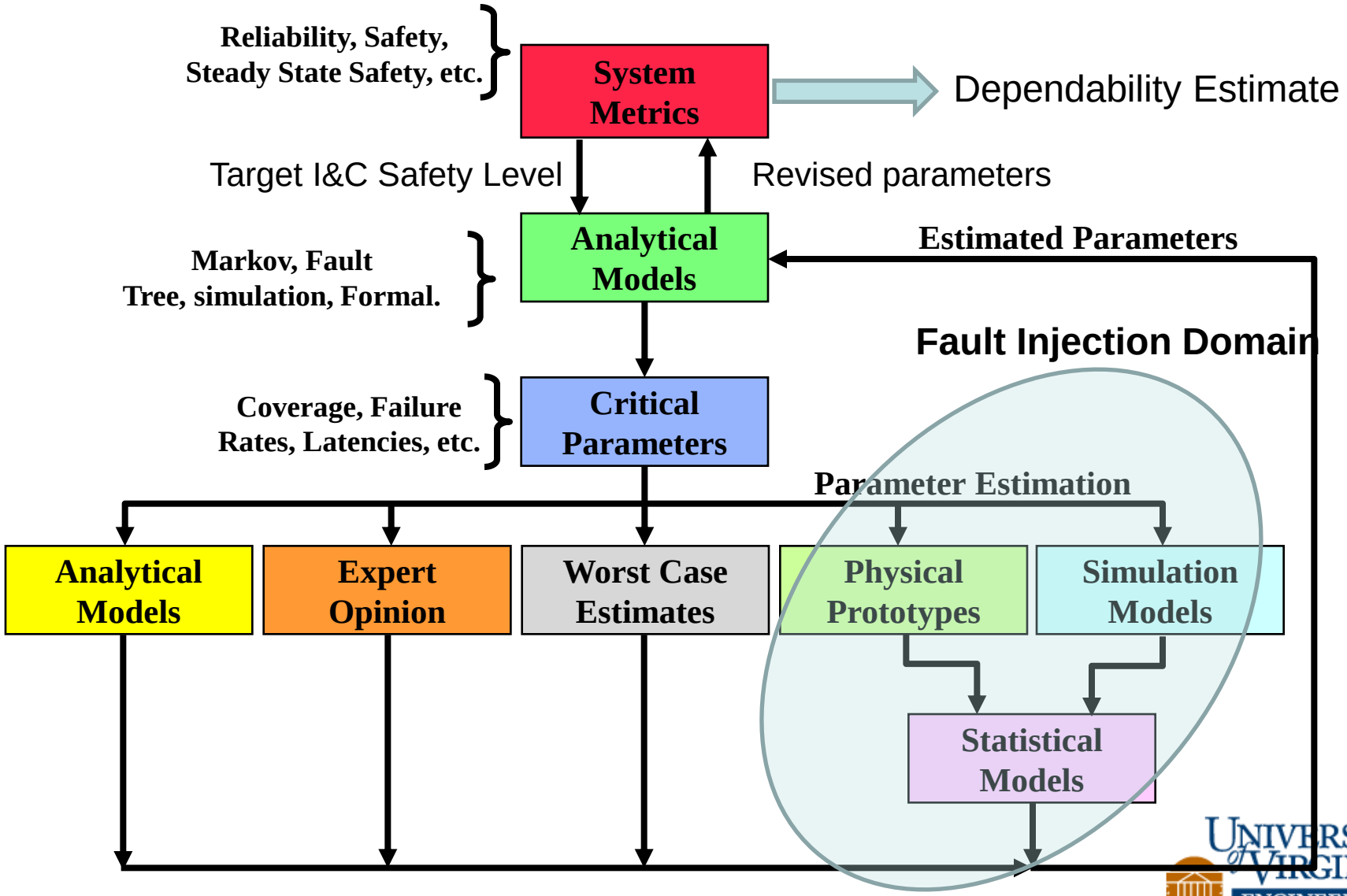
Aim of the Methodology

- A means to validate and verify objectively the dependability attributes of a digital I&C system
  - Support the estimation of quantitative metrics
  - Support the evaluation of qualitative attributes
  - Support modeling activities (PRA, Reliability, and Safety)
- Rigorous in it's foundation
- Strive for practicality and utility.
- Provide useful information to assessors, vendors, and regulators concerning the safety and reliability attributes of a digital I&C system.

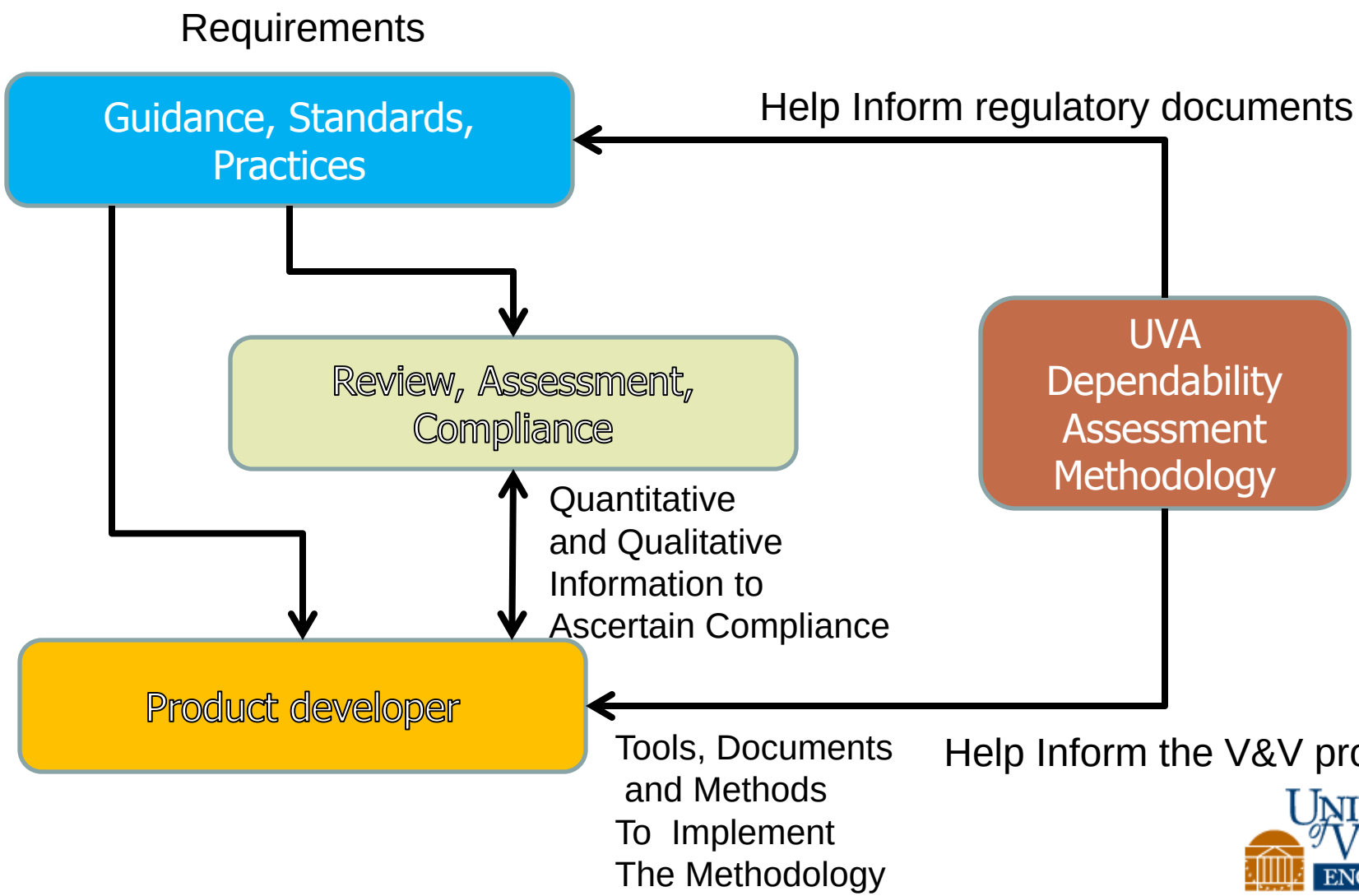
Technical Goals of the Methodology

- Develop, Apply and improve a safety and reliability assessment methodology for digital and computer based I&C systems
  - Consider the integrated hardware/software system
  - Consider bus and network technology issues that may effect safety
  - Consider how different modeling methods can be accommodated.
- Develop modeling, simulation, and fault injection techniques that support the assessment methodology
- Document the quantitative and qualitative results that can be obtained through application of the assessment process, and provide the technical basis upon which NRC can establish the regulatory guidance.
- **Develop tools that support the practical implementation of the assessment methodology**

