Reliability

Embedded Systems

Lirida Alves de Barros-Naviner
Master Program
Outline

Introduction
  Dependability
  Faults

System Analysis
  Deterministic Models
  Probabilistic Models
  Lifetime Models
  Markov Process

Reliability of Electronics Systems

Conclusions
Outline

Introduction
  Dependability
  Faults

System Analysis
  Deterministic Models
  Probabilistic Models
  Lifetime Models
  Markov Process

Reliability of Electronics Systems

Conclusions
Dependability is the ability of a system to deliver service that can *justifiably be trusted*.

Dependability is the ability of a system to avoid *service failures* that are *more frequent or more severe* than is *acceptable*.
Dependability Attributes

- **Availability**: readiness for correct service.
- **Reliability**: continuity of correct service.
- **Safety**: absence of catastrophic consequences on the user(s) and the environment.
- **Integrity**: absence of improper system alterations.
- **Maintainability**: ability to undergo modifications and repairs.
Dependability Attributes

- **Availability**: readiness for correct service.
- **Reliability**: continuity of correct service.
- **Safety**: absence of catastrophic consequences on the user(s) and the environment.
- **Integrity**: absence of improper system alterations.
- **Maintainability**: ability to undergo modifications and repairs.
Dependability Threats

- **Fault**: an *unexpected condition* that can lead the system to achieve *abnormal states*. A fault can lead to an error.
- **Error**: an *undesired change in the state* of the system. An error can lead to an incorrect response of the system.
- **Failure**: an *incorrect response* of the system. It means the service provided by the system differs from the expected one.
Software Faults

![Failure rate vs Time graph]

- **Test & debug**
- **Useful life**
- **Obsolescence**

Useful life Obsolescence Test & debug

Failure rate

Time
Hardware Faults

- Decreasing Failure Rate
- Constant Failure Rate
- Increasing Failure Rate

- Early "Infant Mortality" Failure
- Observed Failure Rate
- Constant (Random) Failures
- Wear Out Failures

Time
Fault Time Duration

Permanent

Transient

Intermittent
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Conclusions
Traditional Approaches

Diagnostics experience

Heuristic approaches
Traditional Approaches

- Diagnostics experience
- Insufficient to analyze complex designs
- Heuristic approaches
Deterministic Models: State

Definition
The state of a component $i$ is defined as

$$x_i = \begin{cases} 
0 & \text{if the component } i \text{ is not functioning} \\
1 & \text{if the component } i \text{ is functioning}
\end{cases}$$

for $i = 1, 2, \ldots, n$

Definition
The state set is defined as the vector composed by the components states

$$\mathbf{x} = (x_1 x_2 \cdots x_n)$$
System State

**Definition**

The **system state** is defined as

\[
\xi(x) = \begin{cases} 
0 & \text{if the system is not functioning with state set } x \\
1 & \text{if the system is functioning with state set } x 
\end{cases}
\]
\[ \xi(x) = \begin{cases} 
0 & \text{if there exists an } i \text{ such that } x_i = 0 \\
1 & \text{if } x_i = 1 \text{ for all } i \in [1; n] 
\end{cases} \]

\[ \xi(x) = \prod_{i=1}^{n} x_i \]
Dependability Block Diagram

Parallel System

\[ \xi(x) = \begin{cases} 
0 & \text{if } x_i = 0 \text{ for all } i \in [1; n] \\
1 & \text{if there exists an } i \text{ such that } x_i = 1 
\end{cases} 
\]

\[ = 1 - \prod_{i=1}^{n} (1 - x_i) \]
Block Diagram: \( k\)-out-of-\( n \) System

\[
\xi(x) = \begin{cases} 
0 & \text{if } \sum_{i=1}^{n} x_i < k \\
1 & \text{if } \sum_{i=1}^{n} x_i \geq k 
\end{cases}
\]
Coherent System

Definition

A system of $n$ components is **coherent** if its function $\xi(x)$ is nondecreasing in $x$ and there are no irrelevant components.
Coherent System

Definition

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Definition

A function $\xi(x)$ is **nondecreasing** in $x$ if

$$\xi(x_1 \cdots x_{i-1} 0 x_{i+1} \cdots x_n) \leq \xi(x_1 \cdots x_{i-1} 1 x_{i+1} \cdots x_n).$$
Coherent System

Definition

A system of $n$ components is coherent if its function $\xi(x)$ is nondecreasing in $x$ and there are no irrelevant components.

