Extending FMECA to System ofSystems (SoS) Interfaces: iFMECA

PI's: Leo Mayoral, Clay Smith

28 October 2009

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- Background & Problem Description
- Proposed Concept
- Possible Model for the SoS Interface
- Technical Foundation
- Extending FMECA Process to SoS Interface Analysis
- Potential Applications
- Summary

APL

Background

- APL interest in understanding how to objectively assess failure modes for large system of systems:
  - Especially when introducing a new system into a complex and existing architecture,
  - Identifying problem interfaces during the design phase,
  - Prioritizing SE resources,
- Question: How can the Systems Engineer characterize ***SoS interface faults*** in order to prioritize resources?

System Box-Level Problem Description

- **Failure mechanisms and failure modes are typically known for individual component systems**
  - Usually these analyses are dictated by contract
  - Full reliability and risk analyses performed within context of the system only
- **Interfaces among components systems can be uncertain**
  - Defined to the level of an internal specification or requirement
  - Not completely enveloped
  - Ambiguous
  - Cause and effects not always deterministic or known a priori
- **Interface issues exist even though all component systems are operating within system specifications**
- **Identify these interactions and prioritize their impact**

System of System Problem

- **A significant number of issues for System of Systems reside in the interfaces among the systems**
- **This iFMECA methodology extends the current FMEA techniques to provide SoS engineers with a risk based prioritization of interfaces**
  - FMECA is one of the most widely used reliability tools (see MIL-STD-1629A)
  - Bottoms up approach
    - Functional or physical breakdown
    - For each interface failure modes are identified
    - For each failure mode identified (known or potential), determine
      - Consequence (narrative description of local, system, and SoS effects)
      - Probability of occurrence
      - Method for detection
    - Determine risk criticality
  - Rank order interfaces using risk criticality number for resource allocation (i.e., which interface to worry about first)

System of System (SoS) Problem

- **A significant number of issues for System of Systems reside in the interfaces among the systems**
- **Interfaces are Often Complex**
  - Multiplexed outputs
  - Protocol Oriented
  - Timing
  - Signal Quality
  - External Coordination
  - Network Delays
- **Challenge is to find a system engineering tool that can help the PM and SE identify problem interfaces efficiently and cheaply.**

FMECA Methodology: Background

- **FMECAs are used in systems to:**
  - Identify Single Point Failures,
  - Prepare diagnostic routines such as flowcharts or fault-finding tables,
  - Prepare preventive maintenance requirements,
  - Design built-in test, failure indications, and redundancy,
  - Analyze testability to ensure that hardware can be economically tested and failures diagnosed,
  - Show as formal record of safety/reliability analysis.
- **Limitations**
  - Combined effects of coexisting failures are not considered
  - Extents upward through system hierarchy, no peer-to-peer interactions
  - Process is extraordinarily tedious and time consuming for complex systems

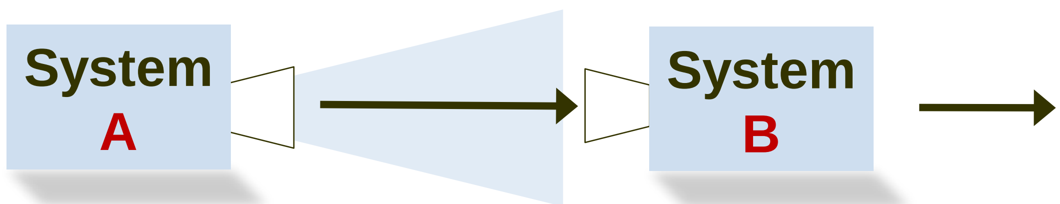
Proposed Concept: iFMECA Methodology

- **Analyze the interface**
  - Decompose each interface to determine failure modes
    - Level of detail may vary
    - Interface dependent, several models exist to accomplish this task
  - Determine the probability of loss
    - Qualitative (ordinal scale) or quantitative (such as loss of margin)
- **Analyze the impact of interface to the function (or system)**
  - Assign a prior probability distribution based on test data, engineering judgment, or rules-of-thumb
  - Later update with Bayesian statistical methods with operational data
- **Analyze the impact of the function to the mission (or SoS)**
  - Assign a prior probability distribution based on test data, engineering judgment, or rules-of-thumb
  - Later update with Bayesian statistical methods with operational data

APL

SoS Interface FMECA (iFMECA)

