Building Aerodynamic Databases Using Enhanced Kriging Surrogate Models

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Outline

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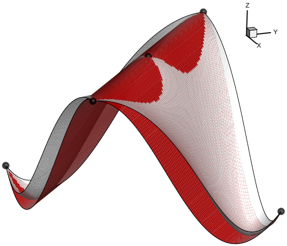
Introduction and Motivation I

- **Analysis:**
  - Theory
  - Experimentation
  - Computation
- **Advancements:**
  - Hardware (processor speed, multi-core systems)
  - Software (parallel programming)
  - Algorithms and other tools (sophisticated methods)
- **Optimization:**
  - Many design iterations – can be very expensive
  - Highly coupled with several disciplines
  - Time consuming to do physical testing and infeasibility

- **Deficiencies:**
  - Computational power (we are at tera/peta flops)
  - Storage (thousands of gigabytes)
  - Numerical errors (discretization, round-off etc.)
- **How to alleviate computational burden?**
  - Surrogate models / Meta models/ Response surfaces



Surrogate Model

Approximation of the exact function using interpolation and/or extrapolation

Introduction and Motivation III

- **Some Applications:**
  - Design Optimization
  - Uncertainty Quantification
  - Aero-database creation
- **Some noteworthy works:**

NASA

- Heavy Lift Launch Vehicle: Ares V
- Reusable Launch Vehicle: X-34

$C^2A^2S^2E$ – DLR

- "Digital Flight" (full flight simulation)

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Training Point Selection

Domain based sampling

- Monte-Carlo
- Latin Hypercube
- Delaunay Triangulation

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Domain based sampling

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- Latin Hypercube
- Delaunay Triangulation

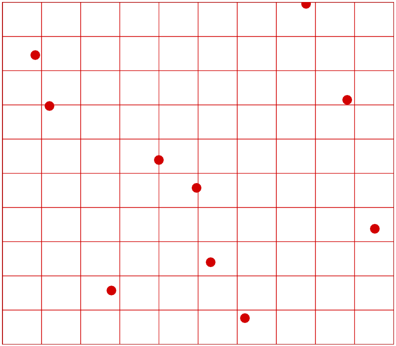
Response based (adaptive)

- Distance / Function values / Gradients / Physics

Monte-Carlo Sampling

Monte-Carlo

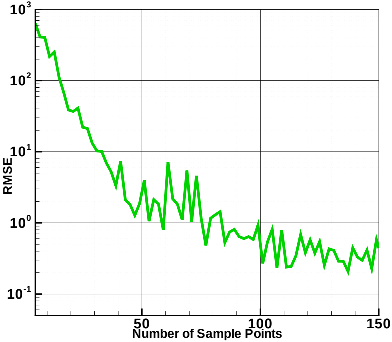
- Random number generator
- Very simple to program
- No control over locations



Latin Hypercube

- McKay - while designing computer experiments
- Equal probability
- N^M bins in the design space
- No two points lie in the same bin

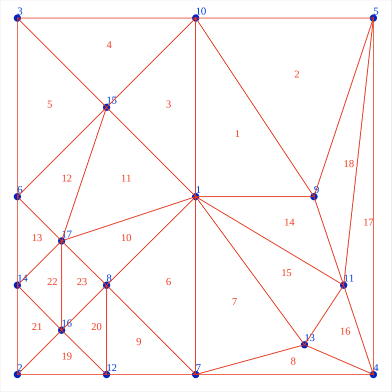
Latin Hypercube Sampling



Typical convergence history

- Random fluctuations
- Each data point is expensive to obtain
- Waste of computational time
- Need for monotonicity

Delaunay Triangulation



Delaunay Triangulation

- Geometrical method
- Split into hyper triangles
- Poor scaling to higher dimensions

