Failure Modes and Effects Analyses for Large Software Intensive Systems

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Outline

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- Steps for Performing an FMEA for a Software Intensive System
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Motivation

- **Demonstrate the application of system safety analysis methods to a large software intensive system of national significance**
- **Required by Air Force Policy Directive 63-12 (1 February 2000)**
  - ❖ **The Air Force will**
    - – Assure the operational safety, suitability, and effectiveness of all systems and end-items currently in, or entering, the operational inventory.
  - ❖ **Definition of Operational Safety:**
    - – The condition of having acceptable risk to life, health, property, and environment caused by a system or end-item when employing that system or end-item in an operational environment. This requires the identification of hazards, assessment of risk, determination mitigating measures, and acceptance of residual risk.

System Characteristics

- Large ground control systems built on conventional Information Technology (IT) platforms
- Software:
  - OS platforms: COTS
  - Middleware (e.g., messaging middleware, DBMS)
    - Mostly COTS, Sometimes NDI, Rarely developed for the system
  - Applications
    - Mostly developed for the system, Sometimes NDI, Rarely COTS
  - Human Interfaces
    - Sometimes developed for the systems, Sometimes NDI, Rarely COTS
- Hardware (all COTS):
  - Computing nodes (consist of processors, internal interconnect, and memory)
  - Network devices (e.g., NIC, router)
  - Storage devices (e.g., RAID, NAS, SAN):
  - Interconnections (gateway, firewall, wires)

Steps for Performing an FMEA for a Software Intensive System

- **Determine the architectural level of analysis (level of indenture)**
- **Identify the units of analysis, their boundaries, and environments**
- **Define Effect Levels and Severity**
- **Define platform failure modes (to be included in each unit analysis)**
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Determine the Architectural Level Of Analysis

- **Unit of analysis (UA) - The unit of software at the level of indenture for which failure modes are identified and analyzed.**
  - Examples: processes/tasks, or collections of processes/tasks that interact with the rest of the system through common interfaces.
- **Tradeoffs for selecting units of analysis:**
  - Smaller units enable a more detailed analysis of the components and interactions.
  - Larger units of analysis may be more cost effective.
  - Limited by the detail and accuracy available in the design documents and code.
    - Example: a detailed analysis of the COTS elements of the system may be impractical.

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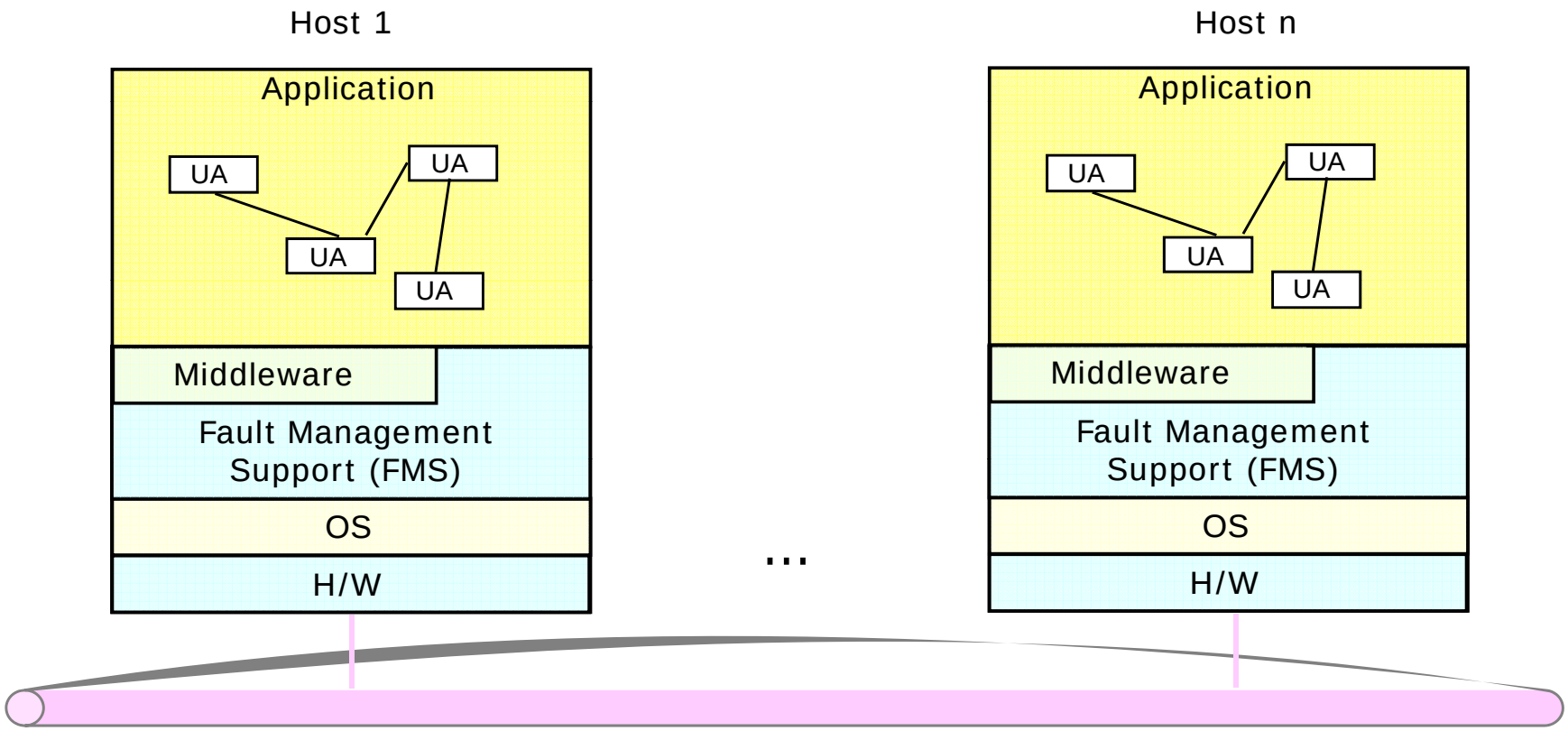
  - ❖ Identify effects, severities, and mitigations for each failure mode