- **Specific area of focus is the off-nominal performance at the interface among component systems**
  - Limiting scope to these failure modes
  - Assuming that system failure is treated already



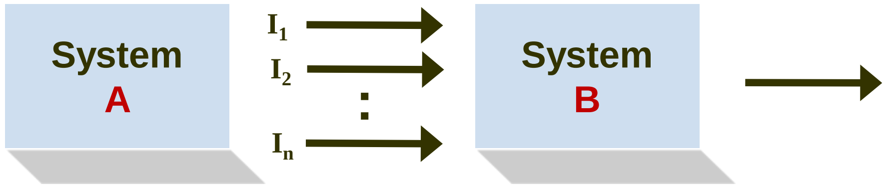
- **For this case, neither System A or B has failed by its own definition, but a portion of A output is not processed by B**
  - Uncertainty exists in the variability of System A output and the variability of System B threshold limit
  - Output spec of A and the input expected range of B may differ

SoS Interface iFMECA

- Probability of loss of function (LOF) for Subsystem B is a function of its inherent failure rate plus the loss of input (LOI) from Subsystem A

$$\Pr(LOF_B) = \lambda_p t \times \Pr(LOI)$$

- For a more generalized case with multiple inputs:



$$\Pr(LOF_B) = \lambda_p t \times \sum \Pr(LOI)_i + \text{combinatorial effects}^*$$

- Assumptions:
  - Inherent failures are covered elsewhere
  - *Combinatorial effects from the interactions of multiple degraded inputs not yet addressed

APL

iFMECA Methodology Criticality Number

- **Mil-Std-1629 Defines a Criticality Number**
- **Propose an Analog for SoS Criticality Number (C_{SoS}):**

$$C_{SoS} = \gamma \cdot \beta \cdot \Pr(LOI)$$

Where,

- γ Conditional probability of LOM given LOF
- β Conditional probability of LOF given LOI
- $\Pr(LOI)$ Probability of output-input mis-match

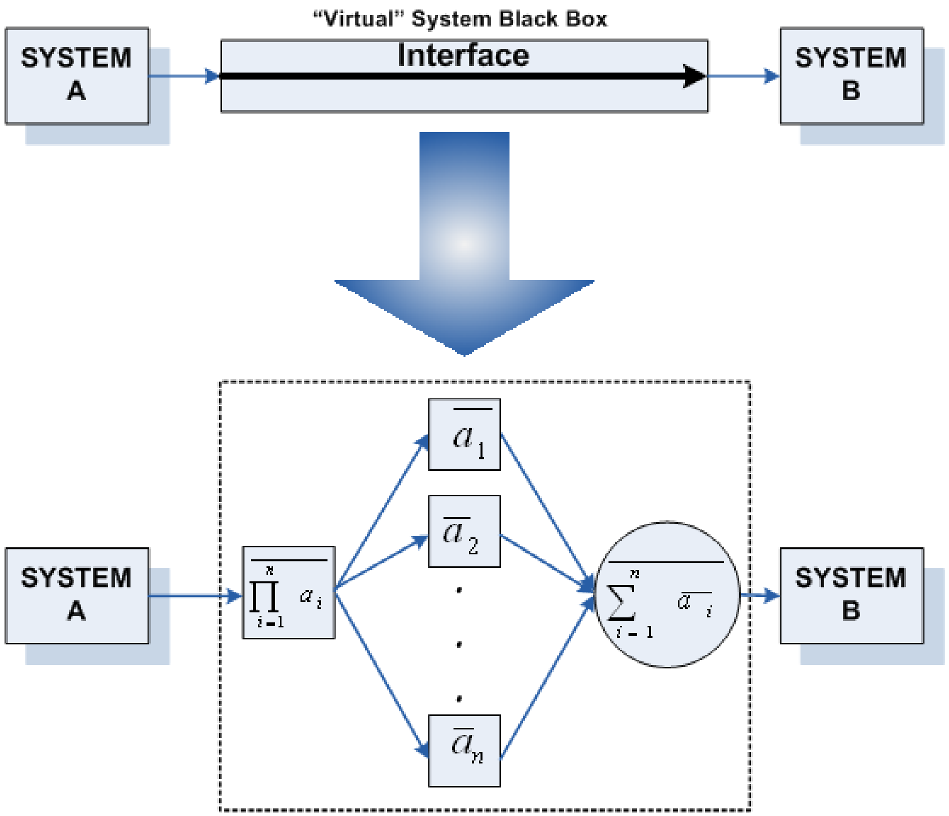
- **Parameters γ and β based on**
  - Operational data
  - System test data
  - Can be subjectively assigned and updated with Bayesian techniques as more operational experience is gathered

