Current Methods for Hair Modeling, Simulation, and Rendering

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Background[1]

Due to the extreme complexity of hair, its simulation continues to be an active research topic. Development of a realistic hair simulation requires solutions for modeling, physical simulation, and an accurate reflection model for rendering. The unique behavior of hair has lead researchers to question whether it should be handled as individual strands or a general volume of hairs and successful methods have been developed for both approaches. No technique has become the standard and the appropriateness of a solution may depend on its intended application, but as the computing power of hardware increases, the solutions for simulating realistic hair continue to improve.

Modeling

Modeling an initial computer generated hairstyle is generally broken down into three stages. A hair strand representation must be connected to a scalp, the general shape of the hair volume must be defined, and then finer details and hair properties can be added.[1] To attach hair to the scalp, methods have been simplified to avoid manually placing thousands of hairs. Common approaches include 2D placement and distribution using uniform or wisp based methods. 2D placement techniques utilize a textured map that is then projected onto the scalp to represent hair placement locations. This method is intuitive for 3D artists to control the hair modeling process and similar 2D maps can also be used as input to vary other hair properties

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[1] Ward, K., Bertails, F., Kim, T., Marschner, S. R., Cani, M., and Lin, M. C. 2007. A Survey on Hair Modeling: Styling, Simulation, and Rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 2 (Mar. 2007), 213-234. DOI= http://dx.doi.org/10.1109/TVCG.2007.30

such as length and color across the scalp.[1] The uniform and wisp distribution techniques allow less artistic control as strands are randomly distributed across each region. Kim's technique uses uniform distribution to initially place the hairs, but then allows each hair to be assigned to an owner cluster for better control.[2] Once hair strands have been distributed over the scalp, the hair must then be modeled to give a desired form and style to the hair as a volume. Since the styling stage is almost always carried out by a digital artist, most systems rely on parametric representations of strands or wisps to provide an intuitive interface for manipulating the hair shape.[2] These generalized shapes can easily be manipulated like any standard NURBS geometry, but then hair clusters are then generated using the volume and placement of the geometry as a guide. In situations where less artistic control and a more natural hairstyle is desired, physical based animation can be used to produce an initial style. Anjyo observed that the single anchor point of a strand of hair is similar to a Cantilever Beam which is embedded in a support at one end.[3] Utilizing this principle, the properties of a cantilever beam can be used to set the rest pose of a hair strand. However, due to the stiff nature of a beam, further force calculations must be applied to the strand to obtain a natural shape. Based on observation, Hadap and Magnenat-Thalmann developed a creative approach to model initial hairstyles as if they were a fluid flowing around obstacles. Dynamic forces such as steams, and vortices are then used to manipulate the form of the hair into the desired style.[2] Borrowing from the field of computer vision and image based modeling, attempts have been made at automatic reconstruction of

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[2] Hadap, S., Cani, M., Lin, M., Kim, T., Bertails, F., Marschner, S., Ward, K., and Kačić-Alesić, Z. 2007. Strands and hair: modeling, animation, and rendering. In *ACM SIGGRAPH 2007 Courses* (San Diego, California, August 05 - 09, 2007). SIGGRAPH '07. ACM, New York, NY, 1-150. DOI= http://doi.acm.org/10.1145/1281500.1281689

[3] Ward, K., Bertails, F., Kim, T., Marschner, S. R., Cani, M., and Lin, M. C. 2007. A Survey on Hair Modeling: Styling, Simulation, and Rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 2 (Mar. 2007), 213-234. DOI= http://dx.doi.org/10.1109/TVCG.2007.30

