Probabilistic Damage Tolerance Analysis for Aircraft Fleets

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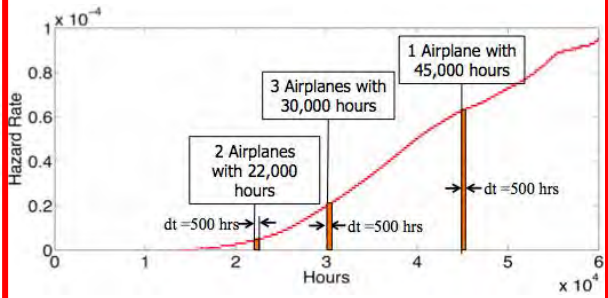
Brisbane, Australia July 20-23, 2015

Program Overview

2007-2011

- ✓ Presentation by Textron Aviation (Beth Gamble) in 2014

Safe-life Approach



- Prob. Life distribution
  - Hazard Rate
  - Sensitivity Analysis

2009-2013

- ✓ Federal Aviation Administration.
  - ✓ Tech Center (Atlantic City). Sohrob Mattagi
  - ✓ Small Airplane Directorate Office (Kansas City). Mike Reyer
  - ✓ Michael Gorelik (Chief Scientific and Technical Advisor F&DT).
- ✓ Textron Aviation.
  - ✓ Cessna (Beth Gamble and Christopher Hurst).
- ✓ Nuss Sustainment Solutions
  - ✓ Marv Nuss.
- ✓ Airframe Digital Twin (NGC)
- ✓ Visiting OEM ASIP engineers to deliver software and do training fall 2015.

- Inspection/Repair Effect
  - Sensitivity Analysis

2012-2016

- Develop a Probabilistically-based fatigue management plan (PFMP) for general aviation

Development Philosophy

- Run any crack growth model
- Consider any repair scenario
- Consider any random variable

Previous S-O-T-A

- Three random variables:
  - ai, Kc, EVD
- Deterministic crack growth curve
- Inspection and repair

SFPOF

1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12

0 2000 4000 6000 8000 10000 12000 14000

Flight Hours

Smart|DT Capabilities

- Loading Generation
  - Computed from exceedance curves (Internal library and user exceedance option) – Weighted usage available.
  - Flight Duration and weight matrices, Design load limit factors, one-g stress, and ground stress as user input.
  - Stresses and/or flights randomizations
  - Spectrum editing option (Rainflow, rise/fall, Dead band)
  - User-defined spectra (Afgrow format)
- Extreme Value Distribution
  - User input, e.g., Gumbel, Frechet , and Weibull.
  - Ultimate/Limit load (deterministic)
  - Computed from exceedance curves, weight matrix, etc. (Gumbel, Frechet , and Weibull)
- Probability calculations
  - SFPOF (survival / no survival term)
  - Hazard fn. (with survival term)
  - Cumulative (with survival term)
- Crack growth
  - Direct Afgrow, Nasgro, & Fastran link
  - Through, Corner, Surface crack growth geometry options
  - Master curve for 2D (ai and Kc) interpolation (user input or developed from NASGRO/AFGROW)
  - Kriging for efficient probabilistic fracture analysis
- Probabilistic methods
  - Weighted Branch Integration Method
  - Standard Monte Carlo
  - Numerical integration for high dimensions
- Inspection capabilities
  - Any number of inspections (arbitrary limit set to 15)
  - Arbitrary repair crack size distribution (lognormal, tabular, Weibull, deterministic)
  - Arbitrary POD (lognormal, tabular)
  - Deterministic POD
  - User defined probability of inspection
  - Different repair scenarios within/between inspections
- Random variables
  - ai, Kc, Evd, da/dN, hole diameter, hole offset,
  - crack aspect ratio, yield stress, ultimate stress.
- Computational implementation
  - Standard Fortran 95/03, Windows and Unix (Intel ifort compiler)
  - HPC Implementation (parallel and vectorized)

Unique capabilities in blue

POF Calculations

The probability that maximum value of the applied stress (during the next flight) will exceed the residual strength σ_{RS}

$$P_f = P\left[s_{Max} > s_{RS}\right]$$

$$POF(t) = \int\int_{s_{RS}<s_{Max}} \int f_{EVD}(evd) f_{a_0}(a_0) f_{K_c}(K_c)\, da_0\, dK_c$$

Integrate EVD random variable analytically (conditional expectation)

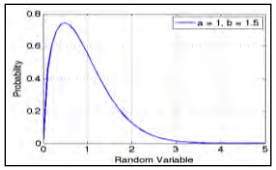
$$POF(t) = \int_{0}^{\infty} \int_{-\infty}^{\infty} \int f_{EVD}(evd) f_{a_0}(a_0) f_{K_c}(K_c)\, dK_c\, da_0$$

Difficult Integral?

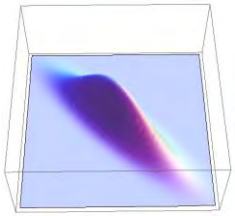
- ✓ Small probabilities: (1E-18 - 1E-5)
- ✓ Time dependent: multiple integrals
- ✓ Inspections

Smart|DT

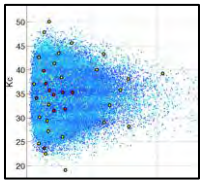
EVD Dist



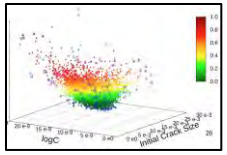
dadN variability



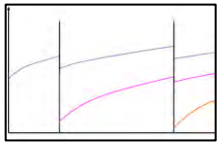
Monte Carlo



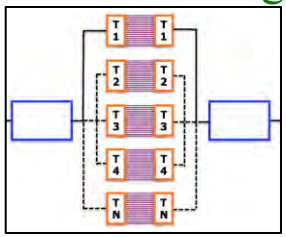
Kriging surrogate



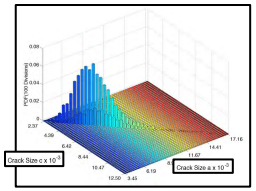
WBI



HPC - multithreading



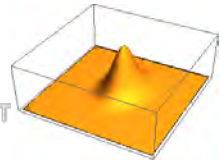
Joint a & c interpolation



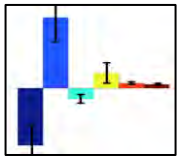
Nasgro/Fastran interface

Afgrow interface w COM

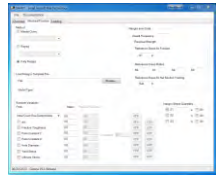
Numerical Integration



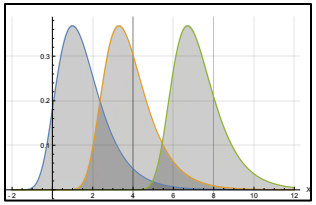
Sensitivity analysis



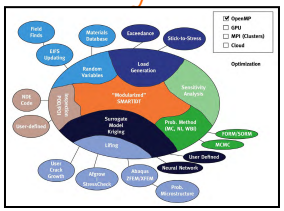
GUI



Importance sampling



Interoperability

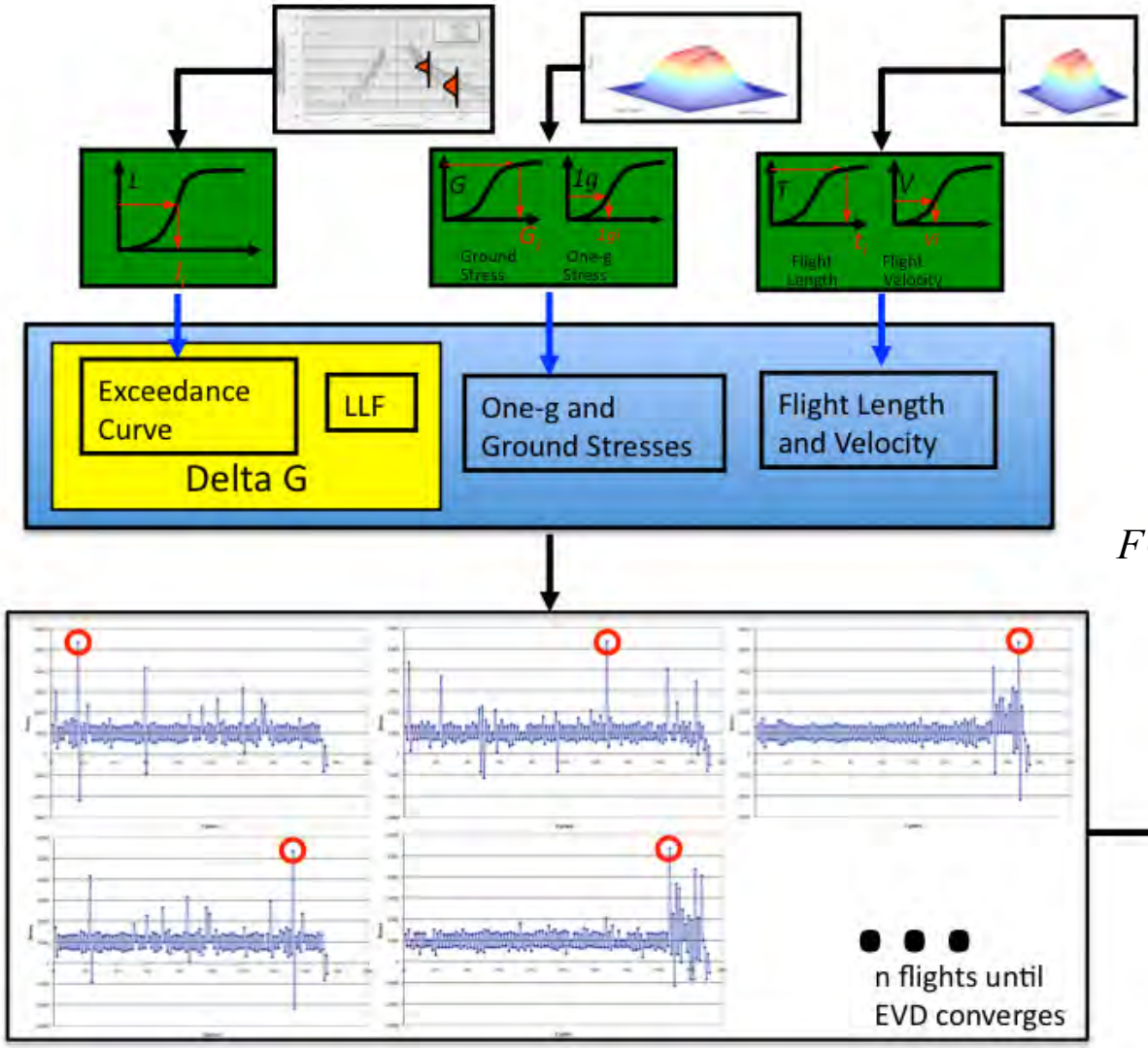


Scriptable

MSD

GPU MPI/Cloud

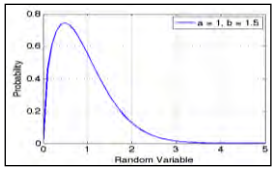
EVD Generation



$$F(x) = \exp\left\{-\left[1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

Smart|DT

EVD Dist



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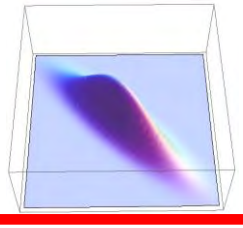
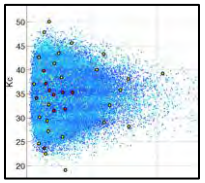
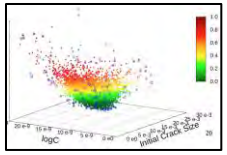


Monte Carlo



Kriging surrogate



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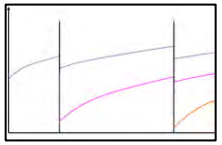

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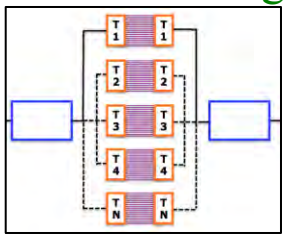

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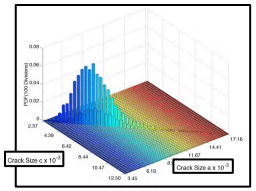
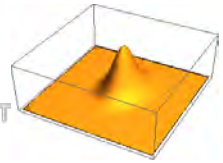


Nasgro/Fastran interface

Afgrow interface w COM

Numerical Integration



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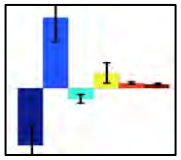

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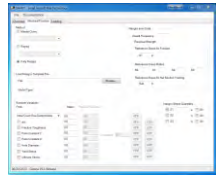

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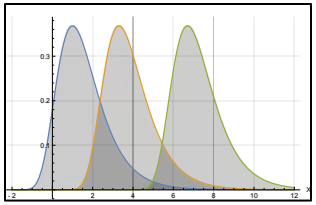
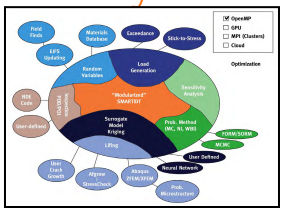


