Animating Complex Hairstyles in Real-Time

Nadia Magnenat-Thalmann and Pascal Volino
MIRALab, University of Geneva

Real-Time Animation of Hairstyles

- Managing Complexity of Hair Simulation
  - More than 100,000 hair strands
  - Mechanical behavior of individual strands
  - Collisions and friction on the skull
  - Collisions and friction between strands
  - Physical state (wetness, styling products)
  - Aerodynamics

- No chances to simulate an explicit mechanical model in real-time.

Real-Time Animation of Hairstyles

- Ideas for Speeding Up Hair Simulation
  - Simplification of the mechanical model
  - Reduction of the degrees of freedom
  - Macroscopic approximations
  - Interpolation

- Techniques
  - Wisp or Cluster models
  - Particle systems of variable topology
  - Volume hair models
  - Free-Form Deformations

Real-Time Animation of Hairstyles

- Wisp or Cluster Models
  - Defined by Watanabe et al [1989]
  - Interpolation on Guide Hairs by Chang et al [2001]
  - Multilayer colliding clusters by Plante et al [2001]
  - Hair strips by Koh et al [2000, 2001]
  - Thin shell approach by Lim et al [2000]
  - Advanced collision handling by Lee et al [2001]

- Level-of-Detail
  - Wisp-tree by Bertails et al [2003]
  - Multiresolution Clusters by Kim et al [2003]
  - Strand-Strip-Cluster adaptive by Ward et al [2003]
Real-Time Animation of Hairstyles

• Other Fast Simulation Models
  – Loosely Connected Particles by Bando et al [2003]
  – Short Hair Model from Guang et al [2002]

• Volumic Models
  – Vector Fields from Yu [2001]
  – Fluid Vector Fields from Hadap et al [2000, 2001]
  – Unsuitable for real-time simulation.

• Free-Form Deformation Models

1. Real-Time FFD Hair Animation

• The main idea: Deforming the complete hairstyle using a mechanically-animated Free-Form Deformation lattice.

• Main advantages:
  – Drastic and controllable reduction of the number of degrees of freedom of the mechanical model
    • => Real-time mechanical simulation
  – Simple and fast interpolation scheme for computing the deformed hairstyle
    • => Real-time motion of any feature of the hairstyle
  – Any hairstyle can be animated
    • => Versatility and design simplicity
2. FFD Hairstyle Deformation

• Interpolating Hairstyle Features in the Lattice
  – Feature locations defined by weighted sums of lattice nodes
    \[ p = \sum_i w_i p_i \]
  – Different interpolation schemes for precomputing weights
    Linear: Speed (3D: 8 nearest nodes)
    Quadratic: Smoothness (3D: 27 nearest nodes)

• Attaching Strand Roots on the Skull
  – Attachment of the hair strands on the skull should be ensured whatever the deformation
  – Strand roots should be defined by the rigid motion of the skull only
  – Continuous transition between rigid motion \((\delta = 0)\) and deformed lattice \((\delta = 1)\) along the hair
    \[ p = \sum_i w_i (\delta p_i + (1-\delta)R_{\lambda(0)}p_i^*) \]

3. Animating the FFD Lattice

• Mechanical Properties to be Simulated
  – Mechanical behavior of hair:
    • Density, Elasticity
    • Interactions between strands
  – External forces exerted on hair:
    • Gravity
    • Aerodynamic effects
  – Collisions between hairs and other objects:
    • Body parts: Skull, shoulders…
    • Other objects
3. Animating the FFD Lattice

- Building Blocks: Lattice Stiffners
  - Mechanical interaction between lattice nodes
    - Weighted contributions of lattice nodes
  - Viscoelastic behavior law \( \sigma(\varepsilon, \varepsilon') \)
    - Relating lattice forces \( f_i \) to positions \( p_j \) and speeds \( p_j' \)

\[
f_i = w_i \sigma \quad \text{with} \quad \varepsilon = \sum_i w_i p_j \quad \text{and} \quad \varepsilon' = \sum_i w_i p_j'
\]

- Particular Lattice Stiffners
  - Lattice Attachment
    - Relates one location of the lattice to a given point in space
      - Weights: Linear interpolation coefficients of the location in the lattice
  - Lattice Spring
    - Relates two locations of the lattice
      - Weights: Linear interpolation coefficients, positive and negative

- Hair Strand Discretization
  - Creating lattice springs between grid edges (>45°)
  - Creating lattice attachment on root

- Mass of each strand distributed on the lattice nodes using weights of linear interpolation of strand segment extremities
3. Animating the FFD Lattice