hairstyles from images. Initial implementations using images were able to generate the volume of simple hairstyles, but then strands were generated within the volume with no guarantee of proper directionality. A better approach by Grabli records images of a subject's hair under highly controlled lighting conditions to produce perfectly registered images with the hair's directional data intact.[4] This method was able to partially reproduce the hair model, but additional filtering and viewpoints are required to improve upon the results. All of these geometry based solutions gain their volume from manual shaping. Physically-based modeling approaches rely on the natural volume created by hair self-collisions to build hair shapes and fluid based approaches must rely on vector fields and dynamics to produce volume.[4] Relying on collisions and dynamics becomes computationally expensive. Because of this, Lee and Ko proposed a method that creates volume bases on the latitude of the strands. Head hull layers are created for each layer of pores and hair-head collisions prevent hair layers from "sinking" into each other and losing the initial volume.[4] Once a global hair shape has been formed, it is often desirable to refine the localized properties of the hair to generate a more unique and realistic appearance. These features often model the finer effects of water or styling products on the hair shape. During this process, local details such as curls, waves, and more natural noise is added to make the hair appear less manufactured.[4] Many of these details can be modeled using procedural functions and modifying magnitude, frequency, and phase of offset functions. Random terms are also incorporated to prevent hair clusters from becoming too uniform and synthetic. To generate these variations, Bertails proposed a mechanical model for static elastic rods. Based on the ellipticity of hair fibers and potential energy minimization, natural curliness can be simu-

[4] Ward, K., Bertails, F., Kim, T., Marschner, S. R., Cani, M., and Lin, M. C. 2007. A Survey on Hair Modeling: Styling, Simulation, and Rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 2 (Mar. 2007), 213-234. DOI= http://dx.doi.org/10.1109/TVCG.2007.30

lated. Bertail's approach shows great potential for prototyping accurate fiber interactions, but it currently isn't appropriate for generating complex hairstyles.[5] For most applications where artist control is a concern, a system of guide curves or geometry is still preferable. Choosing an appropriate hair modeling procedure depends highly on the application and future intentions for simulation.

Simulation

When producing hair simulation systems for feature film production, believability and artistic control take priority over complete accuracy. Due to its overwhelming complexity, no single accurate equation exists to model the motion and interactions of human hair. Therefore, a few basic properties of realistic hair motion have been observed to approximate a realistic simulation. Hair is generally inelastic and as a result, hair should maintain a fixed length. The only constraint against a strand is at the root point. This constraint requires that when the parent object moves, the hair must move, but otherwise the hair has free local movement. During motion, the hair is subject to inertia and a high coefficient of friction. The magnitude of the friction depends on the scale-like composition of each strand. Depending on the strand orientation and direction of motion, the amplitude of friction can vary. After motion, the hair tends to return to its former shape and volume.[6] On a basic level, strands of hair can be represented as a series of nodes connected at a fixed distance. A Verlet integration can then be used to simulate the

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[5] Ward, K., Bertails, F., Kim, T., Marschner, S. R., Cani, M., and Lin, M. C. 2007. A Survey on Hair Modeling: Styling, Simulation, and Rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 2 (Mar. 2007), 213-234. DOI= http://dx.doi.org/10.1109/TVCG.2007.30

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strands. For many years, Verlet integration was chosen over the Euler method due to the prior's stability. However, as computation power increases, it has become possible to use implicit integration methods at a greater cost but with guaranteed stability.[7] After calculating the integration at a particular time step, the computed position must be checked for adhesion to the basic principles of hair motion defined above.[8] As a solution to this possible variation, iterative correction steps can be performed until the calculated position conforms with the expected set of positions. Upon further observation of physical hair behavior, it was decided that a tree structure could better simulate the way hair clusters and moves together due to friction and self-collisions. An Adaptive Wisp Tree builds a hierarchy of nodes that allow strands to react to individual forces, while maintaining a more global clumping effect.[8] A majority of modern hair simulation methods are based off of a spring model, including the production models of Pixar and ILM. The spring based model returns to the basic idea of a chain of nodes at fixed distances, but a second chain of reference nodes is placed slightly above the hair nodes. Each node is assigned a lumped mass of a portion of the hair. The hair nodes are connected to the reference nodes using springs that can be used to compensate against gravity for the desired hair effect. Linear springs are used to maintain the length of each segment, while angular springs are used to maintain orientation of the strands.[7] This approach is well suited to maintaing a modeled rest position for the hair, while allowing the hair to move freely when affected by other forces. Similar techniques have frequently been used to simulate cloth, skin, and flesh, so the

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[7] Hadap, S., Cani, M., Lin, M., Kim, T., Bertails, F., Marschner, S., Ward, K., and Kačić-Alesić, Z. 2007. Strands and hair: modeling, animation, and rendering. In *ACM SIGGRAPH 2007 Courses* (San Diego, California, August 05 - 09, 2007). SIGGRAPH '07. ACM, New York, NY, 1-150. DOI= http://doi.acm.org/10.1145/1281500.1281689

