Implementation of Clustering Analysis in Engineered Resilient Systems Tools for Enhanced Trade Space Exploration of Military Ground Vehicles

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• Performing multidisciplinary design optimization of a military ground vehicle is extremely challenging

• One challenge is related to analyzing large, highly dimensional vehicle design datasets

• Analysis questions to answer regarding these datasets:
  – Do my highest-ranked designs reside in multiple regions of the trade space?
  – How many promising regions are there?
  – Does each region represent variations on a single design concept or multiple design concepts?
  – How can I best characterize the unique features of each design concept?
Clustering

- Simply put, clustering is the process of assigning data points to groups based on how closely their values are to a common group centroid.
- A way to group data that is highly dimensional.
- Different algorithms available.
- Machine learning technique.

**Simple 2-D Clustering Example**

**Original Data**

clustering data using 2 clusters

**Clustered Data**

Cluster 1

Cluster 2

cluster centroids
Clustering for Trade Space Design Populations

- Reduce large, highly dimensional datasets to more manageable, digestible sizes. This can make it easier to draw conclusions.

- Automated way of quantifying and qualifying design differences - *characterizing*; may help answer the question of: “How different are the top ranked vehicle designs?”

- Clusters could be used to provide promising vehicle design groups, and therefore promising characteristics, to be taken to the next stage of vehicle development.
ERS LRV Trade Space Exploration Project

Objectives

• Learn, evaluate, and provide feedback to developers of CREATE-GV and ERS Tools

• Apply these tools to the LRV notional concept vehicle to perform trade space exploration

• Develop new trade space exploration methods for ground vehicles

CREATE-GV: Computational Research and Engineering Acquisition Tools and Environments – Ground Vehicles
ERS: Engineered Resilient Systems
LRV: Light Reconnaissance Vehicle
Notional concept was initially developed based on these requirements:

- Crew of 6
- Power for 96-hour mission
- Silent watch, silent move
- Advanced reconnaissance & surveillance equipment package
- CH-47 internal transport and sling-load transport
Trade Space Exploration Process

Reviewed initial concept & requirements

Performed analysis to build trade space

Revisited concept & varied requirements

Performed analysis to expand trade space

Generated new design set = new concept

Iterative Concept-Analysis Loop
Trade Space Exploration Process

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Cluster Analysis

Cluster 1
Cluster 2
Clustered Data

Cluster centroids

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Trade Space Construction in ERS TradeBuilder

CREATE-GV
1. On-Road Speed
2. Off-Road Speed
3. Max Sandy Grade
4. Off-Road No-Go %
5. Soft-soil mobility

Design Variables

<table>
<thead>
<tr>
<th>#</th>
<th>H</th>
<th>L</th>
<th>W</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H₁</td>
<td>L₁</td>
<td>W₁</td>
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<td>H₂</td>
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<td>H₃</td>
<td>L₃</td>
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</tr>
<tr>
<td>4</td>
<td>H₄</td>
<td>L₄</td>
<td>W₄</td>
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</tr>
</tbody>
</table>

Performance Metrics imported from result files

ERS TradeBuilder
1. Surveillance
2. Crew
3. Stability
4. Silhouette
5. Power density
6. Survivability
7. Transportability
8. Lethality

Performance Metrics evaluated in ERS TradeBuilder

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• Common features from highest-ranked designs:

- CH-47 sling-load transportability
- V-belly, floating floor, higher standoff
- Interior space for crew of 6 + canine
- Full reconnaissance & surveillance kit

These are general features typically seen in the top 25 ranked vehicles, **though not all of the top 25 designs had the same features**
Trade Space Vehicle Design Characterization

• Two areas where differences are seen in the top 25 designs:

  - Characterizing the top ranking designs as a whole may not lead to as useful conclusions regarding which features a single vehicle design should have.
  - We could be unintentionally characterizing multiple vehicle designs, multiple variants, a potential outcome when performing multi-objective design optimization.
Early in the concept development phase, the trade space is large, with a design space that could be spanning regions consisting of two or more completely different vehicle designs. ... and this is not apparent.

We want to understand if potential regions exist early on in the analysis process to understand what unique concepts we may have.