Kriging Surrogate

- Originated in geological statistics
- Predicts the function by stochastic processes
- Highly non-linear and multi-modal functions
- Uses spatial corr. between $F-F$ data points
- The basic formulation of Kriging is given as,

$$\tilde{f} = f(x)^T\beta + Z(x)$$

$\rightarrow f(x)^T$ models the mean behavior using a regression model
$\rightarrow Z(x)$ models the local variation from the mean behavior using a Gaussian process

Multivariate Interpolation and Regression

- Based on Taylor series expansion
- Mathematically,

$$\tilde{f} = \sum_{i=1}^{N_v} a_{vi}(x) f(x_{vi}) + \sum_{i=1}^{N_g} a_{gi}(x) \nabla f(x_{gi})$$

  - N_v, N_g is the number of function and func-grad data points
  - a_{vi} and a_{gi} are the basis functions
  - f and ∇f are the function f and gradient values
- **Tunable parameters:** Taylor order n and others

Choice of local and global surrogate

	Kriging	MIR

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Our theme: Use MIR to guide global Kriging

Adaptive Training Point Selection

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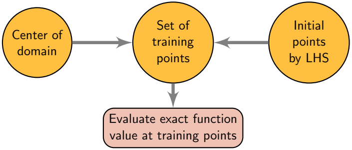

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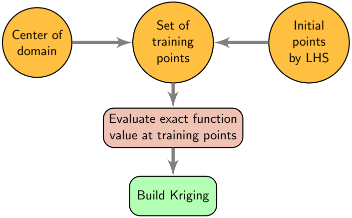

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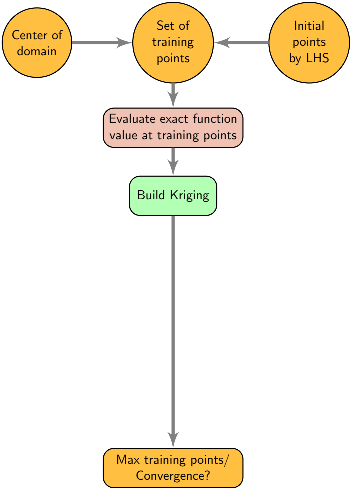

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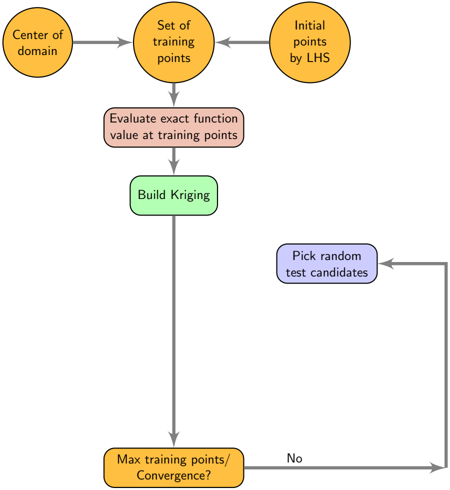

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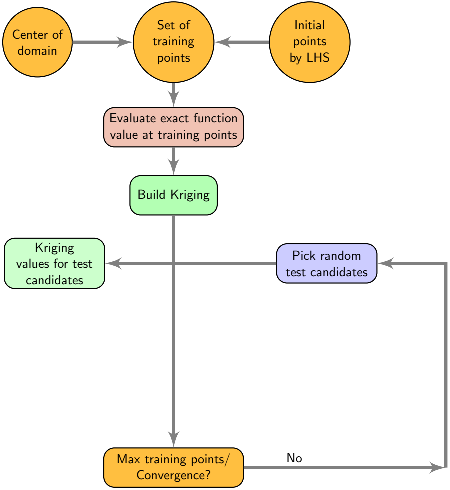

