

A Survey on Hair Modeling

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Abstract. Hair modeling is a vital research area in computer graphics, aiming to create realistic, controllable, and interactive hair models. Recent advancements in computer vision, deep learning, and physical simulations have significantly propelled the field of hair modeling. This paper provides a comprehensive overview of current hair modeling techniques, including generative models, physics-based approaches, interactive editing methods, deep learning-driven methods, and 3D modeling and reconstruction techniques. The fundamental principles, advantages, limitations, and potential applications of these methods are discussed.

Keywords: Hair Modeling, Deep Learning, Physics-Based Methods, Interactive Editing, 3D Reconstruction.

1. Introduction

Hair modeling poses a significant challenge in computer graphics due to the complexity and dynamic nature of hair. Creating high-quality hair models necessitates not only capturing the geometric shape and appearance but also simulating its behavior under various physical conditions. This review article explores multiple angles of hair modeling technologies, highlighting their evolution and current state.

This dissertation provides an overview of the multifaceted advances in current hair modeling techniques, including generative models, physics-based approaches, interactive editing methods, deep learning-driven approaches, and 3D modeling and reconstruction techniques. The thesis explores in detail the fundamentals, advantages, limitations, and potential applications of these approaches. Specifically, the paper describes how to utilize Generative Adversarial Networks (GANs) and diffusion models for hair generation, how to achieve realistic hair dynamics through physical simulation, and multiple interactive hair editing techniques. In addition, the paper provides insights into the application of deep learning in hair modeling, including hair segmentation, 3D reconstruction, and the generation of high-resolution hair geometries. Finally, the paper provides an overview of 3D modeling and reconstruction methods as well as geometric and graphical modeling methods, and describes the application of image processing and computer vision to hair modeling.

2. Methods of modeling hair

2.1. Generative Model Methods

Zhang, Meng et al. introduced GANs for hair modeling, converting 2D orientation maps to 3D volumetric fields encoding hair occupancy and orientation (Figure 1) [1]. And Zhang M also led other teams proposing a view image-based hair modeling method, with images from four directions and they grow hair strands to produce a realistic 3D hair model [2].



Figure 1. The hair generation performance in [1]

Vanessa Sklyarova et al. proposed a text-conditioned diffusion model for realistic 3D hairstyle generation (Figure 2) [3]. The learned hairstyle representations enable semantic editing. Wenpeng Xiao et al. propose a novel approach for automatically animating blowing hair from a still portrait image, handling high-res images [4]. Chen, H. et al. propose a simple hair generative model [5]. By splitting hair images into color, lighting, and pattern, their model uses a vector field from a sketch layer to generate hair patterns. Qiu H et al. devised a self-enhancing module, framing hair generation as a two-phase process boosting hair synthesis with cutting-edge generative models [6].



Figure 2. The generating hair results in [3]

2.2. Physics-Based Methods

Bertails, F et al. presented a physically-based method for predicting hairstyles, accounting for gravity and collisions, using a mechanically accurate rod model (Figure 3) [7]. Selle A et al. simulated complex hair/hair interactions including sticking and clumping behavior, collisions with objects (e.g. head and shoulders) and self-collisions [8]. Akkermans RLC et al. have developed a multiscale model for human hair mechanics, predicting a linear temperature-dependent decrease in yield stress [9].



Figure 3. Virtual versus real hair ringlets in [7]

Koh CK et al. apply a simple physics model to animate control points efficiently, achieving real-time animation [10]. Hair strips are modeled using parametric surfaces, tessellation, and hair textures. Guang Y et al. proposed a method to model short hair: derive hair style from scalp, generate hair model, apply textures, and animate using physically-based approximation [11]. Zinke A et al. presented a technique for hair reconstruction based on thermal imaging (Figure 4) [12]. By using this technique several issues of conventional image-based techniques, such as shadowing and anisotropy in reflectance, can be avoided. Derouet-Jourdan A et al. proposed a method to convert hairstyles to physics-based models, accounting for gravity and frictional contacts [13].

