MOVEP 2012 Tutorial
Safety, Dependability and Performance Analysis of Extended AADL Models

Part 4: Safety and Dependability Analysis

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Contents of Overview

Outline

Safety Assessment

Objectives

- Analyse system behaviour under all possible operational conditions, in particular in presence of malfunctions of its components
- Determine the conditions under which safety hazards can occur
- Ensure that a system meets the safety requirements that are required for its deployment and use

Safety Assessment

Objectives

- Analyse system behaviour under all possible operational conditions, in particular in presence of malfunctions of its components
- Determine the conditions under which safety hazards can occur
- Ensure that a system meets the safety requirements that are required for its deployment and use

Requirements

- Particularly important for safety-critical systems, where unexpected behavior may cause significant loss of money or human lives!
- Carried out in parallel with system design
- Typically needed for certification of safety-critical systems

Safety Assessment

Properties of interest - some examples (qualitative):

- "If no more than 3 components fail, then I never have a total loss of hydraulic power"
- "No single point of failure can cause unavailability of both the primary and secondary power systems"
- "Find all combinations of basic faults which may cause total loss of hydraulic power"

Safety Assessment

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- “If no more than 3 components fail, then I never have a total loss of hydraulic power”
- “No single point of failure can cause unavailability of both the primary and secondary power systems”
- “Find all combinations of basic faults which may cause total loss of hydraulic power”

Properties of interest - some examples (quantitative):

- “The probability of a total loss of hydraulic power is less than 10^{-7}”
- “The probability that both the primary and secondary power systems fail during the same mission is less than 10^{-9}”

Safety Assessment

Safety Assessment Techniques

- Several safety assessment techniques, e,g.:
  - Fault Tree Analysis (FTA)
  - Failure Mode and Effects Analysis (FMEA)

Safety Assessment

Safety Assessment Techniques

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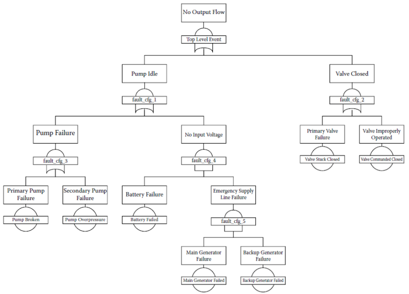
  - Fault Tree Analysis (FTA)
  - Failure Mode and Effects Analysis (FMEA)

Fault Tree



FMEA Table

Ref. No.	*Item*	*Failure Mode*	*Failure Cause*	*Local Effects*	*System Effects*	*Detection Means*	*Severity*	*Corrective Actions*
1	Pump	Fails to operate	Comp. broken No input flow	Coolant temperature increases	Reactor temperature increases	Temperature alarm	Major	Start secondary pump Switch to secondary circuit
2	Valve	Stuck closed	Comp. broken	Excess liquid	Reactor pressure increases	Coolant level sensor	Critical	Open release valve
3		Stuck open	Comp. broken	Insufficient liquid	Reactor temperature increases	Coolant level sensor	Critical	Open tank valve

References

- Safety Critical Systems (Storey, Addison-Wesley 1996)
- System Safety (Leveson, Addison-Wesley 1995)
- Formal Safety Assessment (Bozzano, Villafiorita, Taylor & Francis 2010)

Outline

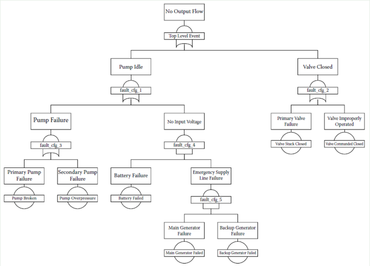
1. Introduction
2. Fault Tree Analysis
3. Failure Mode and Effects Analysis
4. Ongoing Activities
5. Tool Support

Fault Tree Analysis (FTA)

Main Features

- Deductive technique (top-down)
- Graphical representation of the effects of faults on system requirements (using Boolean gates)
- Widespread use in aerospace, avionics, and other domains
- Qualitative model that can be evaluated quantitatively

Fault Tree



Fault Tree Analysis (FTA)

