Game-Ready Hair in Minutes! Hair Mesh Modeling with Physics

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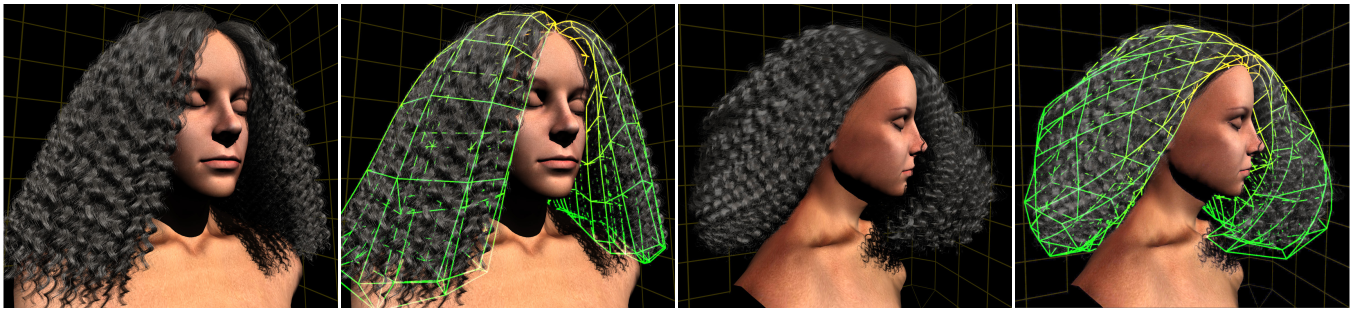

Figure 1: *An example hair model prepared with our system with and without displaying its hair mesh as a wireframe model, (left) resting under gravity and contact, and (right) in motion, simulated using our integrated physics engine that deforms the hair mesh due to head motion.*

Abstract

We present a physics-guided Hair Mesh modeling system for producing game-ready hair models from scratch in minutes! As opposed to hair cards or stripes that are surfaces with hair textures, a Hair Mesh is a volumetric structure that is used for defining a fully detailed strand-based hair model. Hair Meshes are highly effective in hair modeling and simulation. Recently, Hair Meshes have been shown to be orders of magnitude cheaper for real-time rendering on the GPU, as compared to alternative strand-based hair representations. The physics-guided modeling interface we present significantly simplifies the process of preparing a Hair Mesh, along with specifying customized parameters for the physics system that match the target hairstyle, producing hair models that are ready to be simulated and rendered within a game engine.

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1 Introduction

We use the term *Hair Mesh*, coined by Yuksel et al. [2009], to refer to the volumetric embedding that is used for defining strand-based hair models. Individual hair strands are generated within the volume of a Hair Mesh and then deformed via a set of procedural styling operations that produce their small-scale details.

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Yuksel et al. [2009] have shown that Hair Meshes are highly effective for modeling hair, as they allow the user to specify the outer shell of a hair model, while the interior of its volumetric structure is maintained automatically. This brings hair modeling, a previously challenging specialized task, close to polygonal modeling, which is used for modeling virtually all other types of objects, including the character that wears the modeled hair. Wu and Yuksel [2016] have shown that Hair Meshes can be used for real-time hair simulation. More recently, Bhokare et al. [2024] have demonstrated that Hair Meshes allow real-time hair rendering on the GPU that is more than an order of magnitude faster than alternative strand-based hair rendering methods and requires orders of magnitude less data, achieving rasterization speeds of just a few milliseconds for hundreds of characters, using level-of-detail techniques to seamlessly simplify the rendered geometry of their otherwise fully-detailed hair models.

Yet, modeling a Hair Mesh requires polygonal modeling skills, which are difficult to master. Depending on the complexity of the Hair Mesh, modeling it can be a labor-intensive process even for experienced users. Furthermore, after a Hair Mesh is ready, preparing it for simulation involves additional steps, including customized parameter tuning for each hairstyle.

We overcome these inconveniences in working with Hair Meshes using a new physics-guided modeling system. Our system integrates hair dynamics into the polygonal mesh modeling framework for Hair Meshes. This provides two significant improvements:

(1) It allows the use of gravity, collisions, and hair dynamics to aid polygonal shaping operations, making it much easier to form a natural hair shape using various high-level tools.
(2) The integrated physics engine allows interactive adjustment of the hair dynamics parameters while modeling and offering the simulation parameters as additional shaping tools.

