Modeling, Evaluation and Optimization of Interlocking Shell Pieces

Miaojun Yao$^1$ Zhili Chen$^2$
WeiWei Xu$^3$ Huamin Wang$^1$

The Ohio State University$^1$, Adobe$^2$, Zhejiang University$^3$
Problems of 3D Printing

- **Build volume**
  - Makerbot Replicator 2x: [9.7 X 6.0 X 6.1 IN]
  - Form1+: [4.9 X 4.9 X 6.5 IN]
  - Objet30 Pro: [11.8 x 7.9 x 5.9 IN]

- **Printing time/material**
  - Hours to days
  - Hundreds of dollars
Solutions

• Shell modeling
  • Reduce printing material/time

• Partitioning
  • Printability
Goal

- Partitioning of Shell Model
  - Reduce printing material/time
  - Printability
  - Interlocking structure
    - Stable against separation
    - Reusable by parts
  - Arbitrary mesh segmentation input
    - Level set
Example - Dinosaur

Dinosaur
Contribution

- Given an arbitrary mesh segmentation input, our system automatically finds an **optimal installation plan** specifying the **installation order** and the **installation directions** of the pieces, and then builds interlocking shell pieces with **male and female connectors**.
Installation Plan

- *Installation order and installation directions*
- A piece is interlocked if boundaries have conflicting *separation directions*
- Last piece is the *key piece*, not interlocked
Overview

Surface-based Installation Planning
- Key piece selection
- Plan evaluation metrics
- Plan search

Piece and Connector Modeling
- Piece modeling
- Connector modeling
- Key connector modeling

Surface segmentation

Printing
Overview

Surface segmentation

Surface-based Installation Planning
- Key piece selection
- Plan evaluation metrics
- Plan search

Piece and Connector Modeling
- Piece modeling
- Connector modeling
- Key connector modeling

Printing
Piece Modeling
Connector Modeling
Connector Modeling

(a) Connector closeup (before)  
(b) Connector closeup (after)

(c) Multiple pieces (before)  
(d) Multiple pieces (after)
Key Connector Modeling

(a) A cross section view

(b) A photograph
Overview

Surface segmentation

Surface-based Installation Planning
- Key piece selection
- Plan evaluation metrics
- Plan search

Piece and Connector Modeling
- Piece modeling
- Connector modeling
- Key connector modeling

Printing
Key Piece Selection

- Last piece to install
- Slide-in, Flat shape
- Slide-in, Rectangular shape (refined by user)
Overview

Surface segmentation

- Surface-based Installation Planning
  - Key piece selection
  - Plan evaluation metrics
  - Plan search

- Piece and Connector Modeling
  - Piece modeling
  - Connector modeling
  - Key connector modeling

Printing
Plan Evaluation Metrics

1. Volume-based Metric
   - Apply force in separation direction
   - FEM simulation, collision handling
   
   \[ Q = -\max w_i d_i^{\text{max}} \]
Plan Evaluation Metrics

2. Surface-based Metric

- Projective dynamics, 20 times faster
- Bending/stretch/positional constraints

\[ Q = - \max w_i d_i^{\text{max}} \]
Plan Evaluation Metrics

2. Surface-based Metric Demo

Castle
Plan Evaluation Metrics

3. Boundary-based Data-Driven Metric

- Consider local neighborhood of a boundary, fix outer ring
- Sample different separation directions $s$, testing force $f$
- Surface-based simulation and store results in a table
Plan Evaluation Metrics

3. Boundary-based Data-Driven Metric (Cont.)

- Given a plan, quickly look up the table to get the score
- Forces: $f^{\text{tra}} = s_j$, $f^{\text{rot}} = \pm \frac{(x_i - x_a) \times (x_b - x_a)}{\| (x_i - x_a) \times (x_b - x_a) \|}$
Plan Evaluation Metrics

![Graph showing plan evaluation metrics with data points for Volume-based, Surface-based, and Data-driven approaches. The x-axis represents some metric, and the y-axis represents the score. The graph shows a trend where the score increases with the metric value.]
Plan Evaluation Metrics