Interoperability



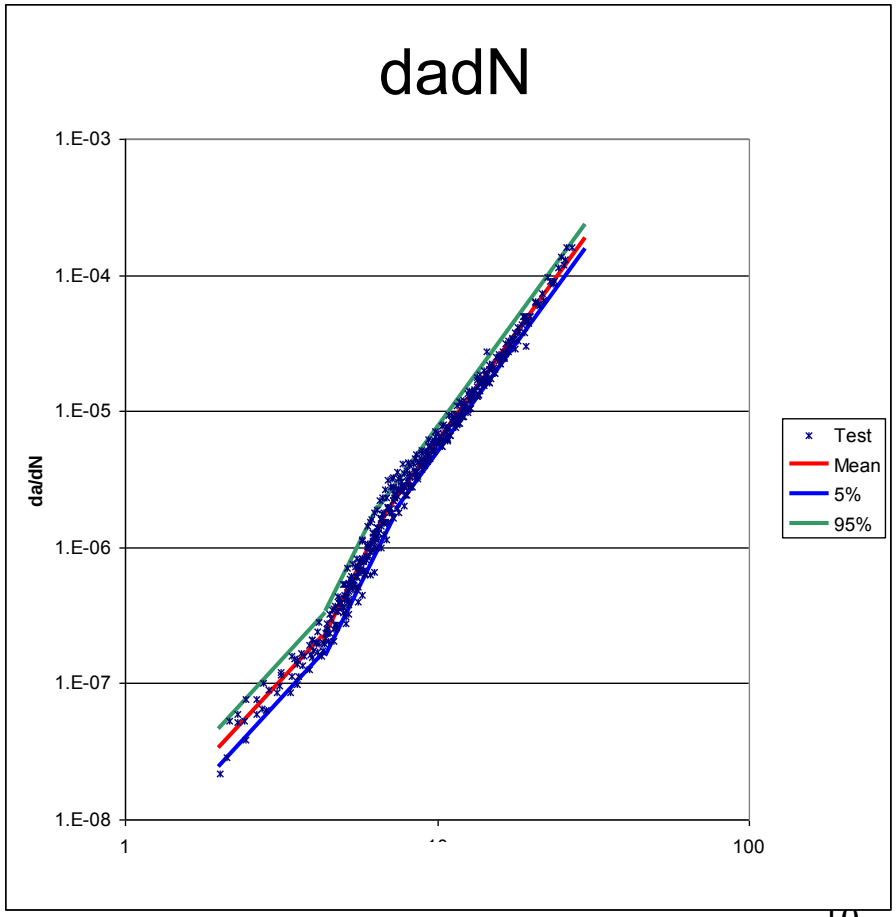
Scriptable

MSD

GPU MPI/Cloud

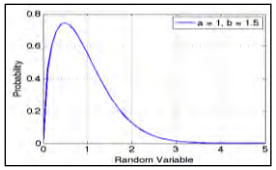
Comprehensive Random Variables

- EIFS, aspect ratio
- dadN, fracture toughness, yield stress, ultimate stress
- Hole size, hole offset
- POD, POI
- :Expandable:



Smart|DT

EVD Dist



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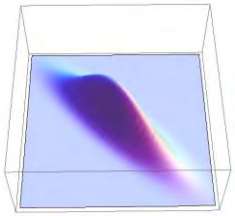
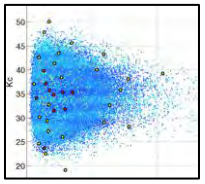


Monte Carlo



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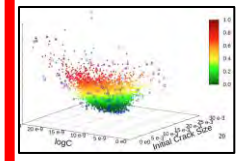

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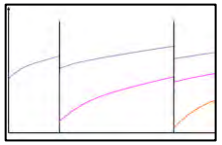

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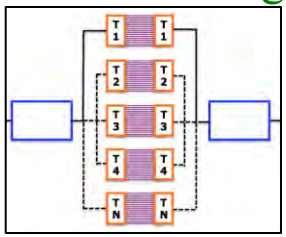
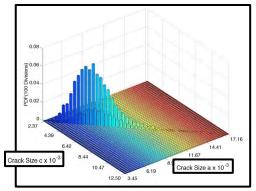


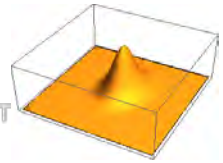
Joint a & c interpolation



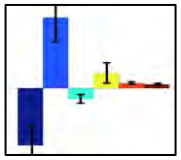
Nasgro/Fastran interface

Afgrow interface w COM

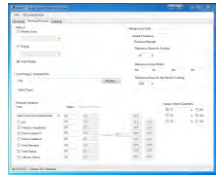
Numerical Integration



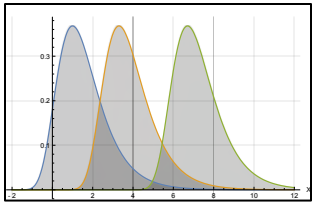
Sensitivity analysis



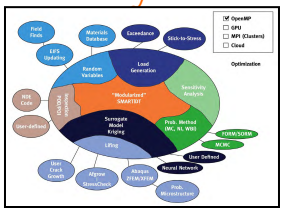
GUI



Importance sampling



Interoperability



Scriptable

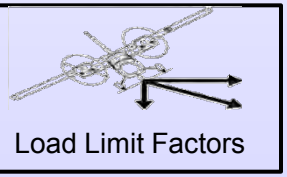
MSD

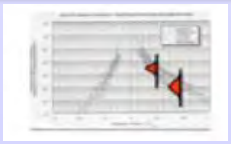
GPU MPI/Cloud

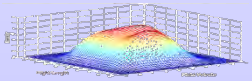
Smart | DT
UTSA

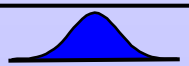
Loading Data

Internally Generated Loading

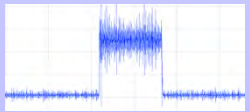

Load Limit Factors


Exceedance Curves

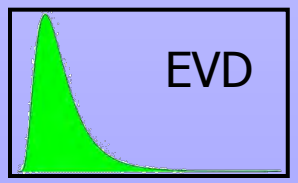

Flt Duration & Velocity Weight Matrix


Sink Rate

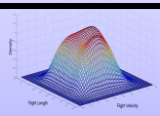
User Loading


User Spectrum


SMF



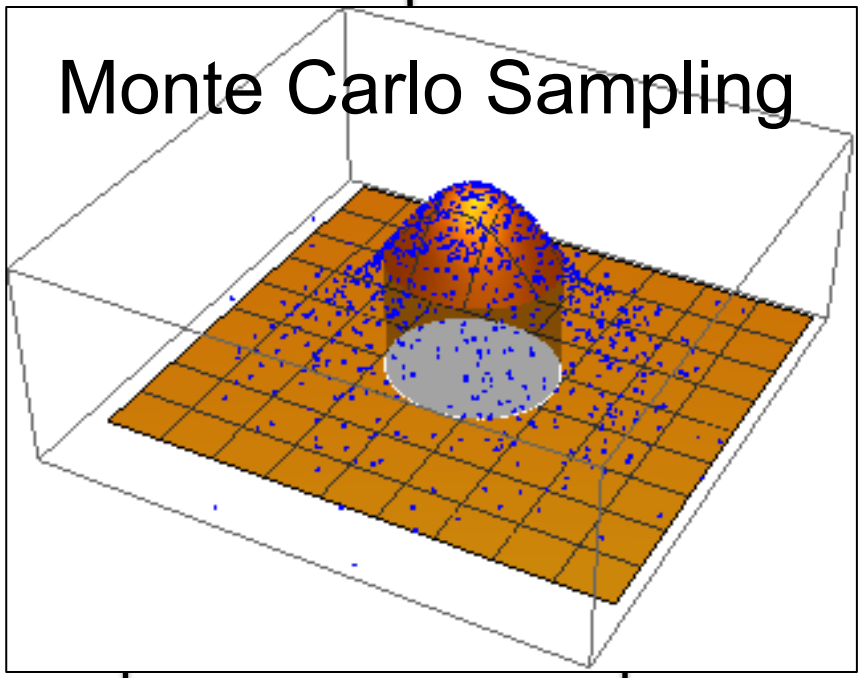
Material Data


da/dN

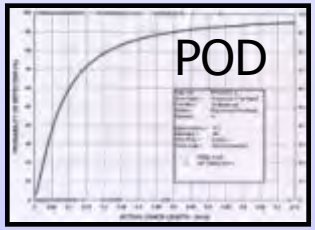

Fracture Toughness

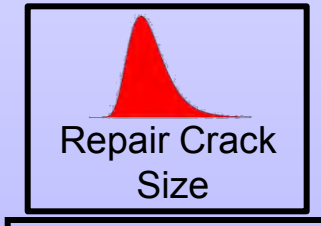

Yield and Ultimate Stress

Monte Carlo Sampling



Inspection Data

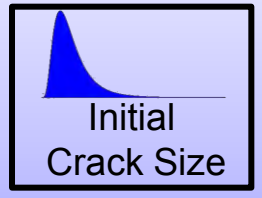



Repair Crack Size

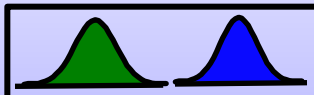
Repair Scenarios

Inspection times

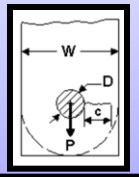
Prob. of Inspecting


Initial Crack Size

Geometry Data

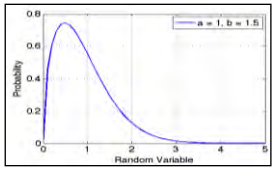

Hole Dia.

