Systematic Sensor Selection Strategy for Turbofan Engine Diagnostics

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Outline

- Background
- Applications
- Results
- Conclusions

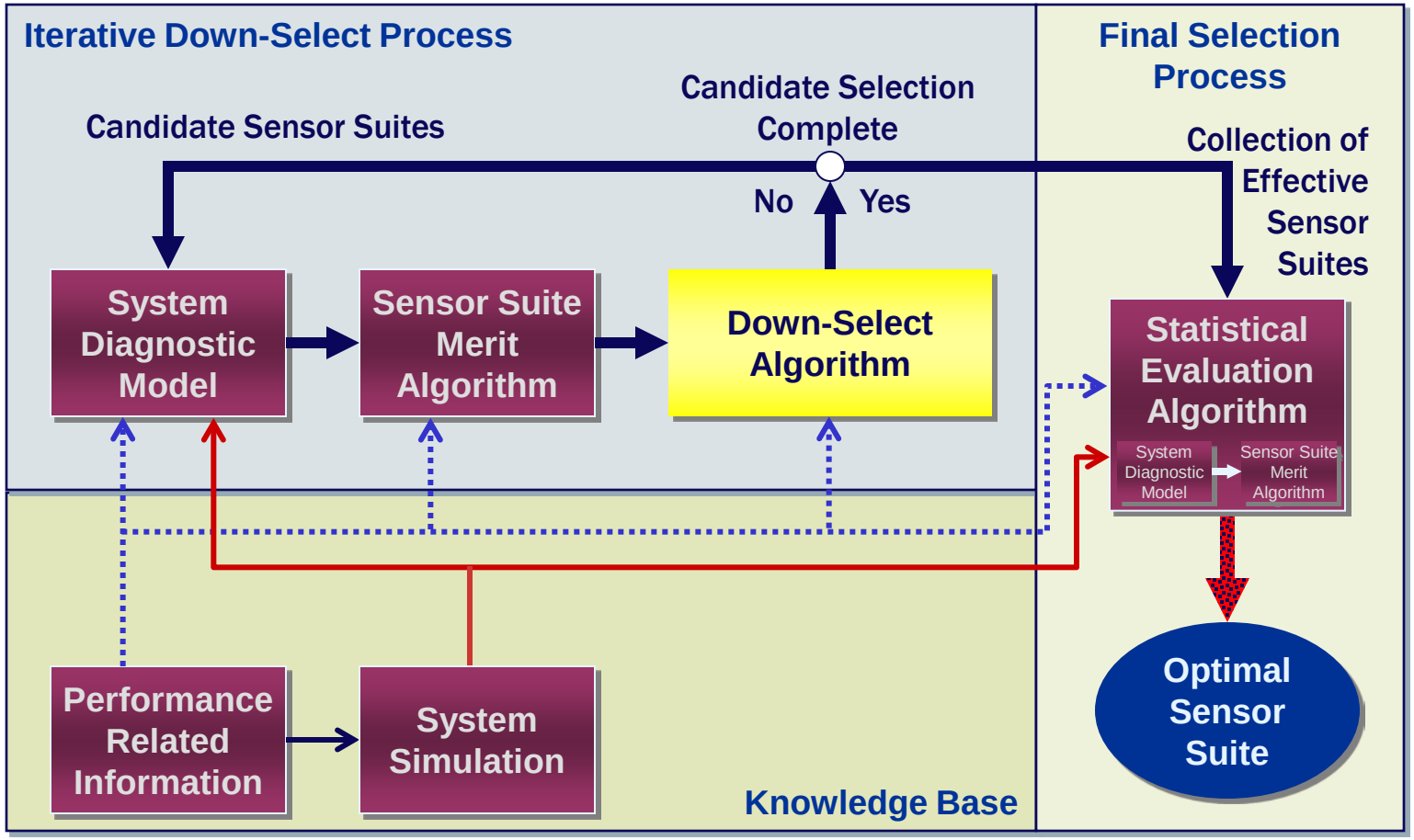
Objective

To demonstrate a process that will select a set of sensors, specified by measurement type and location, to augment a typical aircraft engine sensor suite that will improve gas path diagnostics over a range of flight conditions

Sensor Category Definitions

- Control Sensors – Normally installed on an engine primarily for control purposes
- Optional Sensors – Available but not usually installed on an engine
- Advanced Sensors – Flight quality sensor technology does not exist or is under development

Systematic Sensor Selection Strategy (S4)



Application Specific Non-Application Specific

S4 for Aircraft Engine Diagnostics

- Sequence of studies to evaluate how the selection of sensors can improve aircraft engine diagnostics
- Each study builds upon the one before with increasing complexity
- Two studies have been completed to date
  - Sowers, T., Kopasakis, G., Simon, D., “Application of the Systematic Sensor Selection Strategy for Turbofan Engine Diagnostics”, GT2008-50525, ASME Turbo Expo 2008, Berlin, Germany, June 9-13, 2008
  - Sowers, T., et al, “Expanded Application of the Systematic Sensor Selection Strategy for Turbofan Engine Diagnostics”, GT2009-59251, ASME Turbo Expo 2009, Orlando, Florida, June 8-12, 2009

Initial Application

Objective was to demonstrate that the Systematic Sensor Selection Strategy can be applied to aircraft engine gas path diagnostics and to establish a framework to permit further research.

- Single operating point (cruise)
- Fault conditions were modeled as a shift in a single health parameter
- Proprietary engine model as host system

Found that augmenting the control sensor suite with certain sensors did improve engine health monitoring

Subsequent Study

With the framework established, the objective was to build upon and expand the first study