Distributed Execution Environment

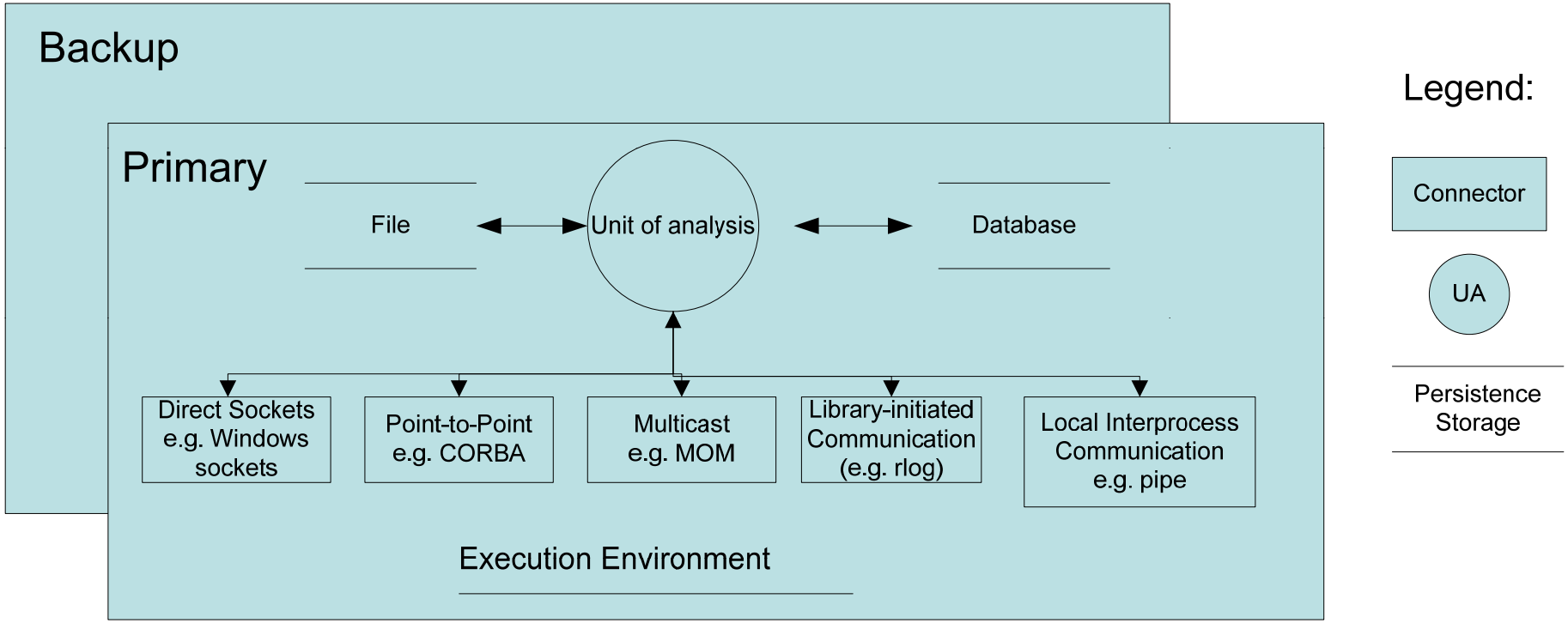
Sample Architectural Depiction (abstracted)



