Modeling Spacecraft Design Activities as Rugged Fitness Landscapes
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Research Task / Overview
- Motivation: DoD Digital/Engineering Strategy
  - 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
- What is the impact of connected data on performance?
  - Need a way to study complex communications and collaboration impacts on design performance
  - A new approach that allows study independent of detailed design models and is domain-agnostic

Goals & Objectives
- Goal: Explore a potential representation for studying 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
- Objective: Evaluate a candidate approach by comparing results with an example detailed design model

Methodology
- Candidate approach is an NK model from a class of mathematical (statistical) models
  - Describes the richness of epistatic interactions
  - 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 be tuned to show that it can be representative of the fitness space defined by complex design models?
- Example detailed design model represents Mars rover performance design trades
  - Includes a variety of potential variables that contribute to performance
  - Covers a range of disciplines that are similar across a range of design problems

Data & Analysis
- Fitness landscape determined by the detailed design model
- Fitness landscapes determined by the NK model, compared to the design model

Create mathematical model fitness landscape using same parameterization
- 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 (wi)
    - This can be assigned at random from the uniform distribution in (0,1]
  - The total fitness (M) of a system is an average of the fitness contributions of each variable
    \[ M = \frac{1}{N} \sum_{i=1}^{N} w_i \]
- Contributions to fitness between coupled variables
  - K defines the number of coupled variables influencing the fitness value of wi
    - K=0 yields a smooth solution fitness landscape with a single peak for the solution with the optimal fitness
    - As K increases relative to N, the fitness landscape becomes rugged with multiple peaks representing local optima
    - For K=N the contributions of each variable are entirely independent of the values of all other variables in the system
  - 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

Fitness landscape determined by the detailed design model
- Mars Rover Design Space Model
  - Select the N variables to be included in evaluation
  - Variables in the following order model the contribution to the fitness calculation for a particular point design
  - N=7 for this dataset example
  - Example: Martian surface map
  - 128 potential system solutions
  - Fitness defined as number of samples collected per mission versus mission cost
  - Most design models do not display fitness they display a comparison of 2 or 3 variables

Create spacecraft fitness landscape from example spacecraft design model
- Compare the model setup of the Mars Rover design model

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
  - 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 Research
- 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
- Additional challenges need to be investigated as part of tuning
  - What is the impact of the definition of the Ks and As
  - How are non-homogenous problem structures handled
  - Are there indications of the parameter K in other aspects of linked digital models

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