Functional View of the Methodology



How the Methodology Can Work in a Regulatory Framework



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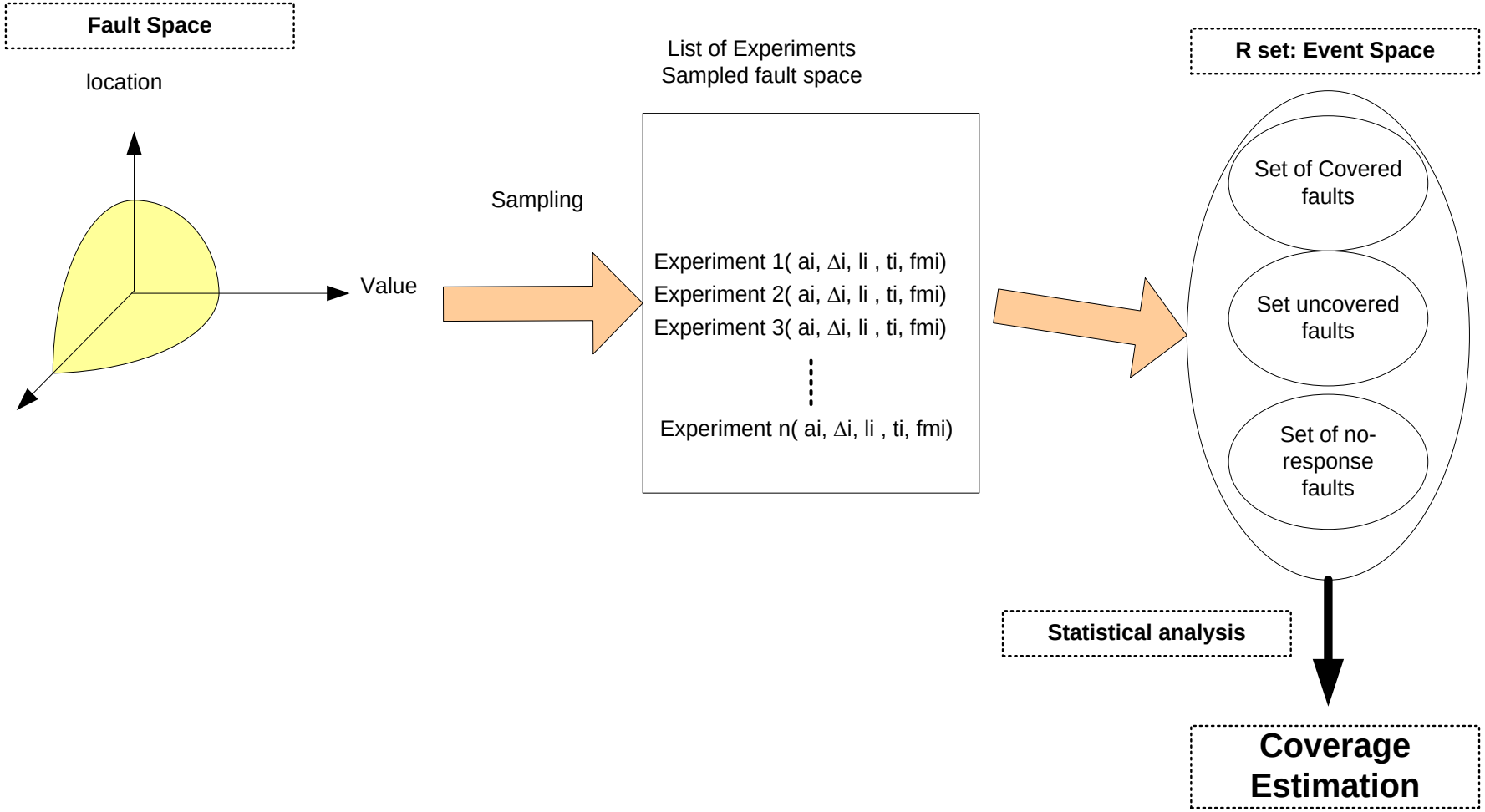
Big Picture of the Fault Injection Process



Fault Coverage Basics

The point estimate for the system fault coverage is obtained

$$\hat{C} = \frac{1}{n}\sum_{i=1}^{n} y(t_i, \Delta_i, \sigma_i, l_i, f_{m_i})$$

- where C^ is the point estimate for the system fault coverage, and *n* is the number of fault injection experiment.
- From Equation 1 we can see that the estimation of fault coverage via fault injection is dependent on five parameters:
  - Fault type, Location, Time, Duration, and Workload profile
- These parameters are dependent experiment attributes of the fault injection process.

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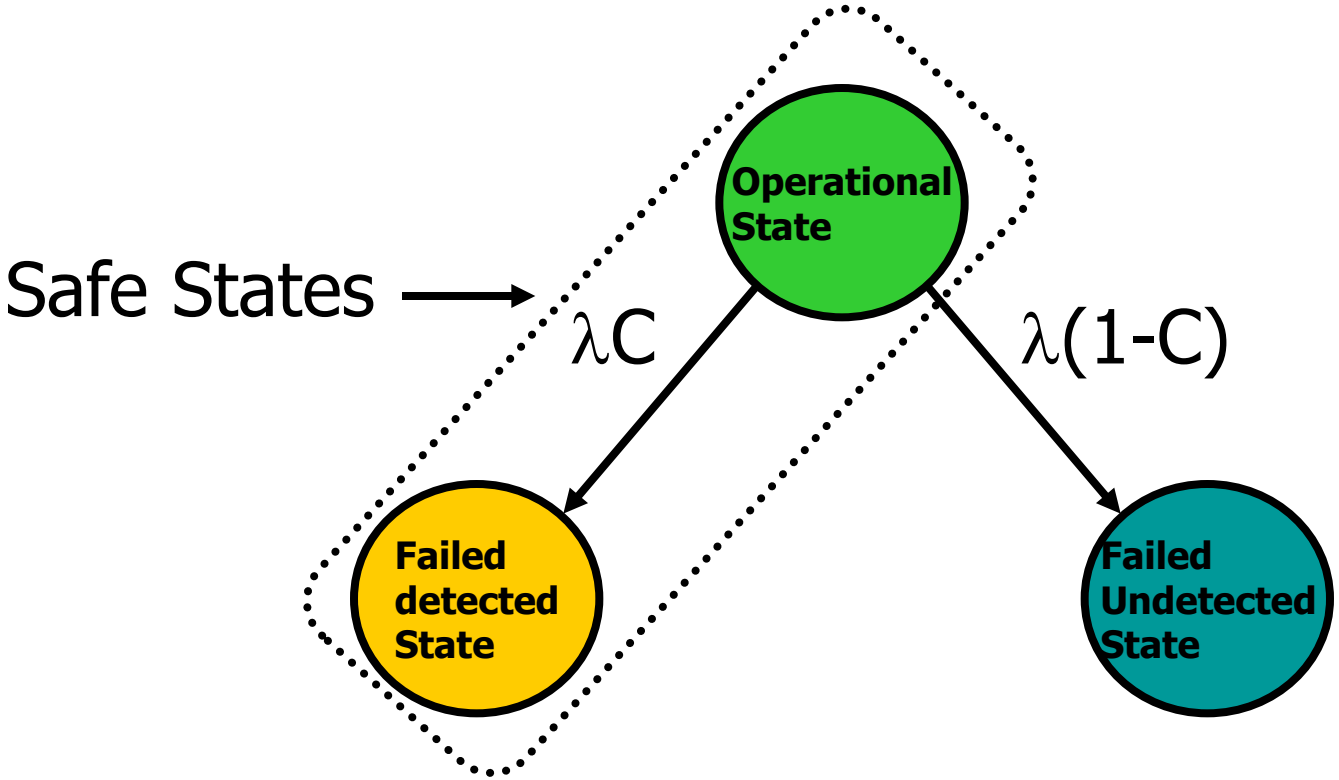
Coverage Example in a Markov Model



Fault coverage, C , is the conditional probability that a system correctly handles a fault, given that a fault has occurred.

Overview of the Benchmark Architecture

Basic architectural principles.

- A federated distributed fault tolerant system
  - Channelized, symmetric, quasi asynchronous operation.
  - Cyclic prioritized static real time scheduler OS.
  - Safety functions utilize both application dependent and application independent fault tolerance features.
  - Highly configurable for different applications.
- Channels are coupled by Profibus DP network.
  - Event triggered, token passing network.
  - Worst case bounded operation wrt token management.
  - Non deterministic messaging service.
- Fault tolerance is achieved through several forms of redundancy and self monitoring.
- Fault containment and isolation is typically at the channel level.