Definition

A function $\xi(x)$ is nondecreasing in $x$ if

$$\xi(x_1 \cdots x_{i-1}0x_{i+1} \cdots x_n) \leq \xi(x_1 \cdots x_{i-1}1x_{i+1} \cdots x_n).$$

Definition

A component $i$ is irrelevant if its state $x_i$ has no impact on the function $\xi(x)$.
Structural Importance

Definition

The **structural importance** of a component \(i\) in a coherent system of \(n\) components is

\[
I_\xi(i) = \frac{1}{2^{n-1}} \sum [\xi(1_i, x) - \xi(0_i, x)]
\]

for \(i = 1, 2, \ldots, n\).
Exercise

Consider a system composed of a processor and a redundant memory structure. The memory structure is based on two independent RAM: each of them contains exactly the same data so as to tolerate memory faults. Suppose the system is coherent with independent components.

- Draw the state block diagram of this system for dependability analysis purpose.
- Give the state function $\xi(x)$.
- Derivate the structural importance for each component in the system.
Path Vector

Definition
A **path vector** for a coherent system is a vector $x$ such as $\xi(x) = 1$.

Definition
A **minimal path** for a coherent system is a path vector $x$ such as $\xi(y) = 0$ for all $y < x$.

Definition
Given two vectors $x$ and $y$, $x < y$ if and only if $x_i \leq y_i$ for $i = 1, 2, \cdots, n$ and $x_i < y_i$ for some $i$.

Definition
A **minimal path set** $P_j$ for a coherent system is a set with all components associated to a given minimal path vector.
Definition

A cut vector for a coherent system is a vector $\mathbf{x}$ such as $\xi(\mathbf{x}) = 0$.

Definition

A minimal cut vector for a coherent system is a cut vector $\mathbf{x}$ such as $\xi(\mathbf{y}) = 1$ for all $\mathbf{y} > \mathbf{x}$.

Definition

A minimal cut set $C_j$ for a coherent system is a set with all components associated to a given minimal cut vector.
Minimal Sets and System State

Minimal Path Set

\[ \xi(x) = \max_j \prod_{i \in P_j} x_i = 1 - \prod_{j=1}^l \left[ 1 - \prod_{i \in P_j} x_i \right] \]

Minimal Cut Set

\[ \xi(x) = \min_j \left[ 1 - \prod_{i \in C_j} (1 - x_i) \right] = \prod_{j=1}^k \left[ 1 - \prod_{i \in C_j} (1 - x_i) \right] \]
Exercise

Consider a system composed of a processor and a redundant memory structure. The memory structure is based on two independent RAM: each of them contains exactly the same data so as to tolerate memory faults. Suppose the system is coherent with independent components.

- Derivate the minimal path vectors of the system.
- Derivate $\xi(x)$ from its minimal path set. Draw the corresponding block diagram.
- Derivate the minimal cut vectors of the system.
- Derivate $\xi(x)$ from its minimal cut set. Draw the corresponding block diagram.
Definition
The random state of a component $i$ is defined as

$$X_i = \begin{cases} 
0 & \text{if the component } i \text{ has failed} \\
1 & \text{if the component } i \text{ is functioning}
\end{cases}$$

for $i = 1, 2, \cdots, n$

Definition
The random state of the set of components in a system is defined as

$$\mathbf{X} = (X_1 X_2 \cdots X_n)$$
Component Reliability

Definition

The **reliability of a component** \( i \) is defined as the **probability** that component \( i \) is functionning [at prescribed time]

\[
q_i = P\{X_i = 1\}
\]

for \( i = 1, 2, \cdots, n \)