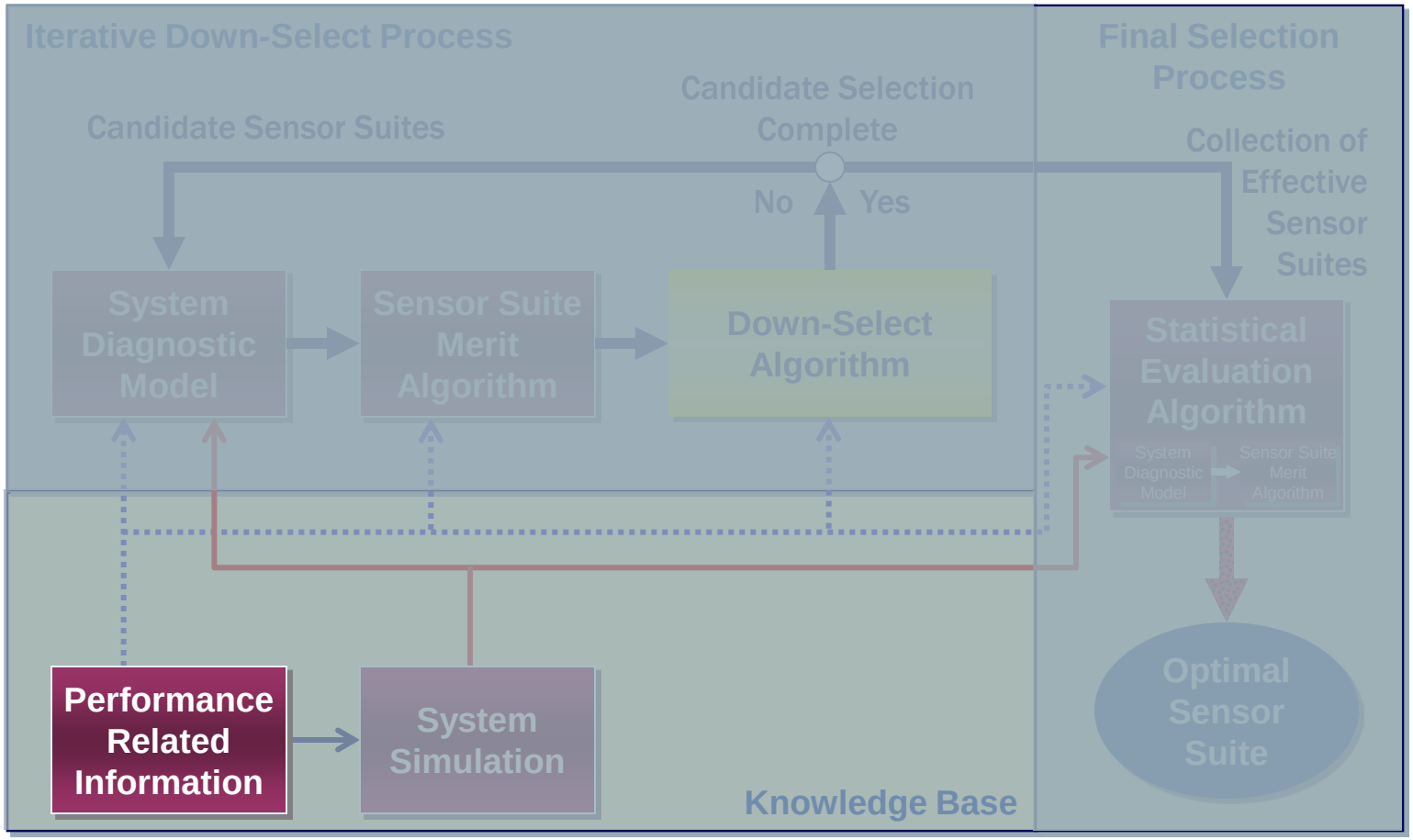
- Consider multiple operating conditions
- More representative fault scenarios
- Open source engine model as host system

The remainder of this presentation will focus on the setup and results of this study

Application

- Use Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) as the host system
- Compare results of candidate sensor categories
  - Control Sensors Only (Baseline)
  - Control with Optional Sensors
  - Control with Optional and Advanced Sensors
- Compare results of Exhaustive Search (Brute Force) to results of a Genetic Algorithm in the Down-Select Algorithm

Systematic Sensor Selection Strategy



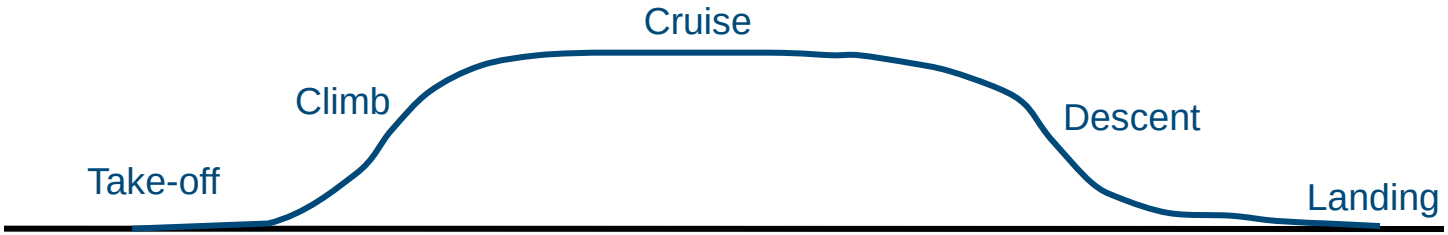
Flight Conditions

Cruise:

- 35K feet
- Mach 0.80
- Throttle at 65%

Take-off:

- Sea Level
- Mach 0.22
- Throttle at 100%



Fault Conditions

5 engine component faults modeled as simultaneous adjustments to the efficiency (η) and flow capacity (γ) health parameters

Engine Component Fault	Maximum Fault Magnitude	Fault Ratio (γ:η)
FAN	7%	1.50
LPC	7%	1.50
HPC	7%	1.50
HPT	7%	-0.75
LPT	7%	-0.75

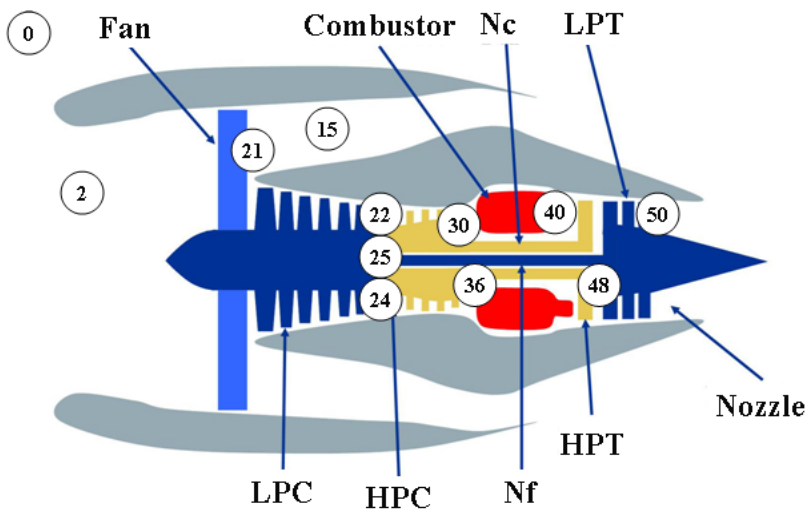
$$\eta_{adjustment} = \frac{F_{Magnitude}}{\sqrt{1+(\gamma:\eta)^2}}$$

$$\gamma_{adjustment} = \eta_{adjustment} \times (\gamma:\eta)$$

Simon, D.L., Bird, J., Davison, C., Volponi, A.J., Iverson, R.E., 2008, "Benchmarking Gas Path Diagnostic Methods: A Public Approach", NASA Technical Memorandum TM-2008-215271; ASME Paper GT2008-51360