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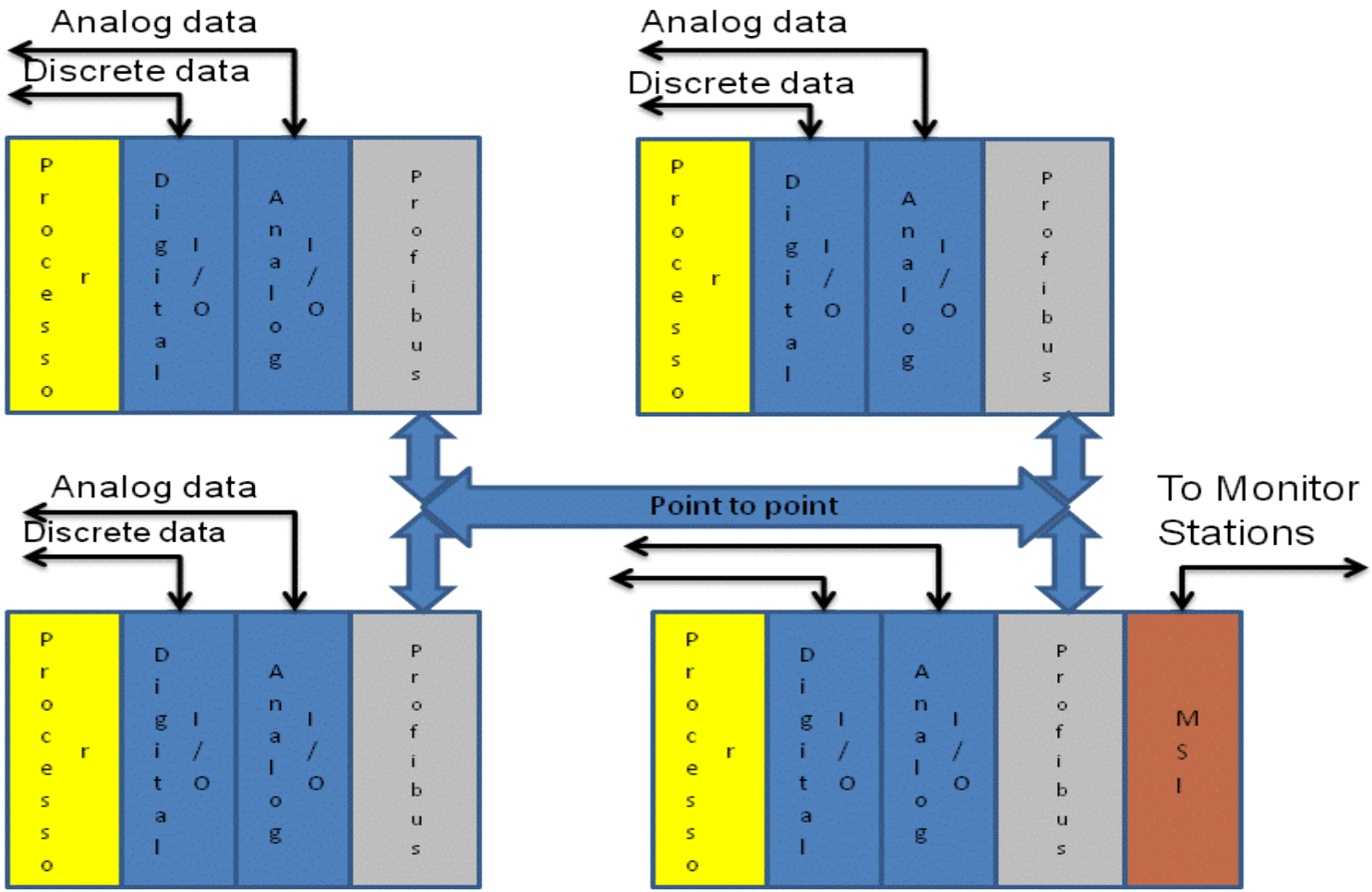
Platform Architecture



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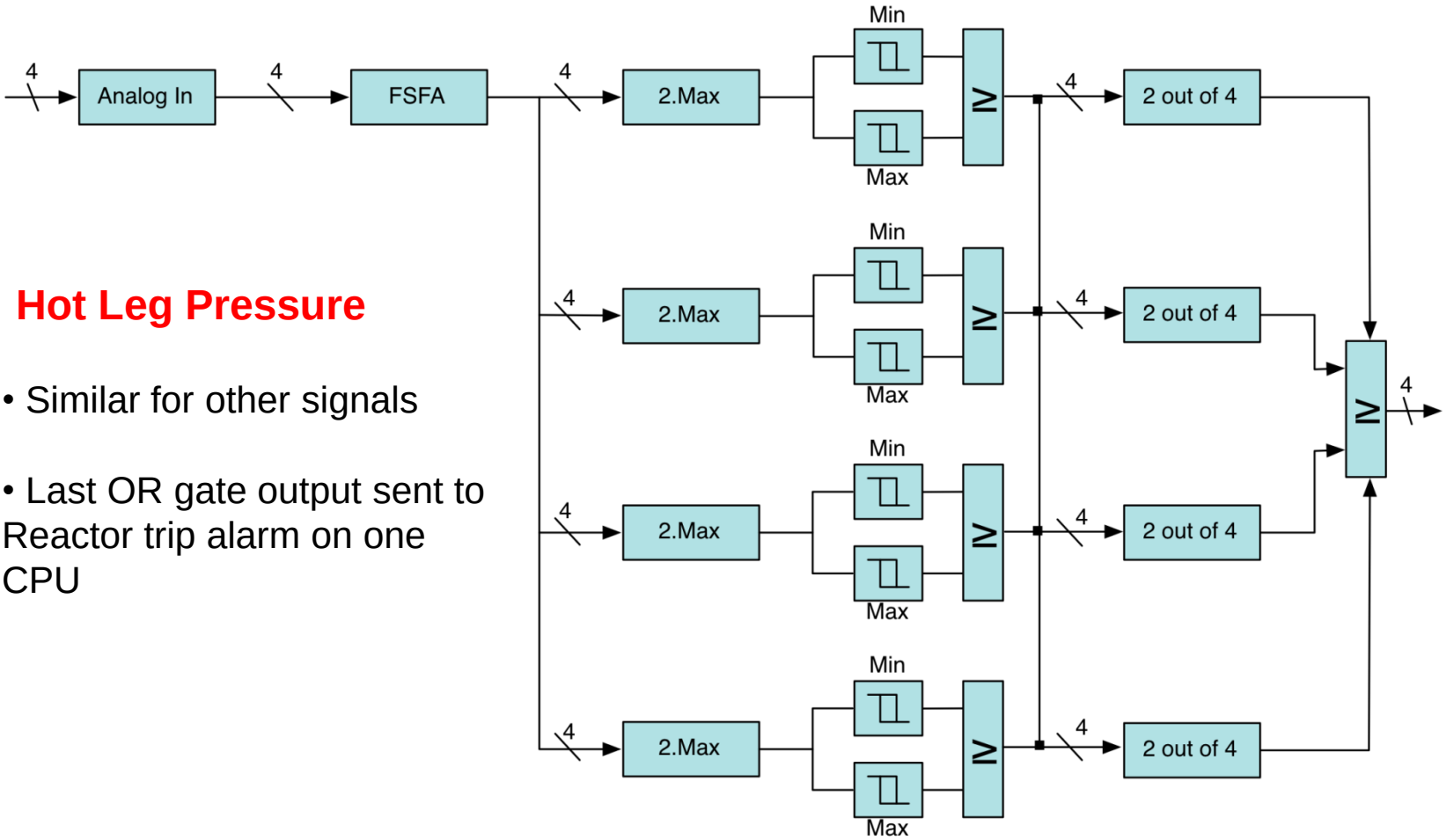
RPS Functional Diagram



Hot Leg Pressure

- Similar for other signals
- Last OR gate output sent to Reactor trip alarm on one CPU

Fault Injection Environment

- Uses LabVIEW 8.6 Development Tool
- Coordinates the following functions
  - analog and digital data acquisition
  - external system reset
  - initiation of fault injection campaign
  - signal-level corruption
  - data logging and analysis

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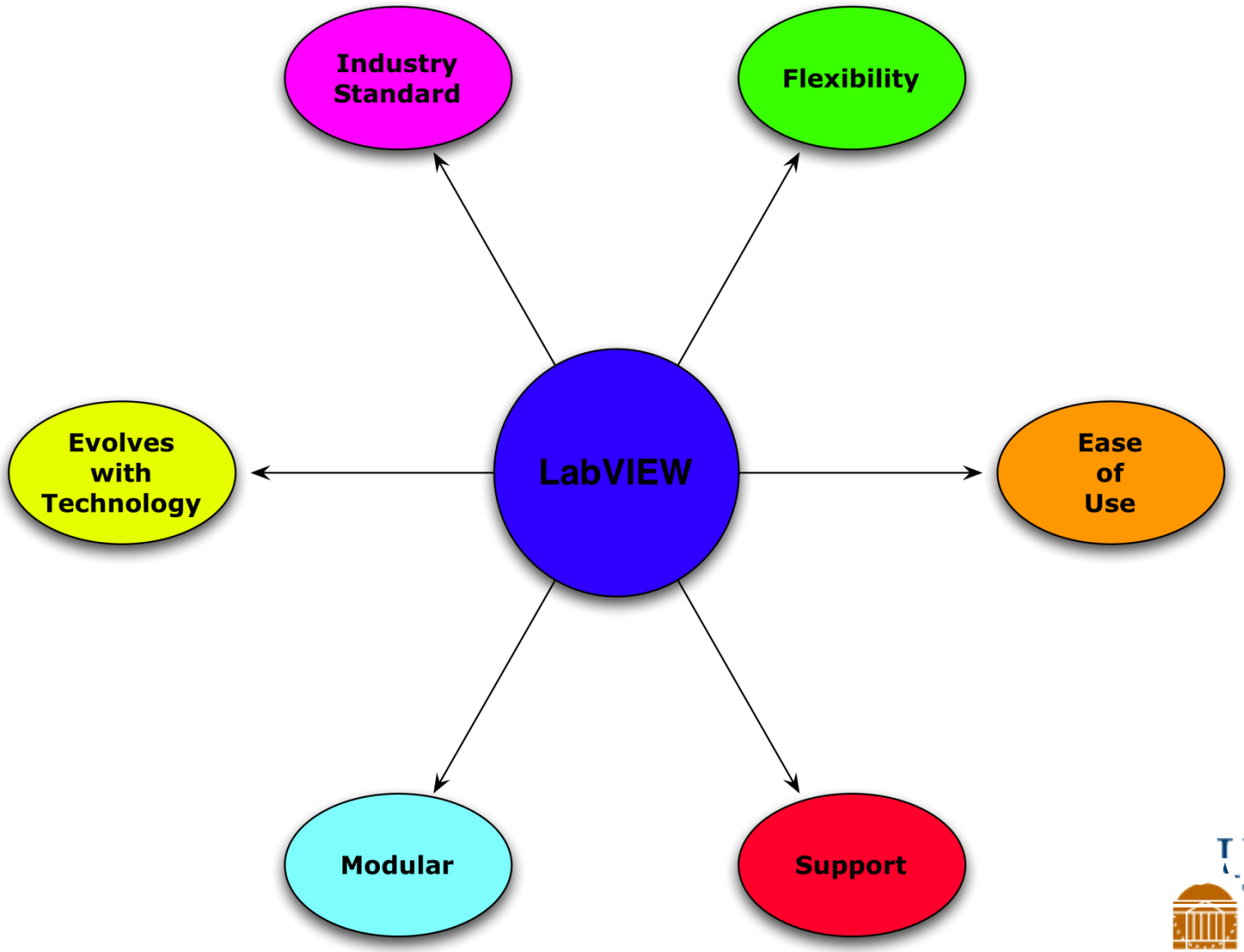
FIE Design Goals