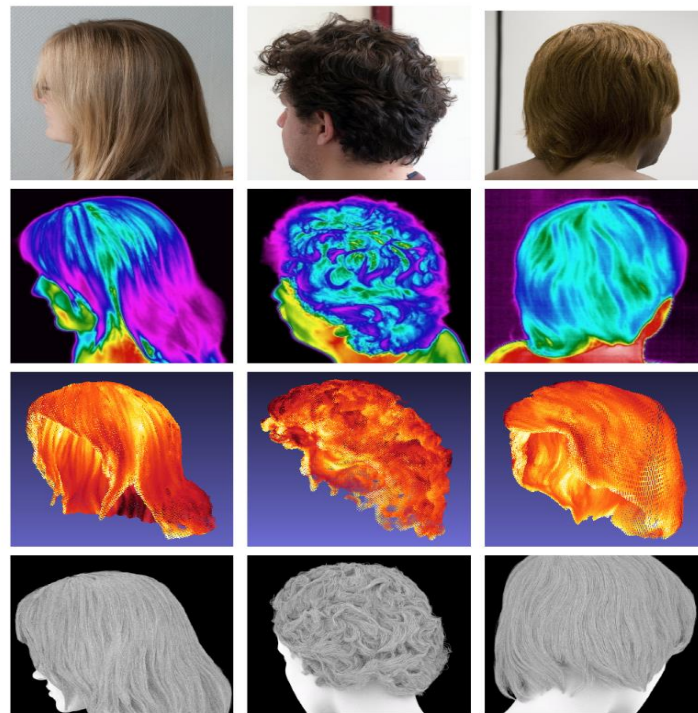


Figure 4. The results of hairstyle reconstruction approach in [12]

2.3. Interactive and Editing Methods

Tan Z et al. proposed an interactive method for portrait hair manipulation (Figure 5) [14]. It separates hair attributes and uses condition modules for precise user control. Wei T. et al. unified text and image conditions in one framework for interactive hair editing, supporting various conditions in a single model [15]. Using the cluster hair model, Xu Z et al. design tool offers comprehensive functionality for interactive hairstyle design, providing two levels of abstraction [16]. Kim T Y et al. introduced Multi-resolution Hair Modeling (MHM) system which enables users to efficiently create and fine-tune various hairstyles [17].

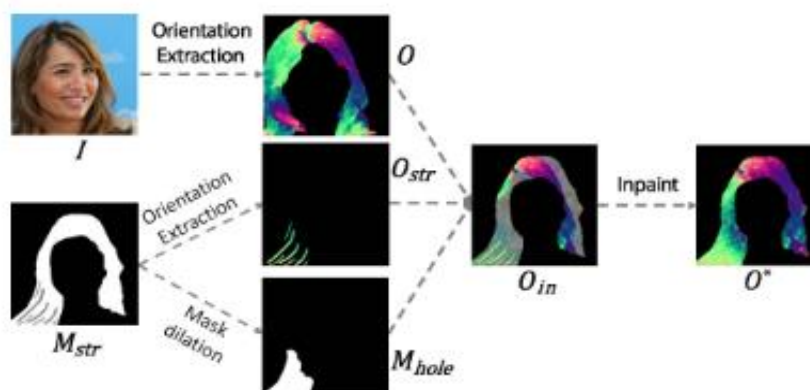


Figure 5. The guided orientation inpainting in [14]

2.4. Deep Learning Methods

Ma Y et al.'s deep network approach combines ToF depth and RGB gradient maps for hair segmentation, refining results with a ToF noise prior (Figure 6) [18].