The set of component reliabilities is given by \( \mathbf{q} = (q_1 q_2 \cdots q_n) \)
System Reliability

Definition

The reliability of a coherent system is defined by

\[ R = P\{\xi(X) = 1\} \]

\[ R = R(q) \]
Alternative Reliability Calculation

\[
R(q) = E\{\xi(X)\}
\]

\[
R(q) = P\{X \text{ is a path vector}\}
\]

\[
R(q) = 1 - P\{X \text{ is a cut vector}\}
\]

\[
R(q) = R(1_i, q).q_i + R(0_i, q)(1 - q_i)
\]
Reliability Importance

Definition

The reliability importance of a component $i$ in a coherent system of $n$ components is given by

$$I_{R(q)}(i) = \frac{\partial R(q)}{\partial q_i} = R(1_i, q) - R(0_i, q)$$

for $i = 1, 2, \cdots, n$
Exercise

Let be a series coherent system with $n$ independent components. Each component $i$ has reliability $q_i$.

- Calculate the reliability based on $P\{\xi(X) = 1\}$.
- Derivate the reliability importance of the $i$th component. Consider $n = 3$ and $q_1 = 0.75$, $q_2 = 0.4$, $q_3 = 0.8$ and calculate the reliability importance of each component.
Exercise

Let be a parallel coherent system with \( n \) independent components. Each component \( i \) has reliability \( q_i \).

- Calculate the reliability based on expected value.
- Derivate the reliability importance of the \( i \)th component.

Consider \( n = 3 \) and \( q_1 = 0.75, q_2 = 0.4, q_3 = 0.8 \) and calculate the reliability importance of each component.
Reliability Bounds

Theorem

The reliability of a coherent system of \( n \) independent components respects

\[
\prod_{i=1}^{n} q_i \leq R(q) \leq 1 - \prod_{i=1}^{n} (1 - q_i)
\]
Bounds: Path and Cut Vectors

Theorem

The reliability of a coherent system of independent components, minimal path sets \( P_1, P_2, \cdots, P_l \) and minimal cut sets \( C_1, C_2, \cdots, C_k \) respects

\[
\prod_{j=1}^{k} \left[ 1 - \prod_{i \in C_j} (1 - q_i) \right] \leq R(q) \leq 1 - \prod_{j=1}^{l} \left[ 1 - \prod_{i \in P_j} q_i \right]
\]
Exercise

Let be the coherent system of figure below with independent components.

Derivate the reliability based on cut vector technique.

Derivate the series arrangement of $k$ banks of parallel subsystems.
Exercise

Let be the coherent system of figure below with independent components.

Derivate the reliability based on cut vector technique.

Derivate the series arrangement of $k$ banks of parallel subsystems.
Exercise

Let be the coherent system of figure below with independent components.

Derivate the reliability bounds of the system based on its minimal path sets and minimal cut sets.

Derivate the reliability based on decomposition technique.
Definition

Reliability is the ability of an item to perform its required functions under stated conditions and for a specified period of time (IEEE definition).

- A *item* or a *component* may mean a simple (i.e logic gate) or a complex system.
- The definition suggests *lifetime item evolution*.
We denote $T$ a continuos nonnegative random variable that represents the **lifetime** of an item.

- Note that *time* may stand to hours but also to number of flips, number of km, etc.