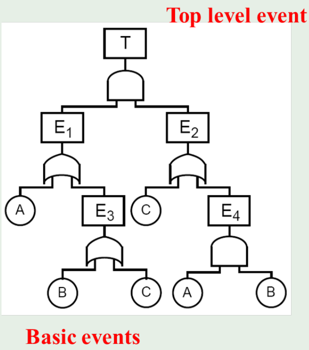
FTA requires:

- Specifying a Top Level Event (TLE) representing an undesired condition
- Find all possible chains of basic events that may cause the TLE to occur

A Fault Tree:

- Is a systematic representation of such chains of events
- Uses logical gates to represent the interrelationships between events and TLE, e.g. AND, OR

Fault Tree

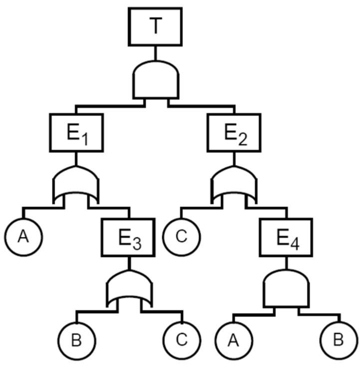


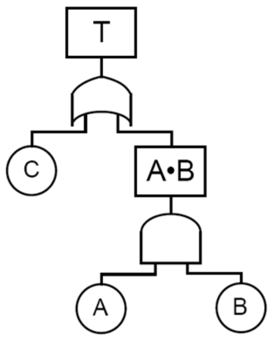
Fault Tree Analysis (FTA)

Logical formula associated to a FT

The FTs below have the same associated logical formula:
$(A \vee (B \vee C) \wedge (C \vee (A \wedge B)) \equiv (C \vee (A \wedge B))$

Logically Equivalent Fault Trees



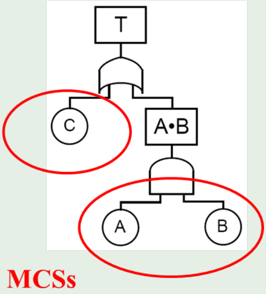


Fault Tree Analysis (FTA)

Minimal Cut Sets (MCSs)

- This shape is of particular interest: representation in terms of Minimal Cut Sets (MCSs)
- Minimal cut set = "smallest set of basic events which, conjoined, cause the top level event to occur"
- Logically: Disjunctive Normal Form (DNF) = disjunction of conjunctions of basic events
- The fault tree on the right has two MCSs: C (single point of failure) and $A \wedge B$ (cut set of order 2)

MCSs



Cut Sets

Fault Configuration

$\mathcal{M} = \langle \mathcal{S}, \mathcal{I}, \mathcal{R}, \mathcal{L} \rangle$ be a Kripke structure with a set of failure mode variables $\mathcal{F} \subseteq \mathcal{P}$. A fault configuration FC is a subset of failure mode variables, that is, $FC \subseteq \mathcal{F}$

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Cut Set

Let $\mathcal{M} = \langle \mathcal{S}, \mathcal{I}, \mathcal{R}, \mathcal{L} \rangle$ be a Kripke structure with a set of failure mode variables $\mathcal{F} \subseteq \mathcal{P}$, let $FC \subseteq \mathcal{F}$ be a fault configuration, and $TLE \in \mathcal{P}$. We say that FC is a cut set of TLE, written $cs(FC, TLE)$ if there exists a trace $s_0, s_1, \ldots, s_k$ for $\mathcal{M}$ such that:

- $s_k \models TLE$
- $\forall f \in \mathcal{F}\ f \in FC \iff \exists i \in \{0, \ldots, k\}\ (s_i \models f)$

Minimal Cut Sets

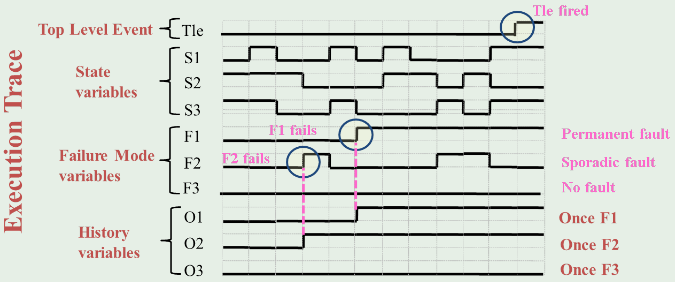
Minimal Cut Sets

Let $\mathcal{M} = \langle \mathcal{S}, \mathcal{I}, \mathcal{R}, \mathcal{L} \rangle$ be a Kripke structure with a set of failure mode variables $\mathcal{F} \subseteq \mathcal{P}$, let $F = 2^{\mathcal{F}}$ be the set of all fault configurations, and $TLE \in \mathcal{P}$.