Hole Offset

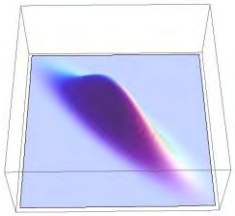


Smart|DT

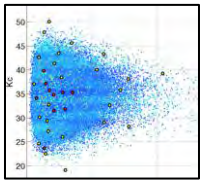
EVD Dist



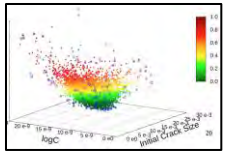
dadN variability



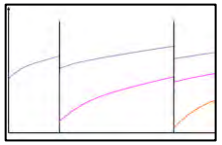
Monte Carlo



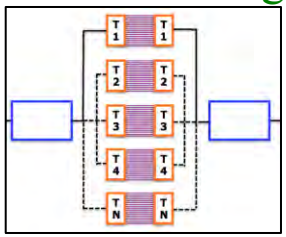
Kriging surrogate



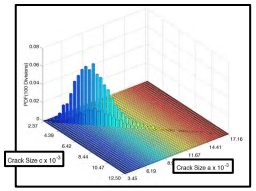
WBI



HPC - multithreading



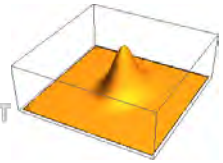
Joint a & c interpolation



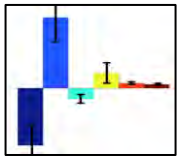
Nasgro/Fastran interface

Afgrow interface w COM

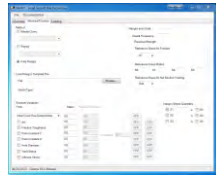
Numerical Integration



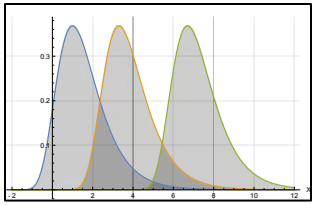
Sensitivity analysis



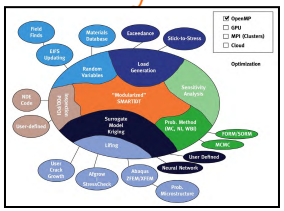
GUI



Importance sampling



Interoperability

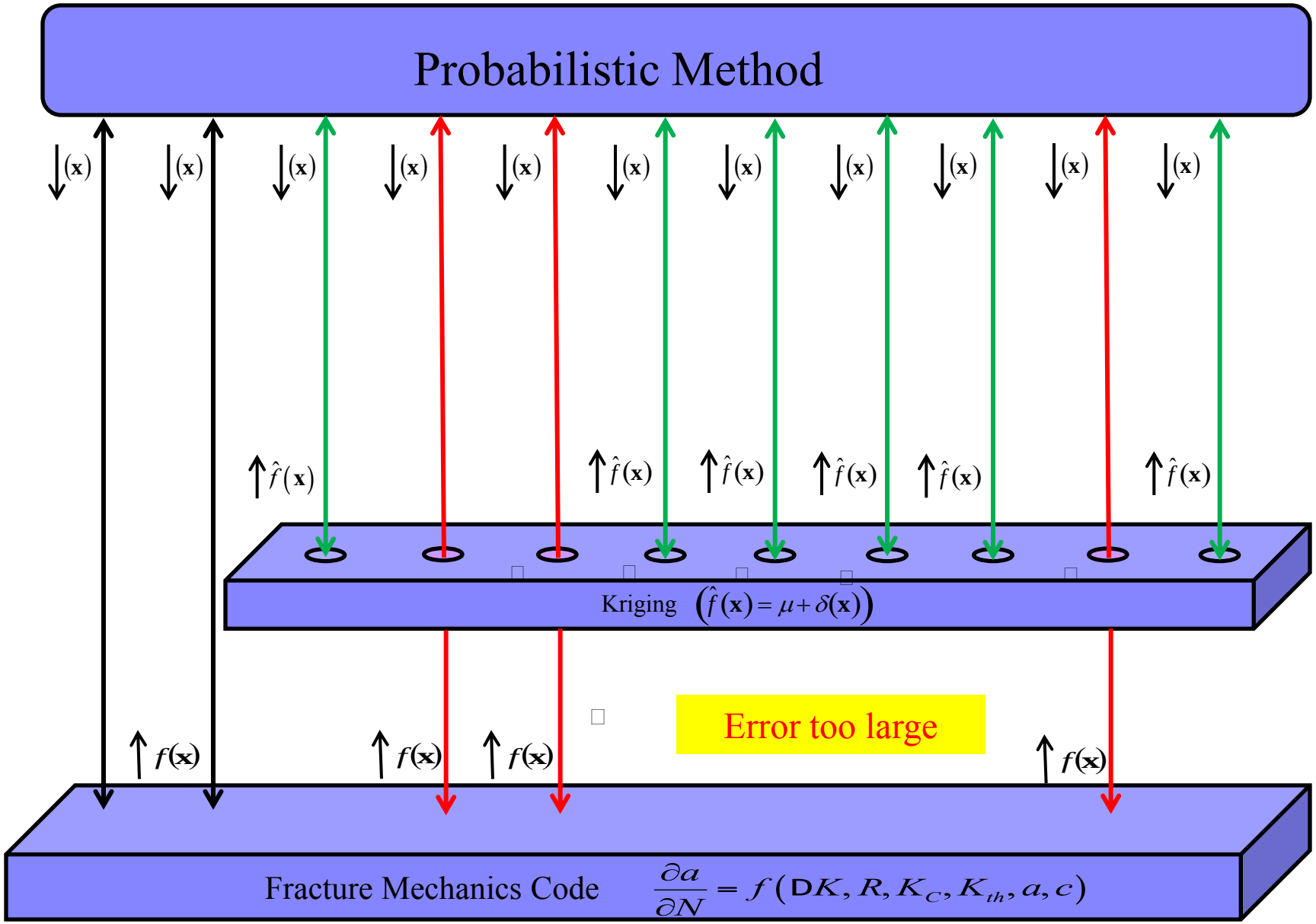


Scriptable

MSD

GPU MPI/Cloud

Surrogate Model Schematic



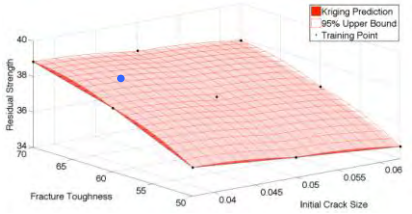
User Defined Error — Initial Training Points (x) Vector of Random Variables

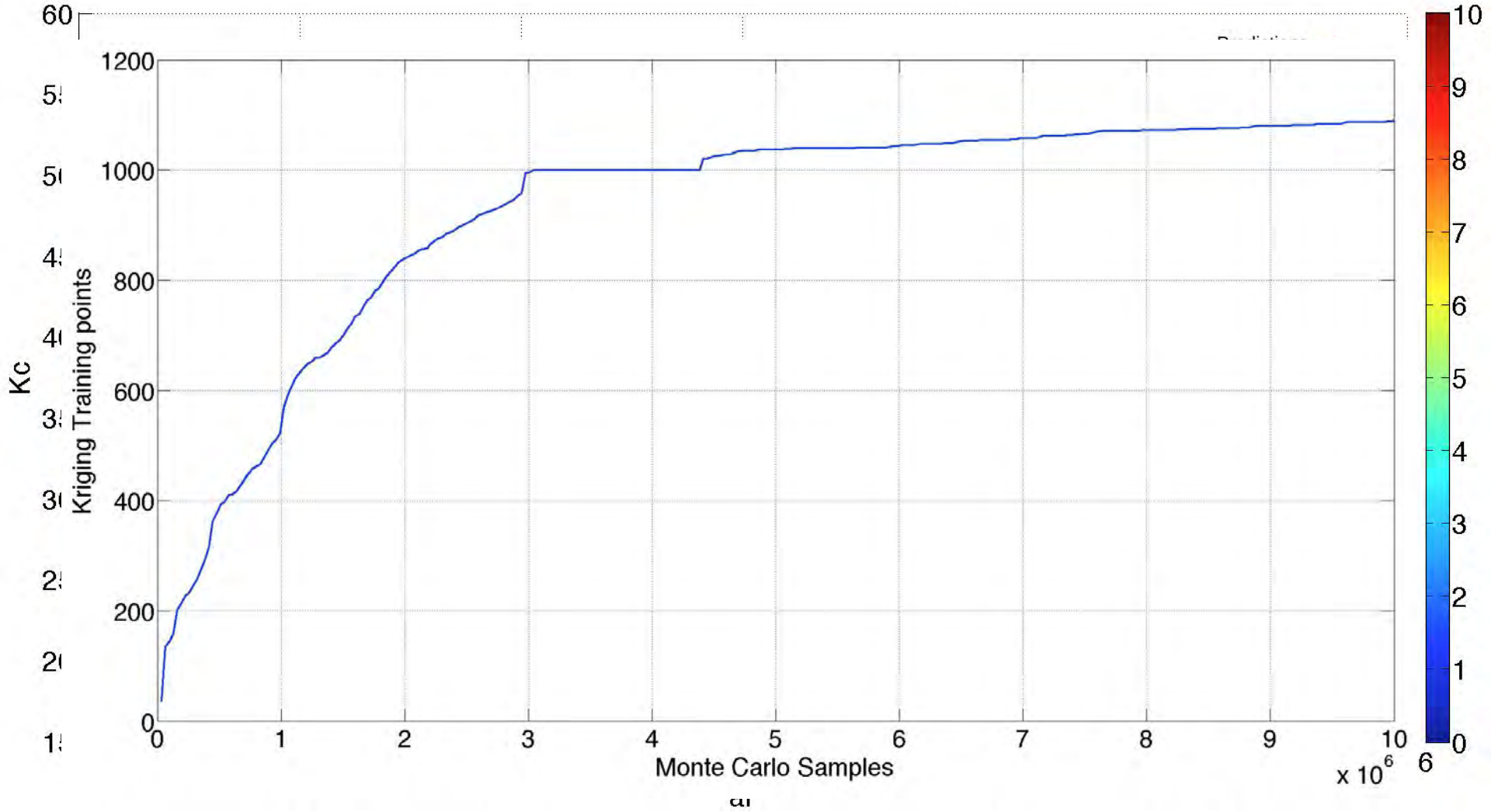
Additional Training Points (Kriging Error> User Error) — Kriged Points (Kriging Error < User Error)

Kriging Summary

- Multiple random variables
  - ai, Kc, Paris C, crack aspect ratio, hole diameter, hole offset, yield stress, ultimate stress, peak stress
- User-defined error for residual strength and crack growth predictions
- Residual strength predictions
- Through, corner, and surface crack size predictions
- HPC implementation (vectorized and parallel)
- Direct link to external crack growth codes:
  - NASGRO and FASTRAN in parallel (File based)
  - AFGROW (COM based)
- Previous training points can be reused
- Independent Kriging surfaces thru time

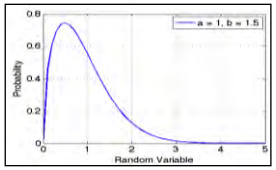
Kriging Schemetic



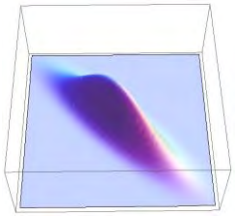


Smart|DT

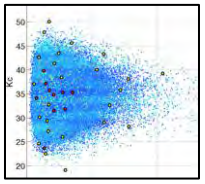
EVD Dist



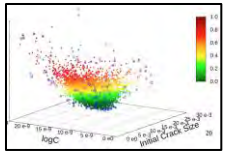
dadN variability



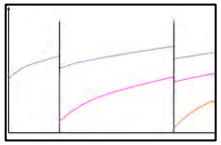
Monte Carlo



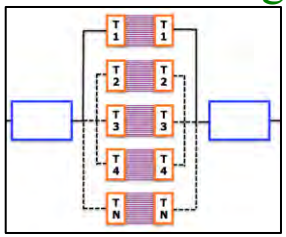
Kriging surrogate



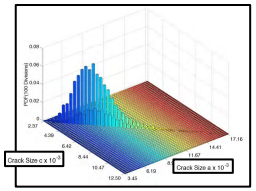
WBI



HPC - multithreading



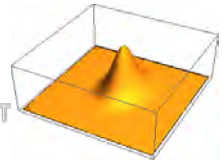
Joint a & c interpolation



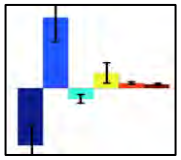
Nasgro/Fastran interface

Afgrow interface w COM

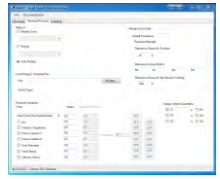
Numerical Integration



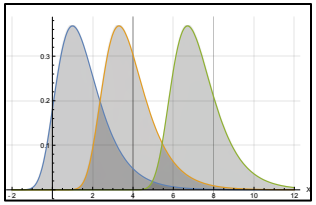
Sensitivity analysis



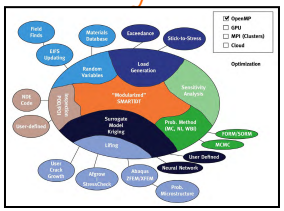
GUI



Importance sampling



Interoperability



Scriptable

MSD

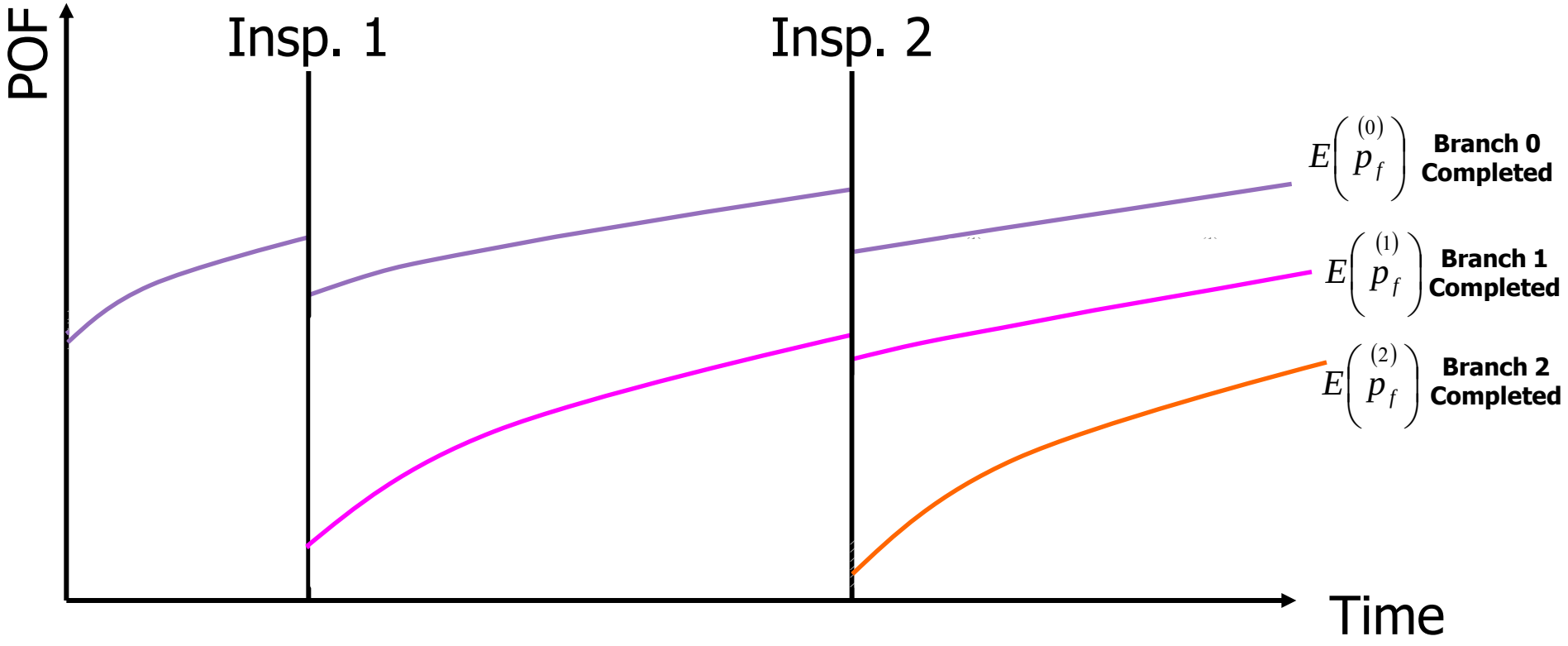
GPU MPI/Cloud

Methodology
WBI

- Decomposes the probability integral into a series of integrals with unimodal crack size PDFs.
- Each integral is represented as a "branch" of the analysis where a branch represents a repair scenario.
- Each branch computed independently.
- Overall POF determined as a sum from all branches.

Material, geometry, and crack growth properties can be changed for each branch (different repair scenarios can be analyzed).