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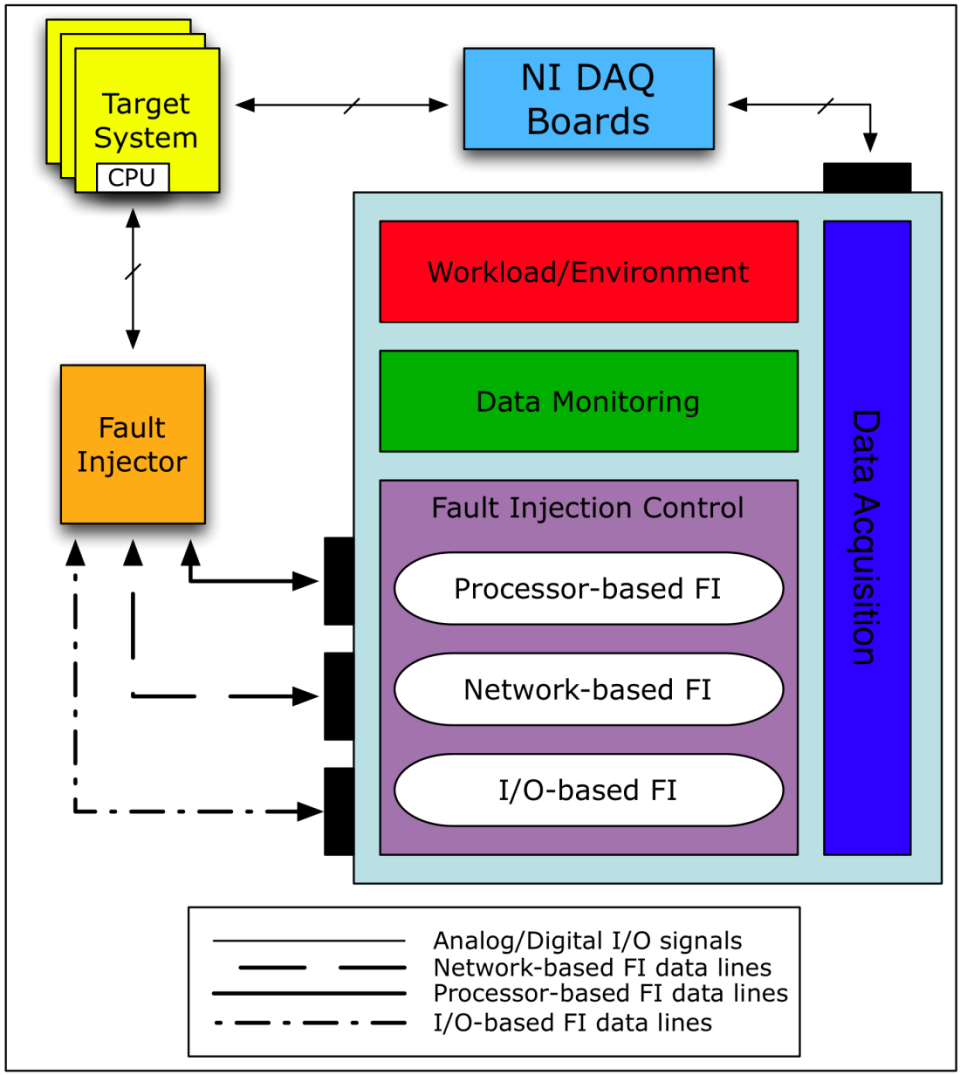
FIE Architecture



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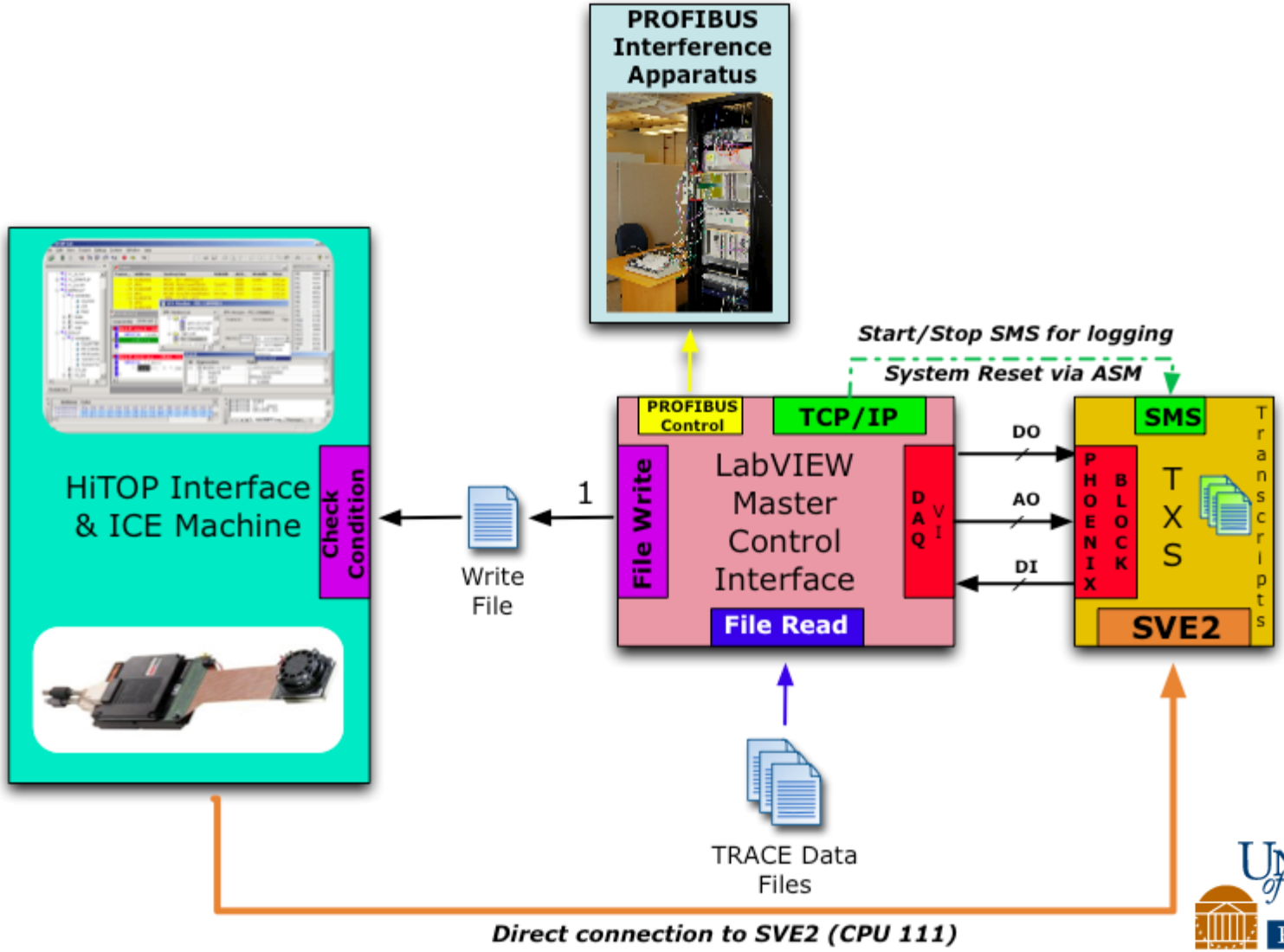
Fault Injection Environment for Benchmark Testing



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FAULT INJECTION ENVIRONMENT

ENVIRONMENT PARAMETERS

RESET PERIOD: 30
Amplitude of Noise: 1
Number Of Faults: 531
PERIOD OF FILE READ: 0.05
Kill Port 1: 6452
SMS TCP/IP PORT: 6432

PROFIBUS INJECTION CONTROLS

EXPERIMENT SELECTOR
Profibus File Read Time (ms): 1

MISCELLANEOUS

FAULT ITERATION: 282
EXTRA INPUT (UNUSED)
TIME INDEX: 13
COUNTDOWN TO INJECTION: -40

SENSOR VALUES

COOLANT FLOW

CF A: 0
CF B: 0
CF C: 0
CF D: 0

HOT LEG PRESSURE

HLP A: 0
HLP B: 0
HLP C: 0
HLP D: 0

STEAM GENERATOR PRESSURE

SGP A: 0
SGP B: 0
SGP C: 0
SGP D: 0

OUTPUTS AND ALARMS

COOLANT FLOW

COOLANT FLOW TRIP: 0

PRESSURIZER PRESSURE

PRESSURIZER PRESSURE TRIP: 0

STEAM GENERATOR PRESSURE

STEAM GEN. PRESSURE TRIP: 0

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Processor Fault Injection Analysis and Results.

