System Reliability Simulation and Optimization by Component Reliability Allocation

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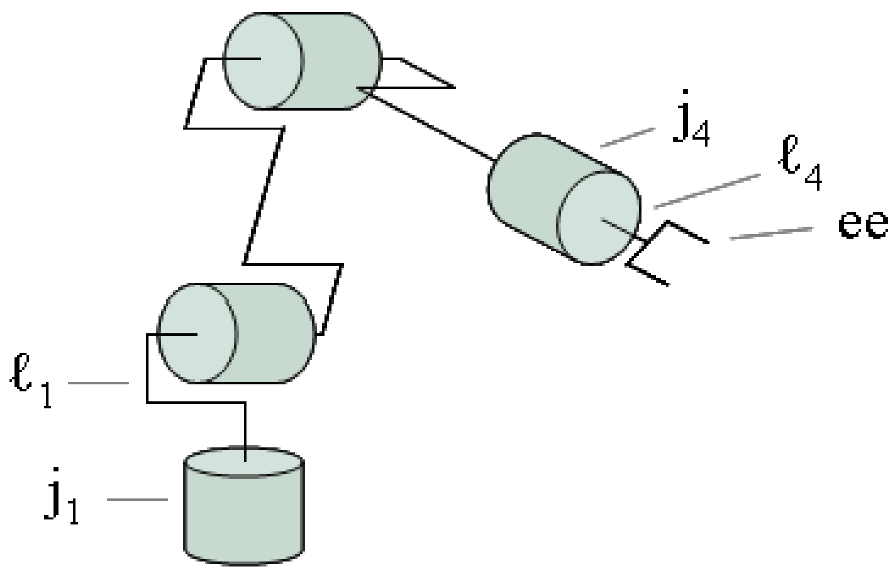
Reliability Allocation and Cost Tradeoffs using Simulation

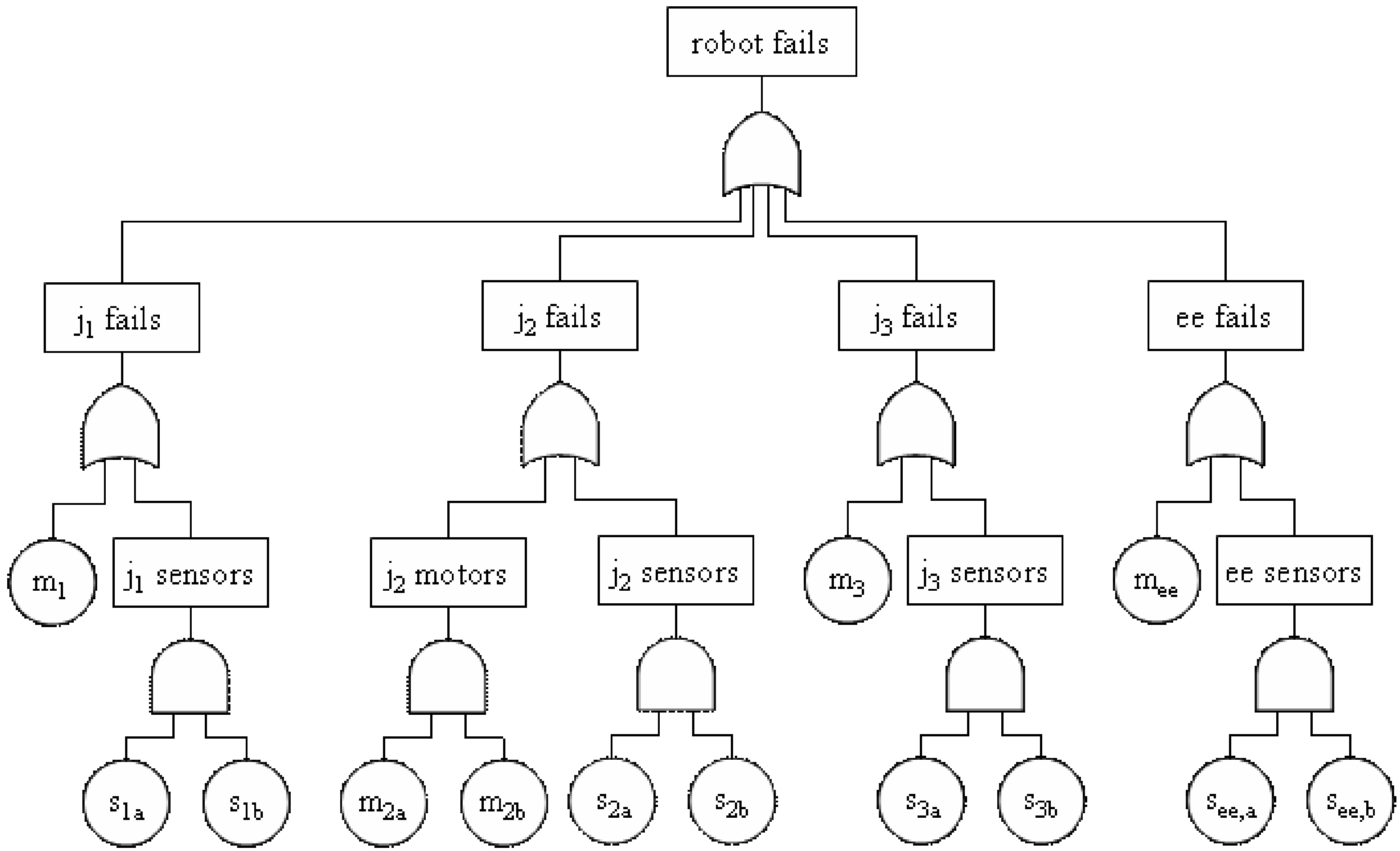
- Reliability allocation for a system is the process of assigning component reliabilities to achieve a system level reliability.
- Reliability comes at a cost.
- The objective of this study is to simulate an engineering system using:
  - Newer simulation methods
  - Developing better failure detection techniques
  - Perform multiobjective optimization
  - Allow for post-optimal tradeoffs