Sensor Data

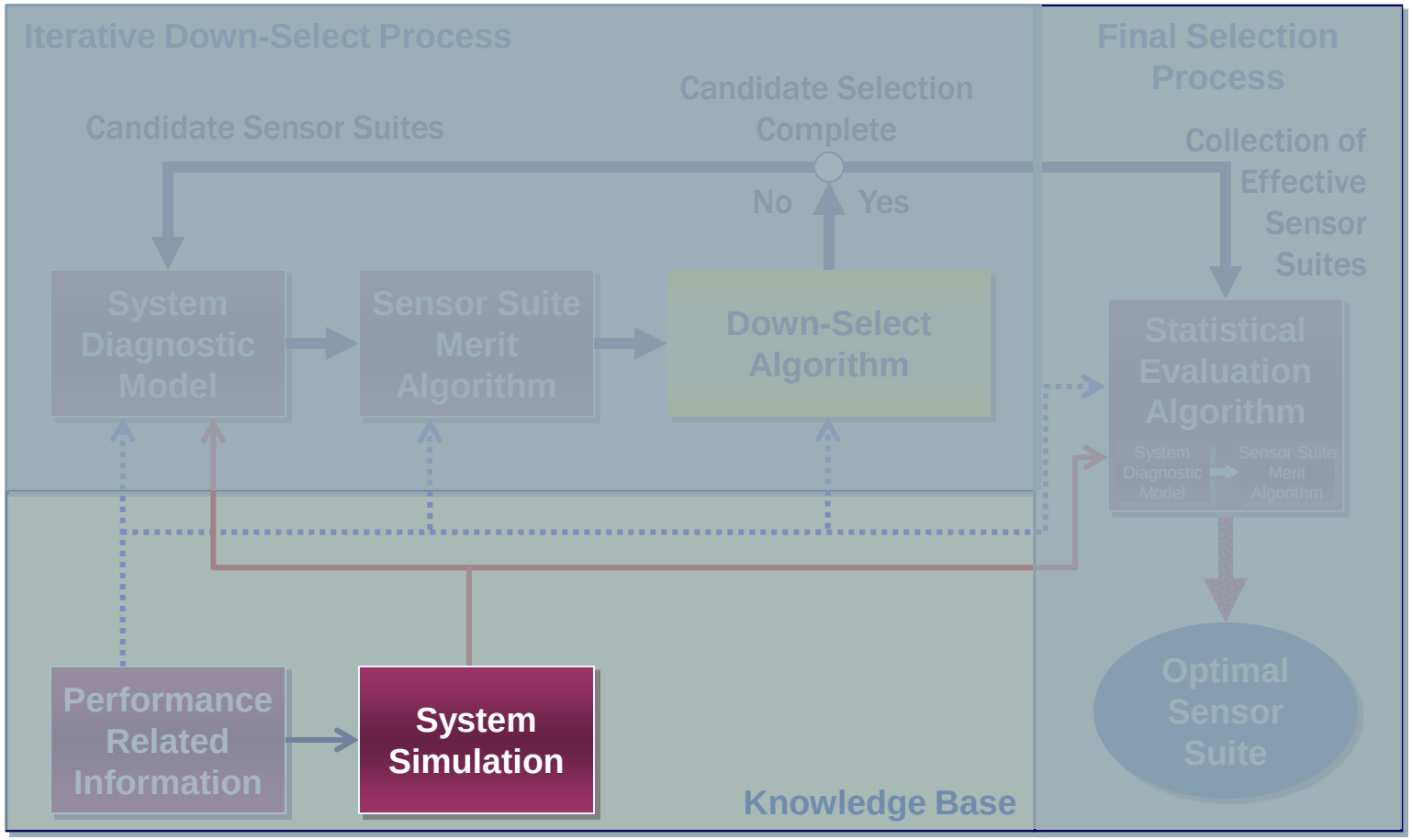
Sensor	Description	Noise %
Nf	Low Pressure Shaft Speed	0.25
Nc	High Pressure Shaft Speed	0.25
P0	Ambient Pressure	n/a
P15	Bypass Discharge Static Pressure	0.50
P2	Fan Inlet Pressure	n/a
P25	High Pressure Compressor Inlet Pressure	0.50
Ps30	High Pressure Compressor Exit Static Pressure	0.50
P40	High Pressure Turbine Inlet Pressure	0.50
P48	Low Pressure Turbine Inlet Pressure	1.00
P50	Low Pressure Turbine Exit Pressure	0.50
T0	Ambient Temperature	n/a
T2	Fan Inlet Temperature	n/a
T21	Fan Exit Temperature	0.75
T24	Low Pressure Compressor Exit Temperature	0.50
T30	High Pressure Compressor Exit Temperature	0.75
T40	High Pressure Turbine Inlet Temperature	1.00
T48	Low Pressure Turbine Inlet Temperature	0.75
T50	Low Pressure Turbine Exit Temperature	0.75
Wf	Fuel Flow Rate	1.00
W21	Fan Inlet Flow Rate	1.00
W22	High Pressure Compressor Inlet Flow Rate	1.00
W36	High Pressure Compressor Exit Flow Rate	1.00
W40	High Pressure Turbine Inlet Flow Rate	1.00
W48	Low Pressure Turbine Inlet Flow Rate	1.00
W50	Low Pressure Turbine Exit Flow Rate	1.00



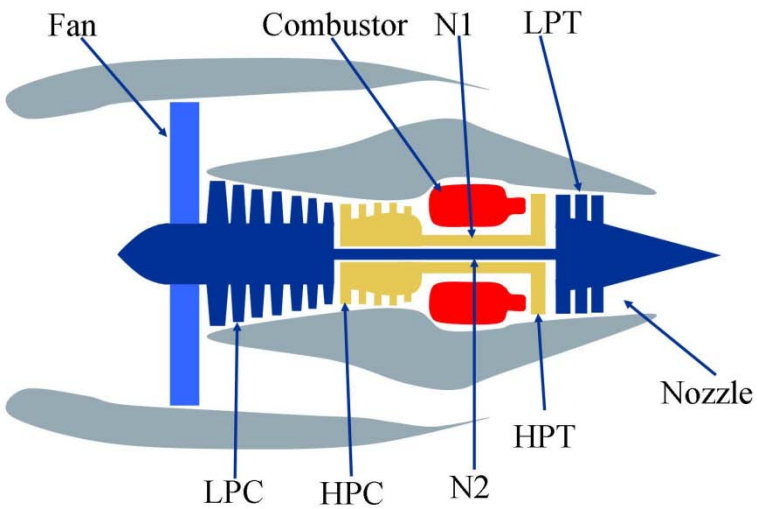
Control Sensors	P0 T0	P2 T2			Nf		T24		Ps30 T30	Wf	T48	Nc	
Optional Sensors				T21		P15	P25					P50 T50	
Advanced Sensors				W21			W22		W36	P40 T40 W40	P48 W48	W50	