Note: Middleware, FMS, and OS units are either platform UA's or special cases of application UA's

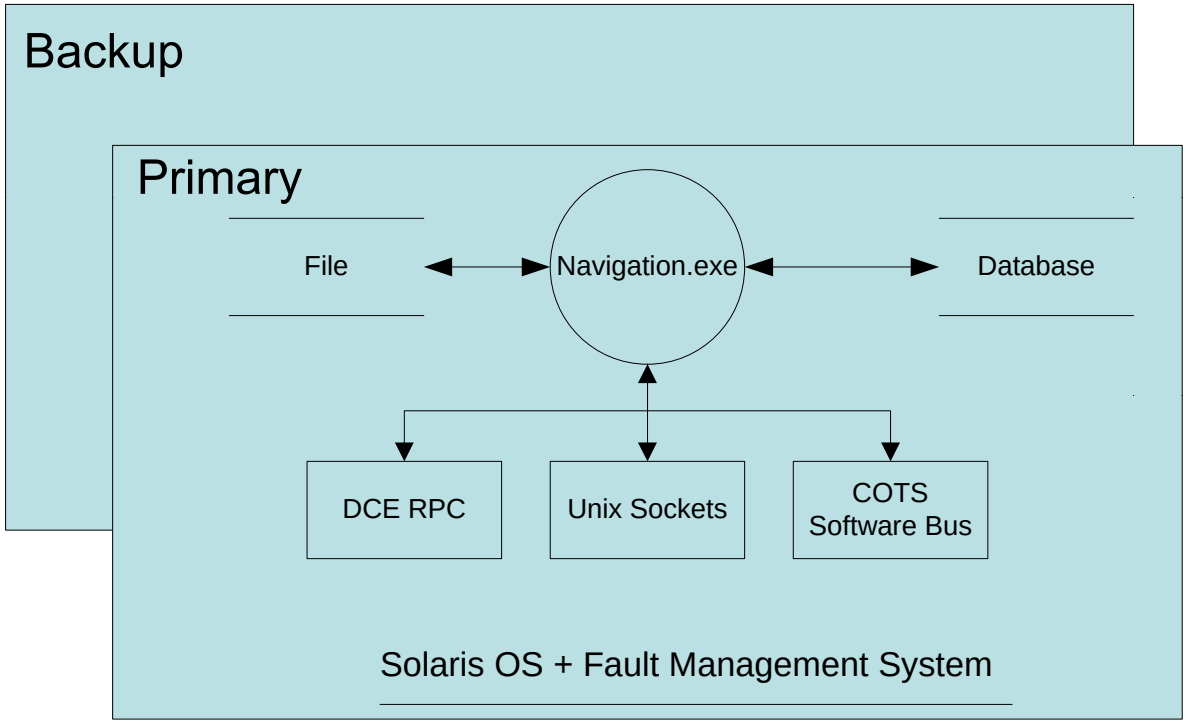
Resultant Boundaries, Environment, and Units of Analysis

- For each unit being analyzed, consider all interactions.
- Primary and backup UA instances should be analyzed individually.



Boundaries, Environment, and units of analysis: An Example

The example UA, Navigation.exe, uses configuration files, stores/retrieves data in a database, and communicates with other units of analysis via RPC, Sockets, and a software bus.



