Approaches to Multidisciplinary Design Optimization

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Abstract	
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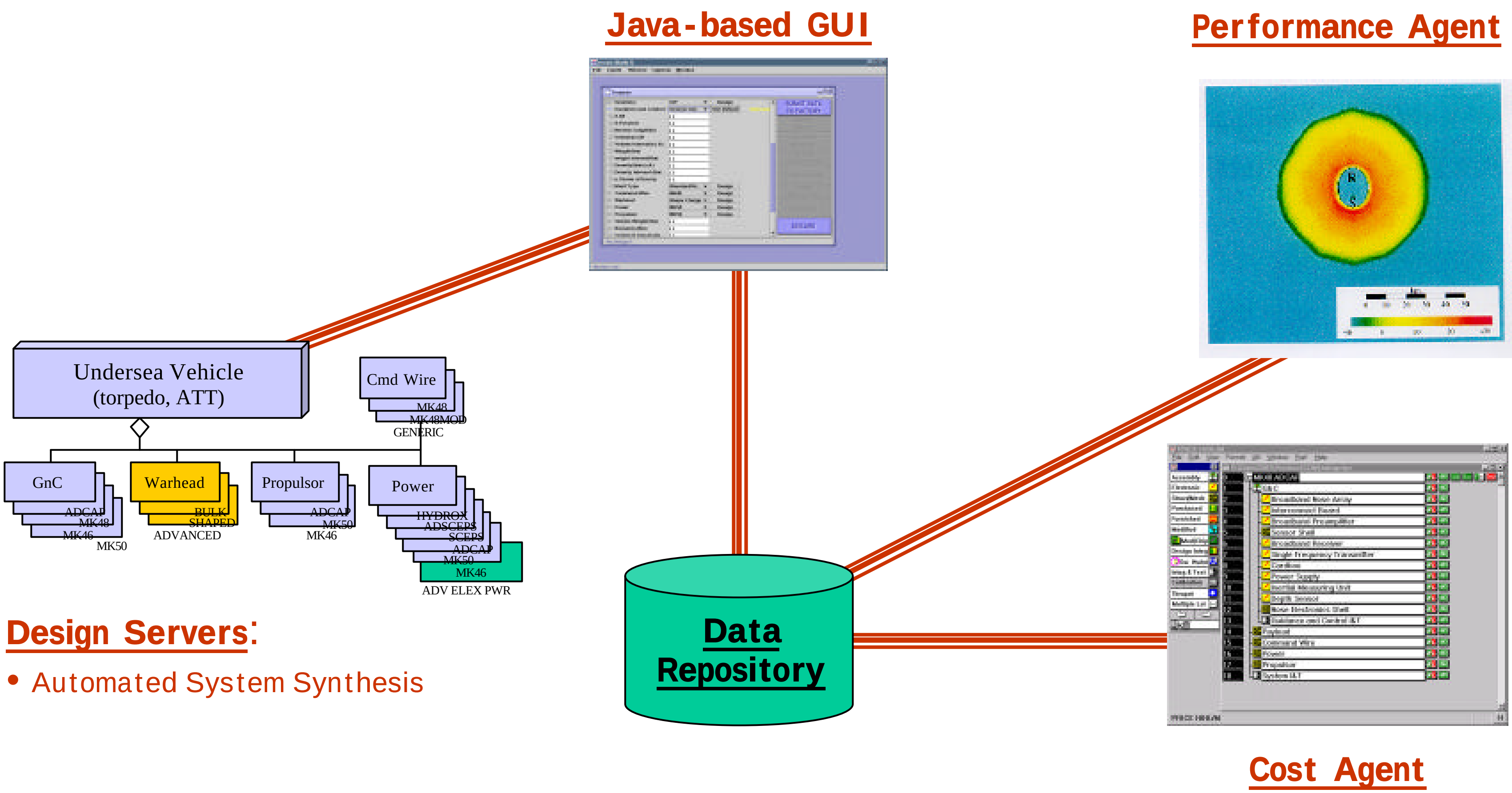
Presentation Overview

- What is multidisciplinary design optimization?
  – Why use it?
  – How is it used?
- Example MDO application
- Computational challenges in MDO
- Example surrogate modeling application

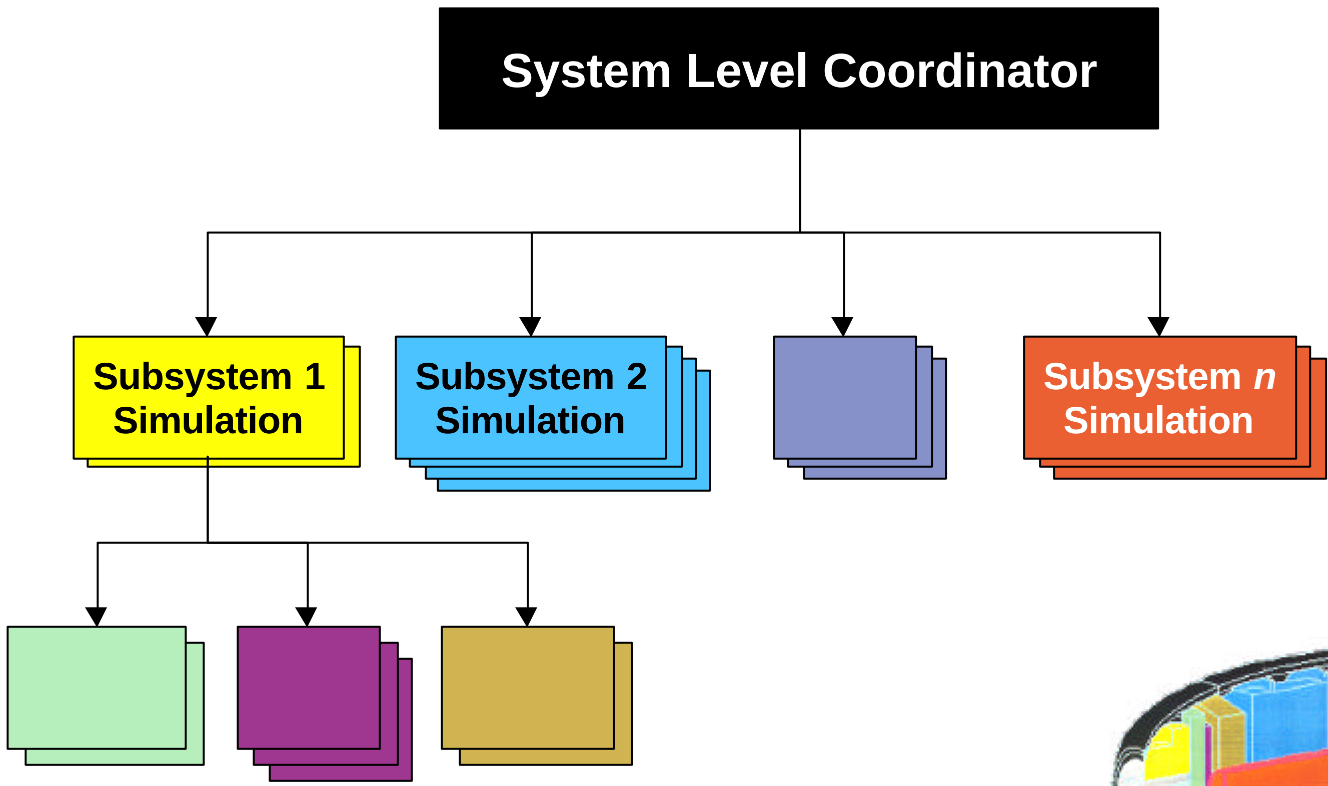
What is MDO?