$$\Delta y = \frac{y_{fault} - y_{nominal}}{\sigma}$$

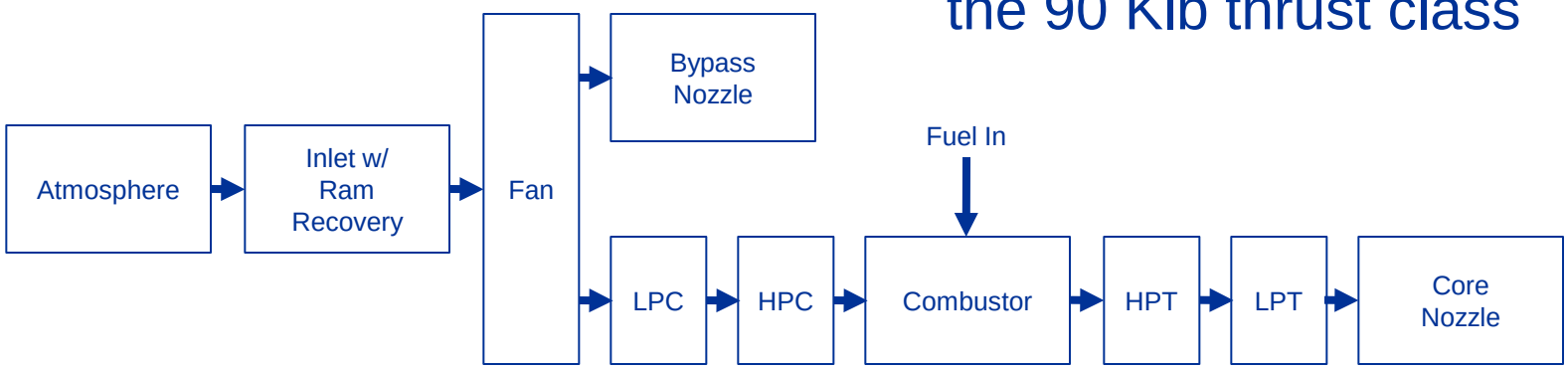
Systematic Sensor Selection Strategy



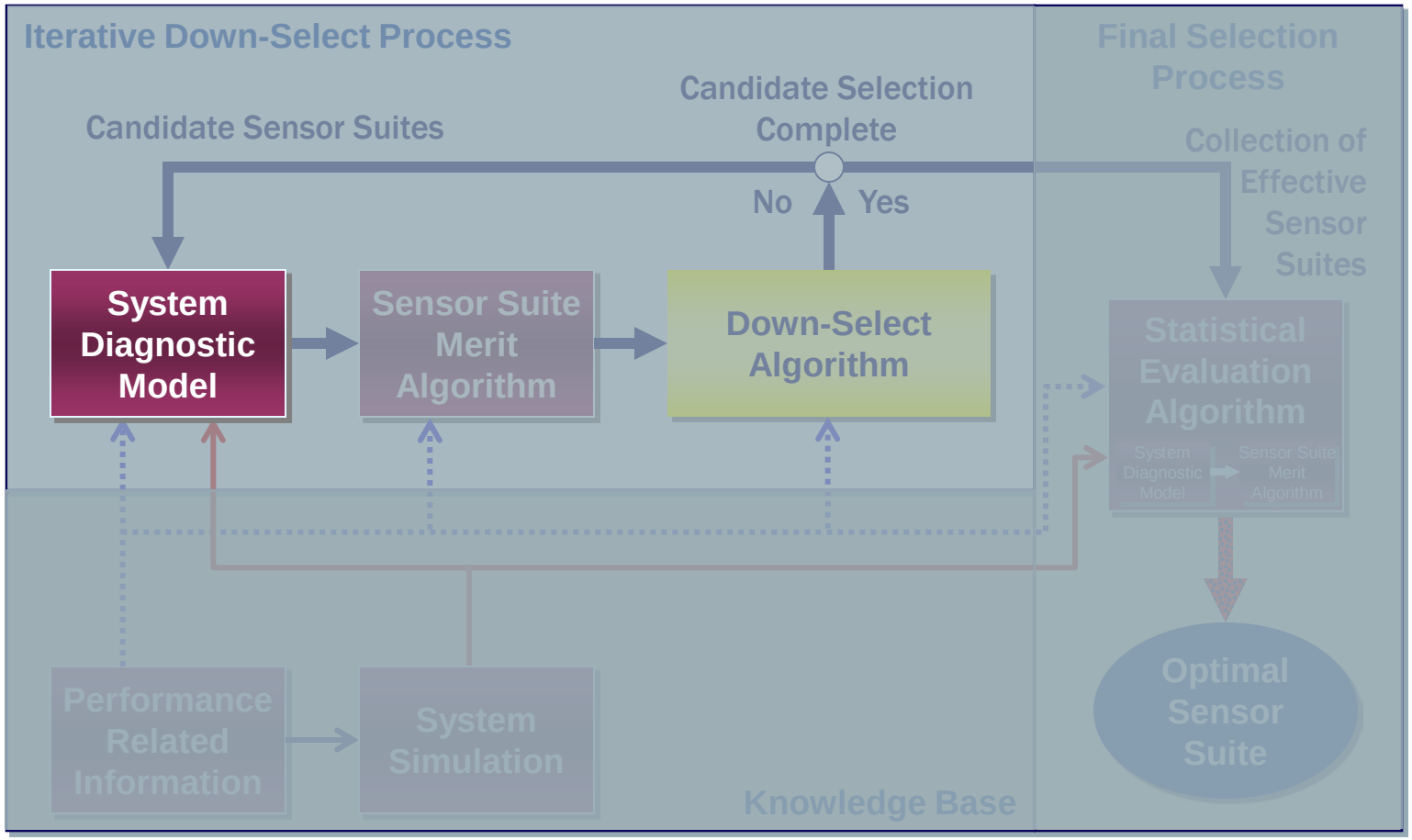
Commercial Modular Aero-Propulsion System Simulation (C-MAPSS)



- Developed by the NASA Glenn Research Center
- Based in Matlab and Simulink
- A non-proprietary model of a large commercial high-bypass engine in the 90 Klb thrust class



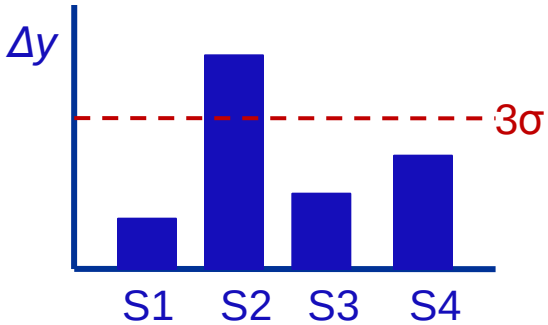
Systematic Sensor Selection Strategy



Part I: Fault Detection

If either one of two limit checks are violated, fault detection is declared

Check 1: Exceed 3σ limit for a single sensor measurement



$$\Delta y = \frac{y_{fault} - y_{baseline}}{\sigma}$$

Check 2: Exceed 0.5 limit for Root Mean Square of sensor suite

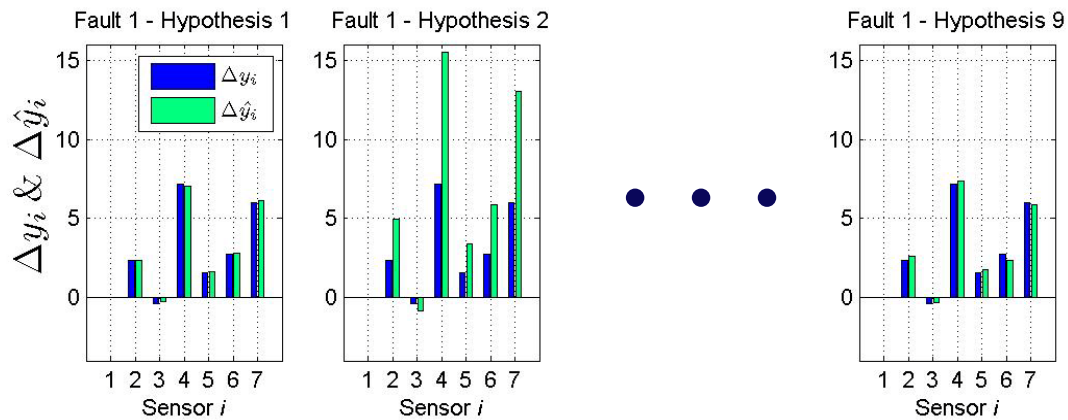
$$RMS_{Detect} = \sqrt{\frac{1}{m}\sum_{i=1}^{m} \Delta y_i^2} > 0.5$$

Part II: Fault Classification

Applies inverse model approach. Fault hypothesis which produces smallest residual estimation error is inferred to be the fault condition.