APL

iFMECA Methodology ... *New SE Tool*

- **Analyze the interface**
  - Decompose each interface to determine the attribute (a_i) failure modes
    - Level of detail may vary
    - Interface dependent, several models exist to accomplish this task
  - Determine the probability of loss
    - Qualitative (ordinal scale) or quantitative (such as loss of margin)
- **Analyze the impact of the interface to the function (or system)**
  - Assign a prior probability distribution based on test data, engineering judgment, or rules-of-thumb
  - Update with Bayesian statistical methods using operational data
- **Analyze the impact of the function to the mission (or SoS)**
  - Assign a prior probability distribution based on test data, engineering judgment, or rules-of-thumb
  - Update with Bayesian statistical methods using operational data

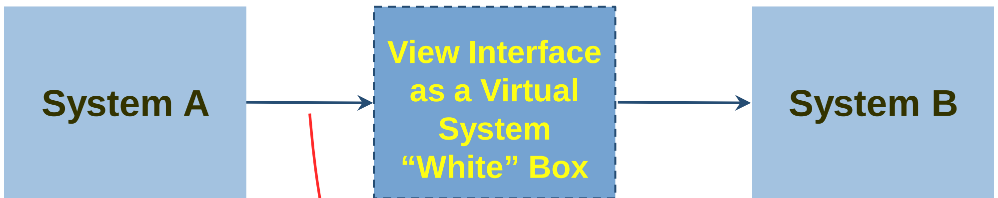
One Possible Concept for Modeling an Interface



Notional Failure Model of a Typical Interface

- A Typical Interface is Comprised of Several Interface Attributes (a_i), e.g OSI Stack
- All a_i Must <u>not</u> Experience a Failure for the Interface to Work
- Viewed as a Logical "And" at the Input
- Viewed as a Logical "Or" at the Output
- All Events (a_i) are Mutually Exclusive (Assumption)
- The Occurrence of Any Event, ($\overline{a_i}$), Causes a Degradation of the Interface

How Would the Data Be Analyzed?



Copper or Optical Connection

- Port or Interface Status is Disable or Shutdown
- Port or Interface Status is errDisable
- Port or Interface Status is Inactive
- Uplink Port or Interface Status is Inactive
- Trunking between a Switch and a Router
- Trunking Mode Mismatch
- Connectivity Issues due to Oversubscription
- Common Port and Interface Problems
- Data Signal Voltage Mismatch
- Data Signal Voltage out of tolerance
- Data Incompatibility
- Noise Coupling
- Crosstalk

Examples of Potential I/F Faults

Wireless

- Frequency Error
- Bandwidth Error
- Modulation Mismatch
- Link Closure
- Doppler Signal Errors
- Signal Dead Spots(R^2 Losses)
- Signal Integrity
- Multipath Errors

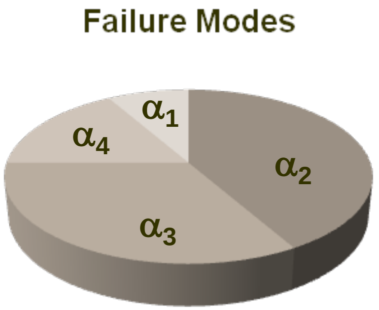
1. Focus on Copper/Fiber and Wireless Connectivity
2. Ignore OSI Layers 5-7 (Session, Presentation, Application Information Layers) for Now
3. Catalogue Top Level Category Interface Faults
   - Look for Statistical Data
   - Interview for Experiential Data
4. Select a Small Subset and Analyze Failure Modes for Each
5. Correlate to Methodology
   - Validate Criticality Number
   - Validate probabilistic margin analysis
6. Document Results Formally

SoS Criticality Number Extends Definition

- **Mil-Std-1629 Analysis Focuses at the Box Level**
- **Standard Criticality Analysis considers part/board failure rate and the system impact**
- **Failure mode *<u>Criticality Number</u>* is used to convey the severity of the fault:**
- **Criticality Number is computed as:**

$$C_m = \beta \cdot \alpha \cdot \lambda_p t$$

  - $\lambda_p\, t$ Part failure rate x time (Poisson Distribution)
  - α failure mode ratio
  - β conditional probability of loss of mission (LOM) Pr(LOM | Failure Mode)