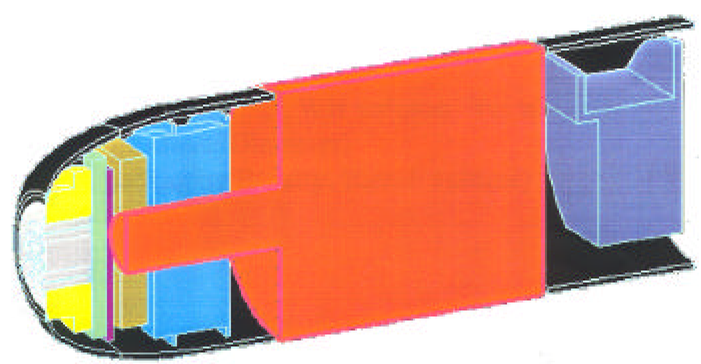
- Multidisciplinary design optimization (MDO):
  - is a methodology for the design of systems in which strong interactions between disciplines motivates designers to simultaneously manipulate variables in several disciplines
  - involves the coordination of multiple disciplinary analyses to realize more effective solutions during the design and optimization of complex systems

Simulation-Based Design Architecture



Design Server Interactions





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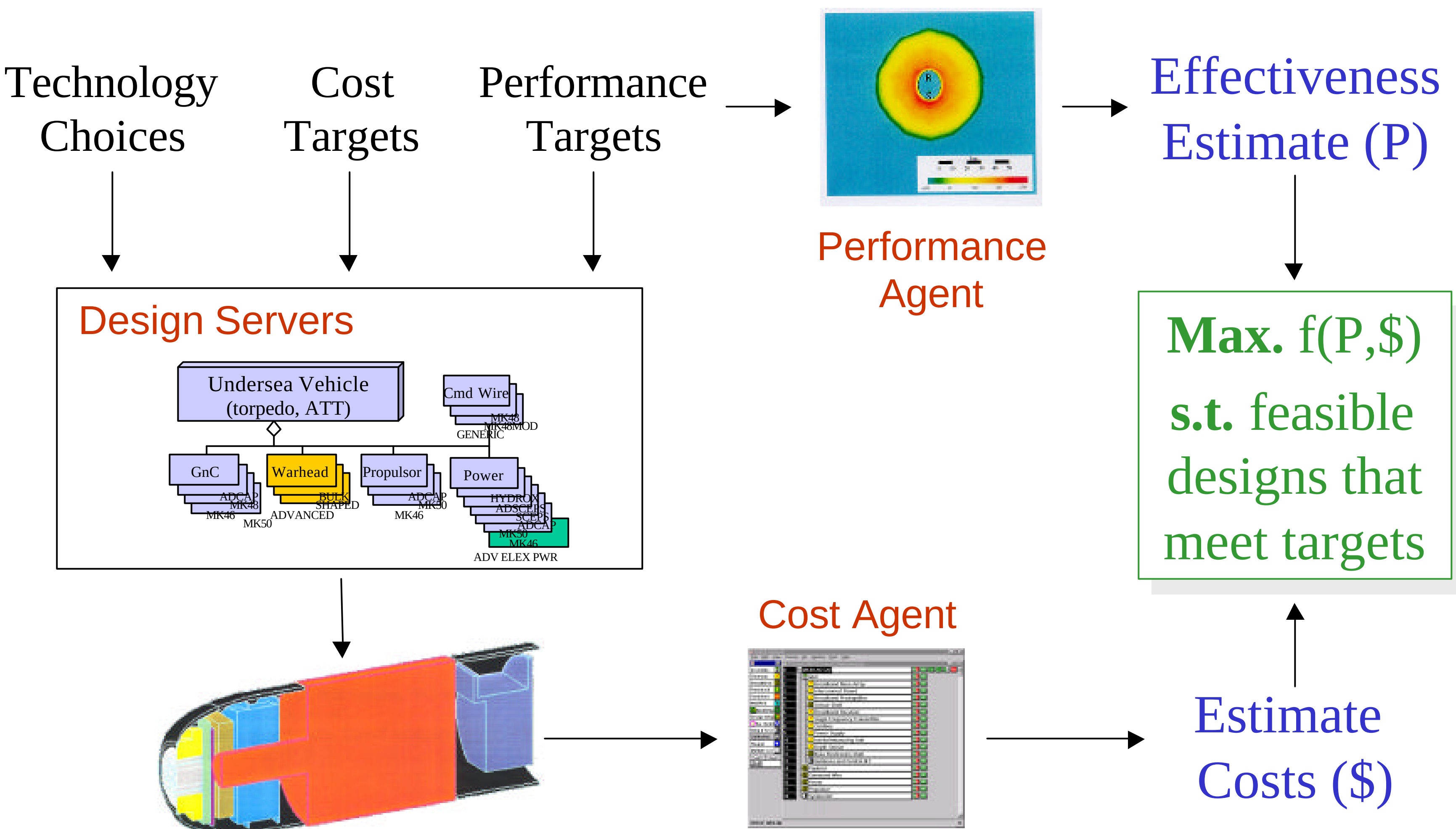
System-level Objective

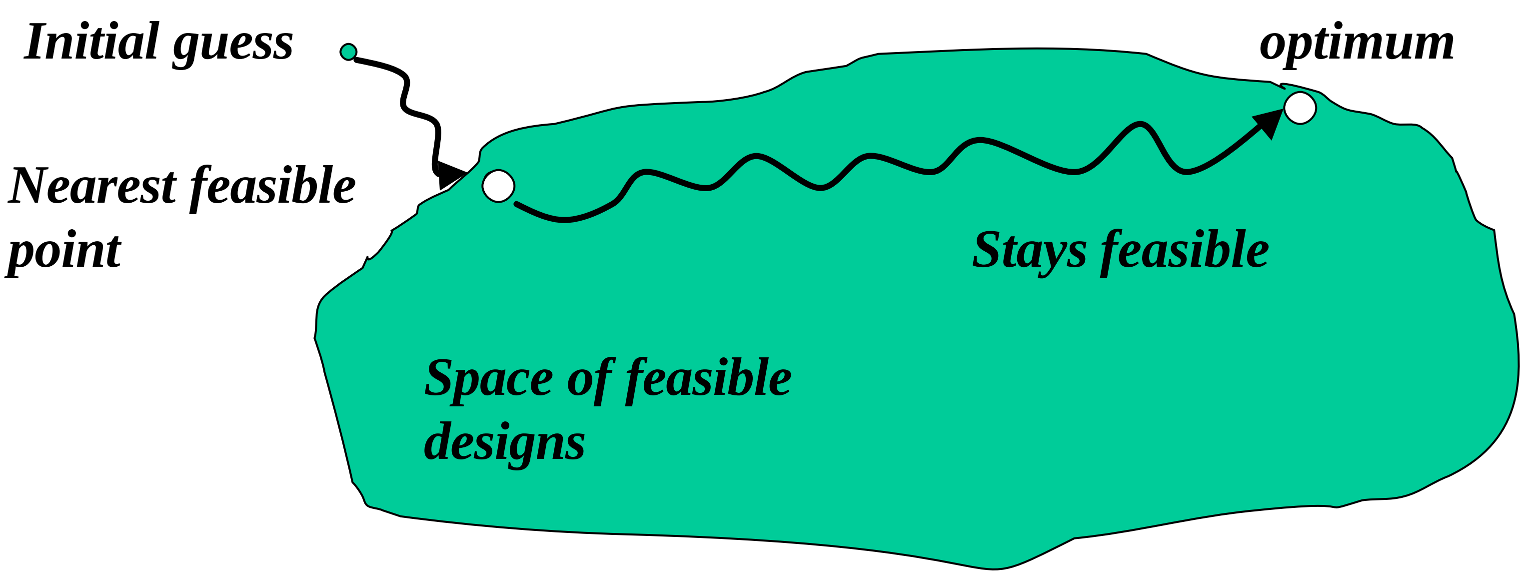


How is it used?