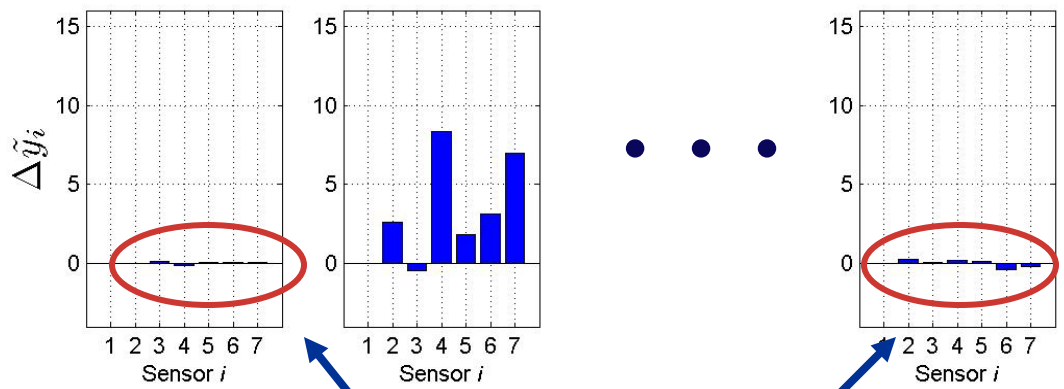
$$\Delta y_i = observed\ \ measurements$$

$$\Delta \hat{y}_i = inverse\ model\ estimates$$



$$residual\ \ estimation\ \ error$$

$$\Delta \tilde{y}_i = \Delta y_i - \Delta \hat{y}_i$$

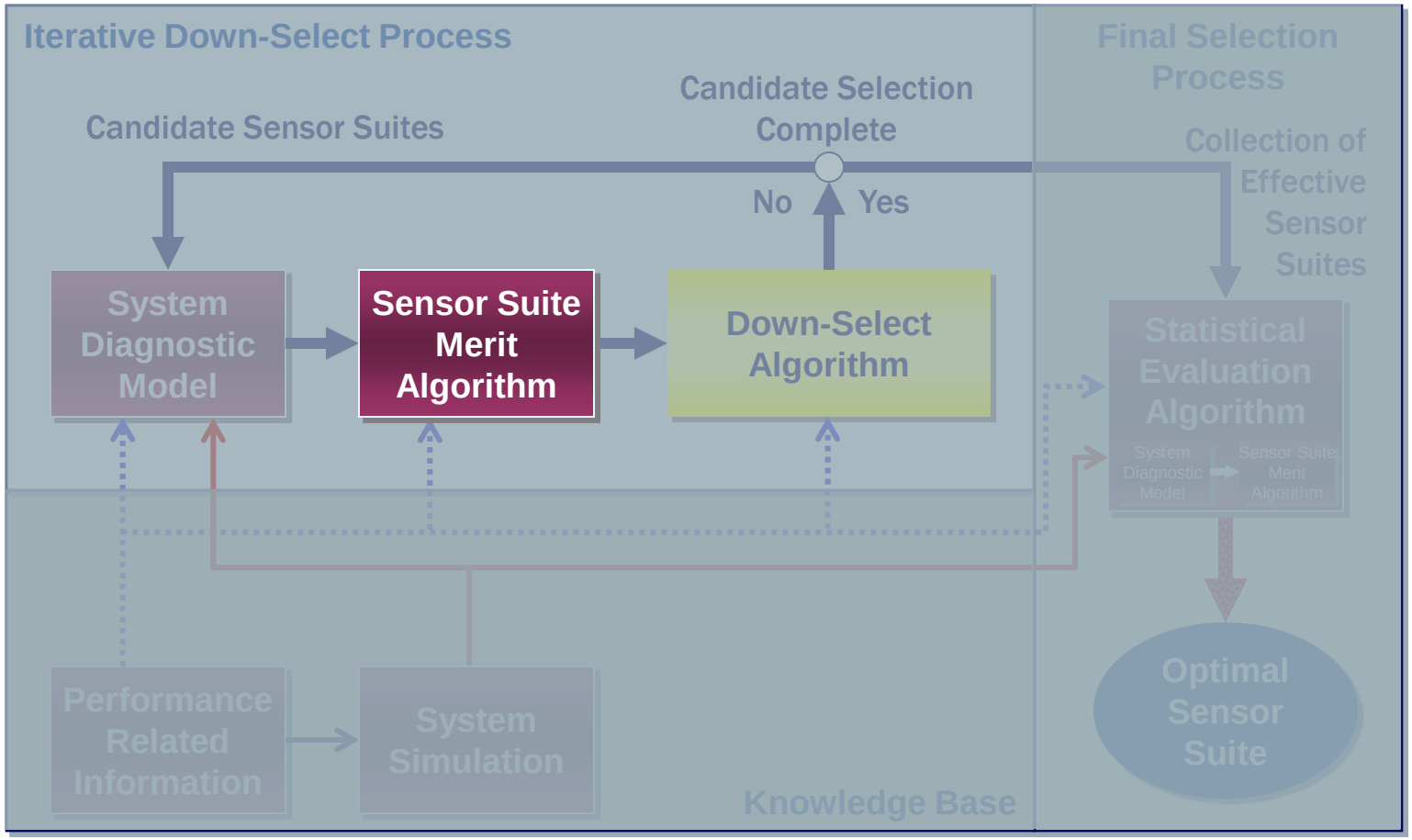


Potential risk of mis-classifying these two faults

Root-Summed-Squared

$$RSS = \sqrt{\sum_{i=1}^{m} \Delta \tilde{y}_i^2}$$

Systematic Sensor Selection Strategy



Merit Algorithm

- Determines the “goodness” of the candidate sensor suite
- Primarily based on the diagnostic performance of the sensor suite for the given fault scenarios