Failure Effect	β Value
Actual loss	1.0
Probable loss	> 0.1 to < 1.0
Possible loss	> 0 to 0.1
No effect	0.0

iFMECA Methodology

- **Extends the FMECA to SoS**
  - Perform a systematic analysis of each SoS interaction
  - Pair-wise comparison for all output-input pairs
- **Propose an Analog for Criticality Number (C_{SoS}):**

$$C_{SoS} = \gamma \cdot \beta \cdot \Pr(LOI)$$

Our methodology extends the Criticality Number to a SoS by adding the conditional nature of the failures between systems.

Where,

- γ — Conditional probability of LOM given LOF
- β — Conditional probability of LOF given LOI
- $\Pr(LOI)$ — Probability of output-input mis-match

Definitions:

LOI – Loss of Input
LOF – Loss of Function
LOM – Loss of Mission

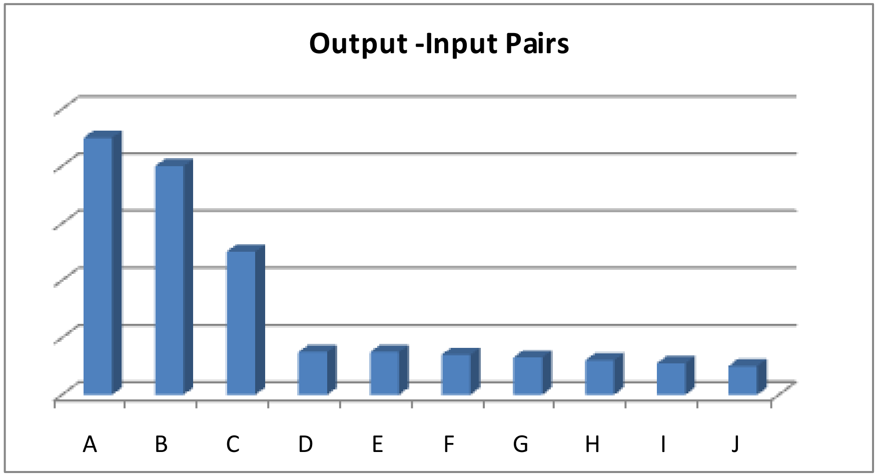
Another method to Analyze in Interface Output-Input Examples

- **Parameters γ and β based on**
  - Operational data
  - System test data
  - Can be subjectively assigned and updated with Bayesian techniques as more operational experience is gathered

- **Probability of occurrence**
  - Probabilistic measure of the interference between the input variability and the variability of the input threshold limit
  - Probability density functions obtained from system designs, testing, operations

iFMECA Methodology Advantages

- **Risk-based prioritization based on calculated C_{SoS}**
  - Input-Output pairs
  - System contribution pairs
    - Input-Output pairs sum within the receiving system
  - Significant Output-Input combinations



- **Provides a *Systems Engineering Tool* for analyzing the trade space for Interfaces when introducing a new system into a SoS**
  - How much should an output signal change?
- **A *New Tool* to help Identify the information needed to communicate potentially mismatched information across SoS interfaces**
  - Included into SoS ICD equivalents

APL

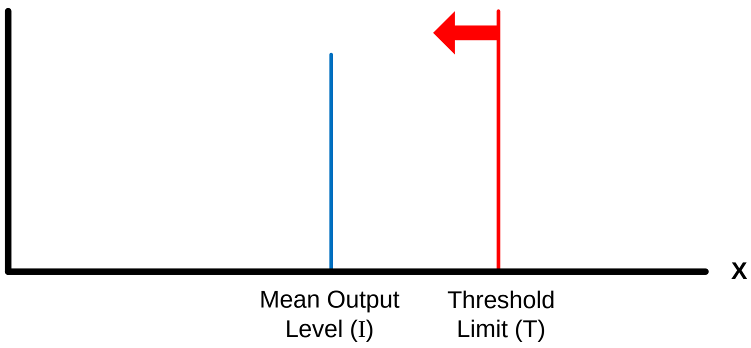
iFMECA Methodology Execution

- **Interfaces will be analyzed <u>not</u> for hardware on either side of the interface**
  - Assumed to be part of the normal FMEA process already in place
- **Interfaces analyzed for**
  - Content communicated
  - Medium of communication
  - Protocol interoperability
  - Stress vs strength
  - Load vs endurance