[8] Ward, K., Bertails, F., Kim, T., Marschner, S. R., Cani, M., and Lin, M. C. 2007. A Survey on Hair Modeling: Styling, Simulation, and Rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 2 (Mar. 2007), 213-234. DOI= http://dx.doi.org/10.1109/TVCG.2007.30

mass-spring method has become appreciated for its versatility in solving dynamic simulations.[7] In order to obtain a realistic rest position for the physical hair and simulate accurate interaction with solid surfaces, two different types of collisions must be handled. Collisions between the hair and surfaces must be solved to prevent interpenetration and hair to hair collisions must be handled to preserve volume and model the friction between strands. Collision detection varies depending on the modeling method used to visualize the hair. In strand based systems, each strip of hair is just a piece of geometry that can be handled using traditional collision detection with a minimal number of computations. Other methods that define a greater number of individualized strands may require sections of the hair to be enveloped in a geometric representation or alternatively, dynamic repulsion or fluid forces can be applied to prevent interpenetration.[9] Currently, all simulation methods strive for realism while trying to balance a reasonable cost for their applications. In production environments, being able to manually influence and control the hair without breaking the realism of the simulation is also a top concern when choosing the appropriate simulation model.

Rendering

The composition of hair fibers is extremely complex and important to defining a model to accurately approximate its light interactions. A single hair fiber is formed by the core, or cortex, the cuticle, several layers of scales, and the medulla. Hair is an anisotropic material, meaning that it reflects more light in the direction of the strand, but it is also a transparent material

[9] Ward, K., Bertails, F., Kim, T., Marschner, S. R., Cani, M., and Lin, M. C. 2007. A Survey on Hair Modeling: Styling, Simulation, and Rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 2 (Mar. 2007), 213-234. DOI= http://dx.doi.org/10.1109/TVCG.2007.30

with light absorbing pigments.[10] Since the structure and pigment of a person's hair can vary immensely, achieving an accurate reflection model that suits all hair types continues to be a challenge. Initial difficulties are caused by the lack of diameter thickness of a single strand of hair. Models that try to render each hair explicitly are faced with the problem of rendering a hair that has a projection much smaller than a single pixel. Pixel blending solves the issue of under-sampling by blending discontinuities, but implicit shading models produce better visual results. An early, but highly successful and frequently used reflection model for the anisotropic properties of hair was proposed by Kajiya. Kajiya's hair model integrates a standard Lambertian shading model over half the visible circumference of a representative cylinder to compute a diffuse component. Next, the anisotropic specular component is determined by finding the cone of reflected light that scatters at mirrored angles along the tangent of the hair geometry. Utilizing the viewpoint vector and the reflection vector, the Phong equation is solved for specular highlights. The sum of the diffuse and specular terms yield a final intensity value.[1] Kajiya's solution for hair rendering is a very efficient approach that produces acceptable results; due to the small number of calculations, his model has become popular for real-time solutions. Beyond anisotropic reflection, real hair also exhibits subsurface scattering. In order to achieve a more realistic hair model, Marschner proposes a reflection model consisting of reflection, transmission to transmission, and transmission to reflection to transmission components. This division of components accounts for highlight separation as light emerges as different angles. His proposed method assigns identical fibers the same scattering function, but the measurement of radiant power intercepted increases with the fiber's width. Also, unlike Kajiya's model,

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[10] Bertails, F., Hadap, S., Cani, M., Lin, M., Kim, T., Marschner, S., Ward, K., and Kačić-Alesić, Z. 2008. Realistic hair simulation: animation and rendering. In *ACM SIGGRAPH 2008 Classes* (Los Angeles, California, August 11 - 15, 2008). SIGGRAPH '08. ACM, New York, NY, 1-154. DOI= http://doi.acm.org/10.1145/1401132.1401247

