Surface Representations and Geometric Modeling

Spring 2010

Subdivision
Subdivision Surfaces

- Generalization of spline curves / surfaces
  - Arbitrary control meshes
  - Successive refinement (subdivision)
  - Converges to smooth limit surface
  - Connection between splines and meshes
Subdivision Surfaces

- Generalization of spline curves / surfaces
  - Arbitrary control meshes
  - Successive refinement (subdivision)
  - Converges to smooth limit surface
  - Connection between splines and meshes
Example: Geri’s Game (Pixar)

- Subdivision used for
  - Geri’s hands and head
  - Clothing
  - Tie and shoes
Example: Geri’s Game  (Pixar)

Woody’s hand (NURBS)  Geri’s hand (subdivision)
Example: Geri’s Game (Pixar)

- Sharp and semi-sharp features
Example: Dassault’s CATIA

- Traditional CAD system based on splines
- Latest version also includes subdivision surfaces
Subdivision Curves

Given a control polygon...

...find a smooth curve related to that polygon.
Subdivision Curve Types

- Approximating
- Interpolating
- Corner Cutting
Approximating
Approximating

Splitting step: split each edge in two
Approximating

Averaging step: relocate each (original) vertex according to some (simple) rule...
Approximating

Start over ...
Approximating

...splitting...
Approximating

...averaging...
Approximating

...and so on...
Approximating

If the rule is designed carefully...

... the control polygons will converge to a smooth limit curve!
Equivalent to …

- Insert *single* new point at mid-edge
- *Filter* entire set of points.

Catmull-Clark rule: Filter with \((1/8, 6/8, 1/8)\)
Corner Cutting

• Subdivision rule:
  – Insert *two* new vertices at $\frac{1}{4}$ and $\frac{3}{4}$ of each edge
  – *Remove* the old vertices
  – Connect the new vertices
B-Spline Curves

• Piecewise polynomial of degree $n$

$$s(u) = \sum_{i=0}^{k} d_i N_i^n(u)$$

B-spline curve

control points

parameter value

basis functions
B-Spline Curves

• Distinguish between odd and even points

• Linear B-spline
  – Odd coefficients (1/2, 1/2)
  – Even coefficient (1)
B-Spline Curves

• Quadratic B-Spline (Chaikin)
  – Odd coefficients \( \frac{1}{4}, \frac{3}{4} \)
  – Even coefficients \( \frac{3}{4}, \frac{1}{4} \)

• Cubic B-Spline (Catmull-Clark)
  – Odd coefficients \( \frac{4}{8}, \frac{4}{8} \)
  – Even coefficients \( \frac{1}{8}, \frac{6}{8}, \frac{1}{8} \)
Cubic B-Spline

\[
\begin{align*}
\frac{1}{8} & \quad \frac{6}{8} & \quad \frac{1}{8} \\
\frac{4}{8} & \quad \frac{4}{8}
\end{align*}
\]

even

odd
Cubic B-Spline

odd

even

\[
\begin{bmatrix}
\frac{4}{8} & \frac{4}{8} \\
\frac{1}{8} & \frac{6}{8} & \frac{1}{8}
\end{bmatrix}
\]
Cubic B-Spline

odd

even

\[
\begin{align*}
\frac{4}{8} & \quad \frac{4}{8} \\
\frac{1}{8} & \quad \frac{6}{8} & \quad \frac{1}{8}
\end{align*}
\]
Cubic B-Spline
Cubic B-Spline

\[
\frac{4}{8} \quad \frac{4}{8} \quad \frac{1}{8} \quad \frac{6}{8} \quad \frac{1}{8}
\]

odd \hspace{1cm} even

\[
\frac{1}{8} \quad \frac{1}{8} \quad \frac{6}{8}
\]
Cubic B-Spline

\[
\begin{array}{ccc}
\frac{4}{8} & \frac{4}{8} & \frac{1}{8} & \frac{6}{8} & \frac{1}{8} \\
\end{array}
\]

odd \hspace{1cm} even

\[
\begin{array}{ccc}
\frac{4}{8} & \frac{4}{8} & \frac{1}{8} & \frac{6}{8} & \frac{1}{8} \\
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Cubic B-Spline
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\begin{align*}
\frac{4}{8} & \quad \frac{4}{8} & \quad \frac{1}{8} & \quad \frac{6}{8} & \quad \frac{1}{8} \\
\text{odd} & & \text{even} & & \\
\end{align*}
\]
Cubic B-Spline