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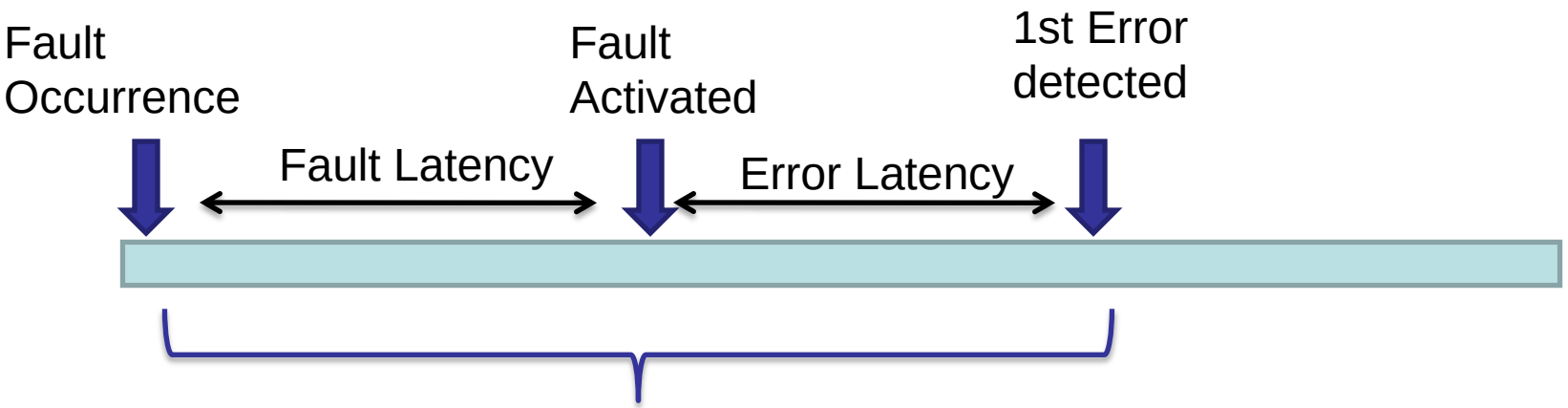
Fault and Error Latency



The total time is observed from a fault injection experiment

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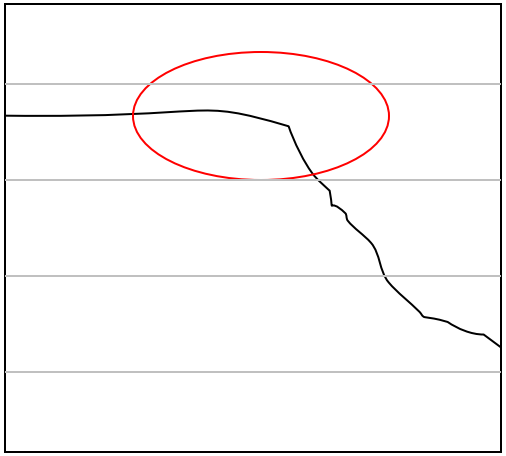
Nature of faults injected

- Faults injected into neighborhood of possible alarm trip events
- Faults injected into
  - Locations in app. map
  - Locations from analyses



LOCA Event

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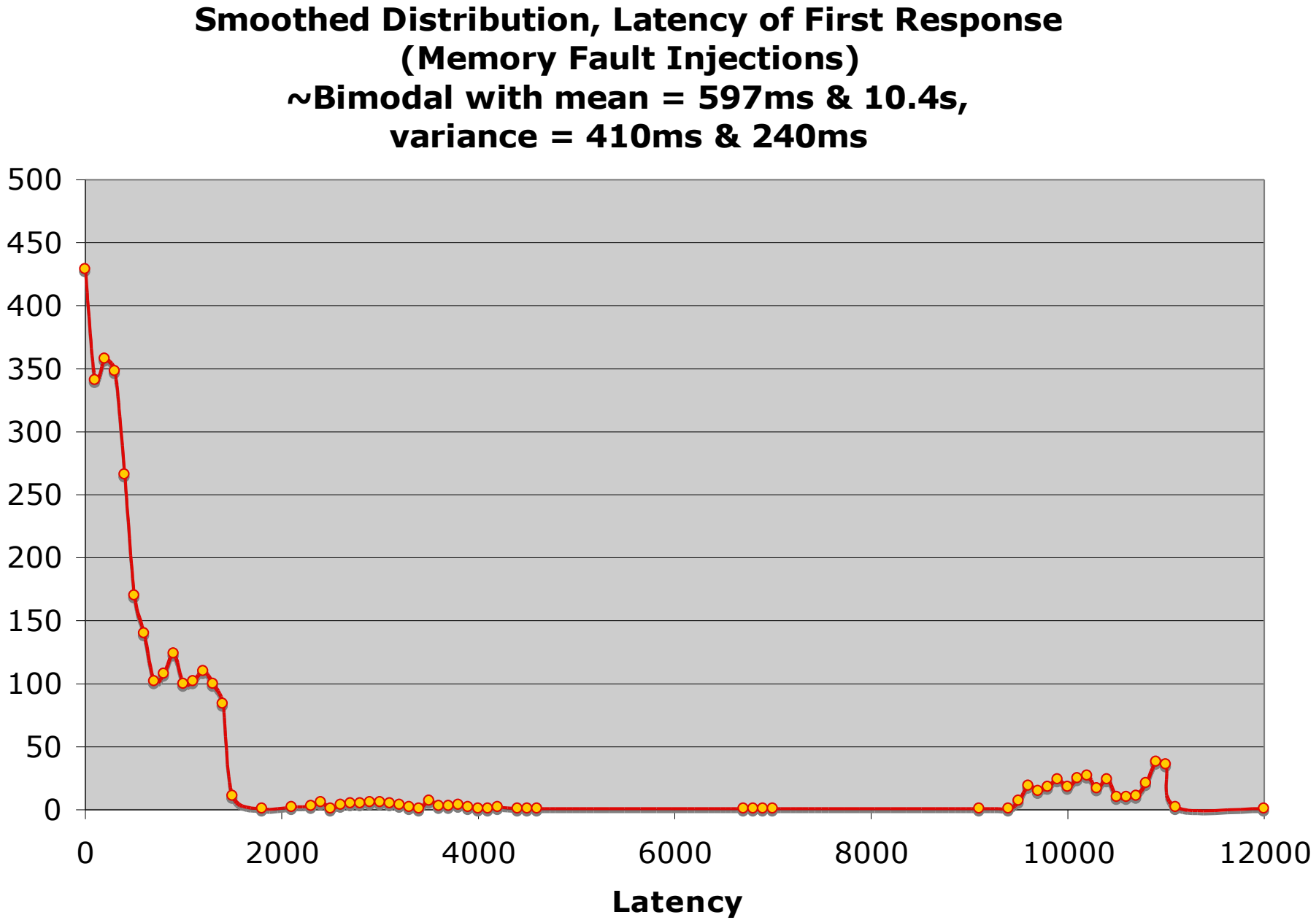
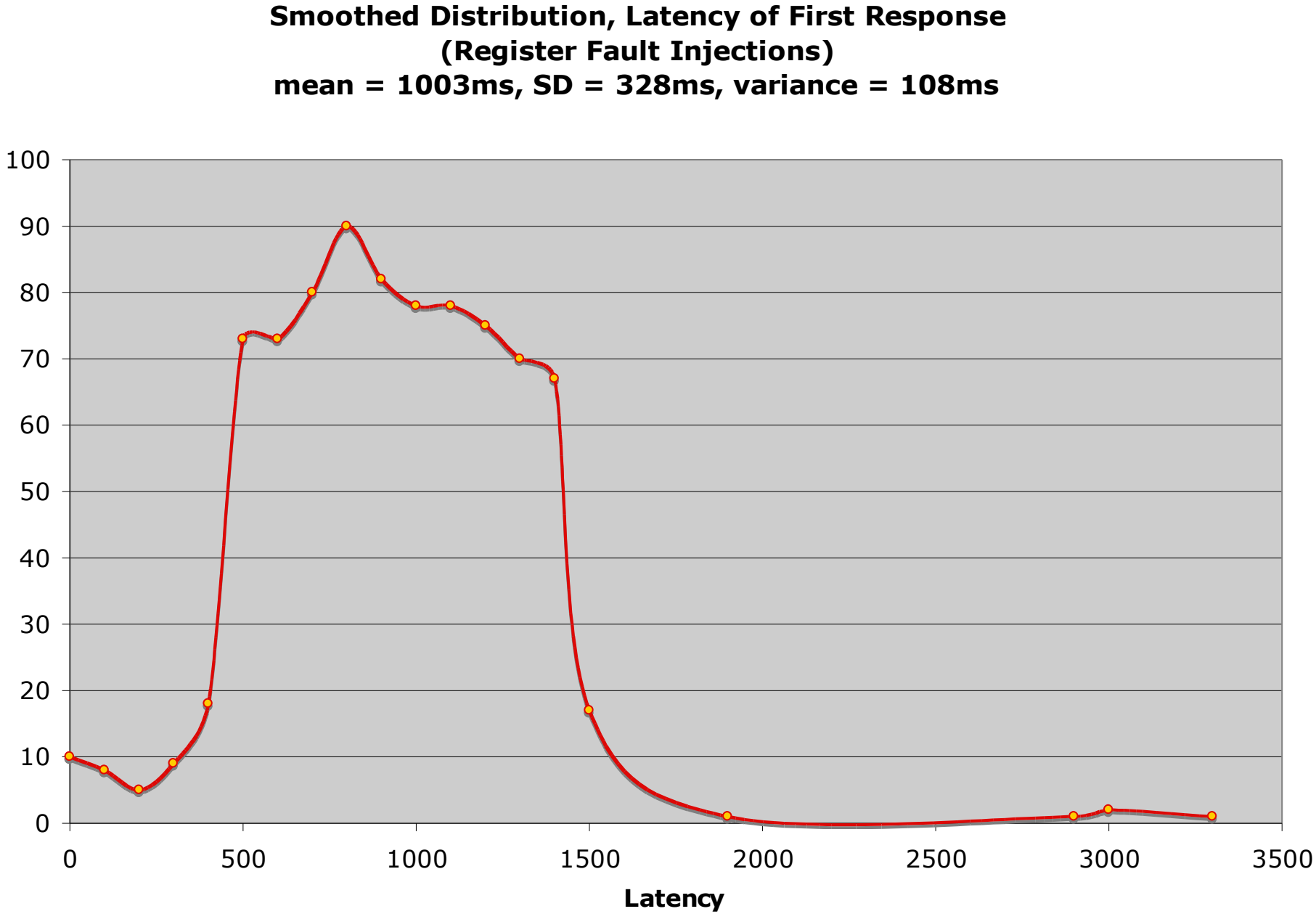
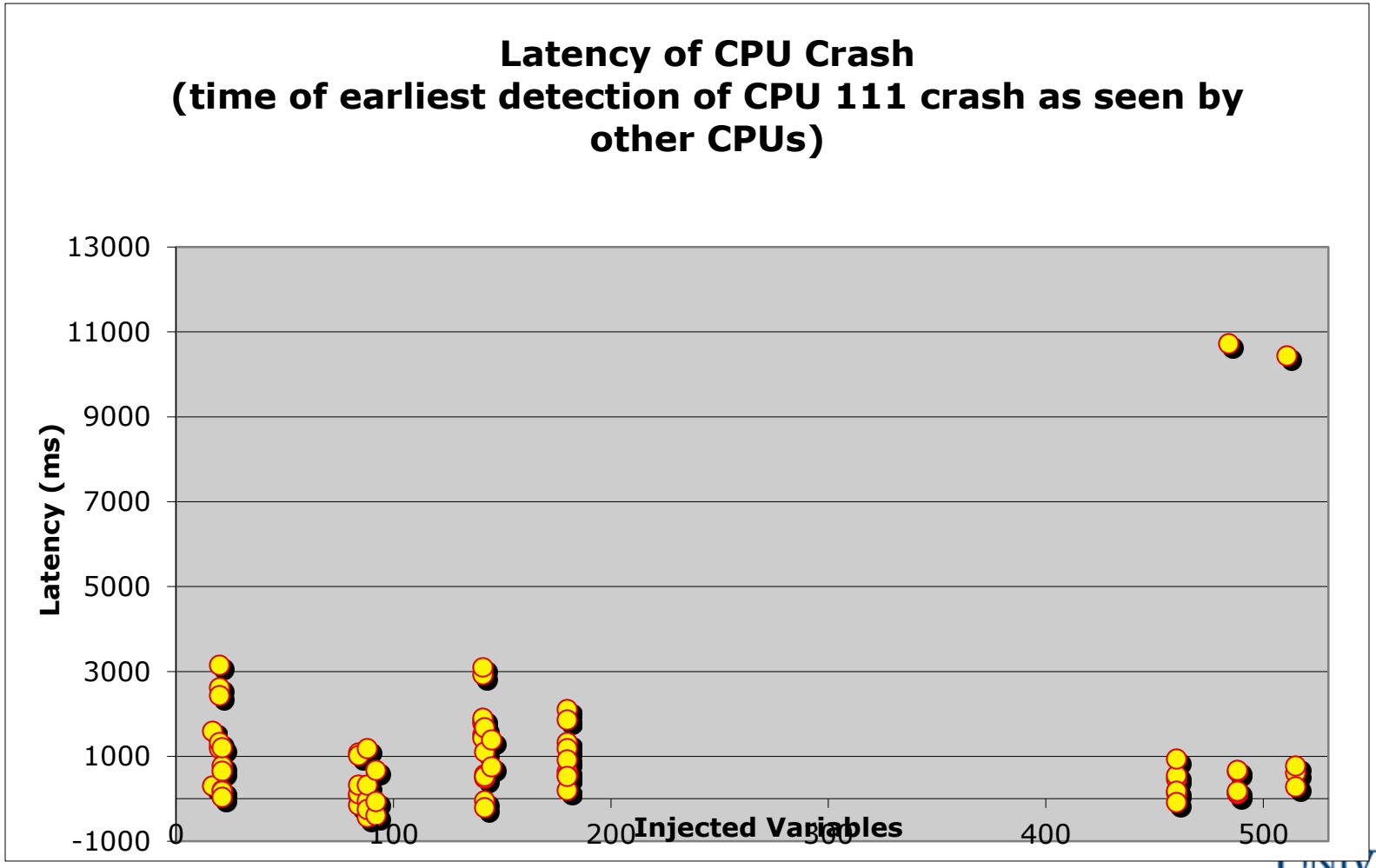