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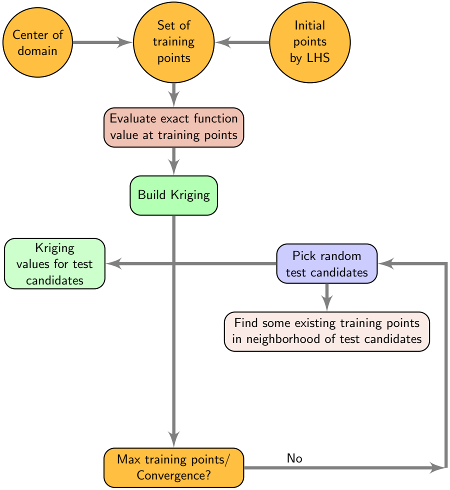

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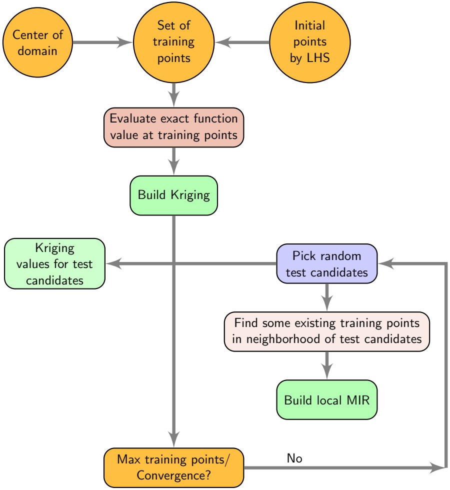

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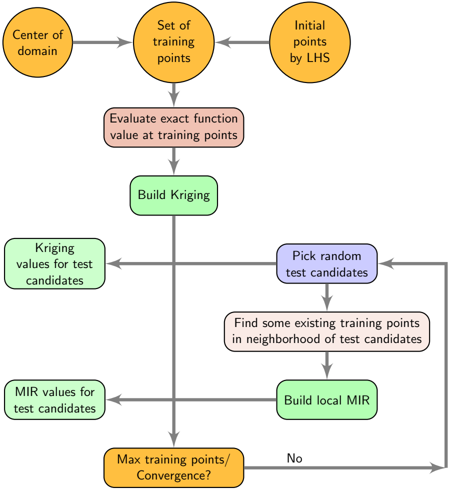

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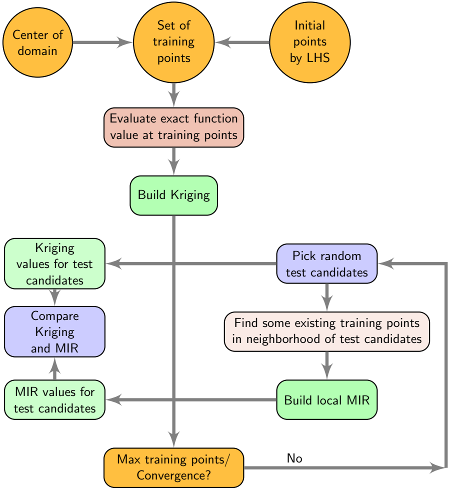

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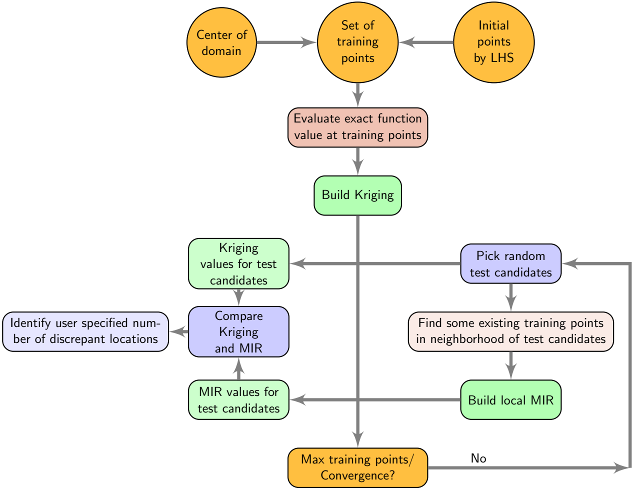