We consider functions that define the distribution of $T$, representing the **failure time** of an item.
Definition

The **probability density function** (PDF) is defined as

$$f(t) = \lim_{\Delta t \to 0} \frac{P\{t \leq T \leq t + \Delta t\}}{\Delta t}$$

- $f(t) = 0$ for $t < 0$
- $f(t) \geq 0$ for $t \geq 0$
- $\int_{0}^{1} f(t)dt = 1$

The PDF indicates the likelihood of failure for any $t$
The cumulative distribution function gives the probability that a failure occurs at a time smaller or equal to $t$ is

$$F(t) = \int_{-\infty}^{t} f(t) \, dt$$

where $f(t)$ is the probability density function (PDF) of the random variable time to failure.

$$P\{t_1 \leq T \leq t_2\} = \int_{t_1}^{t_2} f(t) \, dt = F(t_2) - F(t_1)$$
Reliability (or Survivor) Function

Definition

The reliability function $R(t)$ is defined as

$$R(t) = R(q, t) = P\{T \geq t\} \quad \forall t \geq 0$$

$R(t)$ must be nonincreasing and respect $R(0) = 1$, $\lim_{t \to \infty} R(t) = 0$

- probability of an individual item functioning at time $t$
- fraction of the population of items functioning at time $t$
Hazard Function

Definition

The **hazard function** $h(t)$ is defined as the amount of risk associated to an item at time $t$.

$$
\begin{align*}
    h(t) &= \lim_{\Delta t \to 0} \frac{P\{t \leq T \leq t + \Delta t | T \geq t\}}{P\{t \leq T \leq t + \Delta t\}} \\
    &= \lim_{\Delta t \to 0} \frac{P\{T \geq t\}}{R(t) - R(t + \Delta t)} \\
    &= \lim_{\Delta t \to 0} \frac{R(t) - R(t + \Delta t)}{R(t) \Delta t} \\
    &= \frac{f(t)}{R(t)}
\end{align*}
$$

$h(t)$ represents the instantaneous **failure rate**.

$h(t)$ must respect \( \int_0^\infty h(t) dt = \infty \), $h(t) \geq 0 \quad \forall t \geq 0$
Mean

Definition

$MTTF$ and $MTBF$ are measures related to the mean of the lifetime distribution. The mean is given by

$$\mu = \mathbb{E}\{T\} = \int_0^\infty tf(t)dt = \int_0^\infty R(t)dt$$

- For nonrepairable systems, the mean corresponds to the mean time to failure $MTTF$. It represents the expected value of time before failure.
- For completely repairable items, the mean represents the mean time between failures $MTBF$. 
Variance

Definition

The variance is a measure related to the dispersion of the lifetime distribution. The variance is given by

$$\sigma^2 = \mathbb{V}\{T\} = \mathbb{E}\{(T - \mu^2)\} = \mathbb{E}\{T^2\} - \mathbb{E}^2\{T\}$$

- $\sqrt{\sigma^2}$ represents the standard variation of the distribution.
Fractiles

Definition

The $k$-th fractile is the time $t_k$ to which a specified proportion $k$ of items fail and is given by

$$F(t_k) = P\{T \leq t_k\} = k$$

- The $t_{0.25}$, $t_{0.50}$ and $t_{0.75}$ fractiles are named quartiles of the lifetime distribution.
- The $t_{0.50}$ is the median of the lifetime distribution.
System Lifetime Distributions

- Component $i$
  - Individual representations: $f_i(t)$, $R_i(t)$, $h_i(t)$
  - Individual measures: $\mu_i$, $\sigma^2_i$, $t_{k,i}$
- Combine measures according to the structure function

**Example**

Reliability of a series structure

\[
R(t) = R[R_1(t), R_2(t), \cdots, R_n(t)]
\]

\[
R_1(t).R_2(t).\cdots.R_n(t)
\]
**Lifetime Distributions**

<table>
<thead>
<tr>
<th></th>
<th>Exponential</th>
<th>Weibull</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(t)$</td>
<td>$e^{-\lambda t}$</td>
<td>$e^{-\lambda t}$</td>
<td>$1 - I(\kappa, \lambda t)$</td>
</tr>
<tr>
<td>$f(t)$</td>
<td>$\lambda e^{-\lambda t}$</td>
<td>$\kappa \lambda^\kappa t^{\kappa-1} e^{-\lambda t}$</td>
<td>$\frac{\lambda}{\Gamma(\kappa)} (\lambda t)^{\kappa-1} e^{-\lambda t}$</td>
</tr>
<tr>
<td>$h(t)$</td>
<td>$\lambda$</td>
<td>$\kappa \lambda^\kappa t^{\kappa-1}$</td>
<td>$\frac{f(t)}{R(t)}$</td>
</tr>
</tbody>
</table>
Exponential Distribution