The set of minimal cut sets of TLE is the set of cut sets of TLE that are minimal wrt set inclusion. Formally:

- $CS(TLE) = \{FC \in F \mid cs(FC, TLE)\}$
- $MCS(TLE) = \{cs \in CS(TLE) \mid \forall cs' \in CS(TLE)\ (cs' \subseteq cs \rightarrow cs' = cs)\}$

Cut Sets



- History variables remember past failure events
- O_i is true if and only if F_i is true at some point in the past:

$$\mathcal{R}^o = \begin{cases} O_i \rightarrow next(O_i) \\ \neg O_i \rightarrow (next(O_i) \leftrightarrow next(F_i)) \end{cases}$$

- $F_1 \wedge F_2$ is a cut set

Algorithms for FTA

Symbolic Algorithms for FTA

Several algoritmhs:

- BDD-based algorithms
  - Forward algorithm
  - Backward algorithm
- SAT-based algorithms

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Algorithms Optimizations

- Dynamic Pruning
- Backward algorithm with DCOI (Dynamic Cone of Influence)

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An Example

- BDD-based forward algorithm

function FTA-Forward ($\mathcal{M}$, *Tle*)

FTA-Forward

FTA: BDD-based Forward Algorithm

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$\mathcal{M} := Extend(\mathcal{M}, \mathcal{R}^o)$;

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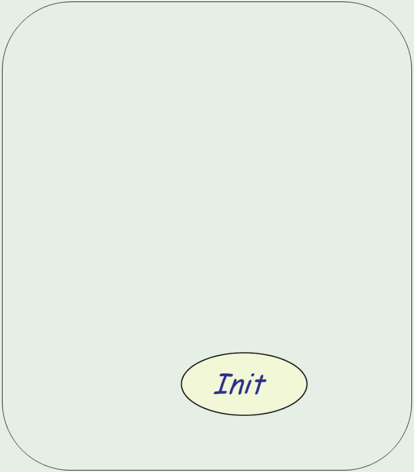

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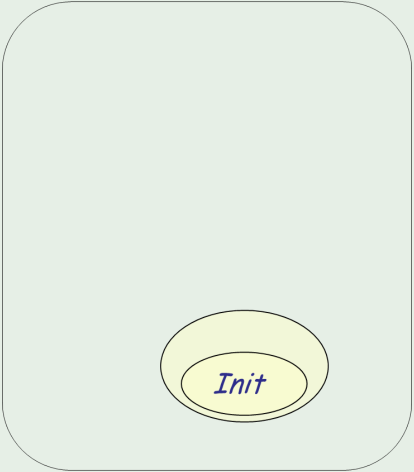

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M := Extend(M, R°);
Reach := I ∩ (o = f);
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while (Front ≠ ∅) do
    temp := Reach;
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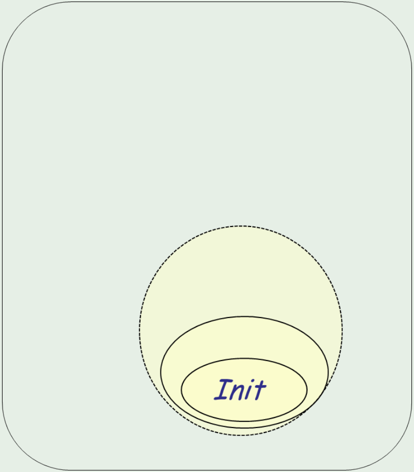

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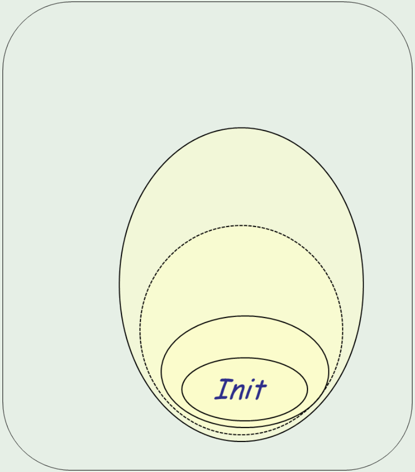