$$Merit = Utility \times Diagnostic_{Average}$$

$$Diagnostic = \sum_{All\ Faults} \frac{F_{CRIT} F_{ID}}{F_{DL}}$$

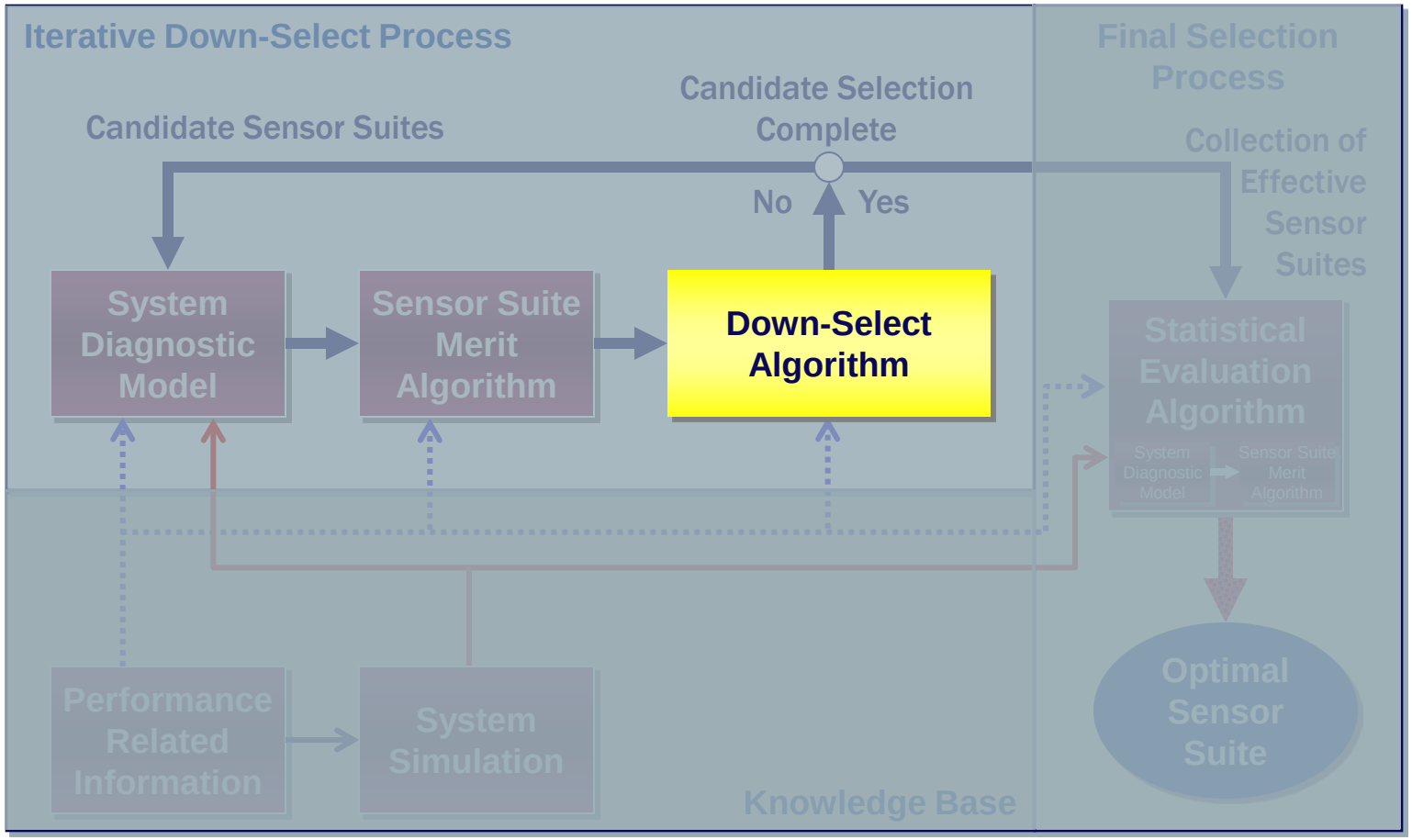
$$where$$

$$F_{CRIT} = 1.0$$

$$F_{ID} = \sum RSS_{INCORRECT} - RSS_{CORRECT}$$

$$F_{DL} = Weight\ value\ of\ \ fault\ magnitude\ where\ \ fault\ is\ sensed$$

Systematic Sensor Selection Strategy



Exhaustive Search (Brute Force)

- Evaluate every possible sensor suite combination to determine the true optimal solution
- Only feasible when the number of combinations is within computational resource capabilities

$$C_h^p = \frac{p!}{h!(p-h)!}$$

h = desired number of sensors in a sensor suite

p = total number of candidate sensors available in the sensor pool

***p* = 14**

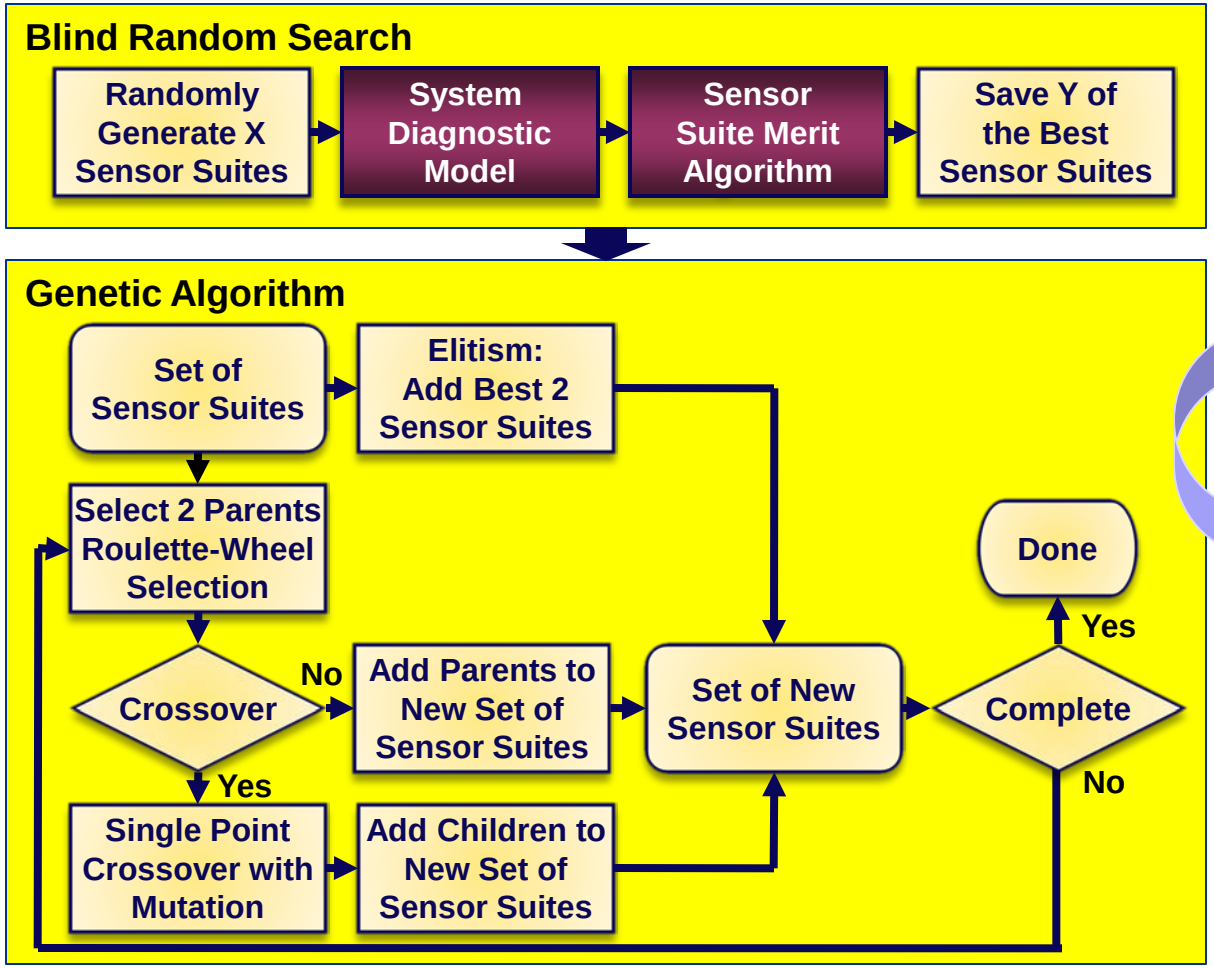
Number of Additional Sensors (h)	Number of Sensor Suite Combinations
1	14
2	91
3	364
4	1,001
5	2,002
6	3,003
7	3,432
8	3,003
9	2,002
10	1,001
11	364
12	91
13	14
14	1
Total	**16,383**