- **Boundary-based Data-Driven Metric**
  Instant to evaluate a plan, search for best 100 plans

- **Surface-based Metric**
  0.2s to evaluate a plan, select the best one from 100

- **Volume-based Metric**
  3.6s to evaluate a plan, only used as ground truth
Overview

Surface-based Installation Planning
- Key piece selection
- Plan evaluation metrics
- Plan search

Piece and Connector Modeling
- Piece modeling
- Connector modeling
- Key connector modeling
Plan Search

• Too many plans, so randomize search

• Pruning/optimization
  • Connectivity pruning (basic)
    Connected to previously installed pieces
  • Intersection pruning (basic)
    Not blocked by previously installed pieces
  • Score-based pruning
    The plan score is determined by the worst piece
  • Local optimization
    Enumerate neighbors of the worst piece
Example – Castle
Stress Test

Stress Tests
Results
Results
# Results

<table>
<thead>
<tr>
<th>Name</th>
<th># of Pieces</th>
<th>$h$ (mm)</th>
<th>Volume Ratio</th>
<th>Time Ratio</th>
<th>Comp. Cost (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squirrel</td>
<td>11</td>
<td>2.2</td>
<td>28.0%</td>
<td>44.4%</td>
<td>130.7</td>
</tr>
<tr>
<td>Lion</td>
<td>12</td>
<td>2.7</td>
<td>47.6%</td>
<td>48.2%</td>
<td>118.0</td>
</tr>
<tr>
<td>Castle</td>
<td>11</td>
<td>2.4</td>
<td>39.8%</td>
<td>55.6%</td>
<td>117.7</td>
</tr>
<tr>
<td>Vase</td>
<td>9</td>
<td>2.3</td>
<td>45.5%</td>
<td>23.2%</td>
<td>126.7</td>
</tr>
<tr>
<td>Angel</td>
<td>10</td>
<td>2.0</td>
<td>28.1%</td>
<td>49.1%</td>
<td>130.3</td>
</tr>
<tr>
<td>Astronaut</td>
<td>11</td>
<td>2.7</td>
<td>54.0%</td>
<td>68.6%</td>
<td>116.4</td>
</tr>
<tr>
<td>Dinosaur</td>
<td>10</td>
<td>2.1</td>
<td>32.9%</td>
<td>46.4%</td>
<td>120.2</td>
</tr>
<tr>
<td>Laurana</td>
<td>10</td>
<td>2.0</td>
<td>26.1%</td>
<td>58.5%</td>
<td>125.1</td>
</tr>
<tr>
<td>Laurana</td>
<td>40</td>
<td>2.0</td>
<td>46.2%</td>
<td>67.1%</td>
<td>306.6</td>
</tr>
<tr>
<td>Buddha</td>
<td>12</td>
<td>2.4</td>
<td>24.5%</td>
<td>47.8%</td>
<td>134.0</td>
</tr>
<tr>
<td>Car</td>
<td>11</td>
<td>1.9</td>
<td>26.6%</td>
<td>48.3%</td>
<td>131.2</td>
</tr>
<tr>
<td>Fist</td>
<td>13</td>
<td>2.0</td>
<td>20.4%</td>
<td>46.9%</td>
<td>145.1</td>
</tr>
<tr>
<td>Octopus</td>
<td>9</td>
<td>2.8</td>
<td>50.3%</td>
<td>61.9%</td>
<td>98.3</td>
</tr>
</tbody>
</table>
Conclusion

• We present a novel computational system to design the interlocking structure of partitioned shell pieces with connectors.

• Future work
  • Better key piece modeling
  • Strength improvement
  • Computational performance improvement
Acknowledgement

IIS-1524992

Adobe

Zhejiang University
Thank You!

Modeling, Evaluation and Optimization of Interlocking Shell Pieces

Miaojun Yao¹, Zhili Chen², Weiwei Xu³, Huamin Wang¹

The Ohio State University¹, Adobe Research², Zhejiang University³