- Using MDO involves:
  - decomposing the system into multiple subsystems or disciplinary analyses
  - developing mathematically models and analyses for:
    - the “parent” system
    - each subsystem and its interactions
  - selecting an appropriate MDO formulation and algorithm
  - solving the MDO problem to generate solutions

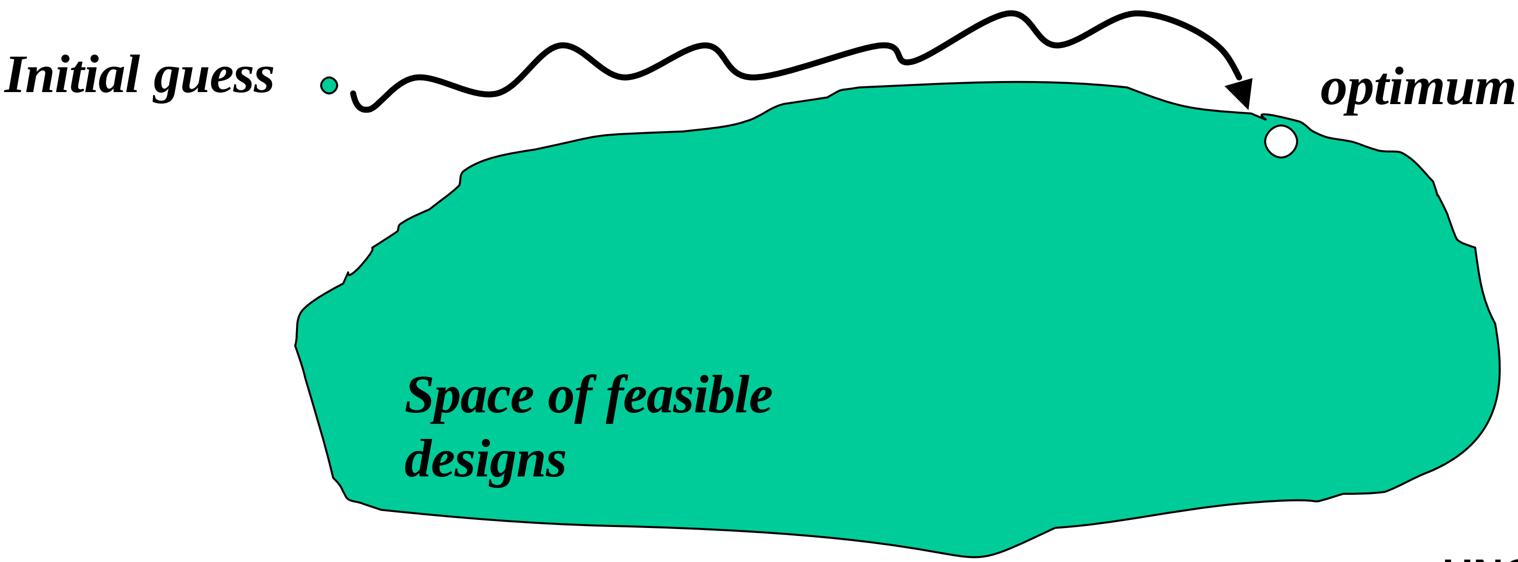
Multiple Discipline Feasible

- Get feasible and stay feasible
- Implies each iteration is a two part process:
  - move to improve design
  - re-establish feasibility



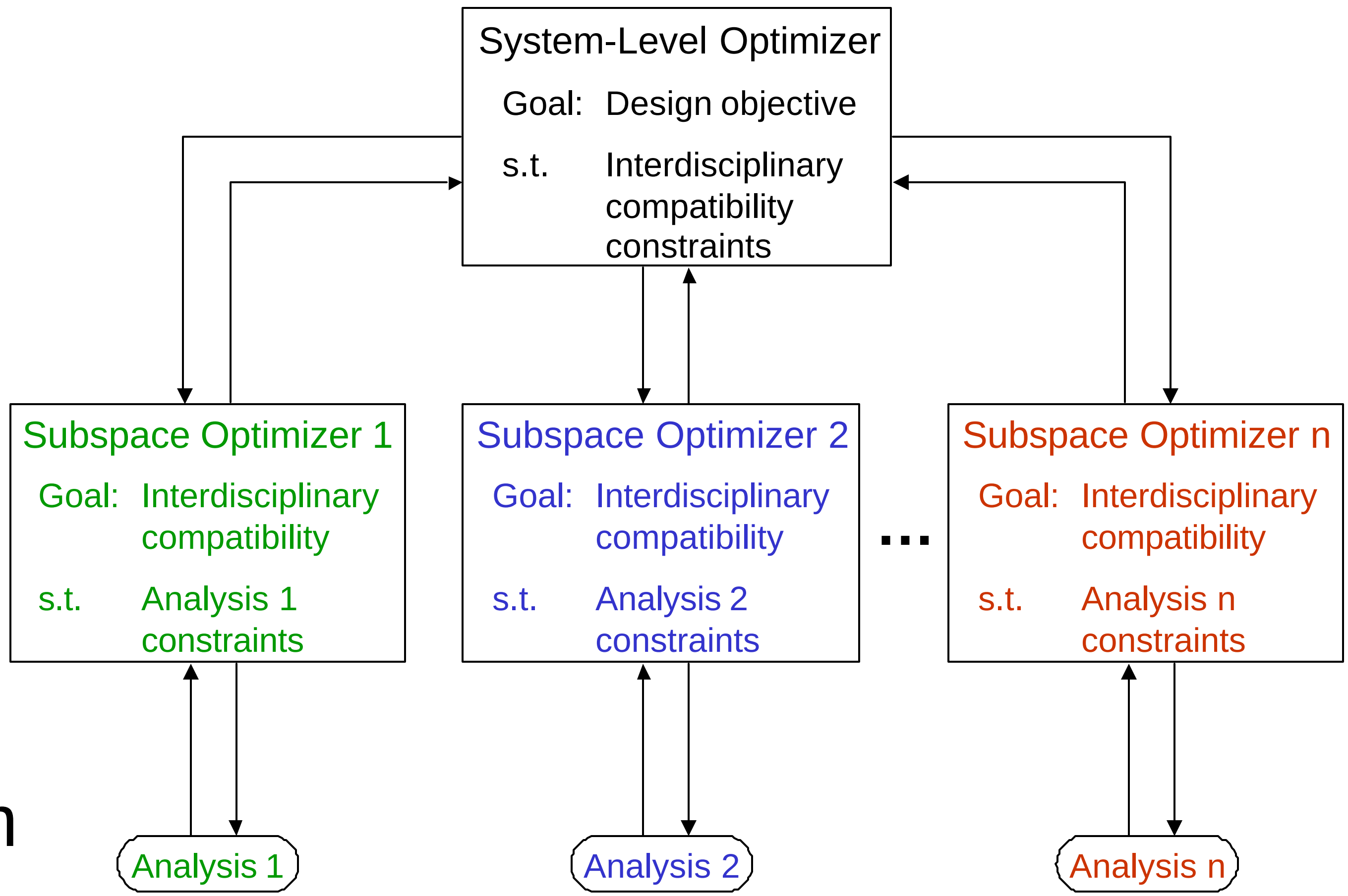
Individual Discipline Feasible

- Go straight to optimum
- Since optimum usually on boundary, not feasible until optimal
  - equivalent to discrepancy = 0



Collaborative Optimization

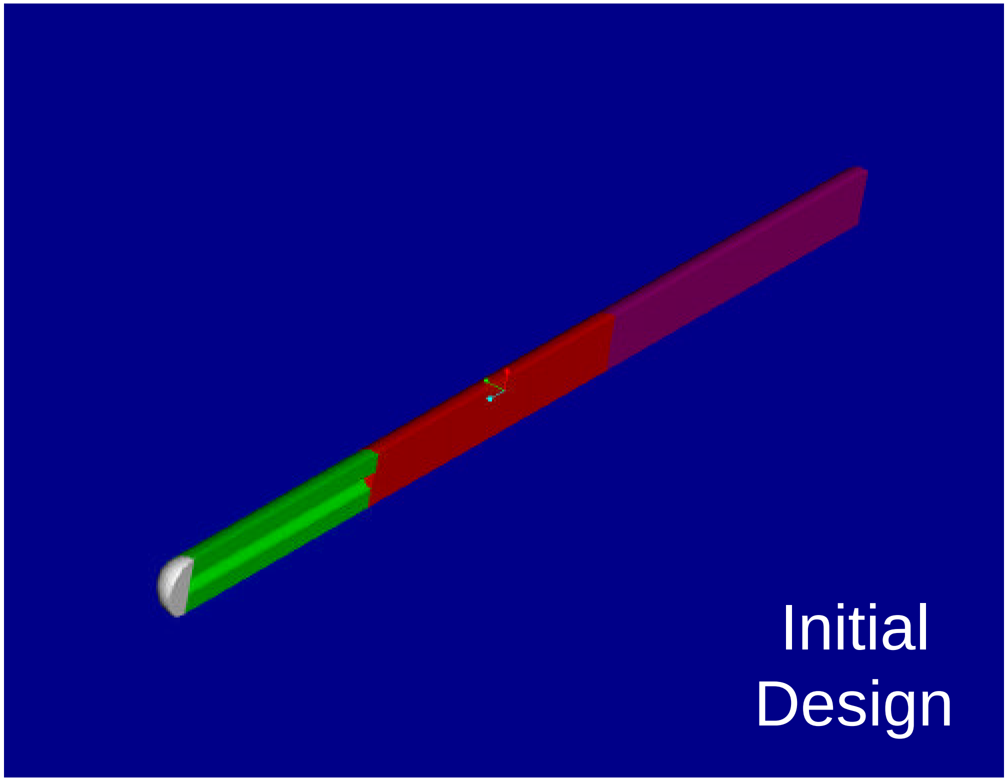
Decompose system into smaller units that can be individually optimized and then synthesized into a system