Four Joint Robot Example

- The system we use is a four-joint robot manipulator (Talon IV Engineer arm) consisting of four motors and eight sensors (two for each joint). One motor has redundancy so we have five motors effectively. Here is a kinematic diagram.



Four-Joint Robot Example - Fault Tree



Adjacency matrix for the system

	SO	M1	S1A	S1B	M2A	M2B	S2A	S2B	M3	S3A	S3B	M4	S4A	S4B	SI
SO	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0
M1	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0
S1A	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0
S1B	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0
M2A	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0
M2B	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0
S2A	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0
S2B	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0
M3	0	0	0	0	0	0	0	0	0	**1**	**1**	0	0	0	0
S3A	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0
S3B	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0
M4	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0
S4A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
S4B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
SI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Determining failure of the system

- Packet travels upstream one step at a time. $\mathbf{v_o}$ is the vector that counts the copies of the packet at each component in the beginning

$$\mathbf{v}_1 = \mathbf{R}\mathbf{v}_0$$

- Where $\mathbf{v}_1$ counts the copies of the packet at each component after step 1. To see if will eventually reach C_{SO}, multiply $\mathbf{v}_0$ successively with **R**, at most n+1 times. Therefore after p steps $\mathbf{v}_p$ will be given by.

$$\mathbf{v}_p = \mathbf{R}^p \mathbf{v}_0$$

- Since we need to find if C_{so} *ever* gets the packet, we need to sum all $\mathbf{v}_i$'s and see if the first element of the sum is non-zero. Let this sum be **s**:

$$\mathbf{s} = \sum_{i=1}^{n+1} \mathbf{R}^i \mathbf{v}_{i-1}$$

Determining failure of the system (contd.)

- In case some of the components fail, we can incorporate this into the adjacency matrix.

$$\mathbf{R}' = \mathbf{R} \times diag(\mathbf{c})$$

- The elements of the vector **c** are all one except those corresponding to components that have failed. These entries are zero. The sum becomes:

$$\mathbf{s} = \sum_{i=1}^{n+1} (\mathbf{R}')^i \, \mathbf{v}_{i-1}$$

- RHS is a geometric progression. We have,

$$\mathbf{s} = (\mathbf{I} - \mathbf{R}')^{-1} \mathbf{v}$$

Implementing the method

- We introduce a packet at C_{Si}, this can be represented by a column vector, all of whose elements are 0 except the last one which is 1:

$$\mathbf{v}_0 = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots & 1 \end{bmatrix}^T$$