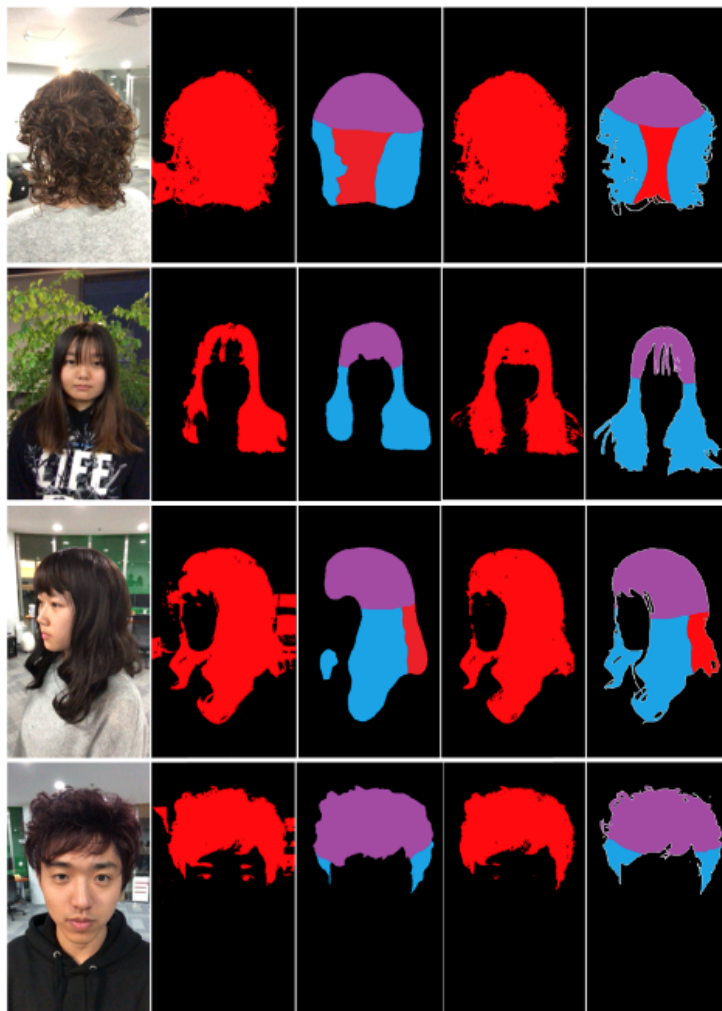


Figure 6. Visual comparisons of RGBD [18] vs. CRFS and DeepLabv3+

Yuxiao Zhou et al. used strand and hairstyle VAEs to encode hair geometry and sparse guide hairs [22]. They also proposed a GAN-based up sampler to generate dense hair, allowing user customization. Zhou Y et al. introduced a deep learning method to generate high-resolution 3D hair geometry from a single image, incorporating collision and visibility considerations [23]. Zhou W, et al. proposed a unified method for hair editing using proxy transfers and feature blending, supporting global and local edits with text, images, and sketches [24].

Vanessa Sklyarova et al. introduced a method for 3D human head reconstruction, focusing on hair and bust. Features improved strand training, latent diffusion modeling, accurate rasterization (Figure 7) [25]. Maxim Nikolaev et al. presented HairFastGAN, a hairstyle transfer model for virtual try-on. Operating in StyleGAN's FS latent space, it enhances inpainting and encoders, achieving high-resolution, near real-time performance [26]. Z Wang et al.'s novel pipeline, uses a volumetric autoencoder to capture and animate real human hair from multi-view RGB images [27]. Kim T et al. proposed a high-quality pose-invariant hairstyle transfer framework using latent optimization without needing multi-view datasets [28].



Figure 7. High-fidelity hair reconstruction from monocular video in [25]

Kips R et al. proposed combining controlled imaging and deep inverse graphics for material capture with non-differentiable renderers (Figure 8) [29]. Chai M et al. presented a neural pipeline for photorealistic hair rendering from 3D models [30]. It uses unsupervised learning to encode hair structure. Li H et al. used an embedding network to predict VAE latent codes and generate hairstyles from images [31]. Their robust, fully automatic framework handles diverse hairstyles, producing 3D models quickly and efficiently, even from challenging images. Lingchen Yang et al. proposed a deep learning framework for modeling dynamic hair from monocular videos [32].



Figure 8. The high visual quality of full model in terms of preserving delicate hair features in [29]

Xiao C et al. system uses self-attention for better stroke understanding and they have created a new dataset for training [33]. Sketch completion tools ease user input. Pektas M.et al.'s method, was evaluated for hairstyle transfer and hair reconstruction [34]. Compared to MichiGAN at 128x128 resolution, their method achieved competitive realistic hair synthesis results and performed better in terms of operating time. Radu Alexandru Rosu et al. introduce Neural Strands, a new framework for precise hair modeling from multi-view images (Figure 9) [35].

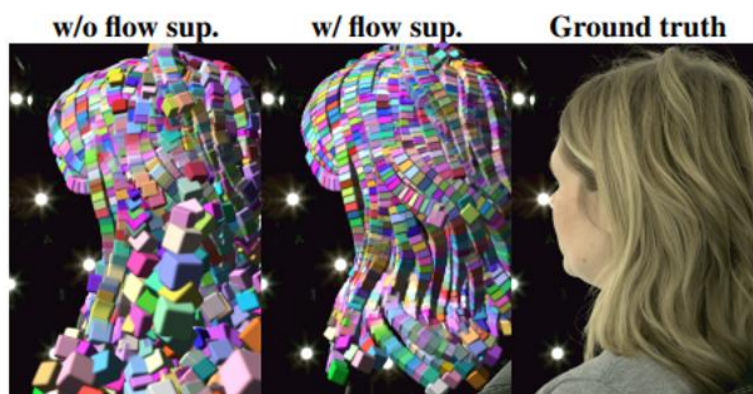


Figure 9. The comparison of 3D models in [35]