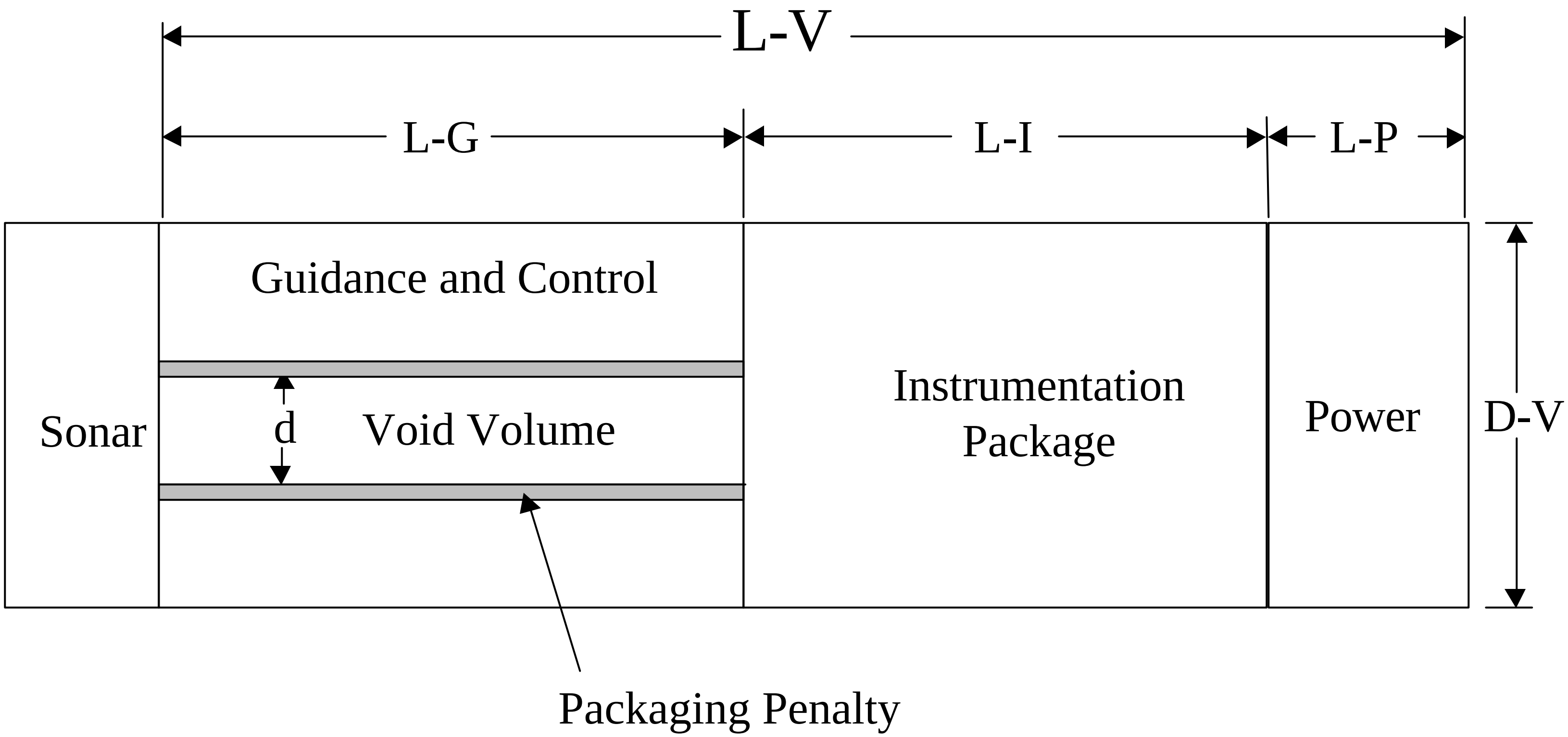
Underwater Exploratory Vehicle

- 4 Subsystems:
  - Guidance & Control
  - Instrumentation
  - Power
  - Propulsion
- Subsystem analyses developed by Erik Halberg (M.S., ME)

- 7 Design Variables:
  - Volumes



Underwater Vehicle Example



Underwater Exploratory Vehicle

L_V, D_V, R

$$\text{Min } P_1(d_8^-) + P_2(d_4^-) + P_3(d_5^- + d_6^- + d_7^-) + P_4(d_1^- + d_2^- + d_3^-)$$