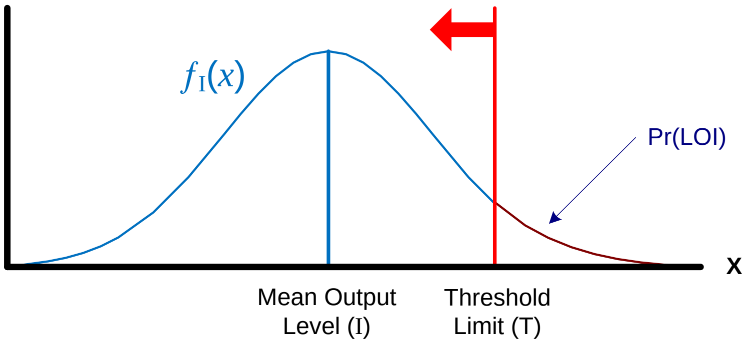
APL

Another method to Analyze in Interface Output-Input Examples

- **Case I**
  - Discrete output with discrete upper bound threshold
  - No variability is shown, therefore output will always be less than threshold
  - Pr(LOI) = Pr(**I** > **T**) = 0

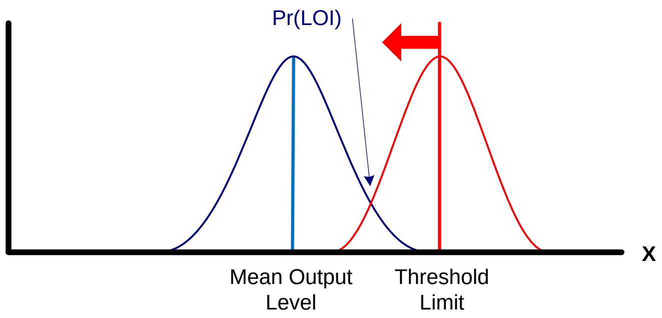


- **Case II**
  - Variation in output with discrete upper bound threshold
  - Some Pr exists that the input level will exceed the threshold
  - Pr(LOI) = Pr(**I** > **T**) = $\int_{T}^{\infty} f_I(x)\,dx$



Another method to Analyze in Interface Output-Input Examples

- **Case III**
  - Variation in output with variation in upper bound threshold
  - Some Pr exists that the input level will exceed the threshold
  - Pr(LOI) = Pr(**I** > **T**) = $\int_{-\infty}^{0} \int_{-y}^{\infty} f_T(y+x) \cdot f_I(x)\, dx\, dy$



- **Many type of interactions exist**
  - Various combinations
  - Various distributions

IRaD Summary

- **Shown that a New SoS Design Tool that Quantifies the Criticality of its Interfaces is Possible**
  - Concept is Based on Modeling the Interface as a Combination of Boolean Variables and Employing Conditional Probability Theory to Propagate the Probability of their Failure
  - Concept is Applicable to Complex Interfaces (e.g. OSI Stack, or multi-attribute)
  - Allows for the Propagation of a Poorly Performing Attribute of an Interface to be Propagated to the Next Hierarchical Level and Address Impacts to Mission
  - Though Not Investigated, Suggests that Marginally Performing Interfaces which can Affect Overall SoS Performance May be Isolated
  - Allows the PM to Adjust Program Resources to Mitigate Poorly Designed Interfaces Early in the Design Phase by Analyzing the I/F Criticality Numbers
  - Tool is Not Radically Different – It is a Simple Extension to the Well-Understood FMECA Tool (Mil-Std-1629)
  - SoS Design Challenge: Developing and Validating the Failure Rates of the Attributes of Interface Data

Potential Follow-On Work

- **Need to Typify the Types and Classes of Failures Similar to How Studies Are being Performed on the Failure of Box-Level Component Parts**
- **Need to Characterize the Statistical Distributions for These Interface Types and Classes of Failures**
  - As a First Approximation, a Typical Normal, Poisson or Exponential Distributions could be Assumed
  - Distributions Need to be Validated on Real World Systems
- **Need to Develop the Data Collection Methodology at the Design Level (Extend the Procedural Language in the Mil-Std-1629 to Address SoS Interfaces)**
- **Publish the Results**

Questions?