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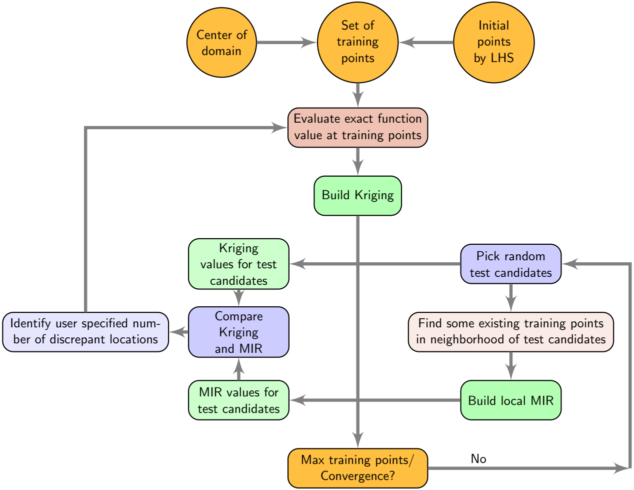

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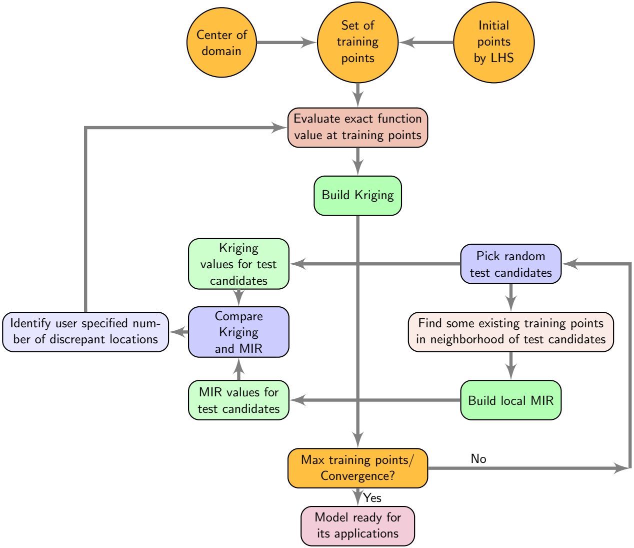

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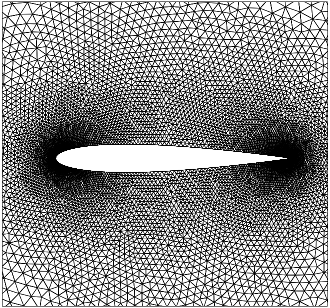
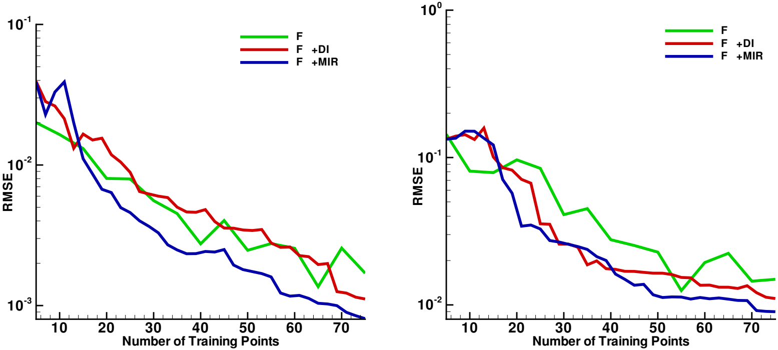
Test Case



