Modeling Spacecraft Design Activities as Rugged Fitness Landscapes

Sponsor: DASD(SE)

By
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Overview

Motivation

Problem Description

Design Spaces for Spacecraft System Design – Mars Rovers

Rugged Fitness Landscapes

Predictions and Tuning the Model

Conclusions and Future Work
Motivation

• DoD Digital Engineering Strategy
  — Published June 2018
  — Modernize design, development, operation and sustainment
  — Transform acquisition and implementation
  — Improve speed for critical capability delivery to the warfighter
  — Connected data in a digital environment
Problem Description

• Aerospace and defense projects are some of the most complex engineered systems
  — Expensive and long duration design and development
  — Multidisciplinary Design Analysis and Optimization (MDAO) does not capture all emergent behaviors

• Design models do not capture the impact of:
  — Modes of communication in design and operation
  — Effects of different communication types
  — Correlation of these to design fitness
  — Other coupling and relationships of design

• We need a way to study complex communications and collaboration in these types of projects to assess the impact on system design performance in the new digital engineering environments
Spacecraft System Design

- Describing the fitness of a spacecraft system
  - Define variables to represent the design and the operational environment
  - Use models and abstraction to represent complexity
  - Interaction and coupled or emergent behavior calculated with dependent model variables
  - Levels of decomposition and variable definition impact how well the model represents reality
  - May be impacted by design team organization and task structure

- Example: Mars Rovers
  - Complex spacecraft with specific mission goals
  - Coupled design solution space to maximize fitness
  - Fitness defined as number of samples collected per mission versus mission cost

Image credit: https://www.nasa.gov/multimedia/imagegallery/image_feature_2154.html
Mars Rover Design Vector

- Mars Rover Design Space Model
  - Can select the N variables to be included in evaluation
    - Variables in the Rover Design model that contribute to the fitness calculation for a particular point design
      - N = 7 for this dataset example
        - For each variable N there were 2 different values considered in the design space
  - Using the selected variables for the design vector the potential valid system configurations are evaluated to determine the fitness of each system
  - 128 solutions generated
  - Fitness defined as number of samples collected per mission versus mission cost
Highlighted design delivers most samples for lowest cost
How fit are the resultant rover designs

Design Fitness - Unsorted

Design Fitness - Sorted
Rugged Fitness Landscapes

• We need a way to look at the impact of team communication and collaboration on design fitness without relying on a detailed design space model
  — Valid over a range of design problems
  — Before lengthy design and development process to build design models

• Candidate approach is an NK model from a class of mathematical (statistical) models
  — Describe the richness of epistatic interactions
    o The value of a given variable is affected by the values of other variables
  — Have been used to describe adaptive evolution in immune response as well as fitness of organizations

• Can the NK model can be tuned to show that it can be representative of the fitness space defined by complex design models?
The Basic NK Model

- Basic model description
  - A system has N variables, each variable can take on A possible values
  - The model assigns a “fitness contribution” to each variable ($w_i$)
  - This can be assigned at random from the uniform distribution on (0,1)
  - The total fitness ($W$) of a system is an average of the fitness contributions of each variable

$$W = \frac{1}{N} \sum_{i=1}^{N} w_i$$

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Assessing System Fitness

• Contributions to fitness between coupled variables
  — K defines the number of coupled variables influencing the fitness value of $w_i$
  — K = 0 yields a smooth solution fitness landscape with a single peak for the solution with the optimal fitness
    o The contributions of each variable to the system fitness are entirely independent of all other variables
  — As K increases relative to N, the fitness landscape becomes rugged with multiple peaks representing local optima
    o For K = N-1 the contributions of each variable are entirely dependent of the values for all other variables in the system

• The statistical model could represent local optima and the distance to reach a local optima
NK model to align with Rover Design
Fitness Landscape

- Match the model setup of the Mars Rover design model
  - N = 7 variables, A = 2 possible values for each variable
  - Results in 128 potential solutions

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How well would an NK Model approximate the fitness space (1)

NK Model - Unsorted

NK Model - Unsorted

NK Model - Unsorted
How well would an NK Model approximate the fitness space (2)
Results and Conclusions

• Created a fitness landscape of potential solutions for Mars rover designs to compare to a randomly generated fitness landscape defined by an NK model
  — K=2 and K=6 have promising potential for representing the design dataset using both the unsorted and sorted fitness plots

• Limitations of this preliminary assessment
  — Single snapshot fitness assessment of the NK model as setup
    ○ Need to apply Monte Carlo analysis and look at confidence intervals to determine if this could be accepted or rejected as a feasible representation
  — Comparison to a single design fitness model
    ○ Other design fitness models may have different results in terms of fitness and tuning the NK model to it
  — The evaluation metric needs to be assessed for determining potential of the representation
    ○ Perhaps sorted fitness is not the best way to evaluate the goodness of fit
Future Work

• There is more work to be done to determine if statistical models can represent a design fitness space
  — More tuning required to align NK model with design fitness models
  — More analysis to be conclusive, versus a single snapshot representation
  — Challenge of dealing with a noisy landscape with randomly generated fitness values
  — Identifying the evaluation metric to determine success of representation

• Additional challenges need to be investigated as part of tuning
  — What is the impact of the definition of the Ns and As
  — How are non-homogenous problem structures handled
  — Are there indications of the parameter K in other aspects of linked digital models
128 designs created
Selecting a point design to explore
Analyze designs: 128 generated solutions