Terrain Characterization

Make Everything as Simple as Possible, but not Simpler
or
A Model-Portable, Compact, Physically Meaningful Characterization of Terrain Surfaces

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Compact Terrain Characterization

Background

- Surface Creation - Curved Regular Gridding
- Surface Decompositions
  - Components: Elevation, Banking, Rutting, Crowning…
  - Frequency ranges
- Modeling Surface Components

Compact Terrain Characterization

- Defining model parameter vector
- Reducing parameter space
- Proof of Concept

Future Work and Conclusions
Creating Curved Regular Grid (CRG)

- Measured data is point cloud of irregularly spaced x-y-z data
- Define path coordinate, $u$
- Define perpendicular and coordinate, $v$
- $(u,v)$ is then a Regularly Spaced Grid, or “Curved Regular Grid” (CRG) for horizontal plane
- CloudSurfer converts point cloud to a CRG automatically

Determining height at each CRG node

- Consider a CRG node (red dot)
- In estimating the CRG node heights, the measured data points (blue x’s) closest to CRG nodes are more influential than those further away
- Influence of node height is based on weighting function that takes into account \(d_i\) and error in the horizontal measurements \(\sigma\)

Surface Creation

- A probability distribution of the height at each CRG node is created
- Consider the median height values represent surface
- Final surface can be imported into software (e.g. Adams)
  - Ride Simulation
- Surface: collection of...

Longitudinal Profile

Transverse Profile
Surface Decomposition

Transverse profiles decomposed into principal components

- First 5 Basis Vectors (Legendre Polynomials)

Surface Decomposition

**Transverse Profile** projected on **Basis Vectors** yields **Components**

![Graphs showing components of surface decomposition](image-url)
Autoregressive Model

Elevation value at a point = Linear combination of previous values + a residual process (uncertainty)

\[ z_k = [\phi_1 z_{k-1} + \phi_2 z_{k-2} + \ldots + \phi_p z_{k-p}] + \text{residual} \]

AR models are parameterized by the \( \phi \) values

Surface Synthesis

Generating **synthetic terrain**

- Model each component
- Generate *synthetic components* with same essential characteristics of measured

Multiply by basis vectors...
Surface Synthesis

Synthetic components can be synthesized, then combined to form a synthetic surface.

Reconstructed surface is unique but statistically similar to original.
Whew!! Let’s recap with an example…

- **Typical 100 meter terrain measurement:**
  - Original point cloud: ~1.2 billion points
  - 10 mm curved regular grid: ~2 million points
  - 5 principal components: ~50 thousand points
  - 10th order AR model of spectrally decomposed components (3 bandwidths): ~200 coefficients

- Still too large to hold in your hand…

- Can we go a step further?
Defining Model Parameter Vector

- Consider a collection of different surfaces, each being indexed by $k$
- Each surface is decomposed into components: elevation, banking, ...
- Each component is further decomposed into different frequencies (wavelengths)
- A unique model is used for each “profile”: AR models are parameterized by $\phi$
- Entire set of parameters for $k^{th}$ surface can be held in vector: $p_k$
- Is there a pattern across different surfaces?
Reducing Parameter Space

- Obtain diverse and extensive surfaces \((k = 1, 2, 3, \ldots n_s)\)
- Decompose and model each surface and obtain a model parameter vector, \(p_k\), for each surface
- Combine all parameter vectors into a single matrix, \(P\)
- Find principal patterns in the parameter vectors using Singular Value Decomposition (SVD)
- Keep the 3 “most important” basis vectors: \(q_1, q_2, q_3\)

\[
P = \begin{bmatrix} p_1 & p_2 & \cdots & p_{n_s} \end{bmatrix}
\]
Approach: Project on Basis Vectors

- Consider surface modeled with 72 parameters
- Estimate parameters using basis vectors

\[ p \approx a_1 q_1 + a_2 q_2 + a_3 q_3 \]

\[ p \approx \begin{bmatrix} q_1 & q_2 & q_3 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \]

- Knowing the basis vectors, written compactly as \( Q = [q_1 \ q_2 \ q_3] \), only the 3 “a” coefficients are needed to characterize the surface

\[ p \xrightarrow{\text{projected}} Q \xrightarrow{\text{Characterization Coefficients}} a_1 \ a_2 \ a_3 \]
Approach: Big Picture

Diverse set of surfaces

Model $p_1$ 

Model $p_2$ 

Model $p_3$ 

Model $p_4$ 

Model $p_5$

Surface to characterize

Model $p_{new}$

$SVD$ 

$q_1$ 

$q_2$ 

$q_3$ 

$Q$

$a_1$ 

$a_2$ 

$a_3$

Projection
Proof of Concept: Model Choice

- Several surfaces are modeled using settings below

<table>
<thead>
<tr>
<th>Model Type</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Distribution</td>
<td>Logistic</td>
</tr>
<tr>
<td>Model Order</td>
<td>10</td>
</tr>
<tr>
<td>Cutoff Frequencies</td>
<td>0.25 [1/m], 0.025 [1/m]</td>
</tr>
<tr>
<td>Principal Components</td>
<td>Elevation, Banking</td>
</tr>
<tr>
<td>Number of Basis Vectors, ( n_b )</td>
<td>3</td>
</tr>
</tbody>
</table>

- Profiles from each surface are plotted and compared to the synthetic profiles using the characteristic coefficients
Proof of Concept: Results

Profile 1

\[
a_1 = -3.016 \\
a_2 = 1.009 \\
a_3 = -1.546
\]
Proof of Concept: Results

Profile 2

\[ a_1 = -2.365 \]
\[ a_2 = -0.938 \]
\[ a_3 = 0.813 \]
Proof of Concept: Results

Profile 3

\[ a_1 = -2.682 \]
\[ a_2 = 0.985 \]
\[ a_3 = -0.548 \]
Future Work

- Concept must be applied to roads outside the set used for SVD
- A more complete and diverse road set is needed to finalize SVD
- Separate models must be investigated
  - Model type: AR, CMC, Hybrid, etc.
  - Frequency bandwidths
  - Surface principal components
  - Model order
  - Characteristic distribution for residuals (Logistic, Normal, Cauchy, etc.)
- Portability between models
  (same characteristic coefficients for multiple models)
- Physical interpretation of coefficients
- Techniques to avoid model instability
Conclusions

• Preliminary results are very encouraging
• Characterization must be applied to new courses outside SVD set
• Numerous modeling choices to be researched
• Thanks!