Problem Setup

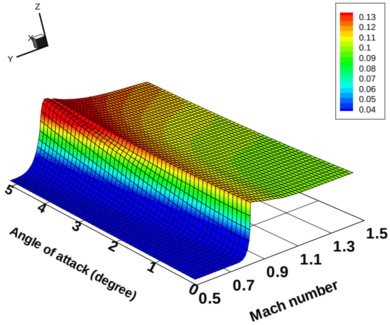
- NACA0012 airfoil
- Eulerian flow solver
- Cell-centered second-order accurate finite-volume approach
- $0.5 < M < 1.5$ and $0^\circ < \alpha < 5^\circ$
- Fine mesh $19,548$ elements
- Coarse mesh $4,433$ elements

Convergence History



Drag Lift

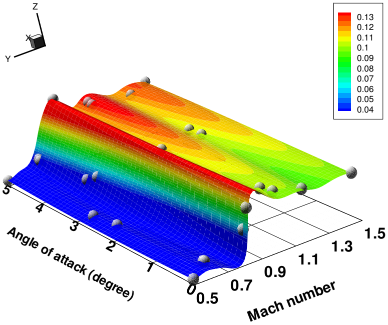
Exact Drag Database



Exact Drag Database

- Solves Euler Equations (Inviscid)
- Cartesian mesh - α vs. M
- 2601 nodes
- Computationally expensive

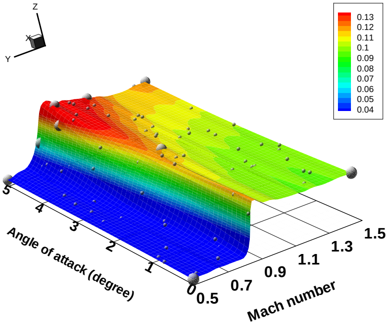
Kriging Drag Database - High Fidelity Model



Kriging Drag Database

- 25 Euler evaluations
- Fine mesh 19,548 elements
- Adaptive sampling strategy
- Not computationally expensive
- Nicely captures transonic behavior

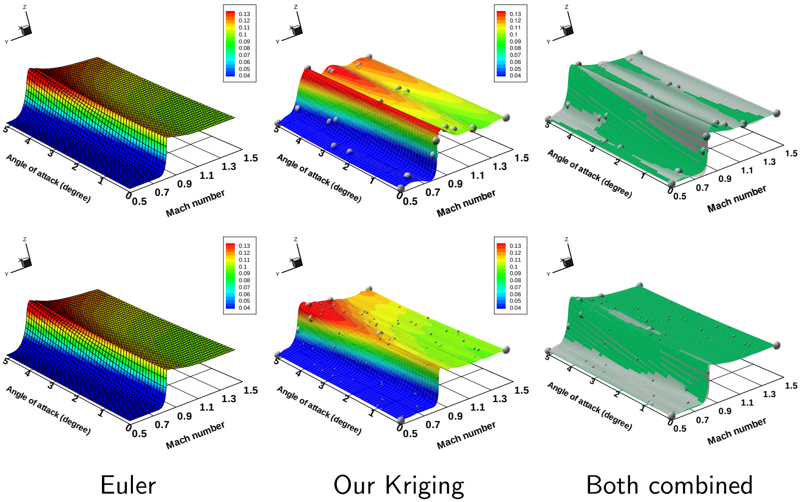
Kriging Drag Database - Variable Fidelity Model



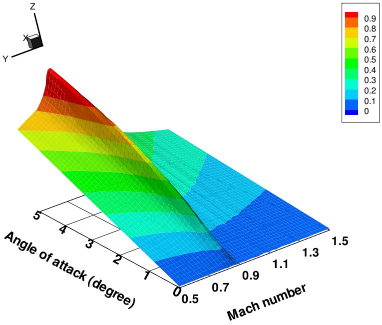
Variable Fidelity

- 9 High fid. training points adaptively
- Fine mesh 19, 548 elements
- 64 Low fid. training points via LHS
- Coarse mesh 4, 433 elements