odd

even
Cubic B-Spline
Cubic B-Spline

odd

\[
\frac{4}{8} \quad \frac{4}{8}
\]

\[
\frac{1}{8} \quad \frac{6}{8} \quad \frac{1}{8}
\]

even

\[
\frac{1}{8}
\]

\[
\frac{6}{8}
\]

\[
\frac{1}{8}
\]
Cubic B-Spline

\[
\begin{align*}
\frac{4}{8} & \quad \frac{4}{8} & \quad \frac{1}{8} & \quad \frac{6}{8} & \quad \frac{1}{8} \\
\end{align*}
\]

odd \quad even
Cubic B-Spline

\[
\begin{align*}
\frac{4}{8} & \quad \frac{4}{8} \\
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\]

odd \quad even
Cubic B-Spline

odd

even
B-Spline Curves

- Subdivision rules for control polygon
  \[ d^0 \to d^1 = Sd^0 \to \ldots \to d^j = Sd^{j-1} = S^j d^0 \]

- Mask of size \( n \) yields \( C^{n-1} \) curve
Interpolating (4-point Scheme)

- Keep old vertices
- Generate new vertices by fitting cubic curve to old vertices
- $C^1$ continuous limit curve

\[
f(x) = ax^3 + bx^2 + cx + d \\
f(j) = p_{i+j}, \quad j = 0, \ldots, 3 \\
q_i = f(3/2) \\
= \frac{1}{16} (-p_i + 9p_{i+1} + 9p_{i+2} - p_{i+3})
\]
Interpolating
Interpolating
Interpolating
Interpolating

demo
Subdivision Surfaces

• No regular structure as for curves
  – Arbitrary number of edge-neighbors
  – Different subdivision rules for each valence
# Classic Subdivision Operators

- **Classification of subdivision schemes**

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primal</strong></td>
<td>Faces are split into sub-faces</td>
</tr>
<tr>
<td><strong>Dual</strong></td>
<td>Vertices are split into multiple vertices</td>
</tr>
<tr>
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## Classic Subdivision Operators

- Classification of subdivision schemes

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Doo-Sabin Subdivision

- Generalization of \textit{bi-quadratic B-Splines}
- Dual, approximating subdivision scheme
- Applied to \textit{polygonal} meshes
- Generates $G^1$ \textit{continuous} limit surfaces:
  - $C^0$ for the set of finite extraordinary points
    - Center of irregular polygons after 1 subdivision step
  - $C^1$ continuous everywhere else
Doo-Sabin Subdivision

\[ V_2 = \frac{1}{n} \times \sum_{j=1}^{n} d_j \]

\[ E_i = \frac{1}{2} \left( d_1 + d_{2i} \right) \]

\[ d'_{1,j} = \frac{1}{4} \left( d_1 + E_j + E_{j-1} + V_j \right) \]
Doo-Sabin Subdivision
## Classic Subdivision Operators

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Catmull-Clark Subdivision

• Generalization of bi-cubic B-Splines
• Primal, approximation subdivision scheme
• Applied to polygonal meshes
• Generates $G^2$ continuous limit surfaces:
  – $C^1$ for the set of finite extraordinary points
    • Vertices with valence $\neq 4$
  – $C^2$ continuous everywhere else
Catmull-Clark Subdivision

$$V_2 = \frac{1}{n} \times \sum_{j=1}^{n} d_j$$

$$E_i = \frac{1}{4} \left( d_1 + d_{2i} + V_i + V_{i+1} \right)$$

$$d'_1 = \frac{(n-3)}{n} d_1 + \frac{2}{n} R + \frac{1}{n} S$$

$$R = \frac{1}{m} \sum_{i=1}^{m} E_i \quad S = \frac{1}{m} \sum_{i=1}^{m} V_i$$
Catmull-Clark Subdivision
Classic Subdivision Operators

- Classification of subdivision schemes

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Loop Subdivision

- Generalization of *box splines*
- Primal, approximating subdivision scheme
- Applied to *triangle* meshes
- Generates $\mathcal{G}^2$ *continuous* limit surfaces:
  - $C^1$ for the set of finite extraordinary points
    - Vertices with valence $\neq 6$
  - $C^2$ continuous everywhere else
Loop Subdivision

\[ E_i = \frac{3}{8} (d_1 + d_i) + \frac{1}{8} (d_{i-1} + d_{i+1}) \]

\[ d'_1 = \alpha_n d_1 + \frac{(1 - \alpha_n)^{n+1}}{n} \sum_{j=2}^{n} d_j \]

\[ \alpha_n = \frac{3}{8} + \left( \frac{3}{8} + \frac{1}{4} \cos \frac{2\pi}{n} \right)^2 \]
Loop Subdivision
# Classic Subdivision Operators