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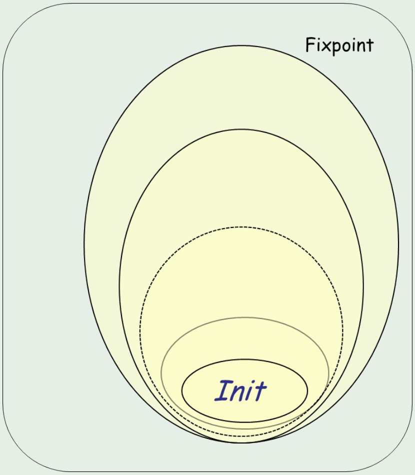

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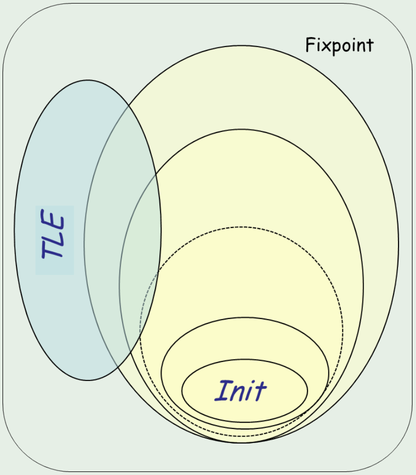

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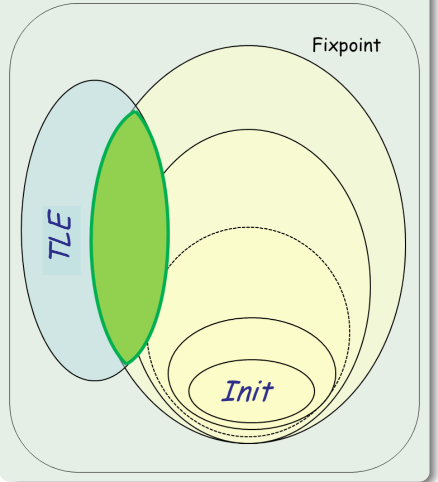

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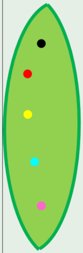

	CS1	CS2	CS3	CS4	CS5
S1	0	1	1	0	1
S2	1	1	0	1	1
S3	1	0	1	0	1
S4	1	0	1	1	1
S5	0	1	1	0	0
F1	0	1	1	1	0
F2	0	0	1	0	1
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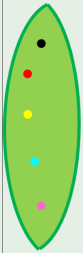

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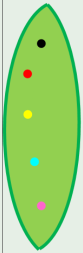

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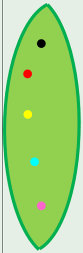

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return $Map_{\underline{o} \to \underline{f}}(MCS)$;

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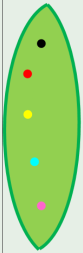

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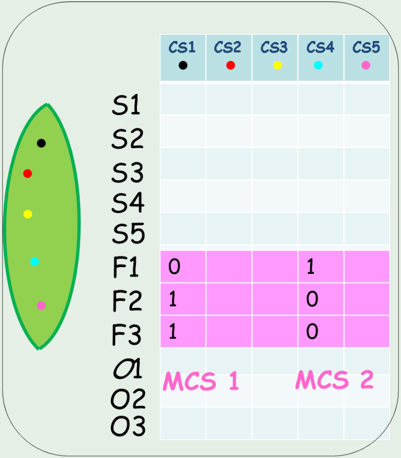
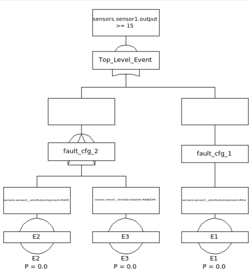


Fault Tree Analysis (FTA)

Dynamic FTs

- Dynamic FTs extend FTs by considering dynamic aspects, such as: ordering constraints, functional dependencies, spares
- Dynamic FTs in COMPASS:
  - Ordering constraints between basic events can be analyzed
  - Priority AND gate (PAND) to display order

Dynamic Fault Tree



References

- FTA (Fault Tree Handbook, U.S. Nuclear Regulatory Commission, 1981)
- FTA (Fault Tree Handbook, NASA 2002)
- Formal FTA (Bozzano, Villafiorita, Taylor & Francis 2010)
- Algorithms for FTA (Bozzano et. al, ATVA 2007)