Our system not only makes it easier to provide a natural shape to the modeled Hair Mesh (Figure 1), but it also automatically pro-

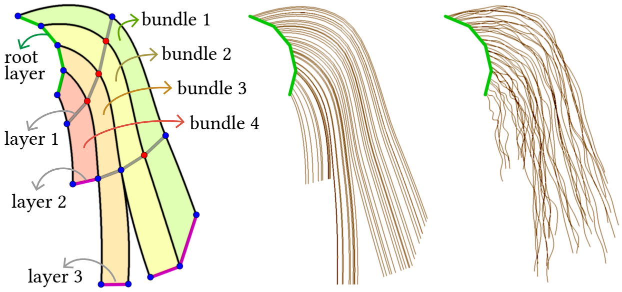

Figure 2: *2D illustration of (a) a Hair Mesh with 4 bundles extruded from a scalp mesh at the root layer, (b) the hair strands generated from the Hair Mesh, and (c) the strands after applying procedural styling operations (source: [Yuksel et al. 2009]).*

duces simulation-ready outputs. Since the Hair Mesh is modeled with gravity and collision constraints, its internal simulation parameters are determined as a part of the modeling process. Using the same physics system, the resulting Hair Mesh models require no additional treatment to be imported into the target game engine.

2 Hair Meshes

A Hair Mesh is a volumetric structure used for defining the high-level shape of a hair model. It is typically generated starting from a polygonal mesh of the scalp surface (i.e., the root later). The polygons of this root later are extruded to form volumetric enclosures that define hair bundles, as illustrated in Figure 2a. Notice that, unlike typical polygonal extrusions, the volumetric structure is maintained and the extruded bundles are curved.

The individual hair strands are generated within these bundles (Figure 2b). Then, procedural *styling* operations are applied to define the small-scale shapes of individual hair strands (Figure 2c).

A Hair Mesh can be shaped using typical polygonal modeling tools. Because it is a volumetric structure, its interior is not visible when rendered as a solid object (before generating hair strands). Therefore, Yuksel et al. [2009] describe an automated approach for shaping the interior of a Hair Mesh based on its outer surface. As a result, the user only needs to model the outer shell of a Hair Mesh, using familiar polygonal modeling tools and concepts.

Hair Meshes have been an integral part of the *Hair Farm* [Cyber Radiance LLC 2012] software plugin for 3ds Max. Hair Farm offers a variety of tools for modeling and animating Hair Meshes, along with many other tools for styling the generated hair strands.

3 Hair Rendering with Hair Meshes

Recently, Bhokare et al. [2024] have shown that Hair Meshes can be used for accelerating real-time hair rendering on the GPU. In this approach, hair strands are generated at render time and never stored. As a result, the hair models represented using Hair Meshes require orders of magnitude less storage, and they render more than an order of magnitude faster than pre-generated hair models. Combining this with level-of-detail techniques that automatically determine the number of hair strands to be generated while rendering, this approach can rasterize hair models for hundreds of characters within a millisecond, making strand-based hair rendering an affordable solution even for low-end GPUs and mobile devices.

Bhokare et al. [2024] also describe a set of procedural styling operations that are fast to compute on the GPU and can form a wide variety of distinct hairstyles.

4 Hair Simulation with Hair Meshes

Simulating individual hair strands and their interactions with each other is prohibitively expensive for most applications. Therefore, a common approach is simulating a small number of *guide* hairs and deforming neighboring hair strands accordingly [Hsu et al. 2024].

Hair Meshes can be used similarly. Instead of guide hairs, the Hair Mesh extrusions are simulated with hair dynamics. This has several important practical advantages over guide-based simulation:

- **Storage:** Hair simulation with Hair Meshes requires no extra per-hair storage. Guide-based simulation, on the other hand, must store weights and indices for each hair strand vertex, which can take even more space than storing a static strand-based hair model itself.
- **Visual quality:** The styling deformations are defined within the volumetric embedding of the Hair Mesh. Therefore, the hairstyle details can be preserved even with extreme Hair Mesh deformations. Using guide strands, however, each hair strand is interpolated independently, which can easily break clumps and introduce unnatural hair movements, particularly with large deformations.
- **Hair-hair interaction:** Hair Meshes inherently encode the topological connections within the volumetric structure, which can be used for simulating the impact of hair-hair interaction with the high-level representation of the Hair Mesh, without explicitly handling collisions between strands. With guide-based simulation, such topological connections must either be generated before and maintained throughout the simulation or handled via dynamic collisions and friction between simulated guide hairs, which can be expensive.
- **Hairstyle preservation:** It is common for guide-based hair simulation to quickly deviate from the initial shape of the hair model, never to return to its original shape. In fact, even after a few minor deformations, the original hairstyle shape can be unrecoverable. On the other hand, Hair Mesh simulation excels at maintaining the original hairstyle. Unless the topology of the Hair Mesh is dynamically altered during simulation, even after extreme deformations, a Hair Mesh often recovers its original form. The styling parameters are not affected unless modified explicitly. This is a crucial property for game models, which would otherwise lose their hairstyles a few seconds into an animation, unless the hair guides are restored through non-physical intervention.