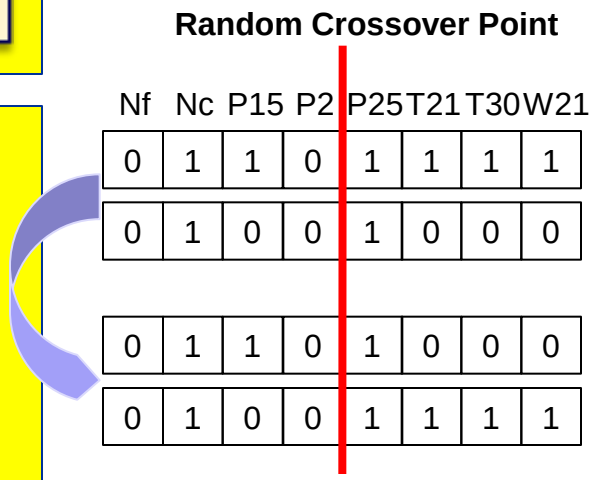
***p* = 21**

Number of Additional Sensors (h)	Number of Sensor Suite Combinations
1	21
2	210
3	1,330
4	5,985
5	20,349
6	54,264
7	116,280
8	203,490
9	293,930
10	352,716
11	352,716
12	293,930
13	203,490
14	116,280
15	54,264
16	20,349
17	5,985
18	1,330
19	210
20	21
21	1
Total	**2,097,151**

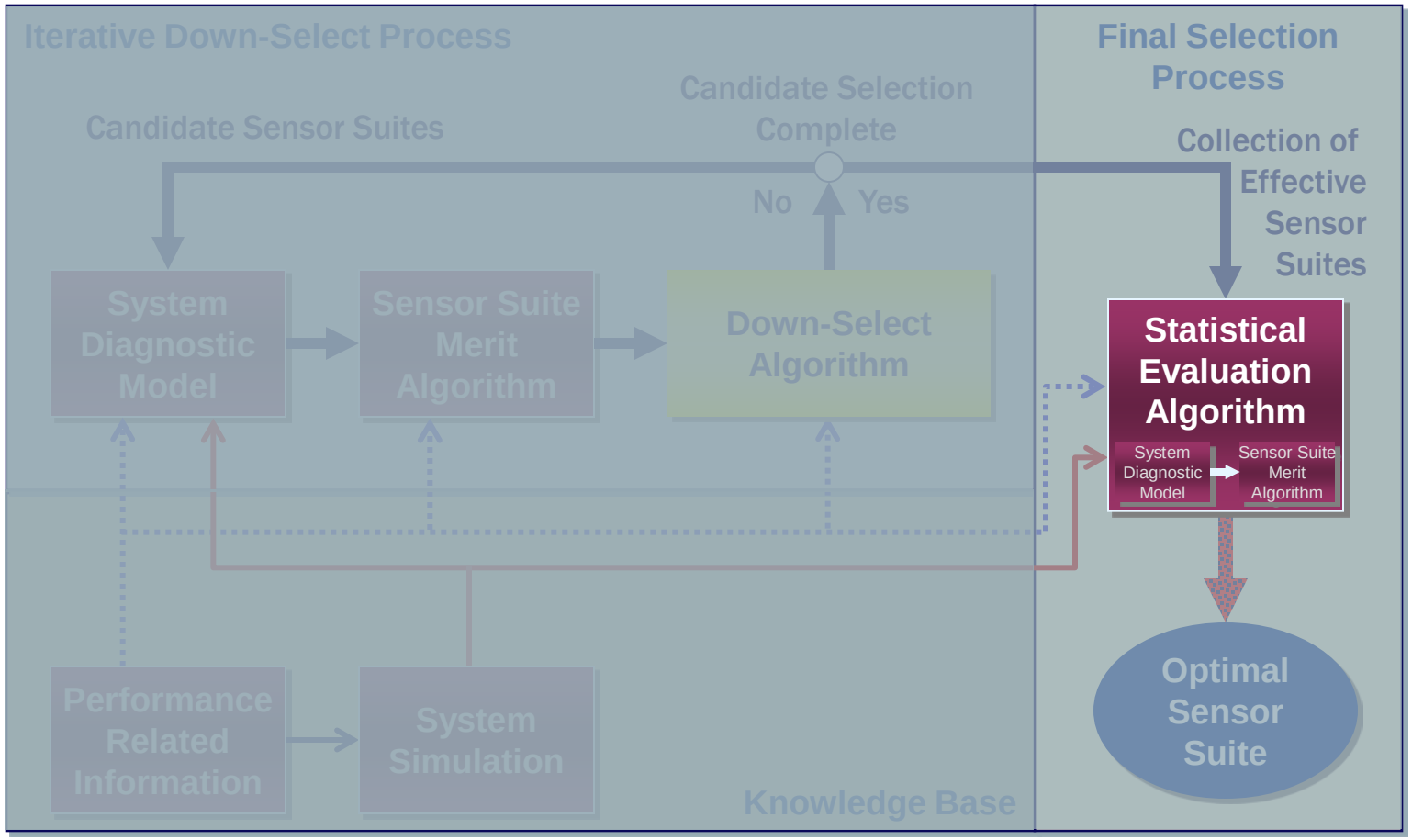
Genetic Algorithm with Blind Random Search

Biology based optimization technique that finds near-optimal solutions



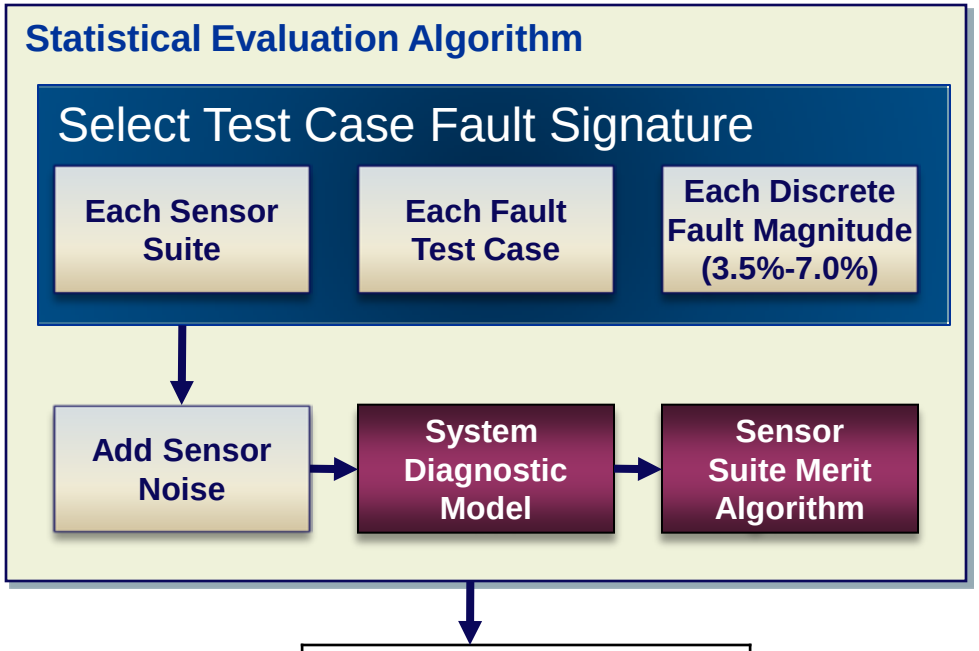


Systematic Sensor Selection Strategy



Final Selection Process

- Performs a Monte Carlo analysis on each “optimal” sensor suite determined by the Iterative Down-Select Process
- Random sensor noise is added to each fault signature
- Results are reported in a confusion matrix