Outline

Failure Mode and Effects Analysis (FMEA)

Main Features

- Inductive technique (bottom-up)
- Tabled representation of the effects of faults on a set of system properties
- Widespread use in aerospace, avionics, and other domains

FMEA Table

Ref. No.	*Item*	*Failure Mode*	*Failure Cause*	*Local Effects*	*System Effects*	*Detection Means*	*Severity*	*Corrective Actions*
1	Pump	Fails to operate	Comp. broken	Coolant temperature increases	Reactor temperature increases	Temperature alarm	Major	Start secondary pump
			No input flow					Switch to secondary circuit
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FMEA Table

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FMEA Table

Let $\mathcal{M} = \langle \mathcal{S}, \mathcal{I}, \mathcal{R}, \mathcal{L} \rangle$ be a Kripke structure with a set of failure mode variables $\mathcal{F} \subseteq \mathcal{P}$, let $FC_j \subseteq \mathcal{F}$ for $j = 1, \ldots, n$ be a set of fault configurations, and $E_l \in \mathcal{P}$ for $l = 1, \ldots, m$. An FMEA table for $\mathcal{M}$ is the set of pairs $\{(FC_j, E_l) \mid cs(FC_j, E_l)\}$.

Cardinality of FMEA Tables

- FMEA table of cardinality k includes fault configurations of cardinality up to k

Compaction of FMEA Tables

FMEA tables may be “redundant”

Compaction of FMEA tables improves readability

- Idea: remove entries with cardinality k that are “subsumed” by other entries of cardinality less than k

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An Example

- Set of faults: $\{F_1, F_2, F_3, F_4, F_5\}$
- Set of events: $\{E\}$

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An Example

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- Set of events: $\{E\}$

An Example (ctd)

FMEA Table of Cardinality 2:

- Fault Configurations of order 1: $\{F_i\}$ for all $i = 1, \ldots, 5$
- Fault Configurations of order 2: $\{F_i, F_j\}$ for all $i, j = 1, \ldots, 5$ with $(i \neq j)$

Compaction of FMEA Tables

An Example (ctd)

Suppose that:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$ are in FMEA table T

Compaction of FMEA Tables

An Example (ctd)

Suppose that:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$ are in FMEA table T

An Example (ctd)

Typically T contains also:

- $(\{F_1, F_i\}, E)$ for $i = 2, 3, 4, 5$
- $(\{F_2, F_i\}, E)$ for $i = 3, 4, 5$
- $(\{F_3, F_i\}, E)$ for $i = 4, 5$

Compaction of FMEA Tables

An Example (ctd)

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- $(\{F_3, F_i\}, E)$ for $i = 4, 5$

An Example (ctd)

Also suppose that:

- $(\{F_4, F_5\}, E)$ is in T

Compaction of FMEA Tables

An Example (ctd)

Complete FMEA Table:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$
- $(\{F_1, F_2\}, E)$, $(\{F_1, F_3\}, E)$, $(\{F_1, F_4\}, E)$, $(\{F_1, F_5\}, E)$, $(\{F_2, F_3\}, E)$, $(\{F_2, F_4\}, E)$, $(\{F_2, F_5\}, E)$, $(\{F_3, F_4\}, E)$, $(\{F_3, F_5\}, E)$, $(\{F_4, F_5\}, E)$

Compaction of FMEA Tables

An Example (ctd)

Complete FMEA Table:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$
- $(\{F_1, F_2\}, E)$, $(\{F_1, F_3\}, E)$, $(\{F_1, F_4\}, E)$, $(\{F_1, F_5\}, E)$, $(\{F_2, F_3\}, E)$, $(\{F_2, F_4\}, E)$, $(\{F_2, F_5\}, E)$, $(\{F_3, F_4\}, E)$, $(\{F_3, F_5\}, E)$, $(\{F_4, F_5\}, E)$

An Example (ctd)

We want to preserve only:

- those pairs such that single faults have an effect on event E: $(\{F_1, F_2\}, E)$, $(\{F_1, F_3\}, E)$, $(\{F_2, F_3\}, E)$
  - Intuition: e.g. $(\{F_1, F_4\}, E)$ is redundant, because F_4 has no effect on E (E is explained by F_1 alone)
- "genuine" pairs (no subset of faults in T): $(\{F_4, F_5\}, E)$