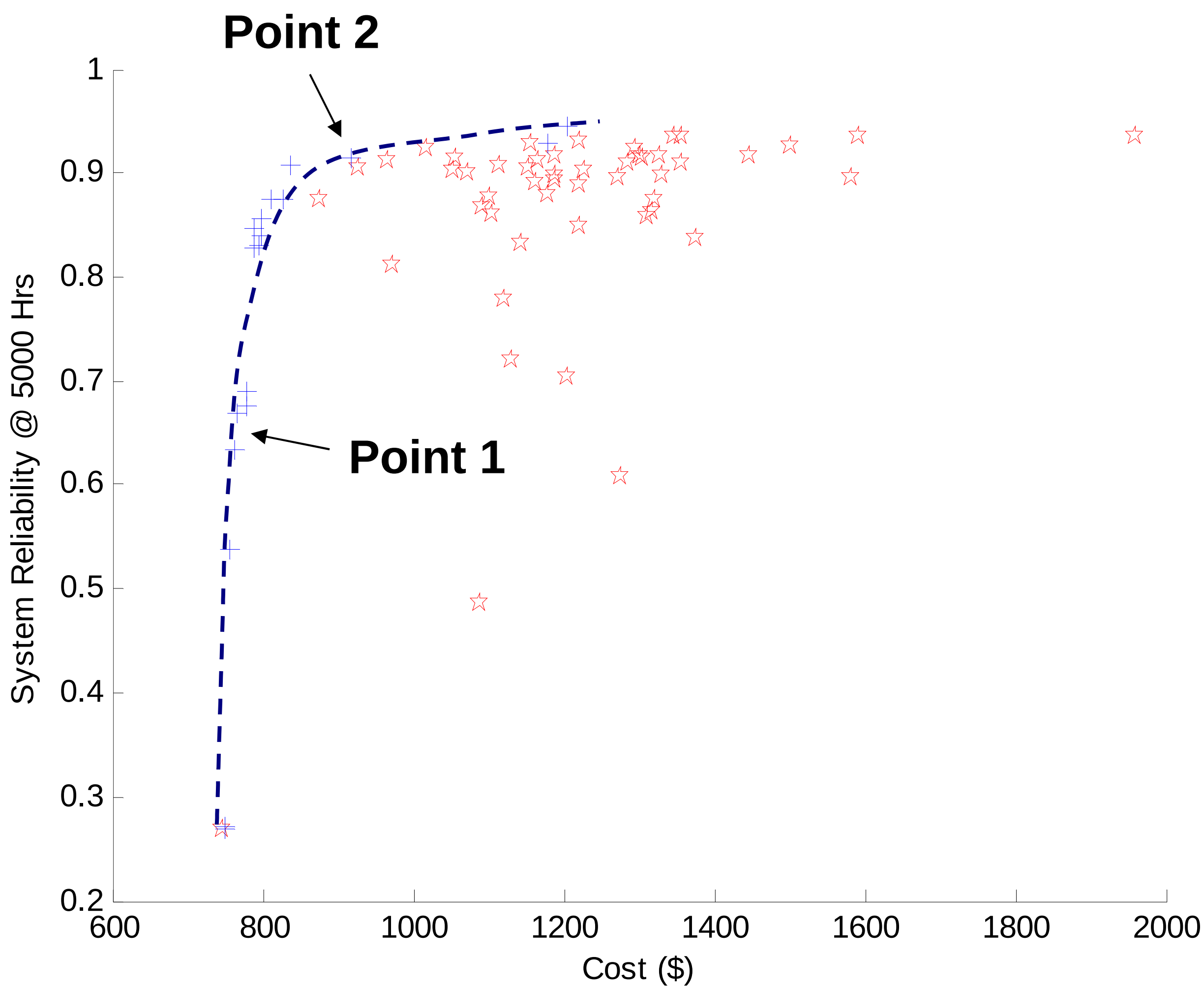
- The sum **s**, is found using the expression shown before.
- The first element of **s**, corresponding to C_{SO} is an indicator of failure:
  - IF the first element is 0, the system has failed
  - IF the first element is 1, the system survives but has been rendered serial.
- The number can also be interpreted as the redundancy remaining in the system. For example, If the first element is 5, there are 5 paths remaining from C_{Si} to C_{SO}.

Parameters used for simulation

	Baseline MTTF (Hrs)	Baseline Cost ($)	COV	B-factor
Motor 1	31519	150	0.5	4
Sensor 1A	4845	50	0.5	4
Sensor 1B	4845	50	0.5	4
Motor 2A	3476.62	61.62	0.5	4
Motor 2B	3476.62	61.62	0.5	4
Sensor 2A	4845	50	0.5	4
Sensor 2B	4845	50	0.5	4
Motor 3	31519	150	0.5	4
Sensor 3A	4845	50	0.5	4
Sensor 3B	4845	50	0.5	4
Motor 4	31519	150	0.5	4
Sensor 4A	4845	50	0.5	4
Sensor 4B	4845	50	0.5	4

*Component and system times-to-failure are assumed to follow a Beta distribution because of its flexibility.

Reliability-Cost Pareto Front



Designs Associated with Points 1 and 2
(Only shaded components are designed)

	MTTF (Hrs)	Cost ($)
Motor 1	**18625**	**99.6**
Sensor 1A	4845	50
Sensor 1B	4845	50
Motor 2A	**2011.3**	**40.4**
Motor 2B	**2873.4**	**51.8**
Sensor 2A	4845	50
Sensor 2B	4845	50
Motor 3	**16225.5**	**92.3**
Sensor 3A	4845	50
Sensor 3B	4845	50
Motor 4	**17531.3**	**96.2**
Sensor 4A	4845	50
Sensor 4B	4845	50
COST		**$780.30**
RELIABILITY		**0.6713**

	MTTF (Hrs)	Cost ($)
Motor 1	**25951.9**	**125.7**
Sensor 1A	4845	50
Sensor 1B	4845	50
Motor 2A	**4143.1**	**74.6**
Motor 2B	**6203.5**	**135**
Sensor 2A	4845	50
Sensor 2B	4845	50
Motor 3	**16128.9**	**92.1**
Sensor 3A	4845	50
Sensor 3B	4845	50
Motor 4	**15759.5**	**91**
Sensor 4A	4845	50
Sensor 4B	4845	50
COST		**$918.40**
RELIABILITY		**0.9125**

Conclusions

- Demonstrated simulation of reliability of a four joint robot
- Developed method for failure identification using partial system failures
- Performed multiobjective optimization using state of the art, NSGA-II which gave a Pareto front
- Future work
  - How to determine the knee region (best reliability with minimal increase in cost) ?
    - Should use a utility function - it will automatically take into account tradeoffs