Implementation
Monte Carlo – Simple Repair

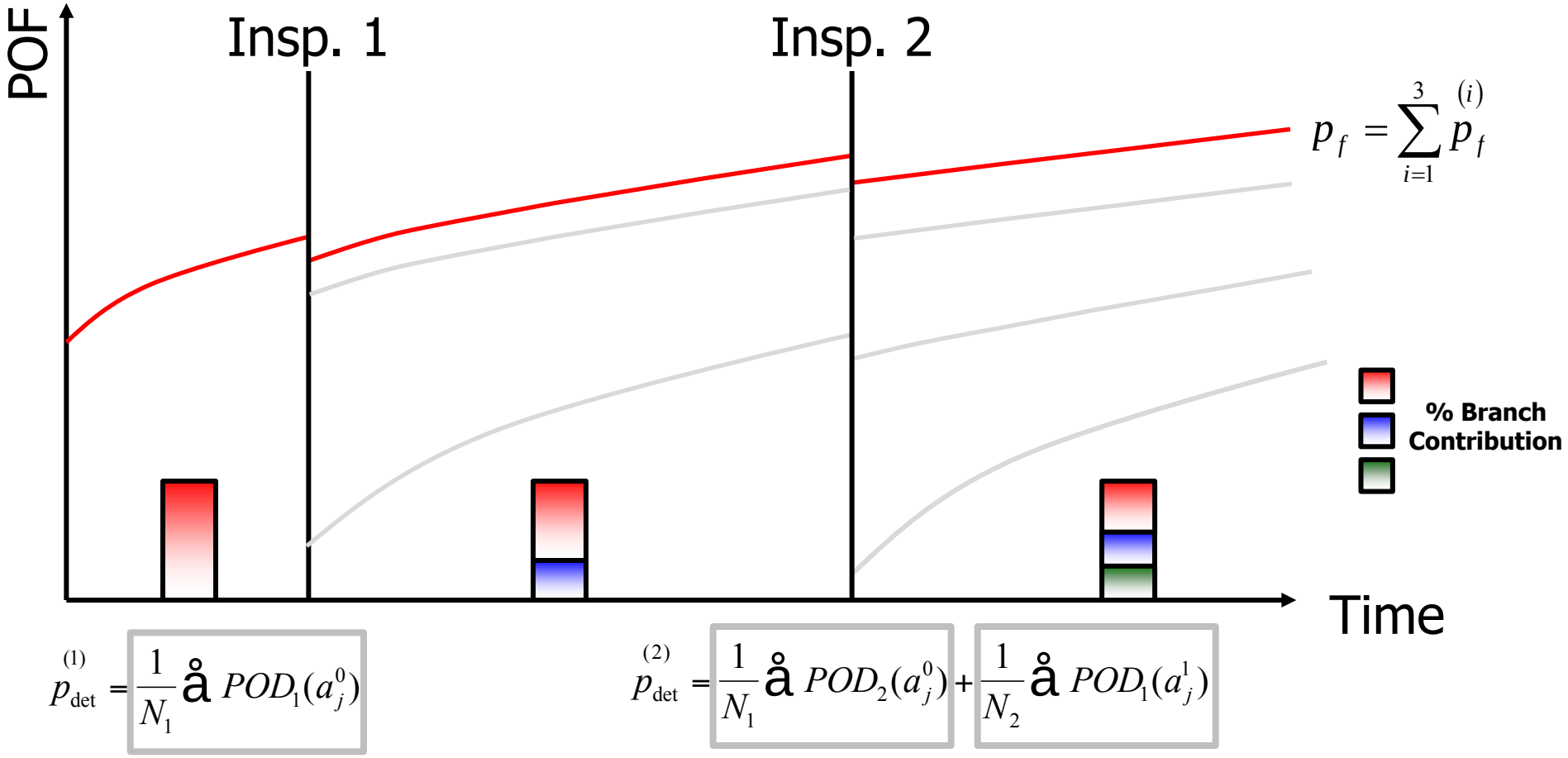


$N = \text{User Samples}$

$$p_{\text{det}}^{(1)} = \frac{1}{N}\sum POD_1(a_j^0)$$

$$p_{\text{det}}^{(2)} = \frac{1}{N}\sum POD_2(a_j^0) + \frac{1}{N}\sum POD_1(a_j^1)$$

Implementation
Monte Carlo – Simple Repair



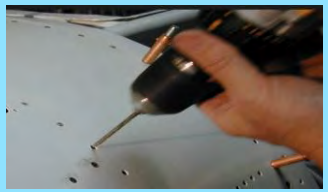
Add the contribution from each branch into the final POF

Multiple Repair Example

Baseline

Insp. 1

Baseline
(no detected)



Oversized Hole
$a_1 < a \le a_2$

Doubler
$a_2 < a \le a_3$

Replacement
$a_3 < a$

Insp. 2

Baseline
(no detected)

Oversized Hole
$a_1 < a \le a_2$

Doubler
$a_2 < a \le a_3$

Replacement
$a_3 < a$

Oversized Hole
$a_1 < a \le a_2$

Doubler
$a_2 < a \le a_3$

Replacement
$a_3 < a$

Doubler
$a_2 < a \le a_3$

Replacement
$a_3 < a$

Baseline
(no detected)

Oversized Hole
$a_1 < a \le a_2$

Doubler
$a_2 < a \le a_3$

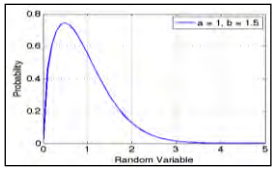
Replacement
0.2 < a

Insp. N

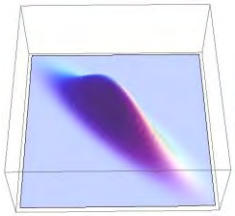
Etc.

Smart|DT

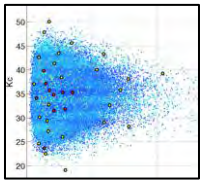
EVD Dist



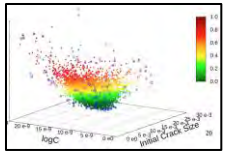
dadN variability



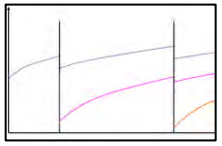
Monte Carlo



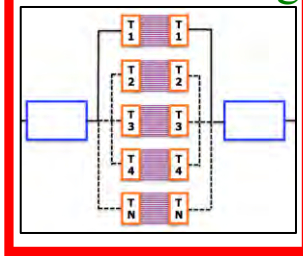
Kriging surrogate



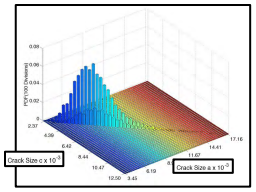
WBI



HPC - multithreading



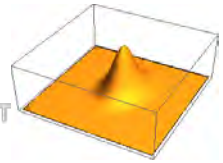
Joint a & c interpolation



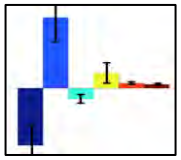
Nasgro/Fastran interface

Afgrow interface w COM

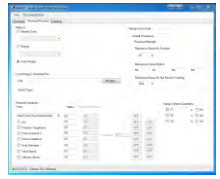
Numerical Integration



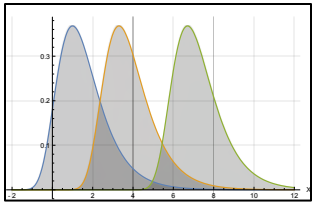
Sensitivity analysis



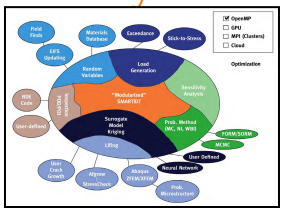
GUI



Importance sampling



Interoperability

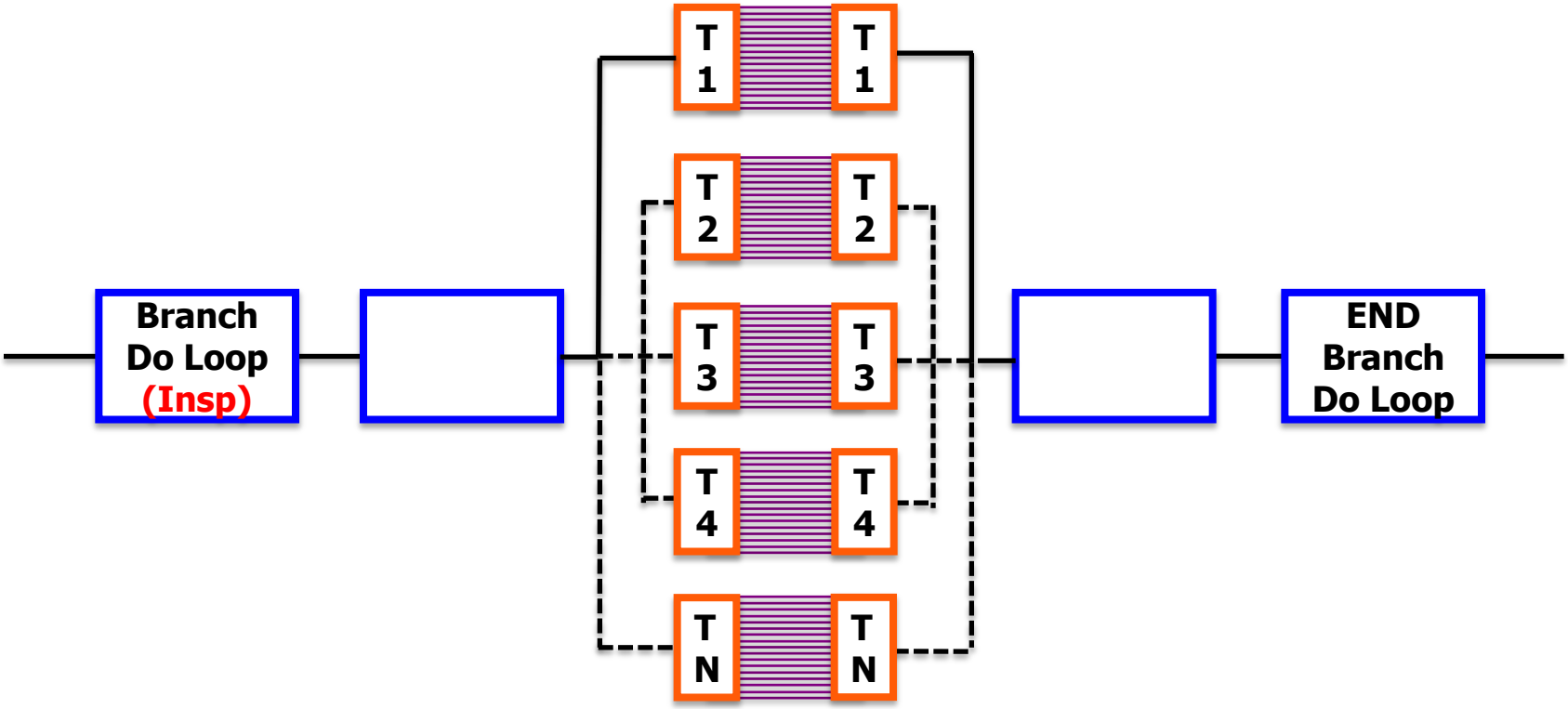


Scriptable

MSD

GPU MPI/Cloud

Parallel & Vectorized Implementation for WBI

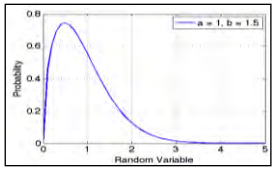


Handbook example problem 1E8 samples speed up:

	1T	4T	8T
Base Code	1.00	1.00	1.00
Vector + Parallel	2.80	8.62	13.24

Smart|DT

EVD Dist



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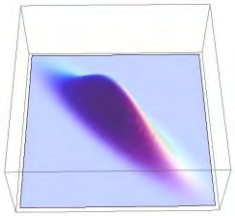
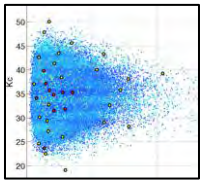


Monte Carlo



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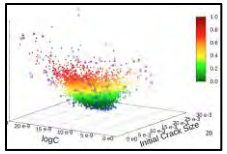

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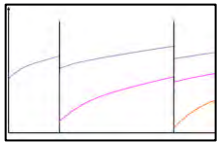

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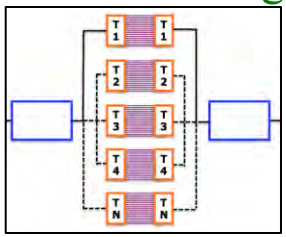
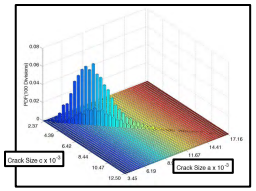


Joint a & c interpolation



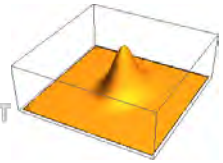
Nasgro/Fastran interface

FASTRAN

Afgrow interface w COM

AFGROW .NET

Numerical Integration



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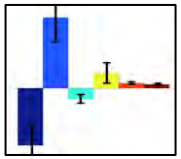
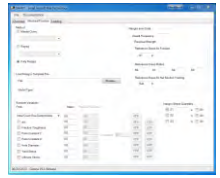
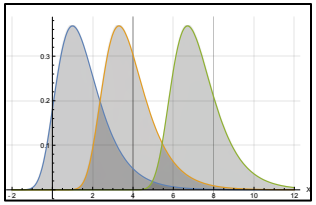