st

$$L_{GC} + L_P + L_I - L_V = 0$$

$$(e^0 - d_E^- + d_E^+)*50/(s^0 - d_S^- + d_S^+) - R = 0$$

$p^0\ dB^0\ \omega^0$

pn^0

$e^0\ hp^0\ sp^0$

s^0

$d_i^-\ d_i^+\ V_{GC}$

$d_B^-\ d_B^+\ V_I$

$d_i^-\ d_i^+\ V_P$

$d_S^-\ d_S^+\ SP$

Guidance & Control

$$\text{Min } \Sigma(d_i^- + d_i^+)\ i = 1,2,3$$

st

$$P(V) + d_3^- - d_3^+ = p^0$$

$$dB(V) + d_2^- - d_2^+ = dB^0$$

$$\omega(V) + d_1^- - d_1^+ = \omega^0$$

Instrumentation

$$\text{Min } d_4^- + d_4^+$$

st

$$Pn(V) + d_4^- - d_4^+ = pn^0$$

Power

$$\text{Min } \Sigma(d_k^- + d_k^+)\ k = 5,6,7$$

st

$$E(V) + d_6^- - d_6^+ = e^0$$

$$HP(V) + d_7^- - d_7^+ = hp^0$$

$$SP(V) + d_5^- - d_5^+ = sp^0$$

Propulsion

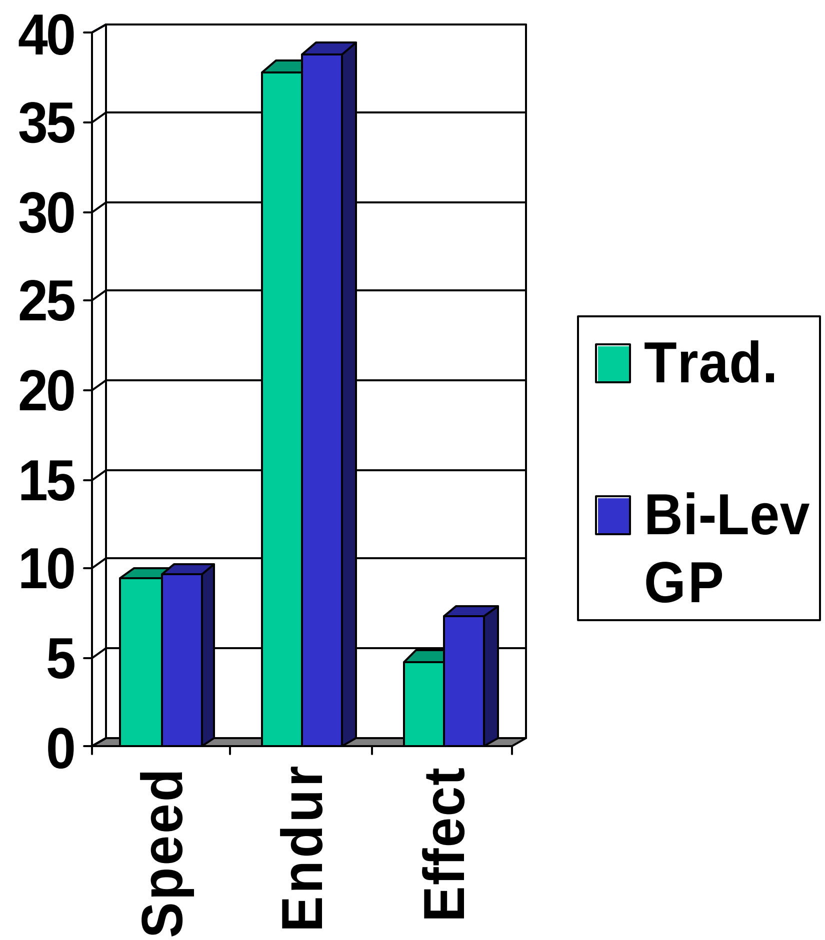
$$\text{Min } d_8^- + d_8^+$$

st

$$S(SP) + d_8^- - d_8^+ = s^0$$

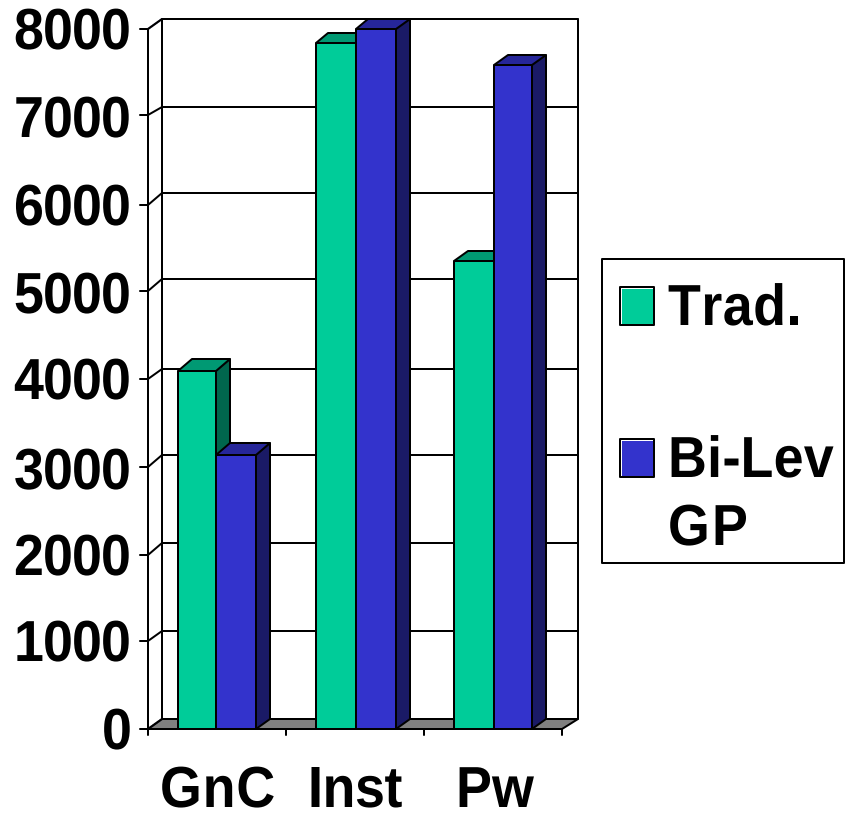
Vehicle Performance

- MDO formulation yields superior performance:
  - Speed
  - Endurance
  - Effectiveness



Vehicle Optimization

- Final Design:
  - Slightly different configurations
- Solution Time:
  - 1 minute vs. 3 hours



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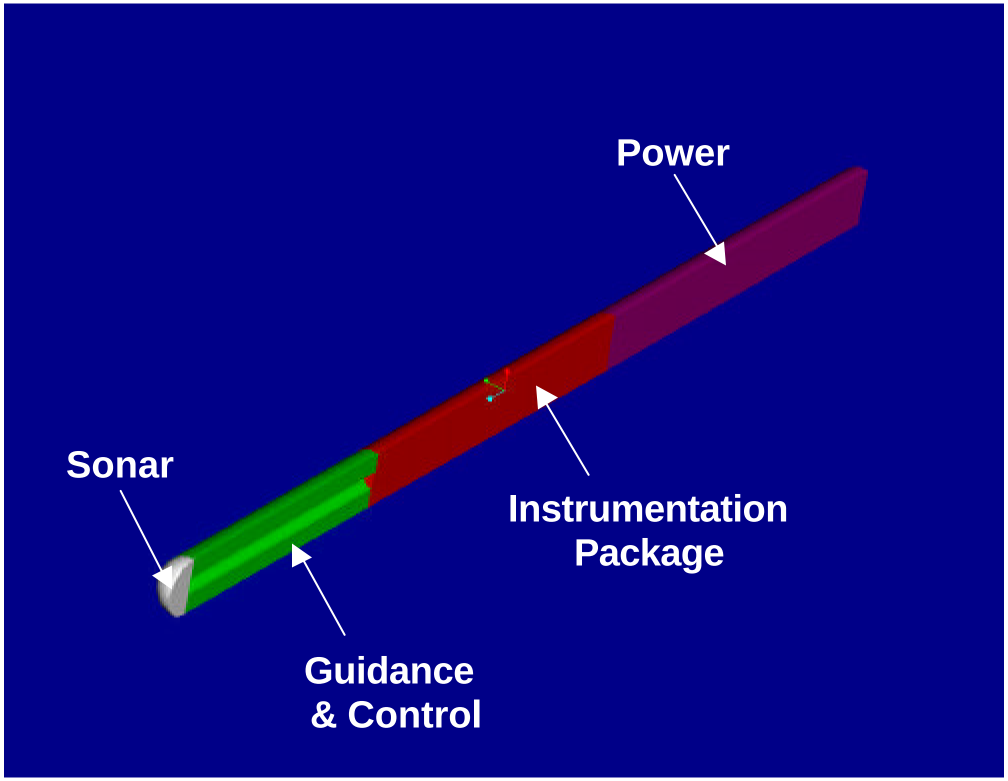
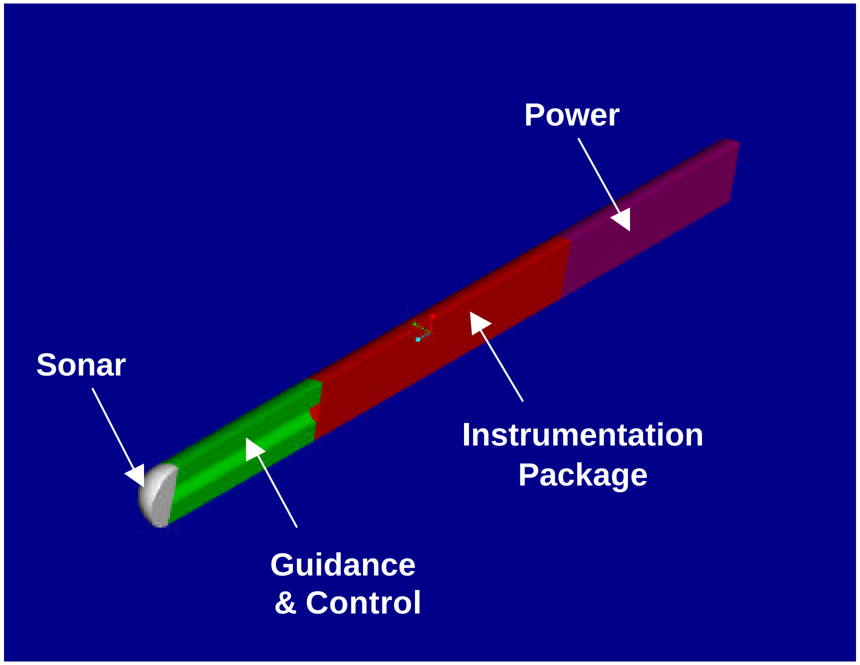
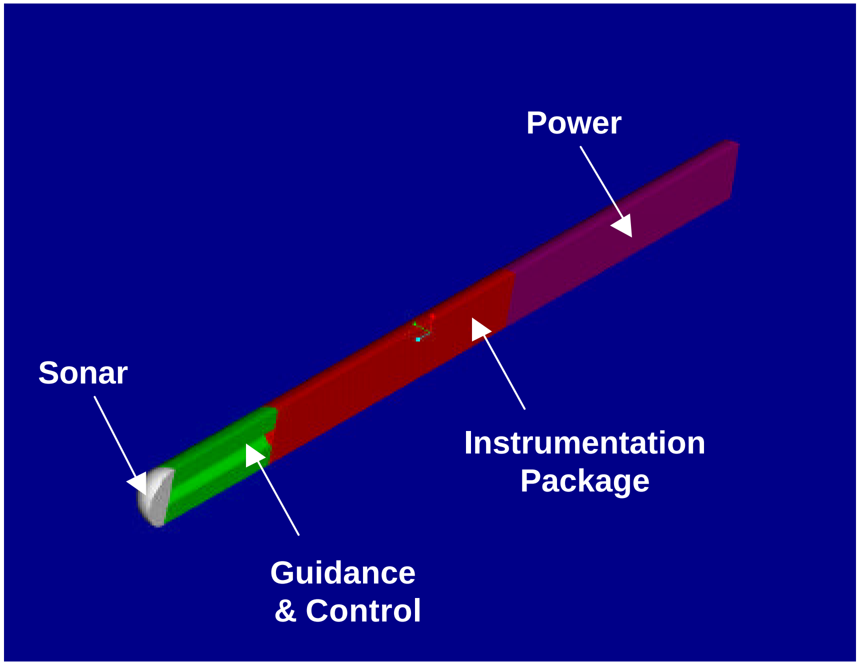
Vehicle Configurations