Smoothed Distribution, Latency of First Response
(Memory Fault Injections)
~Bimodal with mean = 597ms & 10.4s,
variance = 410ms & 240ms
500
450
400
350
300
250
200
150
100
50
0
0
2000
4000
6000
8000
10000
12000
Latency


Smoothed Distribution, Latency of First Response
(Register Fault Injections)
mean = 1003ms, SD = 328ms, variance = 108ms
100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
Latency

Crash latency



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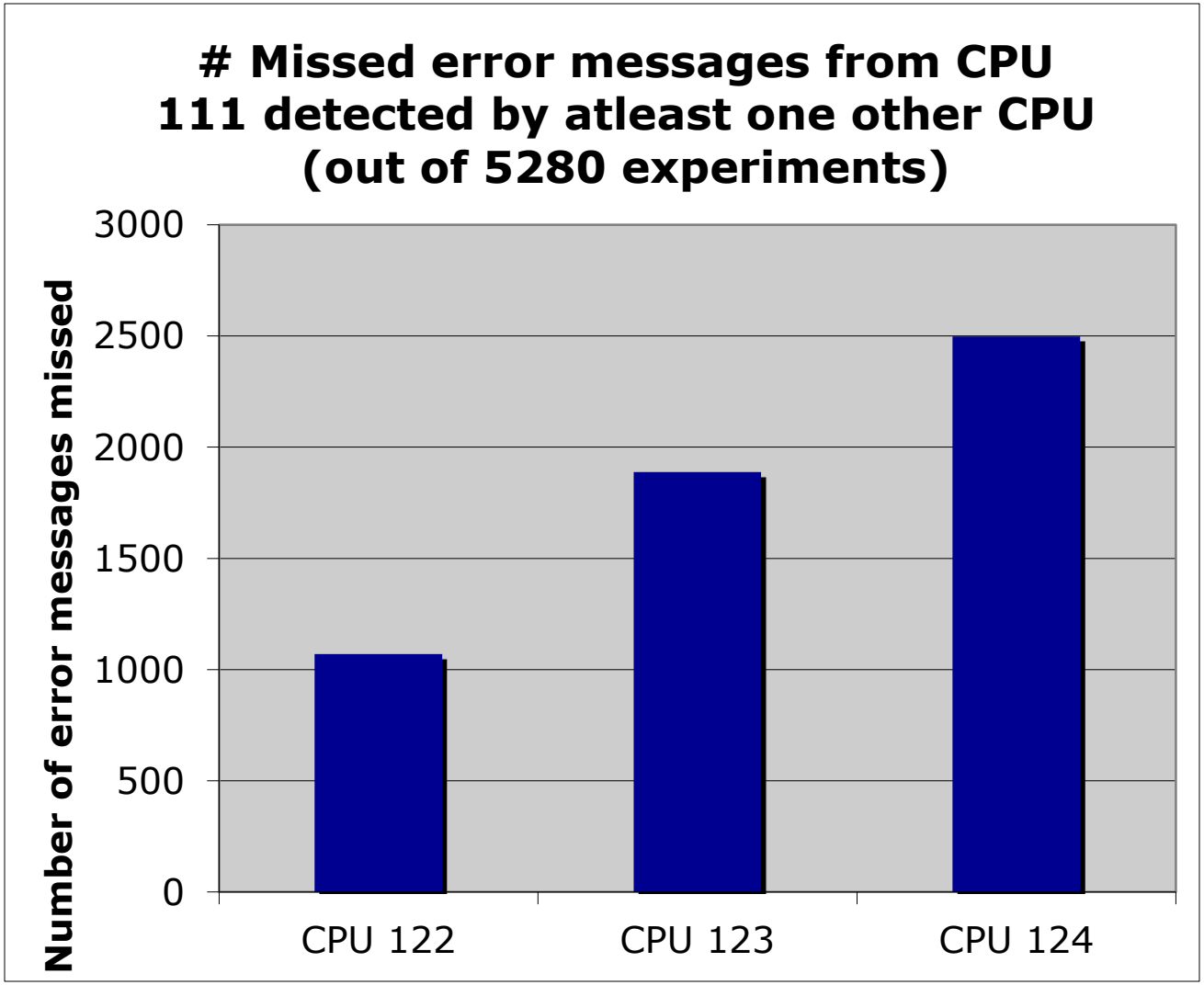
Inconsistency of Error Detection



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Coverage and Error Detection Latency Statistics for Processor Fault Injections

Location	**Point Estimate of C**	**Variance Of C**	**Confidence Bounds of C**	**Mean Error latency**	**Total fault Injections**	**No response faults**
Memory	.999697	9.1883×10^{-8}	$.999102 < C < 1.0$	Bimodal Mean with 597ms and 10.4 s.	5274	1975
Registers	.9998	1.39×10^{-6}	$.9965 < C < 1.0$	1003 ms	1470[1]	622

1- partial set of register fault injections.