- Classification of subdivision schemes

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Butterfly Subdivision

• Primal, interpolating scheme
• Applied to triangle meshes
• Generates $G^1$ continuous limit surfaces:
  – $C^0$ for the set of finite extraordinary points
    • Vertices of valence = 3 or > 7
  – $C^1$ continuous everywhere else
Butterfly Subdivision

\[ E_1 = \frac{1}{2} (d_1 + d_2) + \omega (d_3 + d_4) - \frac{\omega}{2} (d_5 + d_6 + d_7 + d_8) \]

\[ d'_i = d_i \]
Butterfly Subdivision
Remark

- Different masks apply on the boundary
- Example: Loop

\[
\frac{1}{8} \quad \frac{3}{8} \quad \frac{1}{8} \\
\frac{1}{8} \quad \frac{3}{8} \quad \frac{1}{8}
\]

\[
\frac{1}{2} \quad \frac{1}{2} \\
\frac{1}{8} \quad \frac{3}{4} \quad \frac{1}{8}
\]

\text{Interior}

\text{Crease and boundary}

a. Masks for odd vertices

b. Masks for even vertices
Comparison

Doo-Sabin  Catmull-Clark

Loop  Butterfly
Comparison

Loop

Butterfly

Loop

Butterfly

Catmull-Clark

Doo-Sabin

Catmull-Clark

Doo-Sabin
Comparison

Loop  Butterfly  Catmull-Clark  Doo-Sabin

Initial mesh  Loop  Catmull-Clark  Catmull-Clark, after triangulation
Comparison

• Continuity of a scheme determines the quality
• Approximating schemes give best results
• Approximating schemes shrink meshes

• Best schemes: Catmull-Clark & Loop
  – Loop is applied on triangle meshes
  – Catmull-Clark preserves symmetry better
Analysis of Subdivision

• Invariant neighborhoods
  – How many control-points affect a small neighborhood around a point?

• Subdivision scheme can be analyzed by looking at a *local* subdivision matrix
Local Subdivision Matrix

- Example: Cubic B-Splines

\[
\begin{pmatrix}
 p_{j+1} \\
p_{j+1} \\
p_{0} \\
p_{1} \\
p_{2} \\
\end{pmatrix}
= \frac{1}{8}
\begin{pmatrix}
 1 & 6 & 1 & 0 & 0 \\
 0 & 4 & 4 & 0 & 0 \\
 0 & 1 & 6 & 1 & 0 \\
 0 & 0 & 4 & 4 & 0 \\
 0 & 0 & 1 & 6 & 1 \\
\end{pmatrix}
\begin{pmatrix}
 p_{j} \\
p_{j} \\
p_{0} \\
p_{1} \\
p_{2} \\
\end{pmatrix}
\]

- Invariant neighborhood size: 5
Analysis of Subdivision

• Analysis via eigen-decomposition of matrix $S$
  – Compute the eigenvalues
    \[ \{\lambda_0, \lambda_1, \ldots, \lambda_{n-1}\} \]
  – and eigenvectors
    \[ X = \{x_0, x_1, \ldots, x_{n-1}\} \]
  – Let $\lambda_0 \geq \lambda_1 \geq \cdots \geq \lambda_{n-1}$ be real and $X$ a complete set of eigenvectors
Analysis of Subdivision

- Invariance under affine transformations
  \[ \text{transform}(\text{subdivide}(P)) = \text{subdivide}(\text{transform}(P)) \]
Analysis of Subdivision

• Invariance under affine transformations
  – $\text{transform}(\text{subdivide}(P)) = \text{subdivide}(\text{transform}(P))$

• Rules have to be affine combinations
  – Even and odd weights each sum to 1

$$\sum_j S_{2i,j} = \sum_j S_{2i+1,j} = 1$$
Analysis of Subdivision

- Invariance under reversion of point ordering
- Subdivision rules (matrix rows) have to be symmetric
Conclusion: 1 has to be eigenvector of $S$ with eigenvalue $\lambda_0=1$
Limit Behavior - Position