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Computational Challenges in MDO

- In MDO, computer simulation codes are:
  - often “black-box” in nature
  - discipline-specific
  - composed in different languages (e.g., Fortran, C, Java)
  - distributed, both geographically and on different computer platforms
  - computationally expensive due to fidelity of modeling and need for accurate results

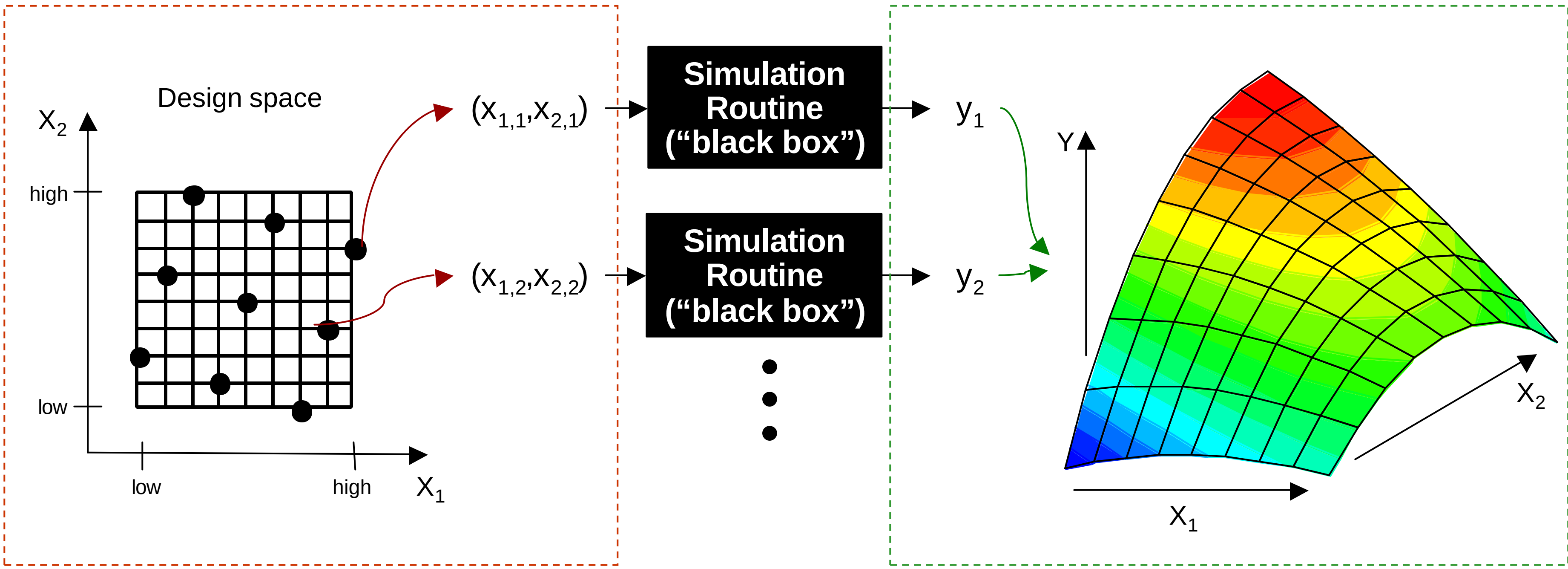
Surrogate Models for MDO

- Surrogate models are fast, simple approximations of computationally-expensive computer simulations and/or analyses
- They provide a “model of a model” which can be used in place of the original computer simulation
- Surrogate modeling can be used to generate “smart objects” that can be used in place of the original analyses and integrated within any SBD infrastructure

Overview of Surrogate Modeling

Generate simulation data using design of experiments capability

Use surrogate modeling capability to construct a "model of the model"



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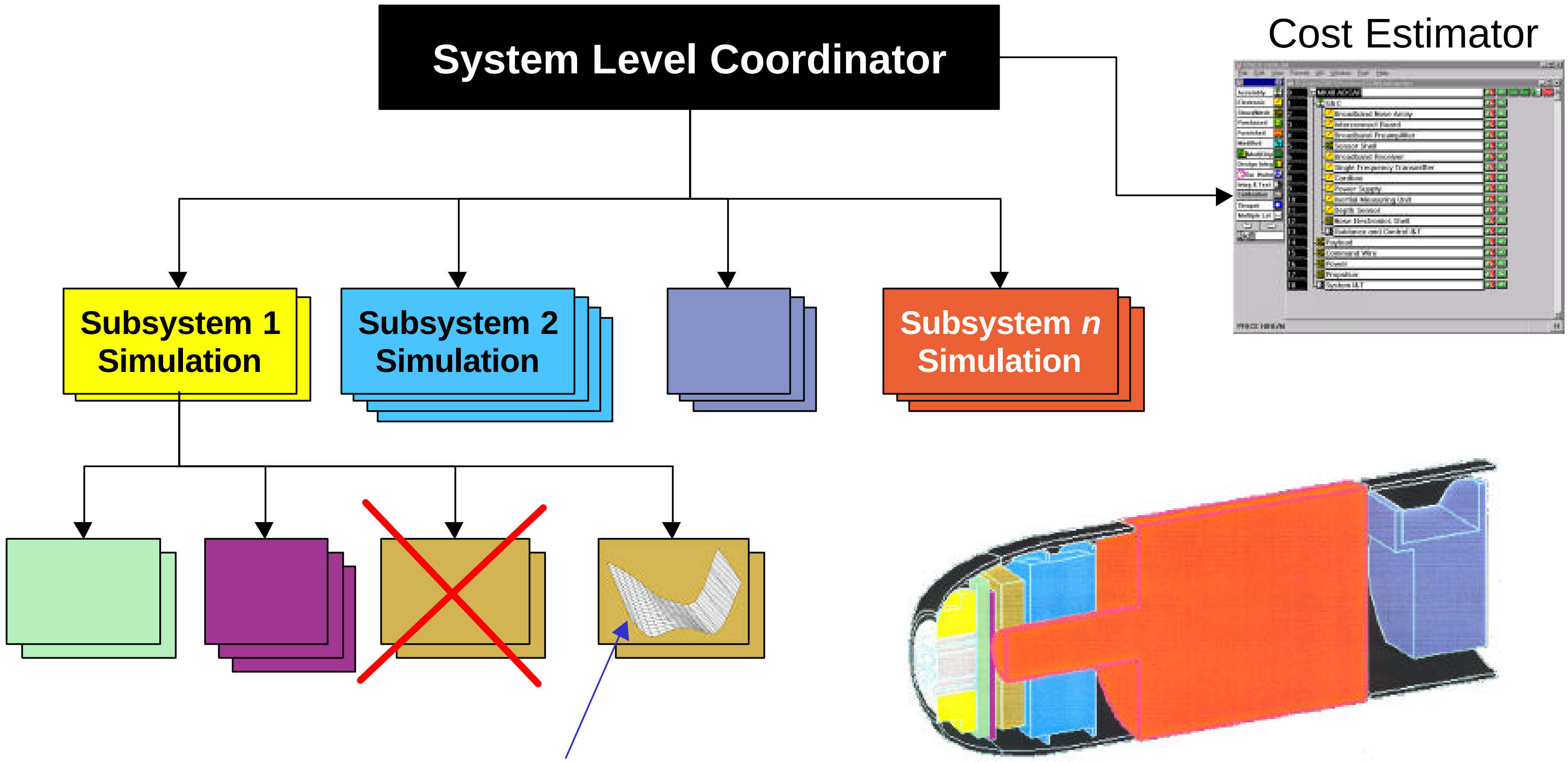
Surrogate Models in MDO