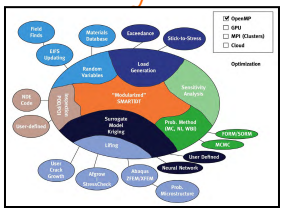
GUI



Importance sampling



Interoperability



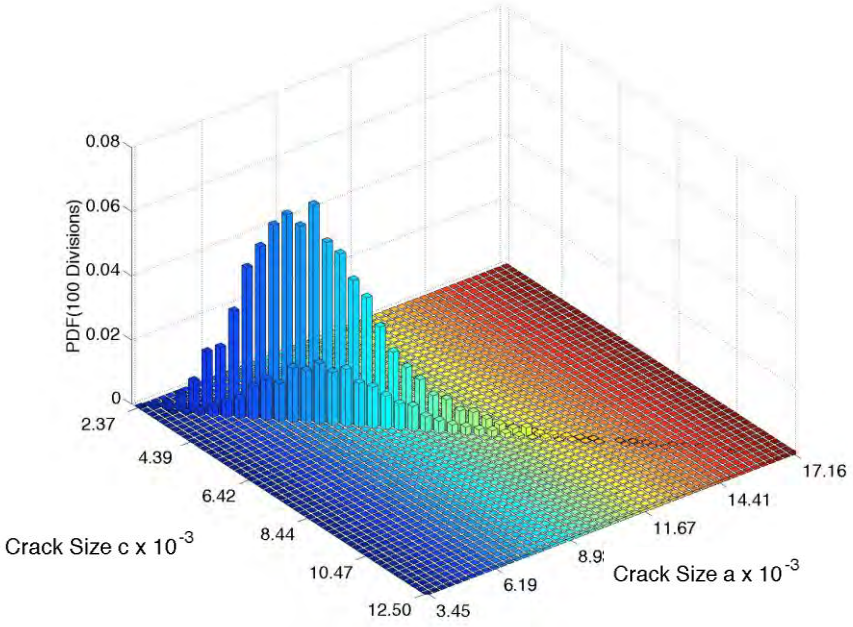
Scriptable

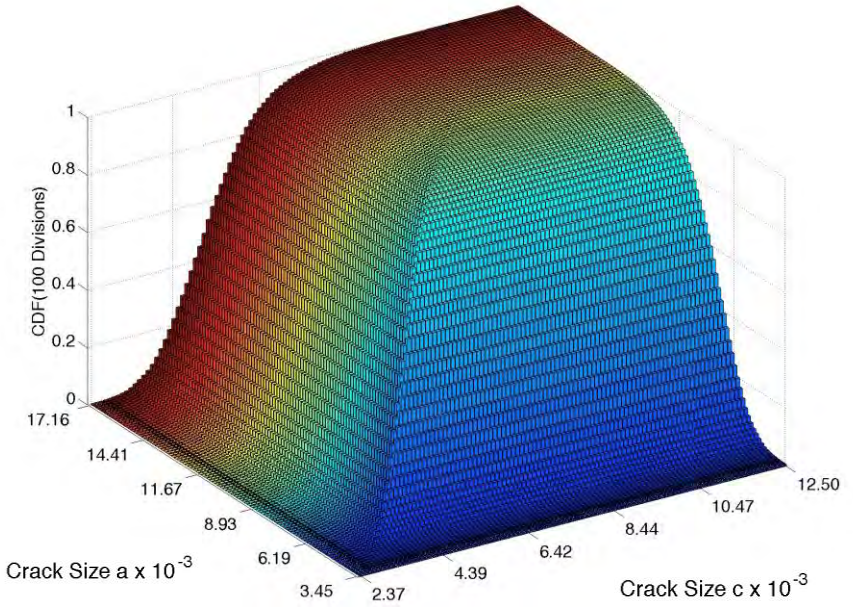
MSD

GPU MPI/Cloud

Crack Size Distributions

Both “a” and “c” crack tips tracked through time.
Joint distribution computed.

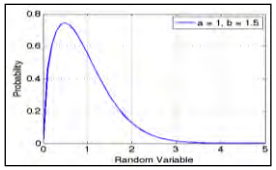




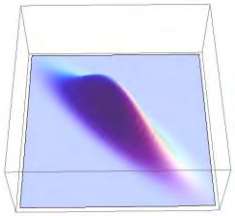
Crack Size at time = 5000

Smart|DT

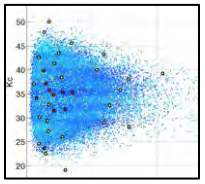
EVD Dist



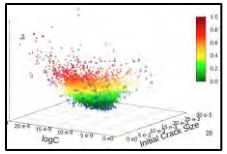
dadN variability



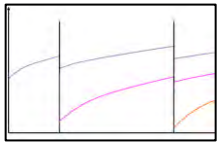
Monte Carlo



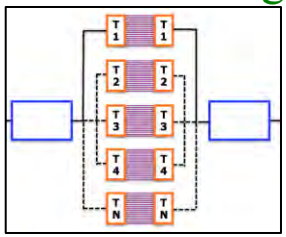
Kriging surrogate



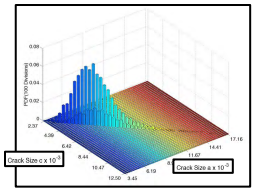
WBI



HPC - multithreading



Joint a & c interpolation

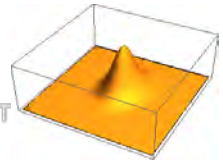


Nasgro/Fastran interface

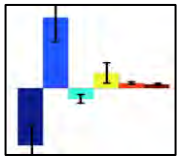
FASTRAN

Afgrow interface w COM

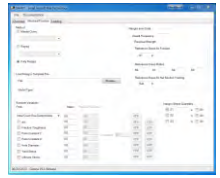
Numerical Integration



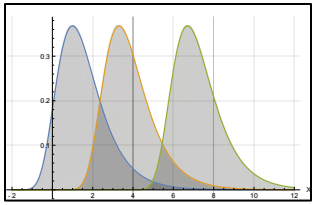
Sensitivity analysis



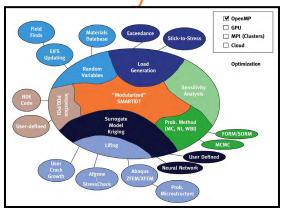
GUI



Importance sampling



Interoperability

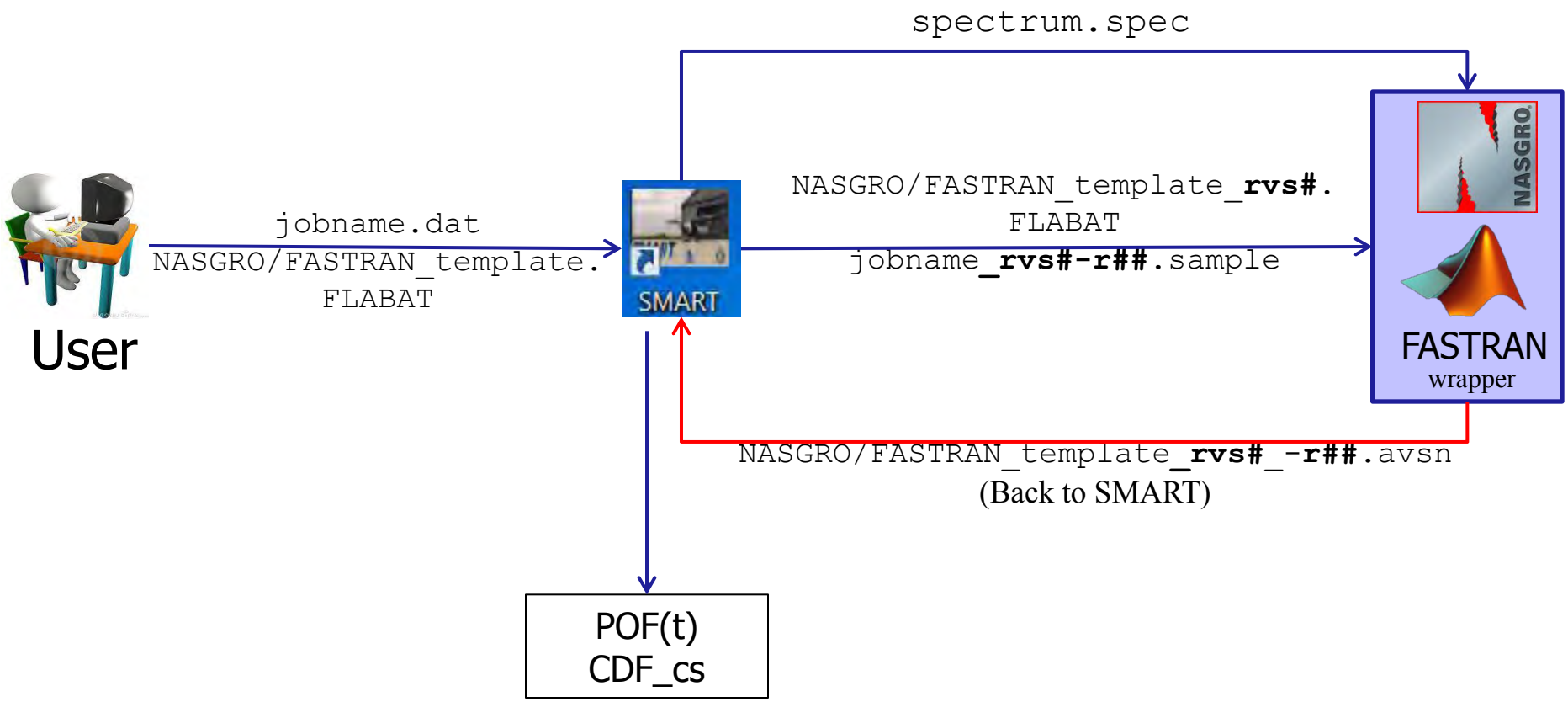


Scriptable

MSD

GPU MPI/Cloud

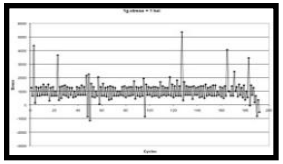
FASTRAN/NASGRO Interface
File based I/O



Fastran & Nasgro run in parallel!

AFGROW Interface: COM driven

SMART$_{DT}$



Spectrum & EVD

Random variables generator

ai, ci, Pc, Pm, Kc, Hd, etc.