Drag Database



Exact Lift Database



Exact Lift Database

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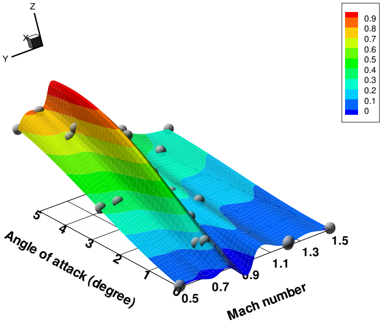

Kriging Lift Database

- 25 Euler evaluations
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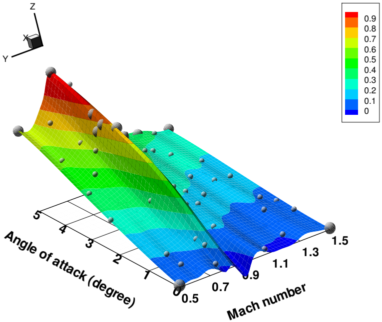
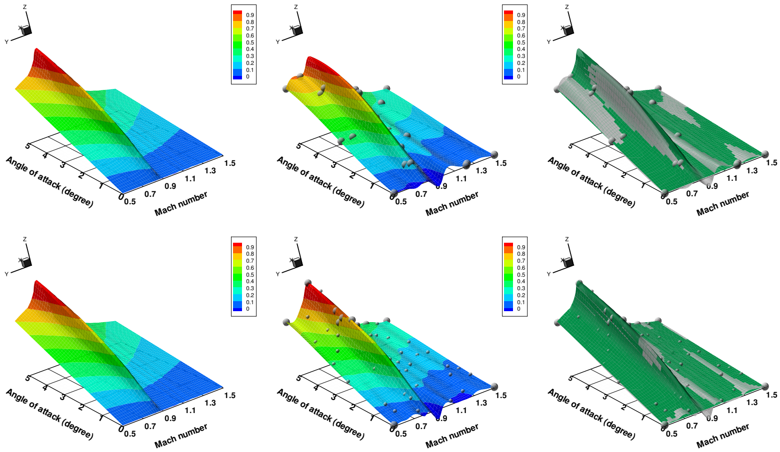


Variable Fidelity

- 15 High fid. training points adaptively
- Fine mesh 19,548 elements
- 40 Low fid. training points via LHS
- Coarse mesh 4,433 elements

Lift Database



Euler | Our Kriging | Both combined

Observations

RMSE comparisons for Kriging models

RMSE	High-fidelity	Variable-fidelity

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RMSE comparisons for Kriging models

RMSE	High-fidelity	Variable-fidelity
Drag Coefficient	0.45868×10^{-2}	0.38118×10^{-2}

Observations

RMSE comparisons for Kriging models

RMSE	High-fidelity	Variable-fidelity
Drag Coefficient	0.45868×10^{-2}	0.38118×10^{-2}
Lift Coefficient	0.32746×10^{-1}	0.27735×10^{-1}

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Conclusions and Potential Applications

- **Conclusions:**
  - Improved convergence of our model

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Acknowledgments

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3. Qiqi Wang – MIR source code

Selected Bibliography

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- Mani, K. and Mavriplis, D. J., "Discrete Adjoint Based Time-Step Adaptation and Error Reduction in Unsteady Flow Problems," AIAA Paper, 2007-3944, 2007.

Any Questions?

Direct Kriging

- Gradient/Hessian terms are included in the formulation
  - Function value estimated using a linear combination of function, gradient and Hessian values
  - Minimize mean-squared-error (MSE) between exact and estimated function value
  - Final form of the gradient/Hessian enhanced direct Cokriging:

$$\hat{\mathcal{J}}(D) = \mu + r^T(D)R^{-1}(Y - \mu I)$$

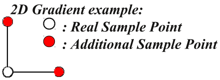
where

$\mu = (I^T R^{-1} I)^{-1}(I^T R^{-1} Y)$	constant mean term
R	correlation matrix between samples
$Y = \left(\mathcal{J}(D_1), \ldots, \left.\frac{d\mathcal{J}}{dD}\right\|_{D_1}, \ldots, \left.\frac{d^2\mathcal{J}}{dD^2}\right\|_{D_1}, \ldots\right)$	vector of sample point information
$r(D)$	correlation between D and samples