Probability density function $f(t) = \lambda e^{-\lambda t}$
Reliability function \( R(t) = e^{-\lambda t} \)
Exponential Distribution (cont.)

Hazard function $h(t) = \lambda$

![Graph showing the hazard function $h(t) = \lambda$ for different values of $\lambda$.](image)
Markov Process

<table>
<thead>
<tr>
<th>State</th>
<th>Time</th>
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</thead>
<tbody>
<tr>
<td>Discrete</td>
<td>Discrete</td>
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<tr>
<td>Discrete</td>
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</tbody>
</table>

Continuous Time Markov Chains (CTMC)

- Memoryless system
- Discrete space
- Exponential distribution (events at constant rates)
One Component System

Nonrepairable component

Repairable component

\( T \xrightarrow{\lambda} F \)

\( T \xleftarrow{\mu} F \)
State Transition Matrices (STM)

\[
M = \begin{pmatrix}
m_{11} & m_{12} & \cdots & m_{1k} \\
m_{21} & m_{22} & \cdots & m_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
m_{k1} & m_{k2} & \cdots & m_{kk}
\end{pmatrix}
\]

Each element \( m_{i,j} \) gives the rate with system passes from state \( i \) to state \( j \).
STM: One Component

\[ M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} -\lambda & \lambda \\ 0 & 0 \end{pmatrix} \]

\[ M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} -\lambda & \lambda \\ \mu & -\mu \end{pmatrix} \]
State Transition Equations (STE)

\[
\begin{pmatrix}
P_1 & P_2 & \cdots & P_k
\end{pmatrix}
\cdot
\begin{pmatrix}
m_{11} & m_{12} & \cdots & m_{1k} \\
m_{21} & m_{22} & \cdots & m_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
m_{k1} & m_{k2} & \cdots & m_{kk}
\end{pmatrix}
= 
\begin{pmatrix}
0 & 0 & \cdots & 0
\end{pmatrix}
\]

\[
\begin{pmatrix}
P_1 & P_2 & \cdots & P_k
\end{pmatrix}
= 
\begin{pmatrix}
1 \\
1 \\
\vdots \\
1
\end{pmatrix}
= 1
\]
State Transition Equations (STE)

\[ M = \begin{pmatrix} m_{TT} & m_{TF} \\ m_{FT} & m_{FF} \end{pmatrix} = \begin{pmatrix} -\lambda & \lambda \\ \mu & -\mu \end{pmatrix} \]

\[-\lambda P_T + \mu P_F = 0 \]
\[\lambda P_T - \mu P_F = 0 \]
\[P_T + P_F = 1 \]

\[ P_T = \frac{\mu}{\lambda + \mu} \text{ and } P_F = \frac{\lambda}{\lambda + \mu} \]
Reliability and STE

\[ R(t) = \sum_{i \in \mathcal{T}} P_{X_i}(t) \]

\[ R(t) = 1 - \sum_{i \in \mathcal{F}} P_{X_i}(t) \]

Assuming repair makes the item perfect, \( \mathcal{T} \) is the set of functioning states, \( \mathcal{F} \) is the set of failing states.
Exercise

Consider a system composed of a processor (component $c_1$) and a redundant memory structure. The memory structure is based on two independent RAM (components $c_2$ and $c_3$): each of them contains exactly the same data so as to tolerate memory faults. Suppose the system is coherent with independent components.