Probabilistic Methods

- Numerical Integration
- Monte Carlo
- Weighted Branch Integration

Surrogate Modeling
Kriging

FORTRAN Interface with C++

C++ COM Wrapper

Spectrum

Material Variables

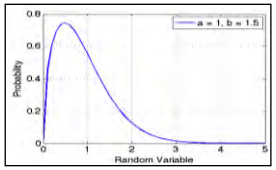
Geometric Variables

Cycles, crack a, crack c, beta a, beta c

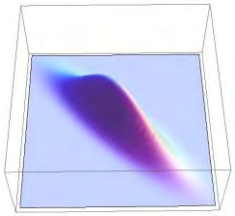
COM = Component Object Model

Smart|DT

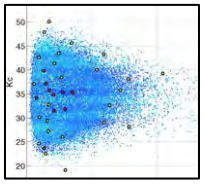
EVD Dist



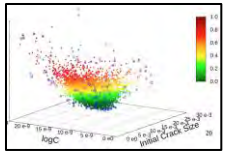
dadN variability



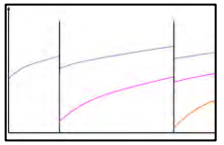
Monte Carlo



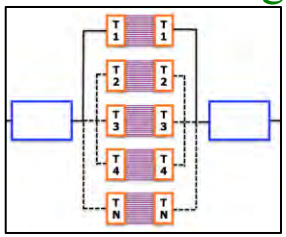
Kriging surrogate



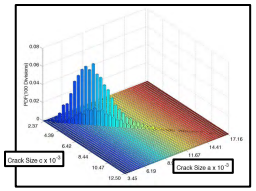
WBI



HPC - multithreading



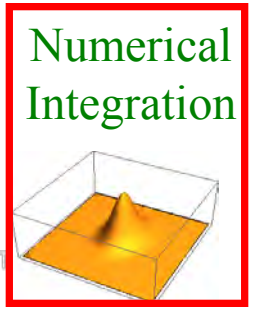
Joint a & c interpolation



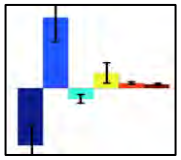
Nasgro/Fastran interface

Afgrow interface w COM

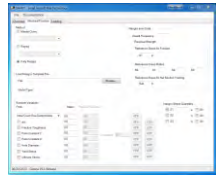
Numerical Integration



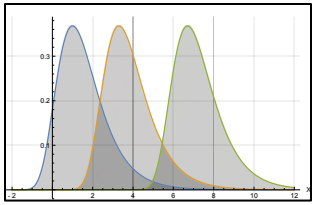
Sensitivity analysis



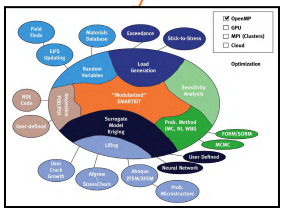
GUI



Importance sampling



Interoperability



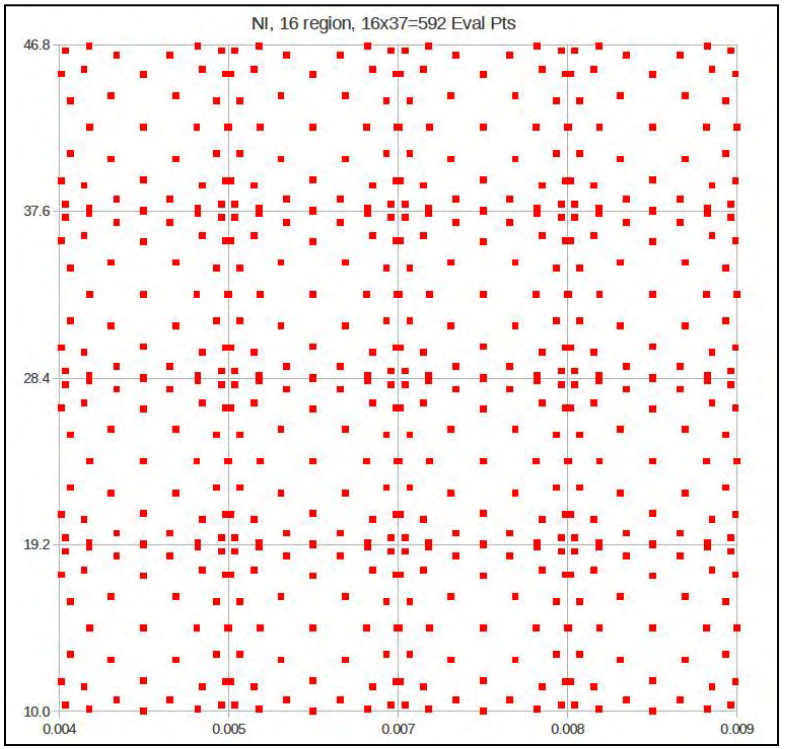
Scriptable

MSD

GPU MPI/Cloud

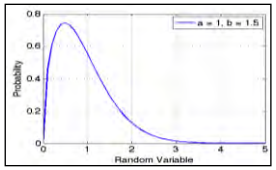
Numerical Integration

- Adaptive numerical integration for the being being implemented. High dimensional integrals being investigated.
  - Open source, free, and academically published.
  - Adaptive strategies
  - Error estimates
  - Specify number of evaluations
  - Specify error
  - High dimensional integrals

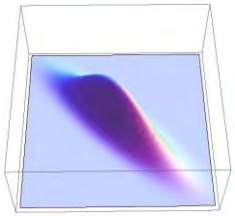


Smart|DT

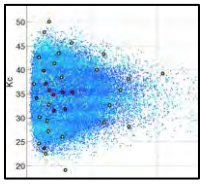
EVD Dist



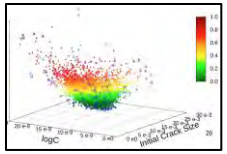
dadN variability



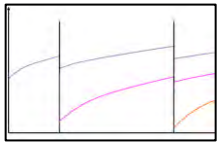
Monte Carlo



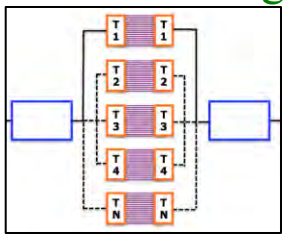
Kriging surrogate



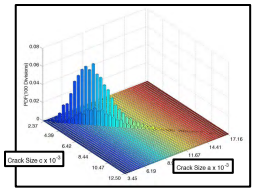
WBI



HPC - multithreading



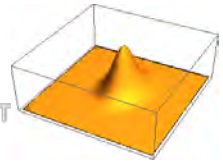
Joint a & c interpolation



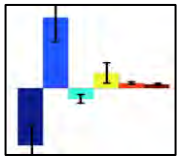
Nasgro/Fastran interface

Afgrow interface w COM

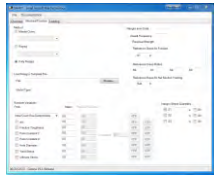
Numerical Integration



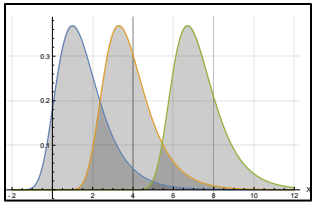
Sensitivity analysis



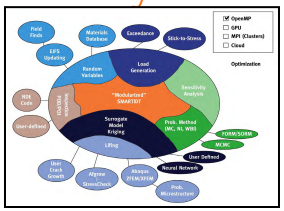
GUI



Importance sampling



Interoperability



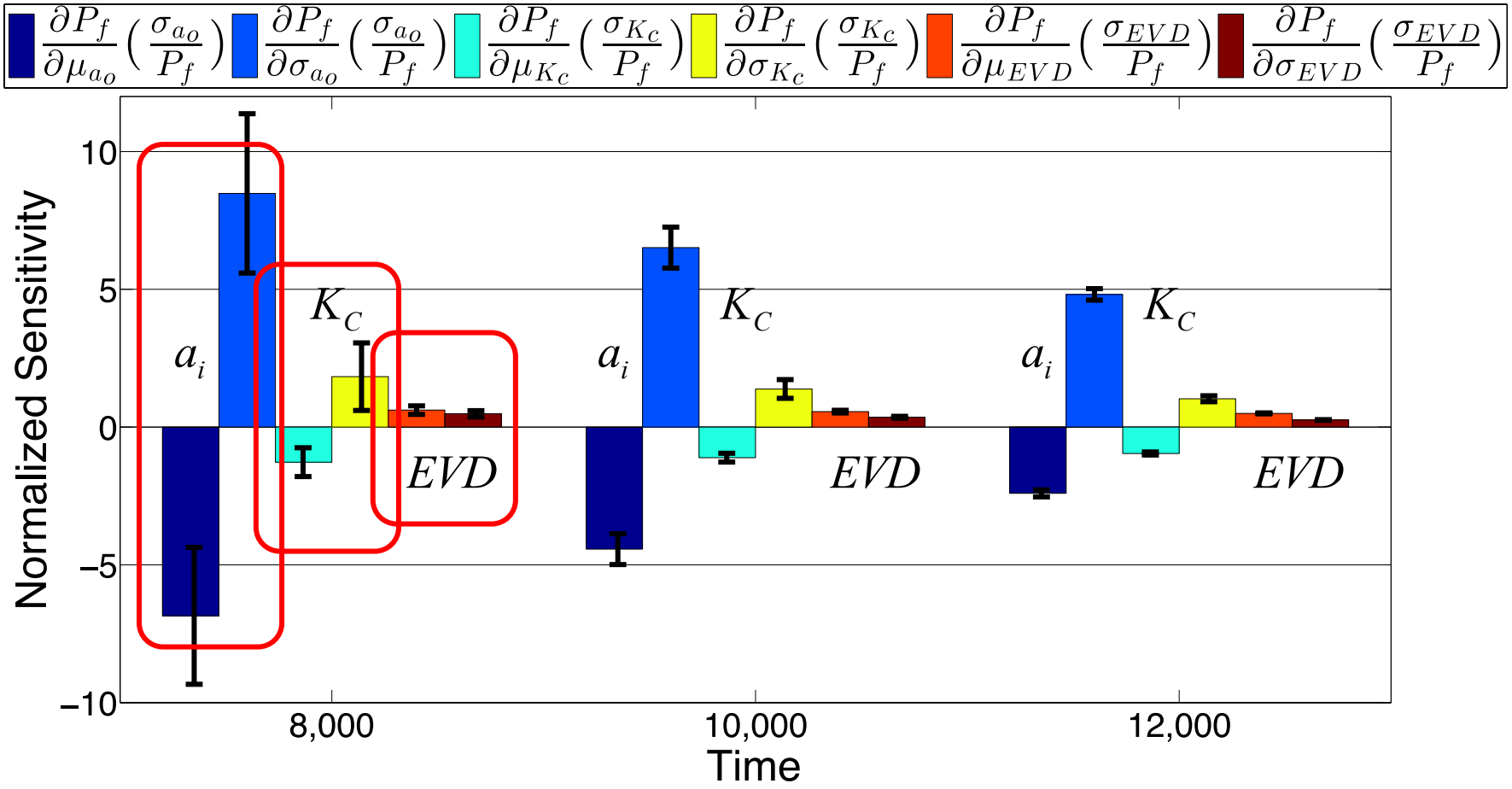
Scriptable

MSD

GPU MPI/Cloud

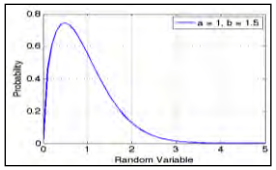
Sensitivity Analysis

Score Fn. Method – post processing method



Smart|DT

EVD Dist



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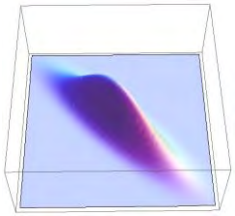
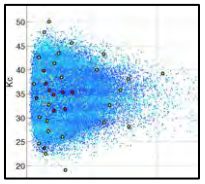
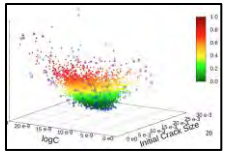


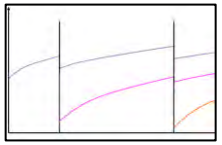
Monte Carlo



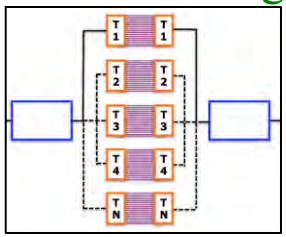
Kriging surrogate



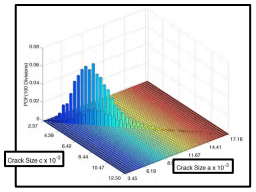
WBI



HPC - multithreading



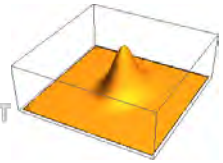
Joint a & c interpolation



Nasgro/Fastran interface

Afgrow interface w COM

Numerical Integration



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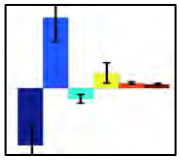
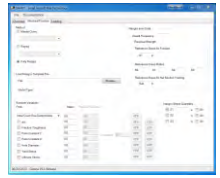


GUI



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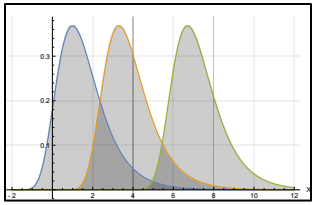
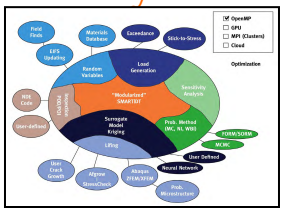