Analyze:

1. Software executable units
2. Three Inter-process communication methods
3. Database operations
4. File input/output
5. FMS
6. Operating System

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Defining Effects

- **Distinguishing between local and higher level effects**
  - Local effect: impact on the unit of analysis
  - Next higher level effect: impact on the services and/or operations of the system
  - End effect: Impact on the end system.
- **Non-local effects are system specific**

Example: Defining Effects

- **Distinguishing between local and higher level effects**
  - Local effect: impact on the UA and immediate context
    - Process loss or degradation
    - Loss of hardware resource (disk, processor, network, interface)
    - Loss or degradation (late, incorrect) or loss of process output
    - Loss of database currency or integrity
  - Intermediate effect: impact on system operations
    - Impact on user of the UA (e.g., operator)
    - Impact on external network (e.g., high traffic, etc.)
    - Impact on database
    - Impact on recovery capability
  - End effect: Impact on end system
    - Satellite systems examples
      - Impact on telemetry, tracking or control
      - Impact on Navigation signal performance (accuracy, integrity, continuity, availability)

Assessing Severity

- **Category I**
  - Catastrophic – Failure which causes system loss
- **Category II**
  - Critical – Failure which causes major system damage resulting in mission loss
- **Category III**
  - Marginal – Failure which results in delay or loss of availability or degrades system operations
- **Category IV**
  - Negligible/Minor - Failure not serious enough to cause system damage; loss of partial functionality for short time

Note: Severity levels adopted from MIL-STD-1629A; When there are multiple effects base the severity on the most sever effect

Example: Assessing Severity

- **Category I**
  - Loss of Space Vehicle (SV)
- **Category II**
  - Undetected database integrity loss in SV
  - Jeopardize SV navigation message integrity
  - Jeopardize SV continuity
  - Undetected incorrect data through external output interfaces
- **Category III**
  - Degrades SV operations
  - Interruption of functionality that does not reach severity of Category II
- **Category IV**
  - Loss of partial functionality for short time

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Characteristics of Software Platform Failures

- Failures occurring in the operating system, fault management system, and other middleware will generally lead to application failures.
- A set of software platform failures should be identified and applied to each UA analysis.
- While the causes of these platform failures may be common, their effects, severity, detection methods, and compensating provisions may vary depending on the UA being evaluated.
- Reusing a set of pre-defined software platform failures will provide more consistent and complete evaluations with reduced effort.

Software Platform Failures List: Platform Example

	Failure Mode		Failure Mode
1	**OS Crash -- multiple causes**	7	**SNMP agent crashes or hangs**
2	**OS hang**	8	**System logging facilities crash or hang**
3	**Unacceptable delay caused by Solaris OS malfunctioning.**	9	**GUI not initializing, crashes, or hangs**
4	**Network File System Crash-multiple failures**	10	**OS & Infrastructure Initialization Error (device drivers, file system, networking)**
5	**Hardware-disk full – Fault management is able to detect this failure**	11	**COTS & NDI Initialization Errors (e.g., software bus)**
6	**Hardware-disk full - Fault management is not able to detect this failure**	12	**Application Initialization Error (.cshrc script, . login script, etc.)**

Example of a Software Platform Failure Mode Analysis

ID	**100**
Host	**TTC**
Function	**Solaris OS**
Failure Mode and Causes	**Crash -- multiple causes**
Mission Phase	**Operational/Primary**
Local Effect	**Loss of application functions**
Next Higher Level Effect	**Loss of local application functions and data**
End Effects	**Local application unable to provide services to users**
Failure Detection Method	**Detected by the Failure Management System**
Compensating Provisions	**Failover to backup host**
Severity Class	**IV**
Remarks	**Severity class assumes that failover from primary to backup host is successful.**

Note: Failure Mode Analysis fields adopted from MIL-STD-1629A

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Software Failure Modes

- **UA internal failure modes**
  - Examples: Crash, hang, incorrect result, untimely result
- **Inter-process communications failure modes**
  - Examples:
    - Failure of multi-cast communication (e.g., software bus, messaging middleware)
    - Failure of point-to-point communication (e.g., RPC)
    - Failure of socket communication (e.g., UDP, TCP)
    - Failure of local inter-process communication (e.g., pipe)
    - Failure of library based communication (e.g., remote login)
- **Database Reads and Writes failure modes**
  - Examples: Failure to connect, read, and write
- **File I/O failure modes**
  - Examples: Failure to open, read, and write
- **Fault management failure modes**
  - Failover/restart mechanisms
    - Example: Failure to restart or failover
  - Hot Standby mechanisms
    - Example: Failure of backup host/application to take over