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Profibus Fault Injection and Results

Marko Miklo, Carl Elks, and Ron Williams

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Fault Injection Approach

- Inject faults to induce specific failure modes – failure mode driven fault injection.
  - Known faults that will cause Token to be corrupted and rejected by the receiving Master station
  - Data Message fault injection increases the "Length" field of the message
    - Preserves all the data, tricking the receiving controller
    - Data passed to the next layer -> we don't know what happens then
  - Observe behavior and response of the network
  - Measure the timeout after each Token loss
- These are the problems that we simulated in our fault injections

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Covering Faults

- Fault/Error Model encompasses
  - Misbehaving Profibus controller
  - Faulty Profibus transceivers
  - Faulty links

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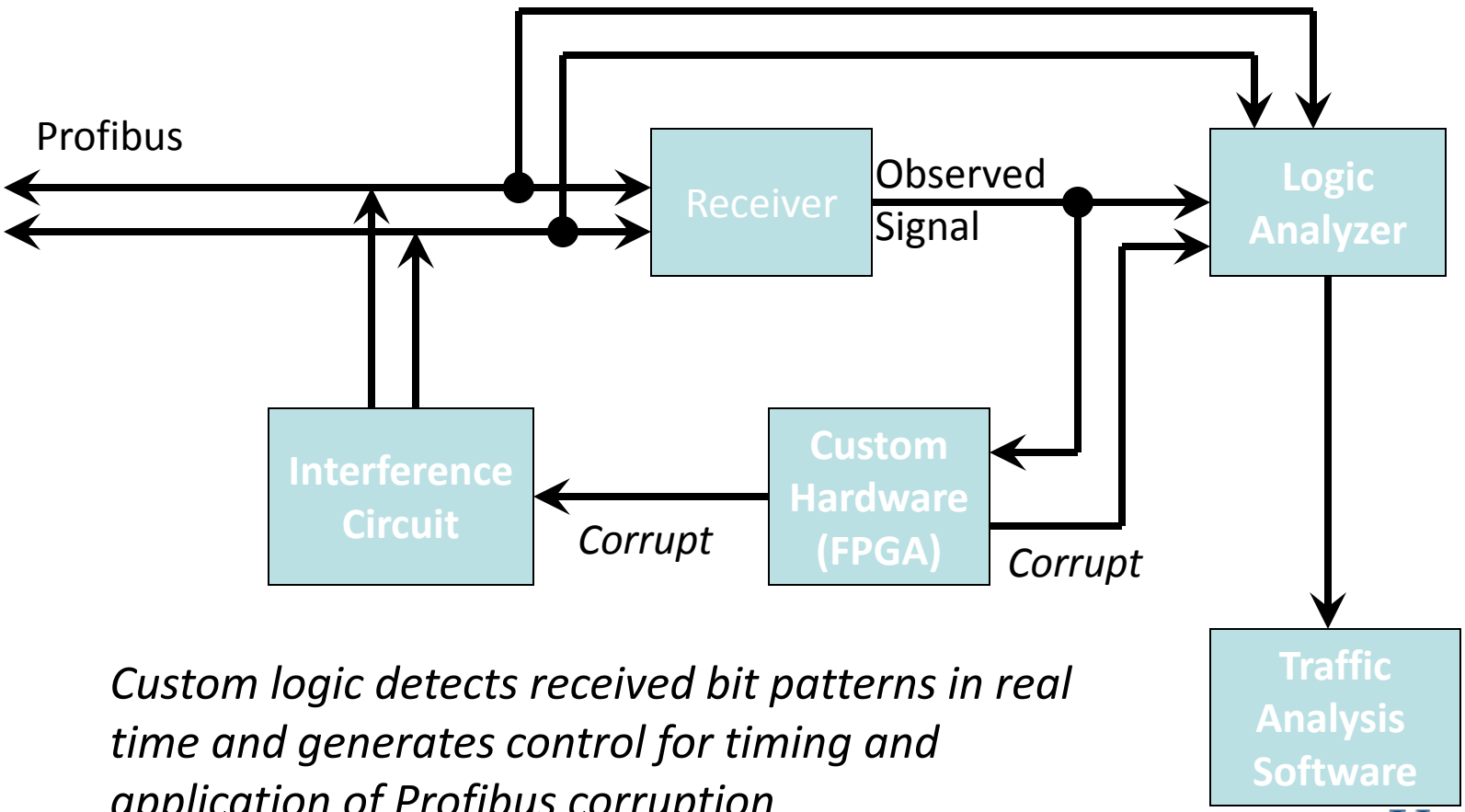
Profibus Fault Injection Functional Representation



Custom logic detects received bit patterns in real time and generates control for timing and application of Profibus corruption

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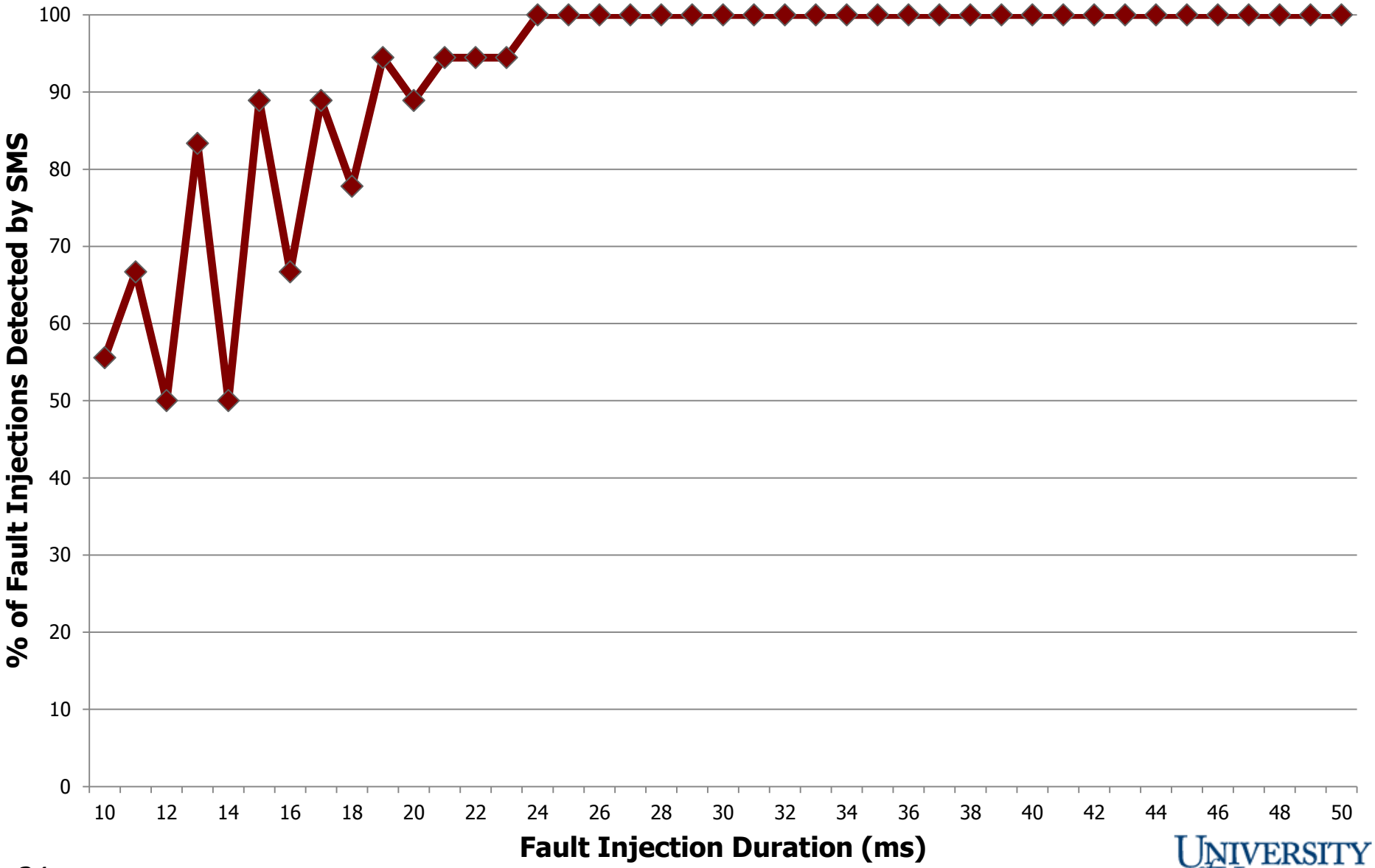
Token Fault Injection Coverage