- Any vector is linear combination of eigenvectors:

\[ \mathbf{p} = \sum_{i=0}^{n-1} a_i \mathbf{x}_i \quad a_i = \mathbf{x}_i^T \mathbf{p} \]

- Apply subdivision matrix:

\[ S\mathbf{p}^0 = S \sum_{i=0}^{n-1} a_i \mathbf{x}_i = \sum_{i=0}^{n-1} a_i S\mathbf{x}_i = \sum_{i=0}^{n-1} a_i \lambda_i \mathbf{x}_i \]
Limit Behavior - Position

- For convergence we need \( 1 = \lambda_0 > \lambda_1 \geq \cdots \geq \lambda_{n-1} \)
- Limit vector:

\[
p^\infty = \lim_{j \to \infty} S^j p^0 = \lim_{j \to \infty} \sum_{i=0}^{n-1} a_i \lambda_i^j x_i = a_0 \cdot 1
\]

\[
p_i^\infty = a_0 = \tilde{x}_0^T p^j \quad \text{independent of } j !
\]
Limit Behavior - Tangent

- Set origin at $a_0$:

$$p^j = \sum_{i=1}^{n-1} a_i \lambda_i^j x_i$$

- Divide by $\lambda_1$

$$\frac{1}{\lambda_1^j} p^j = a_1 x_1 + \sum_{i=2}^{n-1} a_i \left(\frac{\lambda_i}{\lambda_1}\right)^j x_i$$

- Limit tangent given by:

$$t_i^\infty = a_1 = \tilde{x}_1^T p^j$$
Limit Behavior - Tangent

• Curves:
  – All eigenvalues of $S$ except $\lambda_0=1$ should be less than $\lambda_1$ to ensure existence of a tangent, i.e.

  \[ 1 = \lambda_0 > \lambda_1 > \lambda_2 \geq \cdots \geq \lambda_{n-1} \]

• Surfaces:
  – Tangents determined by $\lambda_1$ and $\lambda_2$

  \[ 1 = \lambda_0 > \lambda_1 = \lambda_2 > \lambda_3 \geq \cdots \geq \lambda_{n-1} \]
Example: Cubic Splines

- Subdivision matrix & rules

\[
S = \frac{1}{8} \begin{pmatrix}
1 & 6 & 1 & 0 & 0 \\
0 & 4 & 4 & 0 & 0 \\
0 & 1 & 6 & 1 & 0 \\
0 & 0 & 4 & 4 & 0 \\
0 & 0 & 1 & 6 & 1 \\
\end{pmatrix}
\]

\[
p^{j+1}_{2i} = \frac{1}{8} p^j_{i-1} + \frac{6}{8} p^j_i + \frac{1}{8} p^j_{i+1}
\]

\[
p^{j+1}_{2i+1} = \frac{1}{2} p^j_i + \frac{1}{2} p^j_{i+1}
\]

- Eigenvalues

\[
(\lambda_0, \lambda_1, \lambda_2, \lambda_3, \lambda_4, ) = \left( 1, \frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8} \right)
\]
Example: Cubic Splines

- Eigenvectors

\[
X = \begin{pmatrix}
1 & -1 & 1 & 1 & 0 \\
1 & -\frac{1}{2} & \frac{2}{11} & 0 & 0 \\
1 & 0 & -\frac{1}{11} & 0 & 0 \\
1 & \frac{1}{2} & \frac{2}{11} & 0 & 0 \\
1 & 1 & 1 & 0 & 1
\end{pmatrix}
\]

\[
X^{-1} = \begin{pmatrix}
0 & \frac{1}{6} & \frac{4}{6} & \frac{1}{6} & 0 \\
0 & -1 & 0 & 1 & 0 \\
... & ... & ...
\end{pmatrix}
\]

- Limit position and tangent

\[
p_i^\infty = \hat{x}_0^T p_j = \frac{1}{6} \left( p_{i-1}^j + 4p_i^j + p_{i+1}^j \right)
\]

\[
t_i^\infty = \hat{x}_1^T p_j = p_{i+1}^j - p_i^j
\]
Properties of Subdivision

- Flexible modeling
  - Handle surfaces of arbitrary topology
  - Provably smooth limit surfaces
  - Intuitive control point interaction

- Scalability
  - Level-of-detail rendering
  - Adaptive approximation

- Usability
  - Compact representation
  - Simple and efficient code