Geodesic Convolutional Shape Optimization

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NEURALCONCEPT
IDIAP
EPFL
3D Shape Design

- Design a shape.
- Simulate its performance.
- Redesign.

It works but:

- It takes hours or days to produce a single simulation.
- This constitutes a serious bottleneck in the exploration of the design space.
- Designs are limited by humans’ cognitive biases.
Non Linear Regression

- Drag
- Pressure Coefficients
- Boundary Layer Velocities
- ...

The response surface can be approximated by a CNN.

The model can have any number of parameters.
Reminder: Conventional CNN

• Perform convolutions on rectangular grids.
• Implicitly depends on their Euclidean structure.
Object Representations

- 3D objects are often represented as triangulations or quadrangulations.
- The individual facets are not always regular.
  
  → Need convnets that can operate on those.
From Grid to Meshes

- Perform convolutions on irregular meshes.
- Estimate geodesic distances.
Mesh Convolutions

Let \( f = (f^1, \ldots, f^N) \) be defined at each vertex \( X^i_{1 \leq i \leq N} \) of mesh \( M \).

\[
\begin{align*}
f \ast g &= \sum_{k \in \{1, \ldots, K\}} g_k D_k f, \\
(D_k f)^i &= \sum_{j \in \mathcal{N}^i} f^j \exp\left(-\rho(X^i, X^j) - \alpha_k \rho\right)^2 \right) \exp\left(-\theta(X^i, X^j) - \alpha_k \theta\right)^2, \\
\end{align*}
\]

where \( \rho(\cdot) \) and \( \theta(\cdot) \) are relative geodesic coordinates.

\( \rightarrow \) Slower convolutions because using the GPUs effectively is more difficult.

\( \rightarrow \) But can be optimized to make the cost tolerable.
Geodesic CNN
Aerodynamics Simulation

**Full Simulation (1 h)**

**Deep Network (30 ms)**

<table>
<thead>
<tr>
<th>Physics Type</th>
<th>External Aerodynamics</th>
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<tbody>
<tr>
<td>Dataset size</td>
<td>~1000 shapes</td>
</tr>
<tr>
<td>R2-accuracy</td>
<td>95 %</td>
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</tbody>
</table>
Real Time Prediction

We can now operate on individual vertices.

—> Interactive shape exploration
Differentiable Prediction

CNN

Gradient-Based Optimization
Minimize Drag Under Constraints

Minimizing drag while enclosing a sphere
Naca Profiles

Lift, Drag, Momentum, ....
UAV Design
From UAV To Lifting Body

Sensefly drone (L/D 11.9)

Optimize the wings (L/D 13.7)

Optimize the fuselage as well
From Pickup-Truck to Sports Car
Bicycle Shell

Altair 6, IUT Annecy, 2018

World Human Powered Speed Challenge
Battle Mountain Nevada, 2019

Women world record: 126.48 km/h
Men student world record: 136.74 km/h

https://www.facebook.com/team.velo.carene/
Hydrocontest Boat

Goal:

- Reduce drag.
- Increase stability.
Minimize drag while reaching a target lift and stability.

→ A slightly unexpected shape.
Cantilever Beam
Structural Design

Poor design: Heavy, high stresses

Better design
Structural Design

PReds sigma
Structural Design

Preds

Simulations
Conclusion

Geodesic CNNs can be used to:

- Reliably emulate a simulator.
- Optimize the aerodynamic performance of a shape.

Future work will focus on:

- Exploring the shape-space more thoroughly.
- Allowing the topology to evolve as needed.
- Build training databases from real data.
- Tech Transfer.