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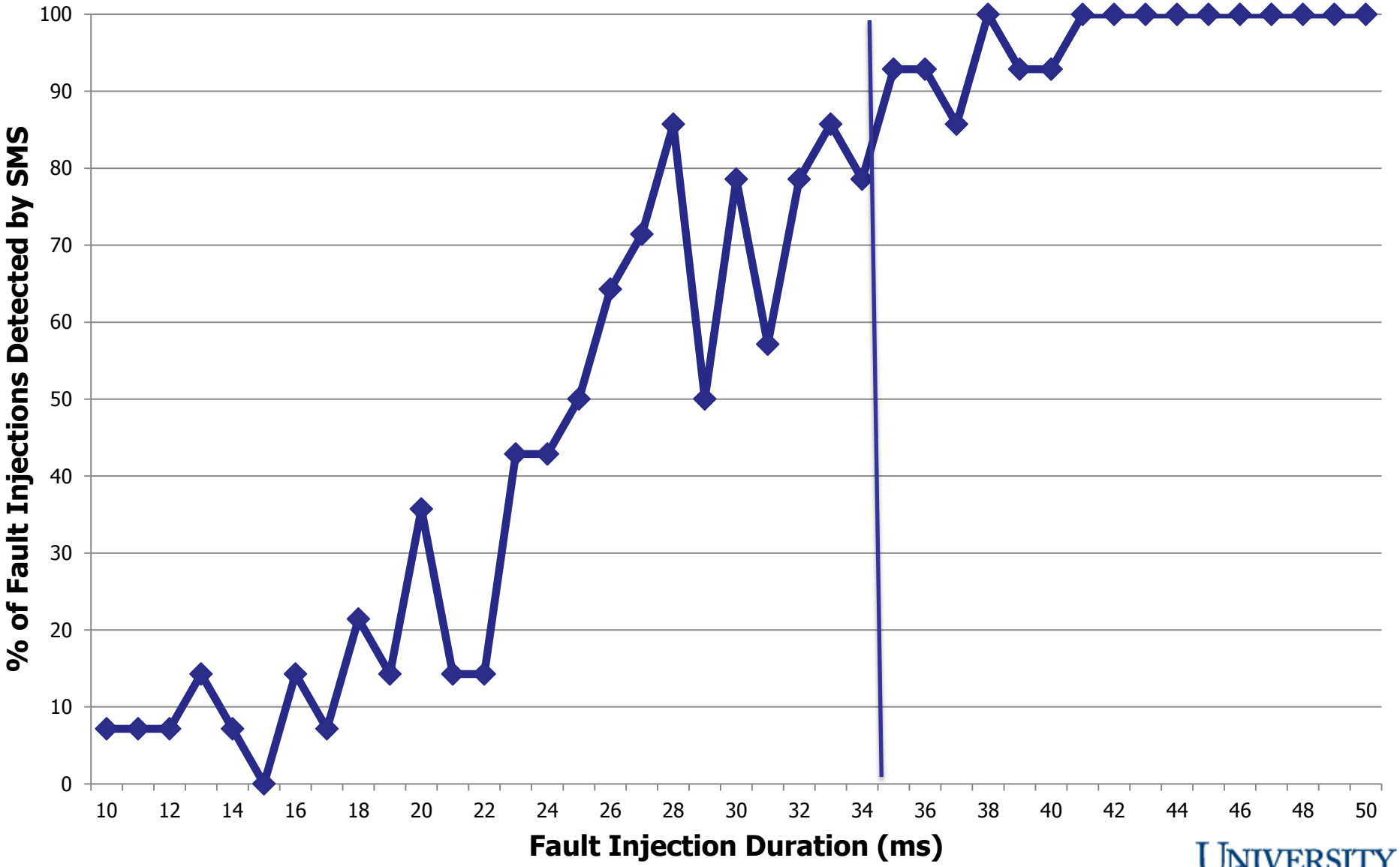
Data Message Fault Injection Coverage



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Profibus Controller Outage Coverage

- We can measure this exactly
- From observations, it is highly dependent on number "Service Messages" in the system
  - We did not control this parameter, just observation from the data.
- As expected, Token FI have much longer "*Unreliability time"* than Data Message FI
  - This is due to the time required to reinsert the Master that was taken out of the Logical Ring

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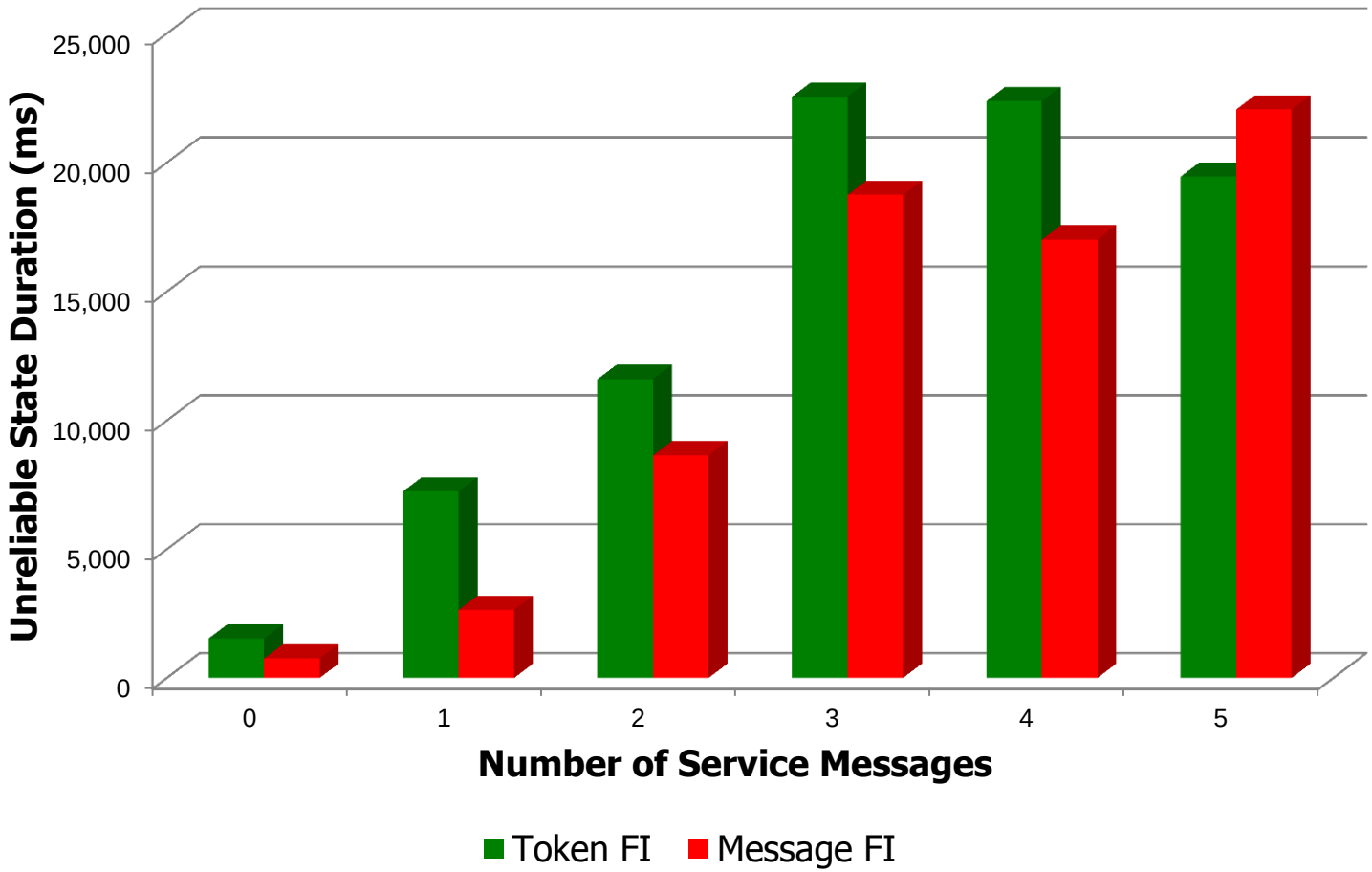
Token FI vs Message FI Outage Coverage



# Service Msgs	Token FI (ms)	Message FI (ms)
0	1,531.51	756.68
1	7,244.86	2,639.03
2	11,607.72	8,644.00
3	22,548.86	18,745.29
4	22,376.83	17,014.75
5	19,454.00	22,053.00

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Significant Findings to Date

- Methodology was successfully deployed.
- Methodology aided us (significantly) in understanding how the Benchmark fault tolerance and safety features work in real time.
- Fault injection campaigns produced results that were used to estimate critical parameters in the availability, reliability and safety models.
- Some of the results could not have been predicted or anticipated ahead of time with traditional testing. (results are still preliminary)
  - Bimodal error latency distribution
  - Service message impact on profibus controller outage (still trying to figure why this is).
  - Error perception inconsistencies
- Benchmark main fault tolerance features appear to be robust to the faults we injected into the system.
- A few bugs found in SPACE development tool.

Significant Findings to Date

- Benchmark system is relatively complex and intricate in its functionality and programming.
  - Assessors, Plant I&C engineers would be better served to take engineering training (as opposed to operator training).
  - Documentation is operator oriented rather than system functionality oriented.
  - Runtime and system fault tolerant operation is somewhat difficult to piece together from the documentation set.
- Guidelines on how to configure the system in a safety application would be helpful. I&C Vendor has some documentation on this, we now have it.
- Faults injected into Profibus suggested that faulted profibus communication can affect system availability and reliability.
- Some profibus failure modes could be malicious (still looking into this).

What's next?

- Triconex system is on deck.
  - A different system architecture, will stress the methodology in different ways.
- NUREG is top priority.
- Have I&C Vendor's feedback on the preliminary testing results.
- Many lessons learned along the way.

Long term

- It's clear that open source tools to enable both vendors and regulators to leverage the methodology are paramount.
  - A set of tools to allow assessors and regulators to analyze, trend and access fault injection data from the vendors.
  - A set of open-source tools to allow the vendors to implement and integrate the methodology into their testing and V&V processes.
- Invensys and I&C Vendor both seem to agree that this would be helpful.
- We are already moving toward a direction of "tool boxes" in our methodology.

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