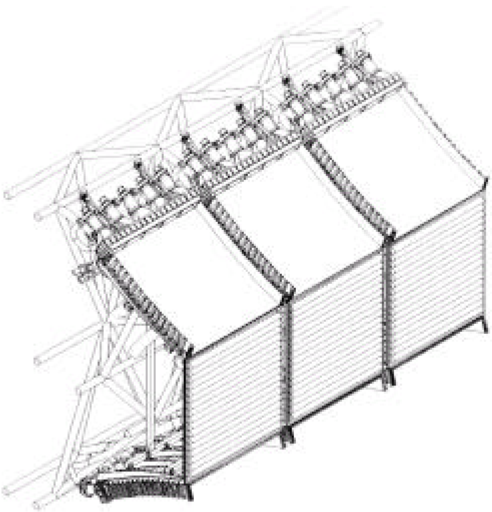


Each sub-system or disciplinary analysis can be replaced by a surrogate model and invoked by the higher-level coordinator

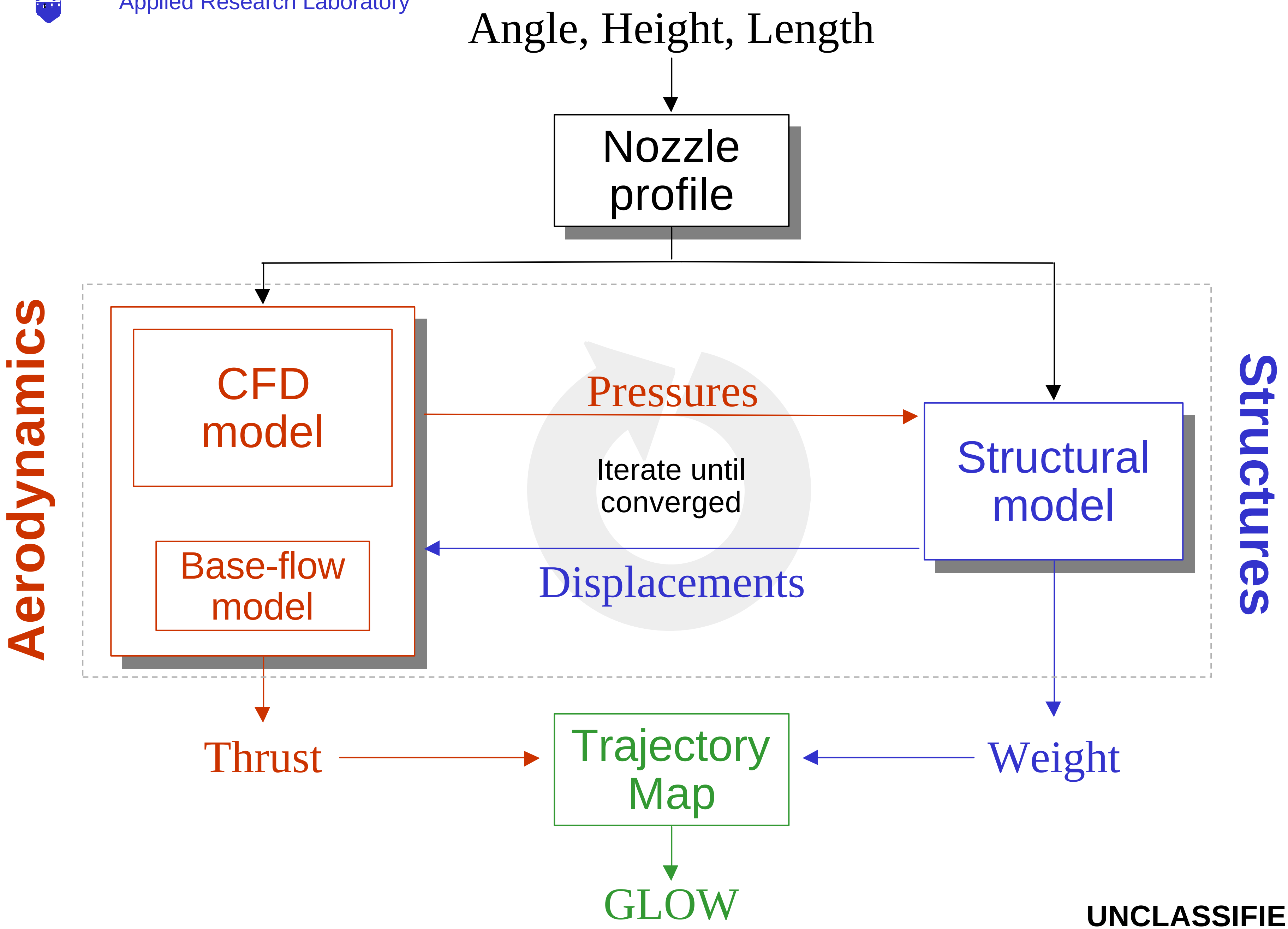
Application: Rocket Nozzle

- Utilize surrogate models to facilitate multidisciplinary design and optimization of an aerospike rocket nozzle for the next generation shuttle