2.5. 3D Modeling and Reconstruction Methods

Z. Wang et al introduced a hybrid neural method for hair capture, preserving geometric properties via multi view optical flow tracking [36]. Uses ray marching on 3D scene flow for optimization. Chai M et al. have developed an efficient data-driven hair matching and modeling algorithm, using a large set of 3D hair exemplars (Figure 10) [37]. Chai M et al. proposed a comprehensive system that reconstructs high-quality 3D hair models from a single portrait photo from a single portrait photo, utilizing shading, occlusions, silhouettes, and a helical hair prior [38]. Hu L et al. introduced a novel data-driven framework that digitizes complete and complex 3D hairstyles from a single photo, utilizing a hairstyle database, a structure assembly algorithm to combine multiple hairstyles [39].

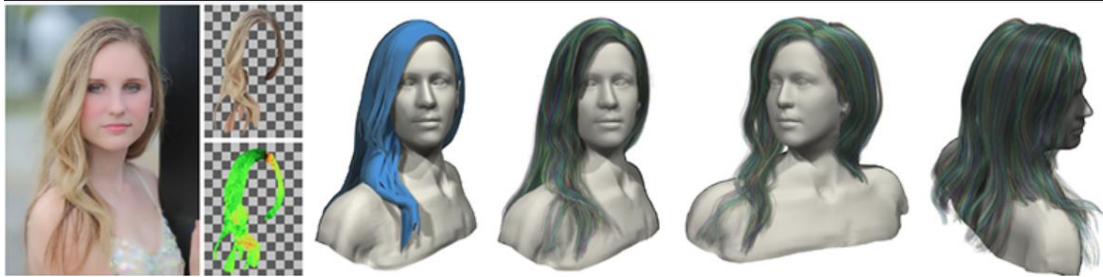


Figure10. Fully automated generation of hair through a single image in [37]

Luo, H. et al.'s GaussianHair representation extends to support editing, relighting, and dynamic rendering of hair offering seamless integration with conventional CG pipeline workflows [40]. Shen Y et al. introduced a deep learning framework generates high-quality 3D hairstyles from 2D sketches enabling interactive multi-view hair modeling (Figure 11) [41]. Paris S et al. introduced a multi-projector, multi-camera approach for triangulating hair geometry, utilizing structure tensors to infer hidden geometry and improve accuracy [42]. Beeler T et al. have presented an algorithm for face capture that successfully reconstructs facial hair fibers as well as the face's underlying skin surface [43]. Zhang M et al. introduced the first fully automatic, high-quality hair modeling pipeline using a single RGB-D camera, featuring an efficient exemplar search for guide geometries [44].

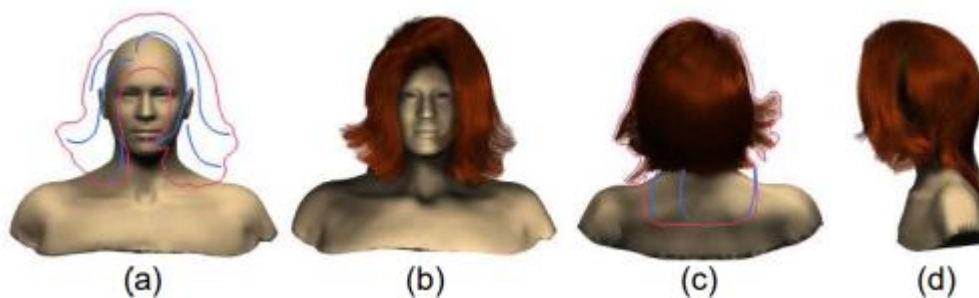


Figure 11. 3D hair reconstruction by 2D sketches in [41]

Jose I et al.'s method enables users to adjust the abstraction level to suit the desired printout scale and achieve consistent visual styles, regardless of the original hairstyle's complexity [45]. Yusuke Takimoto et al. presented a method for estimating 3D orientations, initializing strands smoothly, rendering detailed line segments, reparametrizing strand shapes, and optimizing hair relations hierarchically [46]. Wei et al. proposed a method to model hair geometry from multiple images taken with a handheld camera using local image orientations to synthesize hair fibers, providing flexibility and accuracy in hair model recovery (Figure 12) [47]. Ward K et al.'s representations include strands, clusters, and strips, using subdivision curves/surfaces. ensuring consistent behavior and supports automatic simplification [48].