Example of a Software Failure Mode Analysis

ID	**120**
Host	**Producer CSCI Host**
Function	**Producer CSCI Process**
Failure Mode and Causes	**Tracking software produces incorrect result**
Mission Phase	**Operational/Primary**
Local Effect	**Incorrect result output**
Next Higher Level Effect	**Incorrect result propagated into subsequent calculations resulting in cumulative error**
End Effects	**System integrity lost**
Failure Detection Method	**Reasonableness check on output**
Compensating Provisions	**None**
Severity Class	**II**
Remarks	**Not all errors will be detected; replace reasonableness check with inverse calculation**

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Hardware Failure Modes

- Startup Failure
- Operations Failure (unannounced cessation of function)
- RAM data corruption
- Persistent data corruption
- Communication data corruption
- LAN channel babbling
- Power supply/conditioning short
- Power supply/conditioning open
- Discrete contact stuck at 0
- Discrete contact stuck at 1

Hardware Elements

- Standalone Processors
- Blade server
- Equipment cabinets
- SANs
- NASs
- Routers
- Crypto units
- Firewalls
- CSU/DSU
- LAN Cables
- Wiring Hubs

Failure Modes: Standalone Processors (Servers and Workstations)

- **Startup Failure**
  - Effect: no output
  - Example Mitigation: retry; switch to alternate; repair/replace
- **Operations Failure (unannounced cessation of function)**
  - Effect: no output
  - Example Mitigation: retry; switch to alternate; repair/replace
- **RAM data corruption**
  - Effects: no output (if causes processor crash); corrupted data
  - Example Mitigation: Error correcting codes
- **Persistent data corruption on Direct Attached Storage**
  - Effects: corrupted data
  - Example Mitigation: CRCs, multiple writes for critical data
- **Communication data corruption**
  - Effects: See LAN, NAS, SAN
- **Power supply/conditioning short**
  - Effect: power surge causes overheating; loss of output
  - Example Mitigation: fuses and circuit breakers
- **Power supply/conditioning open**
  - Effect: no power; loss of output
  - Example Mitigation: switch to alternate; repair/replace power supply

Conclusions

- Software focused analysis is necessary in large software intensive systems
- Software architecture provides a basis for defining units of analysis.
- Generally accepted failure modes and local effects can be identified for many categories of units of analysis
- Higher level effects are system specific
- Methodology presented here has been applied to a large scale ground system
- Other methodologies are applicable to smaller scale systems

Acronyms (1)

- CMOS - Complementary Metal–Oxide–Semiconductor
- CORBA - Common Object Request Broker Architecture
- COTS - Commercial Off-The-Shelf
- CRC - Cyclic Redundancy Check
- CSCI - Computer Software Configuration Item
- CSU - Channel Service Unit
- DB - Database
- DBMS - Database Management Software
- DSU - Data Service Unit
- FMEA - Failure Modes & Effects Analysis
- FMECA - Failure Mode, Effects and Criticality Analysis
- FMS - Fault Management Support/System
- GPS AEP - Global Positioning System Architectural Evolution Program
- GUI - Graphical User Interface
- H/W - Hardware
- LAN - Local Area Network

Acronyms (2)

- MOM - Message-Oriented Middleware
- NAS - Network Attached Storage
- NDI - Non-Development Item
- NIC - Network Interface Card
- NFS - Network File System
- OS - Operating System
- RAID - Redundant Array of Independent Drives
- RAM - Random Access Memory
- RPC - Remote Procedure Call
- S/W - Software
- SAN - Storage Area Network
- SNMP - Simple Network Management Protocol
- SV - Space Vehicle
- TCP - Transmission Control Protocol
- UA - Unit of Analysis
- UDP - User Datagram Protocol

References

- **MIL_STD-1629A: www.uscg.mil/hq/gm/risk/E-Guidelines/RBDM/html/vol4/Volume4/Tool-spec_Rec/FMEA/MIL-STD-1629A.pdf**
- **William Greenwell, Gail Haddock, Myron Hecht, Steven Meyers, Eltefaat Shokri, and Elisabeth Nguyen, "Safety Analysis Methods for Software Intensive Satellite Ground Systems", *Space Systems Engineering and Risk Management Conference,* Los Angeles, CA, February, 2008, available from http://www.aero.org/conferences/riskmgmt/**

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