Marschner better synthesized the structure of a hair fiber by adding an azimuthal component that described the focusing and dispersion of light, absorption due to interior pigments, and a fresnel reflection at each interaction.[11] Currently, Marschner's model is considered the most complete physically based hair scattering solution in the industry. After the light interactions for one strand have been modeled, it is then necessary to evaluate the light interactions for an entire volume of strands. Hair is a semi-translucent material; however, light is still blocked from reaching underlying layers and portions of the roots. At the same time, light is also still being transmitted and scattered. Achieving this effect in computer generated imagery requires sampling the global hair geometry and lighting contributions. With each slightest change to the hair or lighting the shadowing must be recomputed. A less expensive solution has been to use radiosity to generate the ambient occlusion of the hair to approximate the effects of self-shadowing. More accurate approaches are based on a density function of the hair volume. A newer approach is the deep shadow maps technique. Rather than storing a single depth, deep shadow maps store a piecewise linear approximation of the transmittance function and produce much more realistic shadowing results. Hair translucency can also be modeled by the transmittance function. Opacity shadow maps, proposed by Kim, generates a set of layered opacity maps from the light direction to represent the light penetration for a subset of Z-depths.[11] By interpolating the maps, opacity shadow maps quickly produce reasonable self-shadowing effects. The complexity of defining light interactions of hair as both individual strands and a collective volume continues to be a problem for achieving believable computer generated hair.

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[11] Bertails, F., Hadap, S., Cani, M., Lin, M., Kim, T., Marschner, S., Ward, K., and Kačić-Alesić, Z. 2008. Realistic hair simulation: animation and rendering. In *ACM SIGGRAPH 2008 Classes* (Los Angeles, California, August 11 - 15, 2008). SIGGRAPH '08. ACM, New York, NY, 1-154. DOI= http://doi.acm.org/10.1145/1401132.1401247

Hair in the Production Environment

Recently, Pixar Animation Studios released a tech memo providing valuable insight into their hair simulation process and how they have built upon several of the methods previously mentioned. The technical artists at pixar propose that the simulation and realistic rendering of hair relies heavily on collective properties, and it should therefore be represented as a volume rather than individual strands. Their approach is based on the observation that hair behaves and interacts with the environment as a bulk entity. As an example, it is demonstrated that we think of hair interacting with light as a surface with a normals despite there being no solid surface definition. Surprisingly, Pixar's modeling approach is most similar to that of Hadap and Magnenat-Thalmann with a mix of node chain hairs and a fluid force representation of the dynamics and additional inspiration was taken from particle based smoke models. Initially, the hair's structure is defined by a set of key hairs that are then interpolated. To define the illumination and simulation properties of the hair, a Cartesian voxel grid is created. The hair density at each vertex of the grid is calculated to construct a volume representation. The actual volume is then produced by summing up the spacial influences of the vertices of the key hairs. An isosurface can be constructed from the volume definition and the surface provides a shading normal that can be used to render hair as a collective. The density values also serve as valuable input for simulation forces. Each individual hair is rendered using Kajiya's illumination model, but that shading normals from the isosurface are used to alter the illumination to provide more realistic appearances. Pixar's approach to hair simulation is fairly standard. They utilize a spring-mass based model that is applied to the key hairs and then interpolated over the rest of the strands. Object collisions are handled by treating each hair strand as a set of fluid particles. To handle hair to hair collisions, particle velocities are spatially diffused. The hair particles are grouped into a voxel grid and energy transfer is modeled after the second order Laplacian diffusion in Newtonian fluids. This model causes particles to be affected by their neighbor's velocity, maintaining the appearance of the hair as a whole. To smooth the hair and prevent interpenetration, nearby strands are constrained to similar velocities. Once the hair has been realistically simulated, the hair must then be able to be controlled or directed without looking unnatural. To handle this problem, Pixar has decided is is best to direct the hair to a target shape using a created force while minimizing the amount of energy introduced into the scene. Density grids are generated for both the staring and ending shapes. To transition between each grid, a gradient force is created. This force naturally pushes the hair particles into their new positions. By emphasizing the collective nature of hair and its fluid behavior, Pixar Animation has been able to achieve realistic hair simulation while maintaining an appropriate level of directability to suit their production pipeline.**[12]**

[12] Petrovic, L., Henne, M., and Anderson, J. 2005. Volumetric methods for simulation and rendering of hair. Tech. Rep. 06-08, Pixar.

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