Figure 12. Example of a typical long wavy hair style in [47]

Noble, P. et al. introduced a technique for modeling and animating cartoon hair [49]. They use an animated NURBS volume to define hair shape and motion, generating hair clumps along its surface. Yu Y et al.'s technique compares hairs to a vector field, efficiently modeling global and local hair flows by combining procedurally defined vector field primitives with local influence [50]. Yamaguchi T et al. developed a method to animate realistic hair using videos of moving hair [51]. Their algorithm grows hair segments, matching orientations from input videos and ensuring temporal smoothness. Liang S et al. described a fully automated system that creates 3D reconstructions from any video enabling superior results compared to 2D methods (Figure 13) [52].

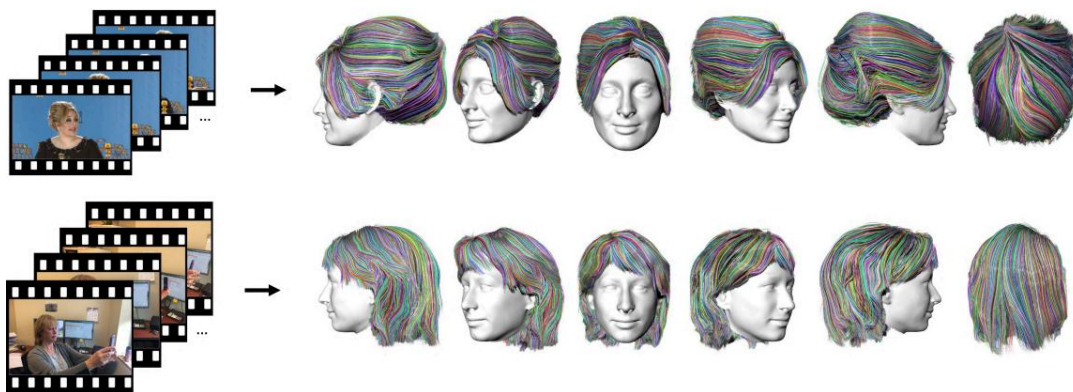


Figure 13. Automatic hair reconstructions produced by video in [52]

Kong W. et al.'s algorithm uses three head images to create a realistic hair volume, guiding hair strands' growth [53]. This produces accurate hair models based on the input images. Sedaghat N et al. introduced a new technique using Continual Cylinders, a 3D geometric object representing hairs as ovals, to easily produce realistic short hairstyles without affecting running time [54]. Attawith et al introduced a novel approach for realistic hair modeling from a hybrid orientation field [55]. The hybrid orientation field is constructed from multiple orientation fields by combining the interior hair strands distribution. Sakai T et al. proposed a new hair representation for 3D CG characters using skeleton-based implicit surfaces [56]. Input skeletons are interpolated, then an implicit hair surface is generated. Zu feng, W. et al 've developed an automated 3D hair modeling method using a virtual head model's geometry (Figure 14) [57]. It simulates hair growth, defines hair density, and maps textures to produce realistic 3D hair with minimal manual input. Qing Zhang et al. presents a method for reconstructing hair dynamics from multi-view videos [58]. It refines initial hair fiber models using

particle and fluid simulations, aligning the dynamics with video inputs and enabling novel hair animations.



Figure 14. 3D hairs of different dividing lines and initial growth directions in [57]

2.6. Geometric and Graphical Modeling Methods

Tao Huang et al. presented a novel real-time technique for rendering strand-based hairs with seamless transitions between different LoD levels while ensuring consistent hair appearance (Figure 15) [59]. Daldegan A et al. introduced a Hair Styler module for designing hairstyles, explain hair rendering using an extended ray-tracing program [60]. Yang X. D. et al. embedded a volume density model in a generalized cylinder to define hair cluster shapes, simplifying global hair design and manipulation [61]. Stheirin A et al. used real functions to define complex solids, creating intricate objects from simple formulae [62]. Nakamura S et al. proposed hair modeling by procedural method to efficiently produce complicated hair such as braid [63]. Sakai T et al.'s technique uses skeleton-based implicit surfaces for hair, non-photorealistic rendering, and auto-animation by adjusting hair skeletons over user-provided keyframes and interpolating control points [64]. Menglei C et al. proposed a fast hair modeling method based on polygonal surface mesh editing to reduce the complexity of current hair modeling systems [65].