- Suppose that components $c_1$, $c_2$ and $c_3$ are nonrepairable with failure rate given by $\lambda_1$, $\lambda_2$, and $\lambda_3$, respectively. Derivate the corresponding Markov chain.
- Derivate the state transition matrix of the system.
- Derivate the reliability of the system based on the state transition equations.
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Reliability of Electronics Systems

Conclusions
Unreliability Sources

**Inputs**
- 'expected' outputs
- Performance
- Power
- Data integrity
- Availability
- Security

**HW/SW system**
- Shocks (mechanical, temperature)
- Radiations
- Design errors
- Software failures
- Malicious attacks
- Human errors
- Unexpected conditions of use
- Process variation
- Ageing
- Noise

**'Expected' outputs**
- Performance
- Power
- Data integrity
- Availability
- Security

Lirida Alves de Barros-Naviner
Master Program
Default/Fault Propagation
Advances in CMOS

- Moore’s law (popular form): \(2 \times \frac{N_{tr}}{mm^2}\) every 18 months

Intel 4004 (1971): 10\(\mu\)m and \(2.3 \times 10^3\) tr

Intel Xeon Phi (2012): 22nm and \(5 \times 10^9\) tr

- Scaling issues
  - Design complexity, test challenge, low power voltage
  - Variability – Modelling
  - Sensitivity to unscaled environmental disturbances

- Scaling effects
  - Yield decrease
  - Reliability decrease
Scaling and Reliability

The diagram illustrates the failure rate over time, categorizing failures into three phases:

1. **Decreasing Failure Rate**
   - Early "Infant Mortality" Failure
   - Observed Failure Rate
   - Constant (Random) Failures

2. **Constant Failure Rate**

3. **Increasing Failure Rate**
   - Wear Out Failures

The x-axis represents time, and the y-axis represents failure rate.
Fault Models: Bit-flip and Stuck-at

\[
\begin{array}{c|c|c|c|c|c}
A & B & C & x & Y \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 1 \\
1 & 1 & 0 & 1 & 0 \\
1 & 1 & 1 & 1 & 0 \\
\end{array}
\]
Fault Models: Bit-flip and Stuck-at

<table>
<thead>
<tr>
<th>A</th>
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<th>Y</th>
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A logic diagram showing the function is also present.
Reliability

\[ R(t) = e^{-\lambda t} \]

Lifetime distribution: exponential law
Failure Rate

\[ \lambda = \frac{1}{MTTF} \]

This corresponds to the hazard function lifetime model.
Mean Time To Failure

\[ \text{MTTF} = \frac{1}{n} \sum_{i=1}^{n} t_i \]

Failures In Time

\[ \text{FIT} = \frac{10^9}{\text{MTTF}} \]
Reliability and MTTF

\[ R(t) = e^{-\frac{t}{MTTF}} \]

MTTF = \( \int_{0}^{\infty} R(t) \, dt \)
Mean Time To Repair

$$\text{MTTR} = \frac{1}{\mu}$$

$\mu$ corresponds to the repair rate
Availability

$$A(T) = \frac{1}{T} \int_{0}^{T} A(t) \, dt$$

$$A(\infty) = \lim_{T \to \infty} A(T) = \frac{MTTF}{MTTF + MTTR} = \frac{\mu}{\mu + \lambda}$$

Stead-state availability (given in downtime per year)
Mean Time Between Failures

MTBF = MTTF + MTTR

Assuming repair makes the item perfect

MTBF = \frac{MTTF}{A(\infty)}
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Reliability of Electronics Systems

Conclusions
Conclusions

- This course focuses on reliability, which is a dependability’s attribute
  - Dependability is an essential quality metric for many systems
- This lesson dealt with different methods for dependability analysis
- The reliability of digital electronics components has specific characteristics
  - Fault models, quality metrics, etc.
- We will explore techniques for reliability improvement and reliability assessment