Interoperability

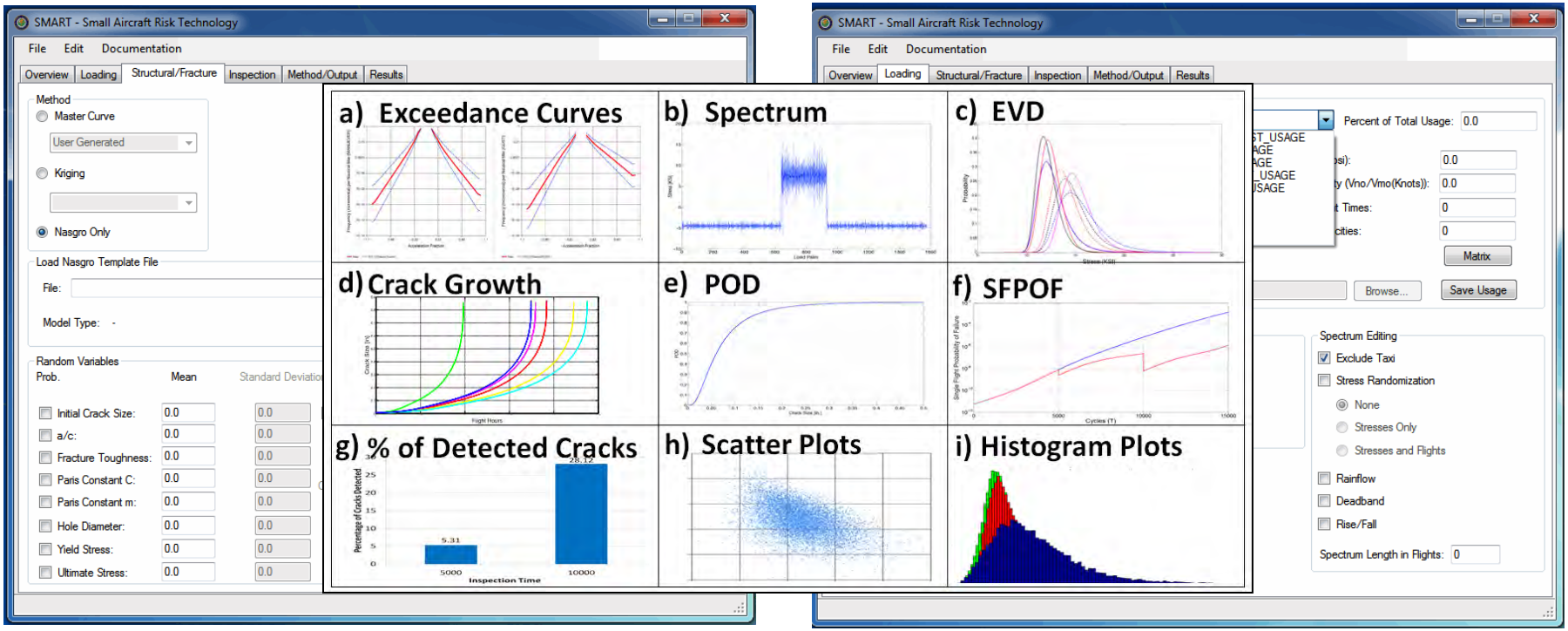


Scriptable

MSD

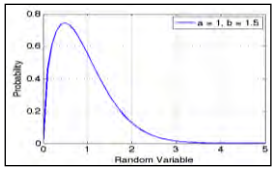
GPU MPI/Cloud

GUI

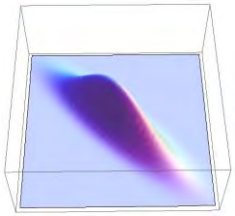

SMART - Small Aircraft Risk Technology
File Edit Documentation
Overview Loading Structural/Fracture Inspection Method/Output Results
Method
Master Curve
User Generated
Kriging
Nasgro Only
Load Nasgro Template File
File:
Model Type: -
Random Variables
Prob. Mean Standard Deviation
Initial Crack Size: 0.0 0.0
a/c: 0.0 0.0
Fracture Toughness: 0.0 0.0
Paris Constant C: 0.0 0.0
Paris Constant m: 0.0 0.0
Hole Diameter: 0.0 0.0
Yield Stress: 0.0 0.0
Ultimate Stress: 0.0 0.0
a) Exceedance Curves
b) Spectrum
c) EVD
d) Crack Growth
e) POD
f) SFPOF
g) % of Detected Cracks
5.31
28.12
5000
10000
Inspection Time
h) Scatter Plots
i) Histogram Plots
SMART - Small Aircraft Risk Technology
File Edit Documentation
Overview Loading Structural/Fracture Inspection Method/Output Results
Percent of Total Usage: 0.0
Matrix
Browse...
Save Usage
Spectrum Editing
Exclude Taxi
Stress Randomization
None
Stresses Only
Stresses and Flights
Rainflow
Deadband
Rise/Fall
Spectrum Length in Flights: 0

Smart|DT

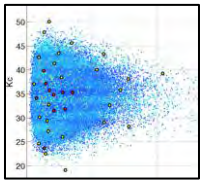
EVD Dist



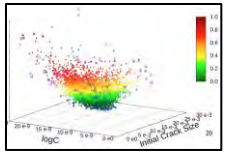
dadN variability



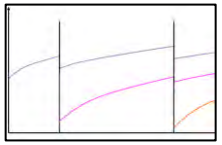
Monte Carlo



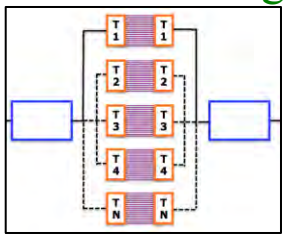
Kriging surrogate



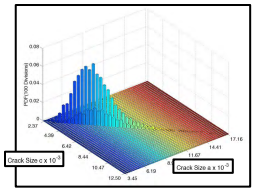
WBI



HPC - multithreading



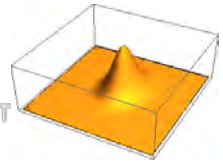
Joint a & c interpolation



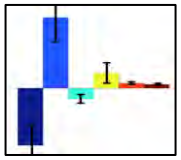
Nasgro/Fastran interface

Afgrow interface w COM

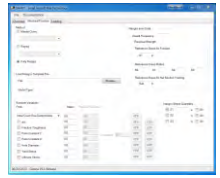
Numerical Integration



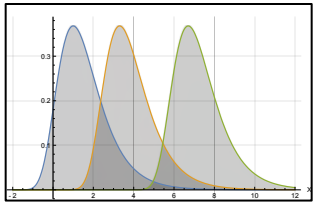
Sensitivity analysis



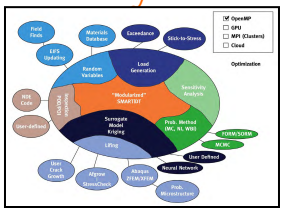
GUI



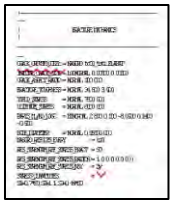
Importance sampling



Interoperability



Scriptable



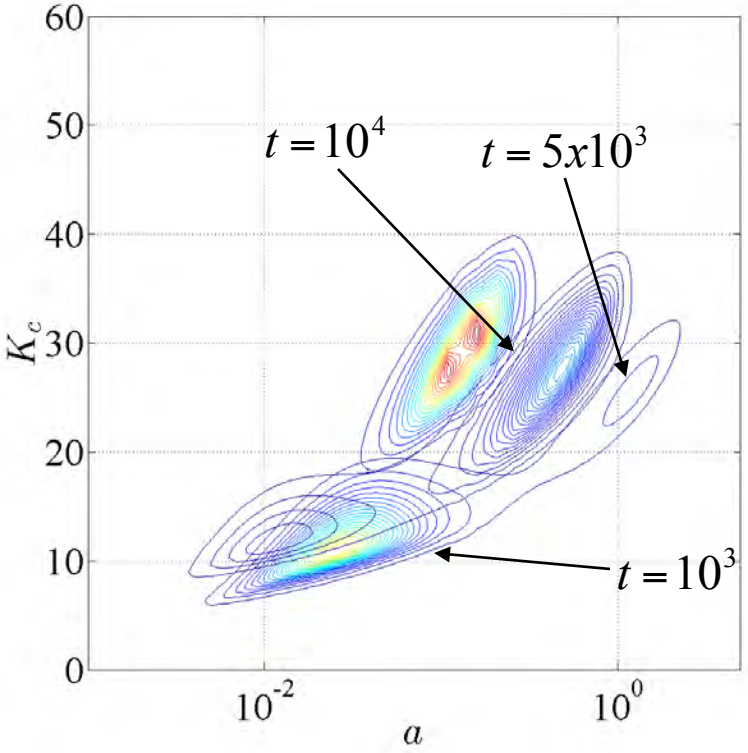
MSD

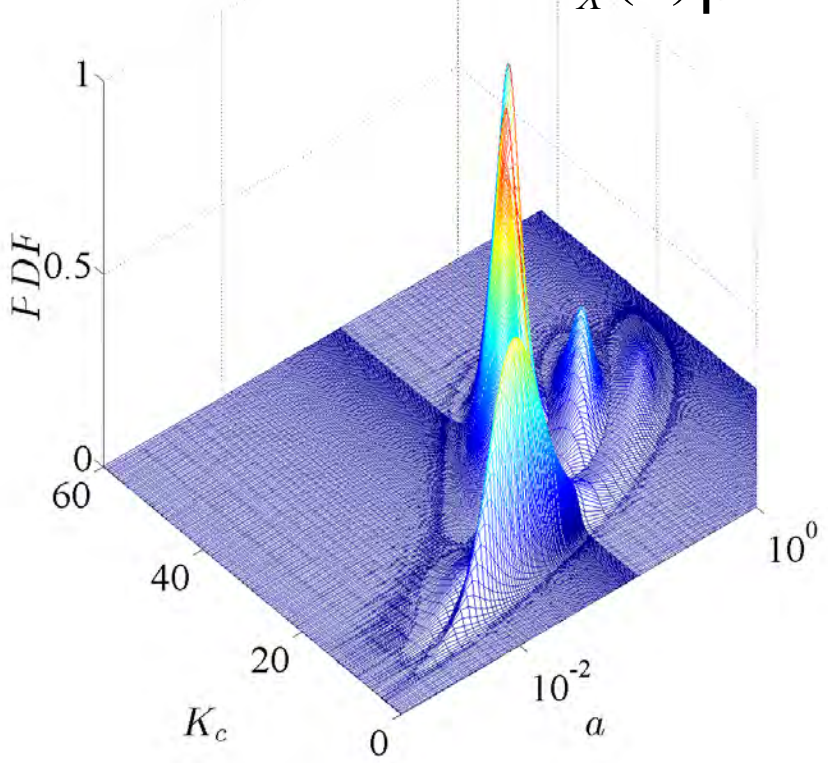
GPU MPI/Cloud

Imp. Sampling–a_i and K_c

Methods to determine optimal parameters for initial crack size, fracture toughness and other random variables.

$$Pf \approx \frac{1}{N}\sum_{i}\left(1 - F_{EVD}\right)\frac{f_X(x)}{h_X(x)}h_X(x)$$



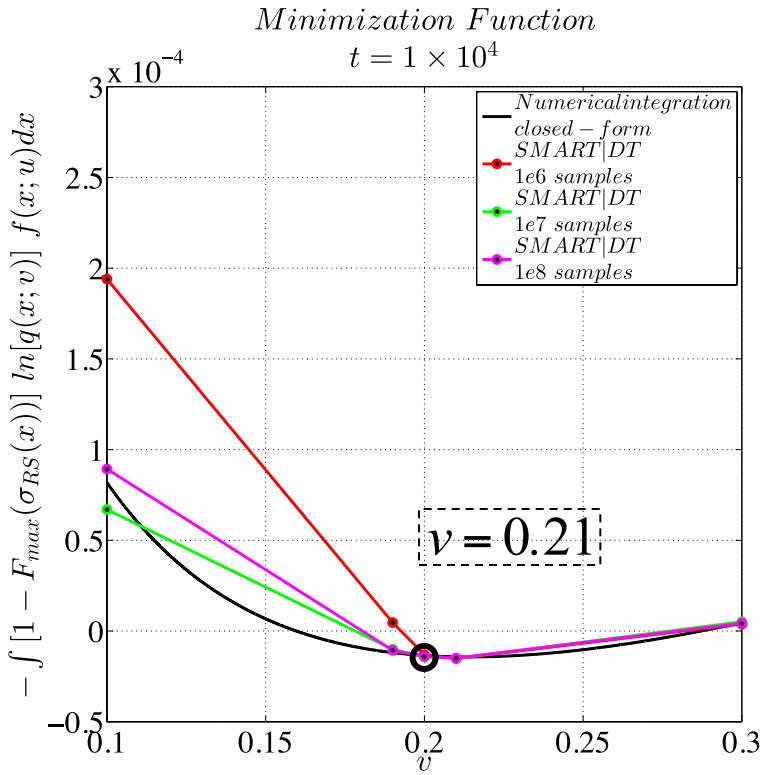


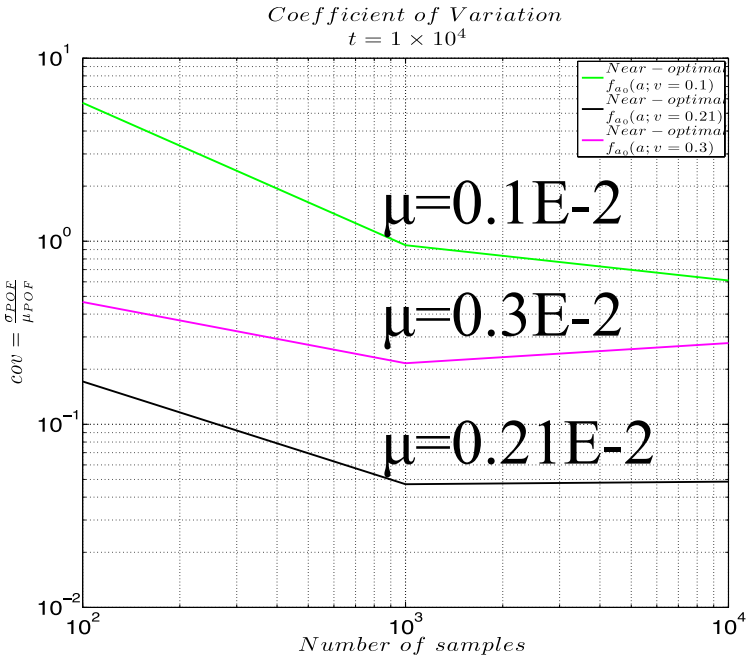
Importance Sampling

- Find the mean (ν) of crack size with 20%c.o.v.
- Comparison
  - Optimization (MATLAB) $\nu = 0.2153$
  - SMART|DT $\nu = 0.21$

Original EIFS:
Lognormal $\mu=1.0*10^{-4}$, $\sigma=0.2\mu$

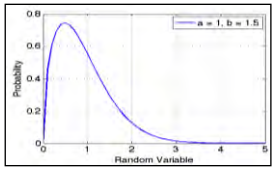
Optimum EIFS:
Lognormal $\mu=0.21*10^{-2}$, $\sigma=0.2\mu$





Smart|DT

EVD Dist



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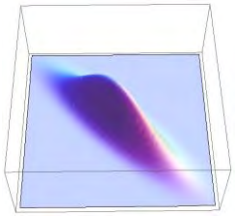

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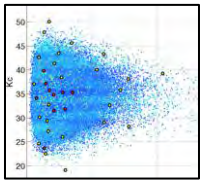

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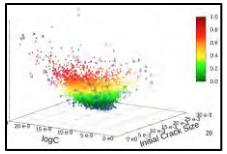