Venture Star RLV



Aerospike Nozzle


Angle, Height, Length
Nozzle profile
Aerodynamics
CFD model
Base-flow model
Pressures
Iterate until converged
Displacements
Structural model
Structures
Thrust
Trajectory Map
Weight
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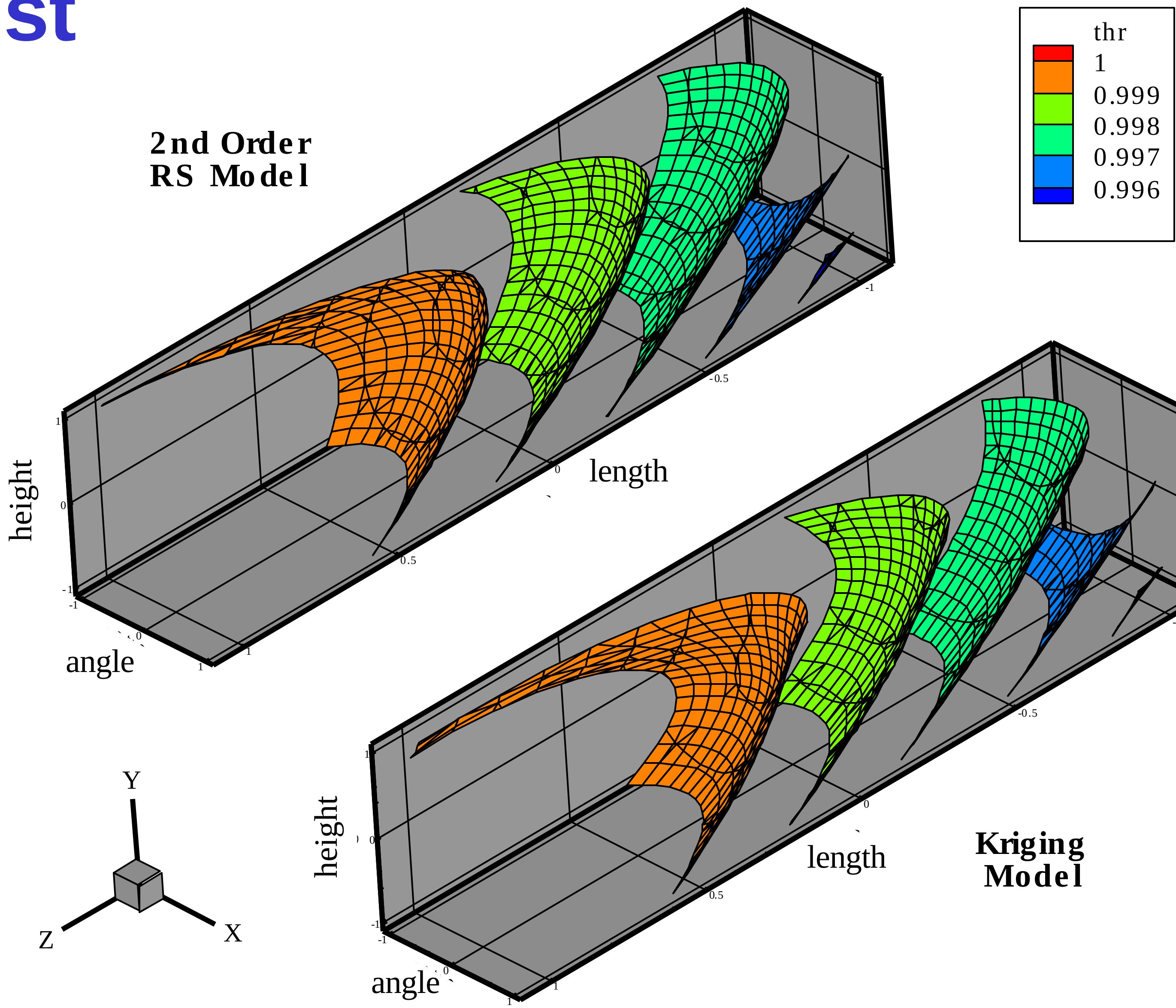
Thrust



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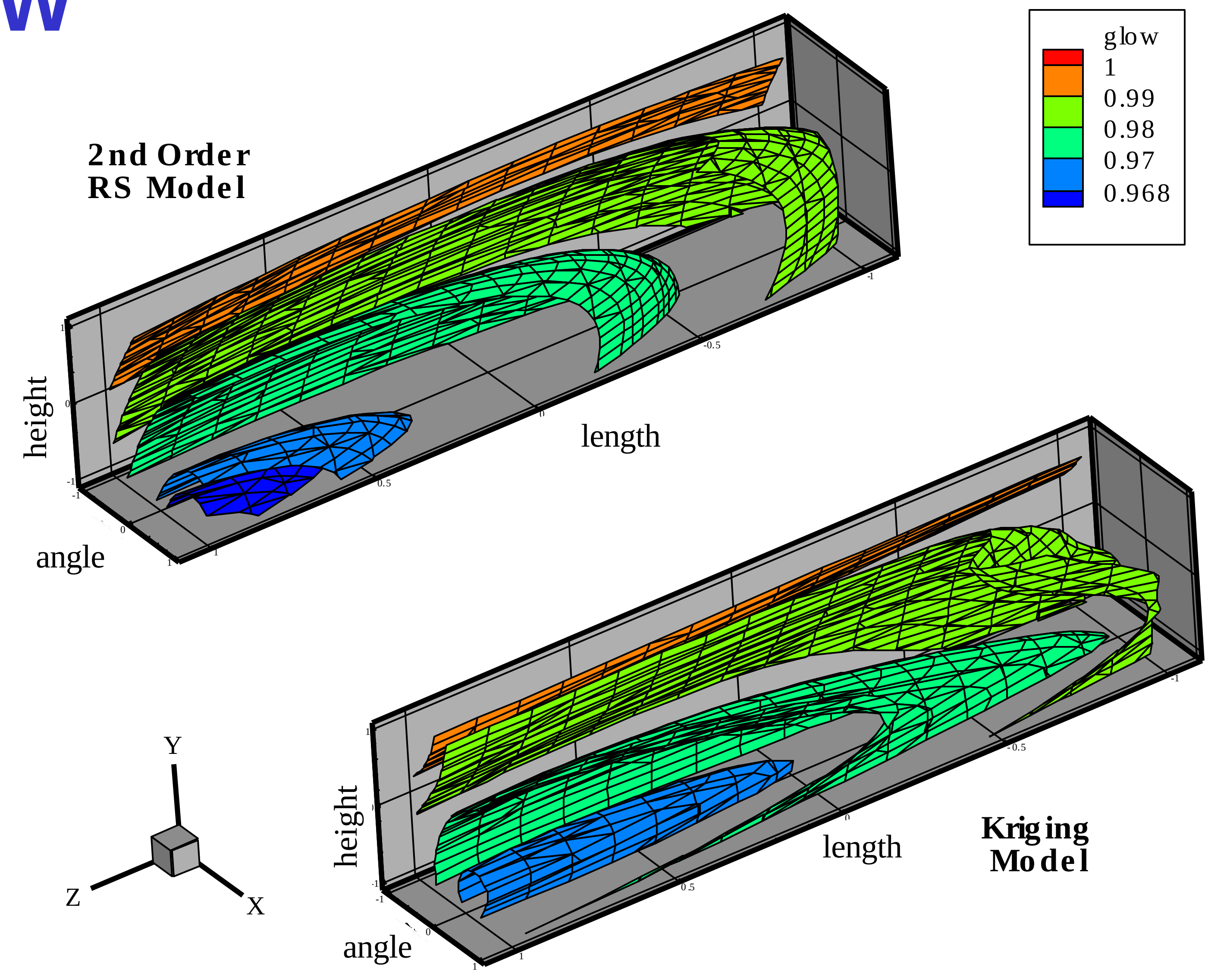

Closing Remarks

- MDO involves the coordination of multiple disciplinary analyses to realize more effective solutions during the design of complex systems

- Surrogate models can be used to address many of the computational challenges associated with MDO

- MDO formulations that incorporate uncertainty are currently being investigated

For Further Reading

- McAllister, C. D. and Simpson, T. W. Multidisciplinary Robust Design Optimization of an Internal Combustion Engine, *ASME Design Technical Conferences - Design Automation Conference (Diaz, A., ed.),* Pittsburgh, PA, September 9-12, ASME, Paper No. DETC2001/DAC-21124.
- McAllister, C. D., Simpson, T. W. and Yukish, M. (2000) Goal Programming Applications in Multidisciplinary Design Optimization, *8th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization,* Long Beach, CA, September 6-8, AIAA, AIAA-2000-4717.
- Simpson, T. W., Mauery, T. M., Korte, J. J. and Mistree, F., "Comparison of Response Surface and Kriging Models for Multidisciplinary Design Optimization," *7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis & Optimization,* AIAA, Vol. 1, 1998, pp. 381-391.
- Koch, P. N., Simpson, T. W., Allen, J. K. and Mistree, F., "Statistical Approximations for Multidisciplinary Optimization: The Problem of Size," *Special Multidisciplinary Design Optimization Issue of Journal of Aircraft,* Vol. 36, No. 1, 1999, pp. 275-286.
- Jin, R., Chen, W. and Simpson, T. W., "Comparative Studies of Metamodeling Techniques under Multiple Modeling Criteria," *8th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization,* Long Beach, CA, AIAA, 2000, AIAA-2000-4801, to appear in *Journal of Structural and Multidisciplinary Optimization*.