Potential example outcome of early concept, highly dimensional, multi-object design optimization.
**Clustering Analysis - Setup**

- **K-means clustering** algorithm used within R (“Hartigan-Wong” version)
- **Chose to generate 10 clusters** based on the “within sum of squares (WSS)” count selection method
- Design variables and characteristics chosen for features:
  - Suspension characteristics (damping ratio and ride frequency) for the front and rear axles
  - Canine
  - Crew size
  - Armor weight

**13 features specified**
Clustering Analysis - Setup

Matrix representation of the trade space

Assigned Cluster added

Clustering Analysis using R

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• Within Sum of Squares cluster count selection method (WSS)

... at 976 clusters, the sum of squares value would equal 0

10 Clusters
Clustering Analysis – Results

Clustered Performance and Cost Distribution

Performance Score

Life Cycle Cost in Millions

Top 25 Line

Clustered Performance and Cost Distribution

- Cluster 1
- Cluster 2
- Cluster 3
- Cluster 4
- Cluster 5
- Cluster 6
- Cluster 7
- Cluster 8
- Cluster 9
- Cluster 10

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Clustering Analysis – Characterization

Plot shows clustering results using 10 specified clusters for the 976 vehicles designs investigated.

**Showing 3 clusters in the top 25:**
- Cluster 7 (C7) : 2 designs
- Cluster 8 (C8) : 14 designs
- Cluster 10 (C10) : 9 designs

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Looking at the same two features as before...

**Cluster 8 Designs:**
Mostly include weapon and canine

**Cluster 10 Designs:**
Mostly do not include a weapon or canine
Clustering Characterization - Features

- Various visualizations used to distinguish the differences between the top 25 designs within clusters 8 and 10 concerning their design variables and characteristics

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### Clustering Characterization - Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Cluster 8</th>
<th>Cluster 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weapon</strong></td>
<td>Most designs include the M2-50 Cal</td>
<td>Most designs don’t include a weapon</td>
</tr>
<tr>
<td><strong>Canine</strong></td>
<td>Most designs include a German Shepherd</td>
<td>Most designs don’t include a canine</td>
</tr>
<tr>
<td><strong>CG Height</strong></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Wheelbase Length</strong></td>
<td>Longer</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Weight Distribution</strong></td>
<td>More centered to rear heavy designs</td>
<td>More front heavy designs</td>
</tr>
<tr>
<td><strong>Front Axle Ride</strong></td>
<td>Stiff, Mostly Overdamped</td>
<td>Less Stiff, Underdamped</td>
</tr>
<tr>
<td>Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rear Axle Ride</strong></td>
<td>Stiff, Mostly Overdamped</td>
<td>Very Stiff, Mostly Overdamped</td>
</tr>
<tr>
<td><strong>Characteristics</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These clustered designs were similar regarding the Tires, Hull and Armor Weight, Crew Size, and Surveillance System features.
• Various visualizations used to distinguish the differences between the top 25 designs within clusters 8 and 10 concerning their performance
## Clustering Characterization - Performance

<table>
<thead>
<tr>
<th>Performance</th>
<th>Cluster 8</th>
<th>Cluster 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crew Effectiveness</strong></td>
<td>Highest score</td>
<td>Meets requirements</td>
</tr>
<tr>
<td><strong>Max Speed</strong></td>
<td>Lower to moderate</td>
<td>Moderate to high</td>
</tr>
<tr>
<td><strong>Max Sand Slope</strong></td>
<td>Medium</td>
<td>Medium to high</td>
</tr>
<tr>
<td><strong>SSF</strong></td>
<td>High</td>
<td>Medium to low</td>
</tr>
<tr>
<td><strong>Visibility (Silhouette)</strong></td>
<td>Larger profile</td>
<td>Smaller profile</td>
</tr>
<tr>
<td><strong>Lethality</strong></td>
<td>Higher</td>
<td>Lower</td>
</tr>
</tbody>
</table>

These clustered designs were similar regarding the **Surveillance**, **No-Go %**, **VCI1**, **V50 Speed**, **HP / ton**, **Survivability**, and **Transportability** performance metrics.
Clustered Characterization - Conclusions

- Highlighted two main clusters in the top 25 ranked vehicle designs and analyzed their features and performance
- Instead of describing one LRV design, now describing two LRV design variations in the top 25 – two designs that have some distinct differences, but with similar overall performance scores

**Cluster 8**
Well-rounded design concerning all of the areas of performance considered

**Cluster 10**
Fast, mobile design, with smaller profile

Two potential variants
Conclusions

New trade space exploration process which utilized a clustering technique highlighted two main vehicle variants out of a set of top performing vehicle designs

• Clustering is a promising trade space analysis process addition to help improve and further automate trade space characterization
• Can help answer important questions about a trade space
• And lead to improved optimal design extraction from trade spaces, and overall improved concept design development
• More to look into: clustering technique tuning and feature selection
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