Our physics simulation is based on *Stable Cosserat Rods* [Hsu et al. 2025] with additional lateral connections and volumetric forces [Wu and Yuksel 2016]. Hard constraints (such as collisions) are handled with *Augmented Vertex Block Descent* [Giles et al. 2025]. The combined simulation forms a fast and stable system for hair dynamics with Hair Meshes that can handle the behavior of various types of hairstyles.

The parameters of this simulation system, such as the stiffness of various forces, vary based on the hairstyle. The small-scale details of a hair model, defined by the procedural styling operations, play an important role in determining the physical properties of a hairstyle. In fact, these styling parameters play a more crucial role in determining the physical properties of a hair model than the shape of the Hair Mesh. For example, curly hair would be more bouncy than straight hair. This can be replicated by lowering the longitudinal stretching stiffness for curly hair, so that the Hair Mesh can extend more easily during simulation.

Therefore, the simulation parameters are exposed in our Hair Mesh modeling framework. In addition, they can be used for shaping the hair model under gravity. The interactive simulation that runs during modeling allows for quickly testing these parameters, which are saved as part of the hair model data, along with the Hair Mesh and the procedural styling parameters.

5 Hair Mesh Modeling with Physics

Our Hair Mesh modeling interface involves some typical polygonal modeling tools. Its main difference is the integration of a real-time Hair Mesh simulation system that is active during modeling.

The integrated Hair Mesh simulation provides several important benefits. First of all, it makes various shaping operations substantially easier than traditional polygonal modeling approaches.

For example, using traditional polygonal modeling tools without the integrated physics system, a Hair Mesh extrusion on a scalp polygon linearly extends it off the scalp surface in the direction of the local surface normal. Since hair typically bends downward under gravity, the user must manually bend the extruded mesh to give it a natural shape. This is not a difficult task for a user with some polygonal modeling experience, for a single polygon extruded up to a few levels. Extruding multiple faces together, however, can be more difficult when different bundles must have different shapes. An often easier alternative is extruding one polygon (or a small number of polygons) at a time, but then completing all the necessary extrusions separately becomes labor-intensive. Although specialized tools in Hair Farm can aid this process, it can still take several minutes to model an initial set of extrusions. Shaping those extrusions afterward can be another labor-intensive process.

With our physics-guided Hair Mesh modeling system, extruded polygons automatically bend down due to gravity. Since the Hair Mesh simulation considers hair-hair interactions and collisions, all polygons of the scalp surface can be extruded all at once. The physics system helps to automatically give the extrusions a natural shape under gravity. After this initial extrusion, high-level tools make further modifications and shaping operations much easier. For example, the lengths of all extrusions can be collectively adjusted either by a target amount or down to a certain height.

Another important benefit of the physics-guided extrusions is that the cross-sectional areas of the bundles automatically become proportional to their corresponding scalp areas. Indeed, a typical hair model would have this property. In fact, our simulation system also considers bundles carrying other bundles on top of them and thereby getting compressed more than the others. It is extremely difficult to achieve such properties using either traditional polygonal modeling methods or other direct hair strand modeling software.

The physics simulation parameters can also be used as shaping tools. For example, the volume of the Hair Mesh model can be adjusted by altering the rest volumes of bundles.

The hair styling operations that are defined within the Hair Mesh volume are based on the texture coordinates of the Hair Mesh, so that they remain fixed while the Hair Mesh animates. These texture coordinates can be copied from the input scalp polygons. However, ideally, the texture-space layout of the hair mesh should follow the shapes of its tip faces. Our system can automatically adjust these texture coordinates during modeling.

Like any other deformable object, if naively initialized, a Hair Mesh sags under gravity as soon as the simulation begins. This can be eliminated using sag-free initialization [Hsu et al. 2022], but it requires properly specifying the contact points of the hair mesh with the character's body, which can be a challenge without a specialized simulation system that can automate this step.

In our system, however, the Hair Mesh model is designed under gravity while the simulation is running. Therefore, our system requires no additional steps for a sag-free initialization. The modeled state of the Hair Mesh already contains the internal forces that preserve the modeled shape of the hairstyle under gravity.

Our system outputs the modeled Hair Mesh together with its styling and simulation parameters. Using the same simulation system within a game engine, these resulting hair models are ready to be placed in game without any additional processing.

6 Conclusion

We have presented a modeling interface for Hair Meshes that integrates hair dynamics with Hair Mesh simulation, making Hair Mesh modeling easier than ever, allowing interactive testing of simulation parameters, and making it possible to prepare game-ready hair models within minutes.

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