- **Decimation of the Model**
  - Number of lattice stiffeners reduced at will
  - Similar stiffeners are consolidated
  - Parallelism and projections in the space of lattice node weights
  - Optimal accuracy - speed tradeoff
    - Initial strands
    - Initial model: 12100 strands, 3500 attachments
    - Low decimation: 800 strands, 200 attachments
    - High decimation: 200 strands, 50 attachments

- **The Ether Model**
  - Weak viscoelastic forces attaching the lattice nodes to rest position (rigid motion of the head)
    - Modeled as lattice attachments
    - Stabilize and damp the motion of the hairs
    - Improve the robustness of the model for realistic or not-so-realistic head motions
    - Additional custom parameters for simulating hair stiffness (short hair, styling gel, ...)
    - May include additional physical effects (aerodynamics)

- **Collision Effects**
  - Between the hair and the body
    - Head
    - Shoulders
  - Metaball-based model of body parts
    - Approximate modeling with a low number of primitives
    - Easy animation of body deformations
    - Attached to the rigid head motion (skull) or the body skeleton (shoulders)

- **Collisions with Metaballs**
  - 6th-order polynomial metaballs (n=3) modeled as lattice attachments
    - Potential: $\phi = \begin{cases} \frac{1}{r^6} & \text{if } s \geq 0 \\ 0 & \text{elsewhere} \end{cases}$ with $s = \frac{r^6 - \varepsilon^6}{r^6}$
    - Force: $\sigma = \begin{cases} \frac{6}{r^5} (2\varepsilon^3 - s^3) (s + \varepsilon) & \text{if } s \geq 0 \\ 0 & \text{elsewhere} \end{cases}$
3. Animating the FFD Lattice

- Customizing Metaballs on Lattice Nodes
  - Low number of metaballs
  - Their center are attached to the skeleton
  - Their radius is customized to each lattice node according to its position

\[ e_i = r_i^2 m_i \gamma \]

- Normalizing the strength of the metaballs
  - The base potential of the metaball should be chosen so as to give same repulsion (acceleration) whatever:
    - The mass of the lattice node
    - The radius of the metaball

\[ e_i = \rho_i \frac{1 - \exp(-\frac{\rho_i - \rho_0}{\rho})}{\rho - \rho_0} \]

3. Animating the FFD Lattice

- Customizing Metaballs on Lattice Nodes
  - The metaball radius is chosen so as to:
    - Keep nodes outside the skull to a given distance from the surface
    - Prevent nodes inside the skull from moving deeper

- Metaball-Based Collision Handling
  - Approximate collision response
  - Low computational overhead
  - Suited for animation
3. Animating the FFD Lattice

- **Numerical Integration**
  - Particle system integrated by using the implicit Inverse Euler method
  - Using the Conjugate Gradient as linear system solver
  - On-the-fly matrix assembly for capturing all the nonlinearities of the mechanical system
  - Good robustness with any mechanical system when using constant time steps

4. Scalability and Level-of-Detail

- **Performance and Level-of-Detail**
  - Computation times for a 1/25 s frame on a 3GHz Pentium4 PC computer

<table>
<thead>
<tr>
<th>Mech Mod</th>
<th>Lat Size</th>
<th>0 Att</th>
<th>0 Spr</th>
<th>0 Meta</th>
<th>50 Att</th>
<th>50 Spr</th>
<th>50 Meta</th>
<th>100 Att</th>
<th>100 Spr</th>
<th>100 Meta</th>
<th>200 Att</th>
<th>200 Spr</th>
<th>200 Meta</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10x10</td>
<td></td>
<td>1.1 ms</td>
<td>5.2 ms</td>
<td>10.1 ms</td>
<td>13.8 ms</td>
<td>21.4 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5x5x5</td>
<td></td>
<td>0.1 ms</td>
<td>0.2 ms</td>
<td>2.1 ms</td>
<td>3.8 ms</td>
<td>7.6 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Options for Adjusting the Accuracy Tradeoff**
  - Number of lattice attachments
    - The more attachments, the more accurate the mechanical behavior of the hairs
  - Size of the free-form deformation grid
    - The finer the grid, the richer and diverse the deformation patterns of the hair
  - Number of metaballs
    - The more metaballs, the more accurate the collisions between the hair and the body
4. Scalability and Level-of-Detail

- Benefits of the FFD Model
  - Scalability, for efficient LOD implementations
  - Compatible with any hair rendering method
  - Weak reliance on the strand nature of hairs
  - Total freedom of hairstyle design using any standard design tool