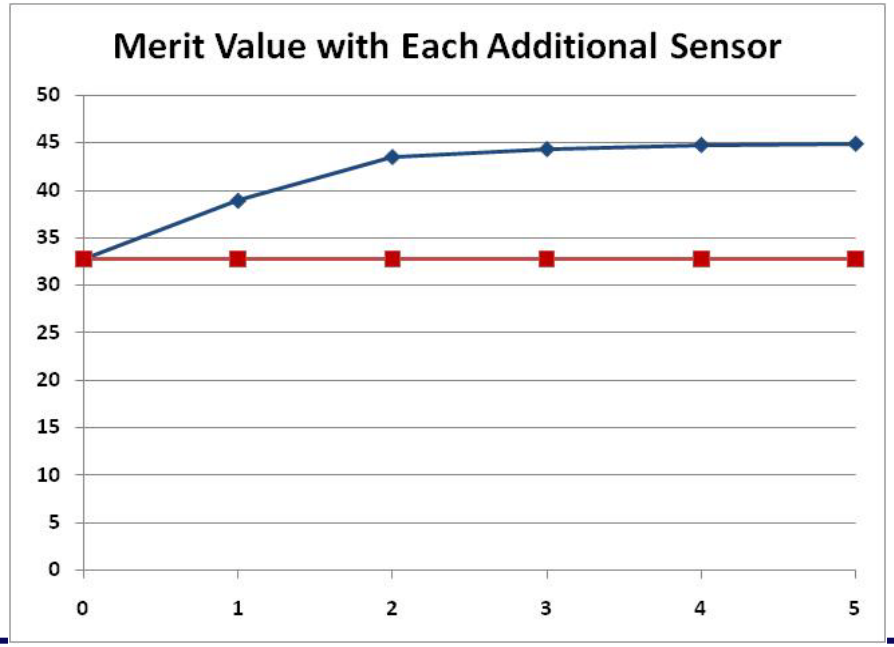
		Inferred Fault			
		Fault 1	Fault 2	No Fault	Accuracy
True Fault	Fault 1				%
	Fault 2				%
	Nominal				%

Best Sensor Suites

Optional Only at Take-off and Cruise Conditions Using Exhaustive Search

- Determined best sensor suite for increasing suite size
- Results are identical to those from Genetic Algorithm
- Diminished benefit after 2 additional sensors

Average Merit	Merit Δ	Add. Sensor	P15	T21	P25	T50	P50
32.75	-	0					
38.93	6.18	1			X		
43.55	4.62	2			X	X	
44.38	0.83	3			X	X	X
44.82	0.44	4	X		X	X	X
44.94	0.12	5	X	X	X	X	X



Best Sensor Suites

Optional and Advance at Take-off and Cruise Conditions Combined using Exhaustive Search

Average Merit	Merit Δ	Add. Sensor	Optional Sensor					Advanced Sensors								
			P15	T21	P25	T50	P50	W21	W22	W36	T40	P40	W40	P48	W48	W50
32.75	-	0														
38.93	6.18	1			X											
43.55	4.62	2			X	X										
47.89	4.34	3			X	X						X				
48.47	0.58	4			X	X					X	X				
51.23	2.76	5			X	X		X			X	X				
52.13	0.90	6			X	X			X	X	X	X				
52.67	0.54	7	X		X	X	X			X	X	X				
52.99	0.32	8			X	X	X			X	X	X			X	X
53.38	0.39	9	X		X	X	X			X	X	X			X	X
53.69	0.31	10			X	X	X		X	X	X	X	X		X	X
54.08	0.39	11	X		X	X	X		X	X	X	X	X		X	X
54.54	0.46	12	X		X	X	X	X	X	X	X	X	X		X	X
54.54	0.00	13	X		X	X	X	X	X	X	X	X	X	X	X	X
54.54	0.00	14	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Best Sensor Suites

Optional and Advance at Take-off and Cruise Conditions Combined using a Genetic Algorithm

Average Merit	Merit Δ	Add. Sensor	Optional Sensor					Advanced Sensors								
			P15	T21	P25	T50	P50	W21	W22	W36	T40	P40	W40	P48	W48	W50
32.75	-	0														
38.93	6.18	1			X											
43.55	4.62	2			X	X										
47.89	4.34	3			X	X						X				
48.28 (48.47)	0.39	4			X	X			X		■	X				
50.64 (51.23)	2.36	5		X	X	X		X			■	X				
52.13	1.49	6			X	X			■	■	X	X	X			X
52.64 (52.67)	0.51	7	X		X	X	X			■	X	X				X
52.99	0.35	8			X	X	X			X	X	X			X	X
53.23 (53.38)	0.24	9	X		X	X	■		X	X	X	X	X		■	X
53.69	0.46	10			X	X	X		X	X	X	X	X		X	X
54.05 (54.08)	0.36	11	X		X	X	X	X	■	X	X	X	X		X	X
54.54	0.49	12	X		X	X	X	X	X	X	X	X	X		X	X
54.54	0.00	13	X		X	X	X	X	X	X	X	X	X	X	X	X
54.54	0.00	14	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Diagnostic Confusion Matrices

Cruise Flight Condition

Control Sensors

		Inferred Fault Condition						
		Fan	LPC	HPC	HPT	LPT	No Fault	Accuracy
True Fault Condition	Fan	944	0	0	0	**56**	0	94.4%
	LPC	0	0	0	0	0	**1000**	0.0%
	HPC	0	0	999	0	0	**1**	99.9%
	HPT	0	0	0	1000	0	0	100.0%
	LPT	**39**	0	0	0	961	0	96.1%
	Nominal	0	0	0	0	0	100	100.0%

Control Sensors with P25, T50 and P40

		Inferred Fault Condition						
		Fan	LPC	HPC	HPT	LPT	No Fault	Accuracy
True Fault Condition	Fan	1000	0	0	0	0	0	100.0%
	LPC	0	0	0	0	0	**1000**	0.0%
	HPC	0	0	1000	0	0	0	100.0%
	HPT	0	0	0	1000	0	0	100.0%
	LPT	0	0	0	0	1000	0	100.0%
	Nominal	0	0	0	0	0	100	100.0%

Second Study Conclusions

- The health assessment capability of the control sensor suite can be improved with the addition of certain sensors which in this problem setup could include P25, T50 and P40
- Results of the Genetic Algorithm were within 1.16% of the results of the Exhaustive Search suggesting that it is a viable optimization technique to incorporate when Exhaustive Search is not feasible
- S4 is a modular procedure that is flexible to the diagnostic application of the end user

Current Work

- Third Study
  - Focus on the Diagnostic System Model and the Sensor Suite Merit Algorithm
- S4 User's Guide
  - Explains the process and how to apply it
  - Has an example application using C-MAPSS which is a simplified version of the second study of this presentation
  - Being expanded to include software to be made available on the NASA Software Repository

Thank you