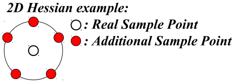
  - Determine required derivatives of correlation function (up to fourth order) with automatic differentiation

Indirect Kriging

- Additional samples are created by using gradient and Hessian information



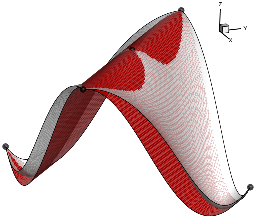
$$\mathcal{J}_{add} = \mathcal{J}(D_i) + \frac{d\mathcal{J}}{dD}\Big|_{D_i} \Delta D$$



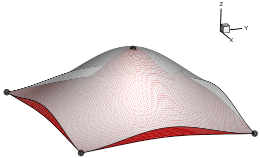
$$\mathcal{J}_{add} = \mathcal{J}(D_i) + \frac{d\mathcal{J}}{dD}\Big|_{D_i} \Delta D + \frac{1}{2}\Delta D^T \left.\frac{d^2\mathcal{J}}{dD^2}\right|_{D_i} \Delta D$$

  - Major parameters: distance between real and additional points ΔD and number of additional points per real sample point
  - Worse R matrix conditioning with smaller distances and larger number of additional points
    $\rightarrow$ Severe trade-offs for these parameters

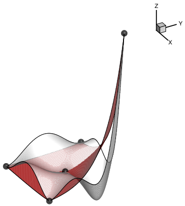
Analytic Test Functions



Cos



Runge

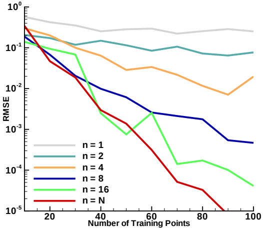


Exponential

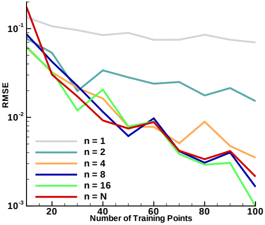
Analytic test functions on hypercube $[-2, 2]^M$

1. Cosine: $f_1(x_1, \ldots, x_M) = \cos(x_1 + \ldots + x_M)$
2. Runge: $f_2(x_1, \ldots, x_M) = \frac{1}{1+x_1^2+\ldots+x_M^2}$
3. Exponential: $f_3(x_1, \ldots, x_M) = e^{(x_1+\ldots+x_M)}$

Effect of Taylor order (2D)



Cosine



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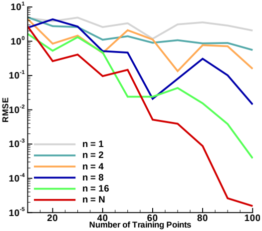
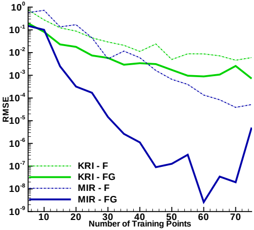


Exponential

Remarks:

- Higher *n*, generally accurate – not always
- Higher *n* mandates more computational time
- Choice of an optimum Taylor order: tedious task

Original Kriging vs. MIR in two dimensions



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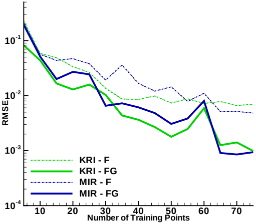

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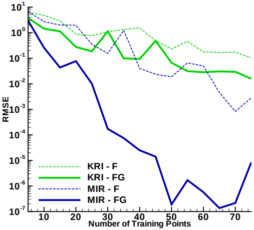

Exponential

Remarks:

- **Advantage:** Rapid convergence
- **Disadvantage:** Computation, tunable parameters