Compaction of FMEA Tables

An Example (ctd)

Compact FMEA Table:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$
- $(\{F_1, F_2\}, E)$, $(\{F_1, F_3\}, E)$, $(\{F_2, F_3\}, E)$
- $(\{F_4, F_5\}, E)$

Compaction of FMEA Tables

An Example (ctd)

Compact FMEA Table:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$
- $(\{F_1, F_2\}, E)$, $(\{F_1, F_3\}, E)$, $(\{F_2, F_3\}, E)$
- $(\{F_4, F_5\}, E)$

An Example (ctd)

- 6 entries out of 13 have been removed

Compaction of FMEA Tables

An Example (ctd)

Compact FMEA Table:

- $(\{F_1\}, E)$, $(\{F_2\}, E)$, $(\{F_3\}, E)$
- $(\{F_1, F_2\}, E)$, $(\{F_1, F_3\}, E)$, $(\{F_2, F_3\}, E)$
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An Example (ctd)

- 6 entries out of 13 have been removed

An Example (ctd)

- This idea can be generalized to FMEA tables of arbitrary cardinality and arbitrary number of events:
  - Definition is by induction on the cardinality of the table
  - Compact FMEA tables are defined independently for each event E_j

References

- FMEA (Fault Tree Handbook, U.S. Nuclear Regulatory Commission, 1981)
- FMEA (Fault Tree Handbook with Aerospace Applications, NASA 2002)
- Formal FMEA (Bozzano, Villafiorita, Taylor & Francis 2010)

Outline

Ongoing Activities

Compositional FTA

- Build system-level FT from FTs of sub-components
- Reduce workload in FT generation
- Fits into contract-based system development and verification

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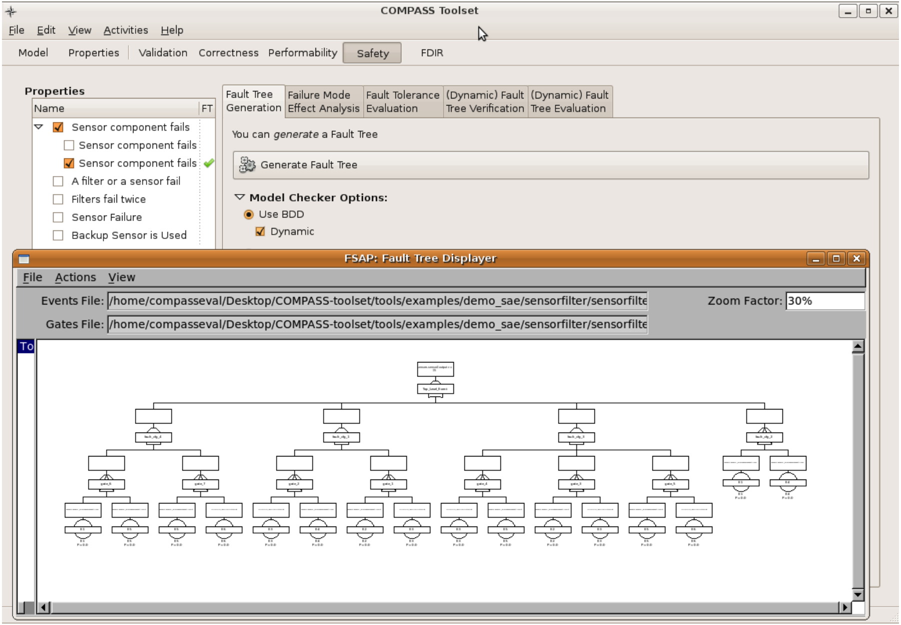
Hierarchical FTs