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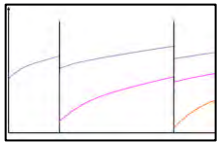

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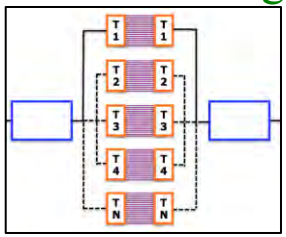

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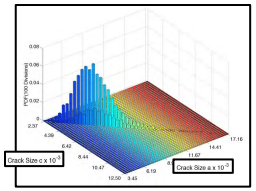

Nasgro interface

Afgrow interface w COM

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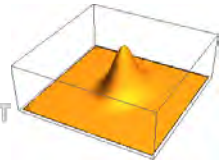

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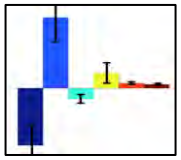

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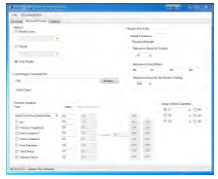

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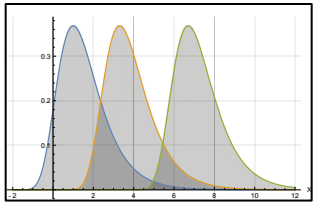

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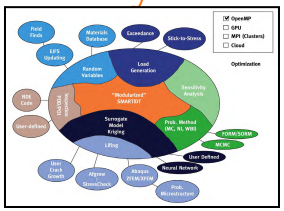
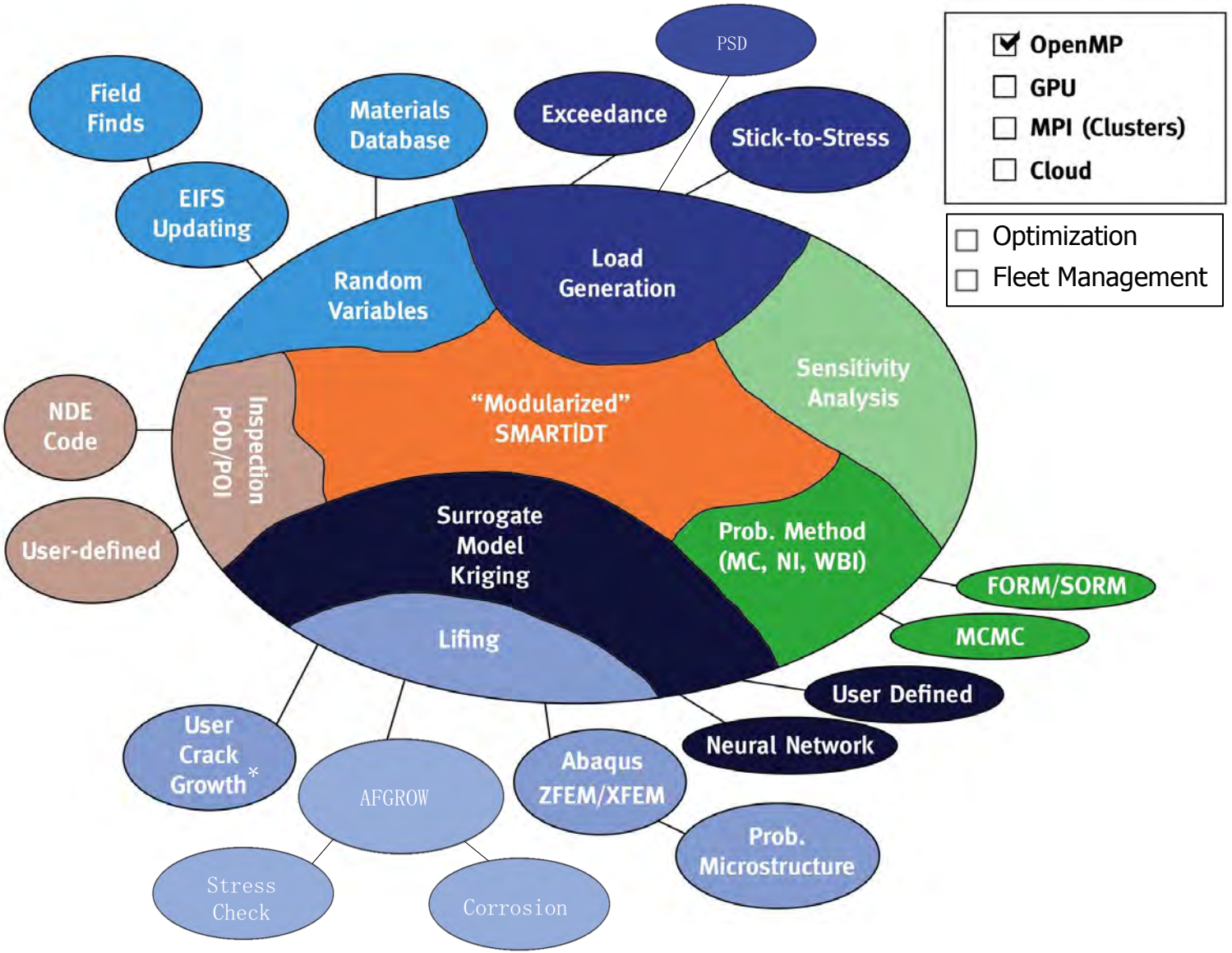


Scriptable

MSD

GPU MPI/Cloud

Plays well with Others



Potential Future Efforts

- MSD
  - Expand to risk assessment method to structures with MSD
- Play well with others
  - Python scripts and/or COM enabled
- Provide flexibility for future enhancements
  - User access to algorithms (modularization and COM-enable software)
- Take advantages of full range of computer capabilities
  - Multithreading, {GPU, MPI, Cloud, Intel Mic}

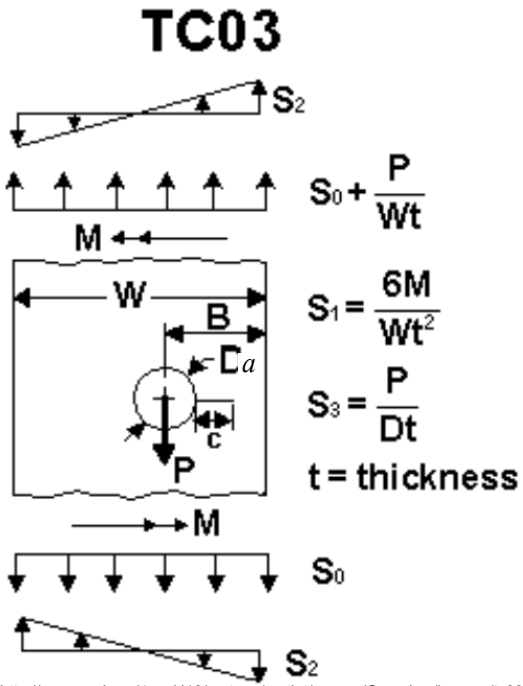
Example Problem

Hypothetical high performance single-engine airplane with a maximum take-off-weight of 4,000 pounds

Variable	Value
Usage	Single Engine Unpressurized Basic Executive Usage
Design LLF Maneuver	3.8, -1.52
Design LLF Gust	3.155, -1.155
Ground Stress (psi)	-4,550
One-g stress (psi)	7,100
Flight Length and Velocity Matrix	
Flight Length and Weight Matrix	
Average Velocity (Vno/Vmo (Knots))	165

Dur/Wei		0.80	0.85	0.90	0.95	1.00
0.50:	0.05	0.00	0.00	0.00	0.20	0.80
0.60:	0.05	0.00	0.00	0.00	0.20	0.80
0.70:	0.10	0.00	0.00	0.00	0.15	0.85
0.80:	0.15	0.00	0.00	0.00	0.15	0.85
0.90:	0.20	0.00	0.00	0.00	0.10	0.90
1.00:	0.25	0.00	0.00	0.00	0.10	0.90
1.10:	0.15	0.00	0.00	0.00	0.05	0.95
1.20:	0.05	0.00	0.00	0.00	0.05	0.95

NI – NASGRO 5 RVs

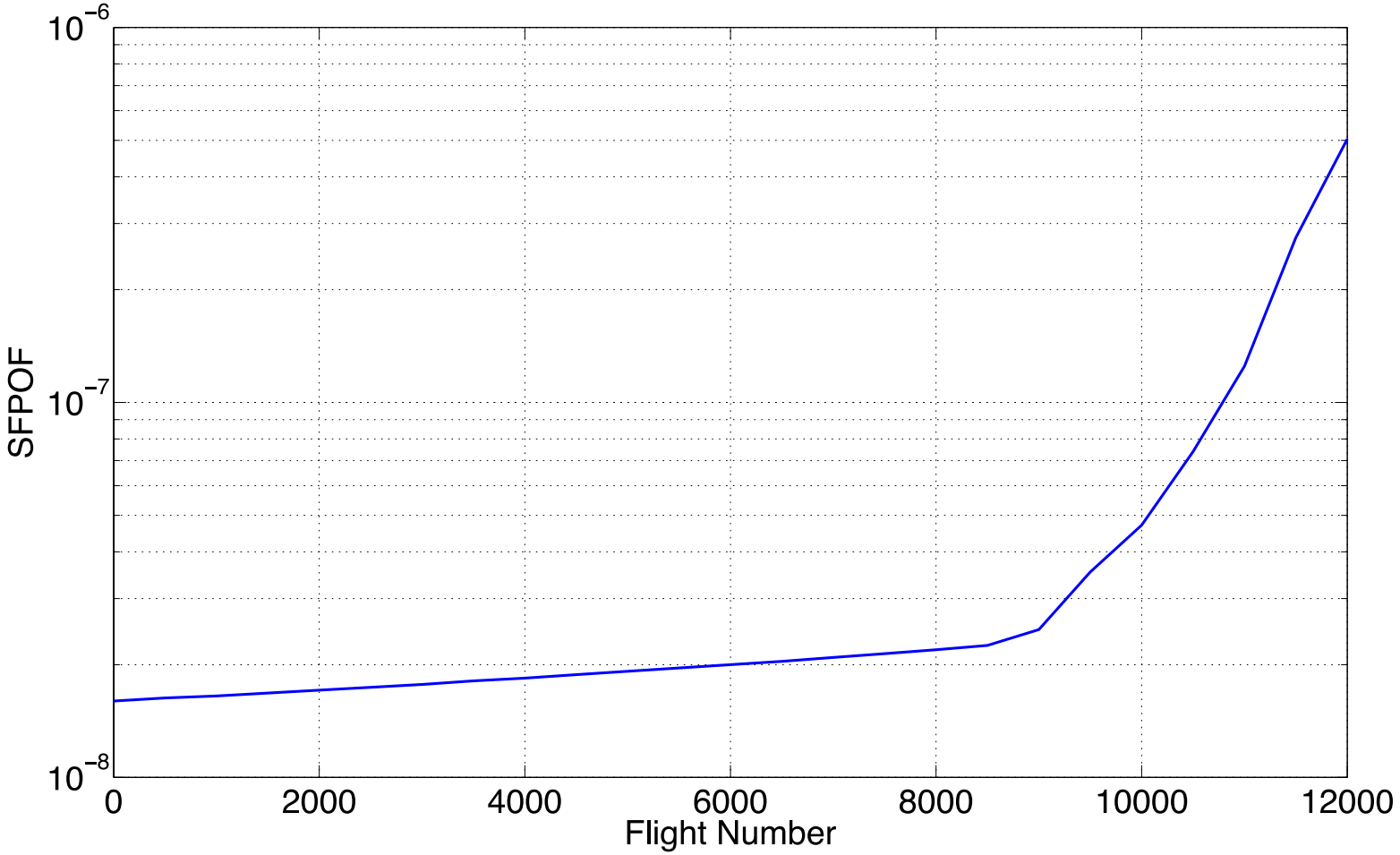


Source: http://www.swri.org/4org/d18/mateng/matint/nasgro/Overview/images/tc03.bmp

	Random Variables	Distribution	Parameters
a_0	Initial Crack Size	Lognormal	Mean = 0.05 in Standard deviation = 0.005 in
K_c	Fracture Toughness	Normal	Mean = 30 ksi√ in Standard deviation = 3.0 ksi√ in
P_C	Log_{10}(Paris C)	Normal	Mean = -8.1 Standard deviation = 0.142
D	Hole Diameter	Normal	Mean = 0.15625 in Standard deviation = 0.0052 in
ED	Hole Offset	Normal	Mean = 2.5 in Standard deviation = 0.0625 in
s_{max}	Maximum Stress	Gumble	Location = 12.35 Scale = 1.66 Shape = 0.023

	Deterministic Variables	Value
m	Paris m	2.7
s_y	Yield Stress	50
s_u	Ultimate Stress	70
B	Hole offset	2.5 in
W	Width	10.0 in
t	Thickness	0.09 in

Converged Results



Acknowledgements

- Probabilistic Damage Tolerance-Based Maintenance Planning for Small Airplanes, Sep. 2009-Aug. 2012, Federal Aviation Administration, Grant 09-G-016
- Probabilistic Fatigue Management Program for General Aviation, Sep. 2012-Aug. 2016, Federal Aviation Administration, Grant 12-G-012
  - Sohrob Mattaghi (FAA Tech Center) – Program Manager
  - Michael Reyer (Ks City) - Sponsor

Thank you!!

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