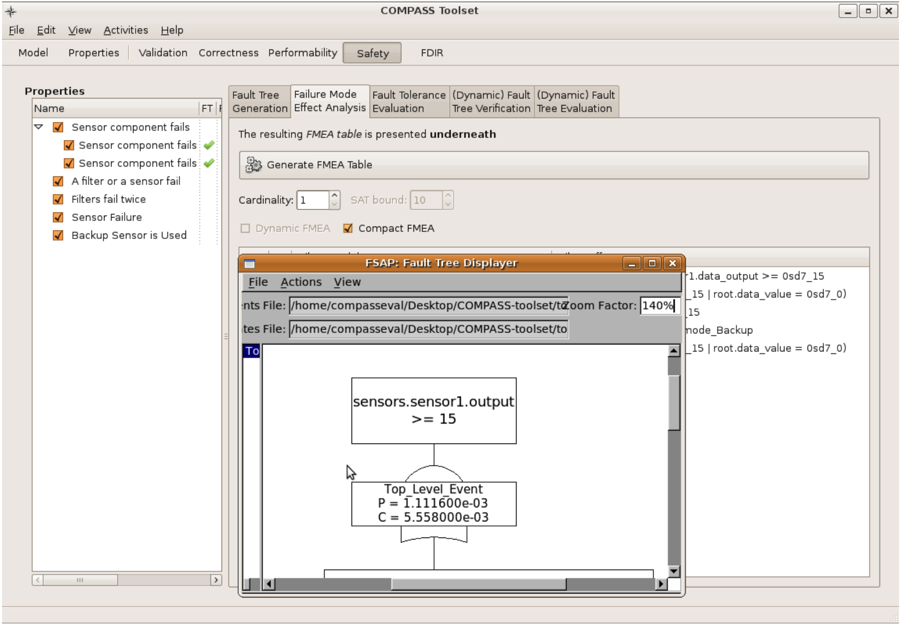
- Generate multi-level FTs
- Improve readability and avoid MCSs enumeration
- FT structure based upon system structure
- Can be integrated with compositional generation of FTs

Outline

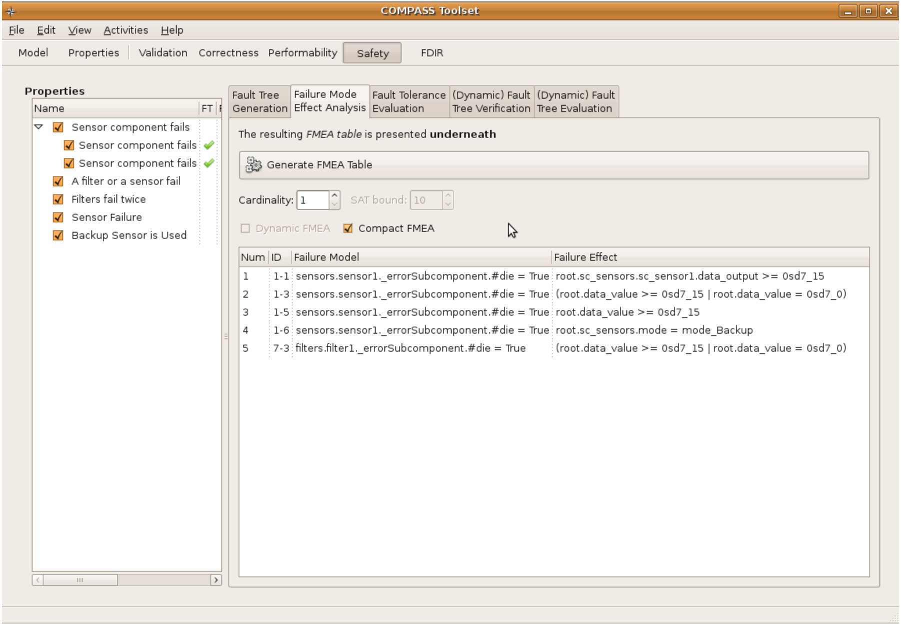
Fault Tree Analysis



Probabilistic Risk Assessment Tree Analysis



Failure Modes and Effects Analysis



Num	ID	Failure Model	Failure Effect
1	1-1	sensors.sensor1._errorSubcomponent.#die = True	root.sc_sensors.sc_sensor1.data_output >= 0sd7_15
2	1-3	sensors.sensor1._errorSubcomponent.#die = True	(root.data_value >= 0sd7_15 | root.data_value = 0sd7_0)
3	1-5	sensors.sensor1._errorSubcomponent.#die = True	root.data_value >= 0sd7_15
4	1-6	sensors.sensor1._errorSubcomponent.#die = True	root.sc_sensors.mode = mode_Backup
5	7-3	filters.filter1._errorSubcomponent.#die = True	(root.data_value >= 0sd7_15 | root.data_value = 0sd7_0)