Figure 15. Comparison of three different hair path tracking techniques in [59]

2.7. Image Processing and Computer Vision Methods

Piuzé E et al. presented a novel hair representation based on generalized helicoids, characterized by curvature parameters and elevation angle [66]. Bonneel N et al. used a melanin-based model to capture natural hair absorption and matching the photo with a dataset of rendered images to find similar model parameters [67]. Chai M et al. developed an application-driven hair modeling method for portrait manipulation [68]. It uses heuristics and a precise 2D strand tracing algorithm to create realistic 3D hair models. Chen L H et al. presented an integrated system for 3D computer graphics (CG) hair image synthesis based on a trigonal prism wisp model [69]. Yeh, C. et al. proposed a 2.5D cartoon hair modeling method [70]. They segment hair strands from an input image, optimize depth

ordering using a Gestalt psychology-based metric, and fill occluded hair parts. And they also proposed a novel approach to model cartoon hair from an anime-style image which simulates an artist's workflow and has a broader range of view angles than the method proposed by Yeh et al [80]. [2015]. Zhao Min et al. introduced a Gaussian mixture model described hair color distribution, with segmentation thresholds in Cb-Cr determined via Expectation-Maximization [71].

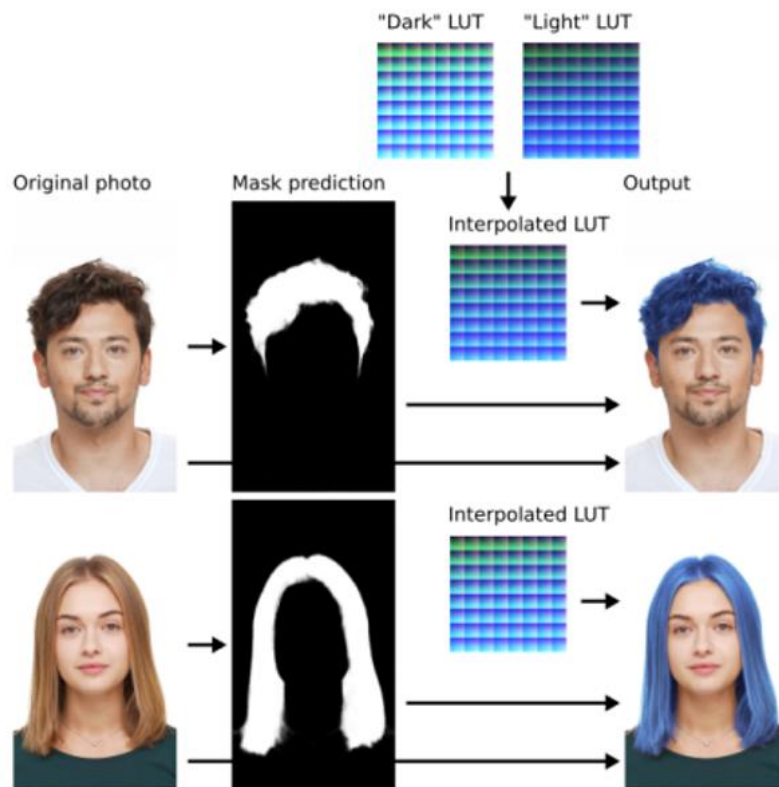


Figure 16. The LUT process in [72]

Tkachenka A et al introduced a mobile solution demands lightness and speed 10-30x with real-time performance at 30+ fps (Figure 16) [72]. Attia M et al. based on the novel proposed methodology for realistic hair simulation using image blending techniques as a tool for validation of hair segmentation and inpainting methods [73]. Ma, Y. et al. presented a computational photography approach from the input front [74]. In particular, their technique can handle challenging segmentation cases such as dark hair, similar hair/background, similar hair/foreground, hair viewed at different angles, etc. Pektas M et al. have created a style transfer method with Hair Blending Block for seamless hair integration, proven superior in tests [75]. It offers real-time hair synthesis and transfer at 11.6 fps. Chaeyeon Chung et al. presented a pose-invariant hairstyle transfer method using optical flow [76]. They use a Semantic-region-aware Inpainting Mask for high-quality occlusion inpainting. Chai M et al. introduced a novel single-view hair modeling method and demonstrating dynamic hair reconstruction from videos [77]. Yu X et al. presented a hybrid image-CAD based solution for creating realistic hair models (Figure 17) [78]. Cheng L et al. introduced a method to generate 3D hair geometry from a front hair image, accurately recovering hair outline and details [79]. Their results show realistic reconstruction from real-world images.

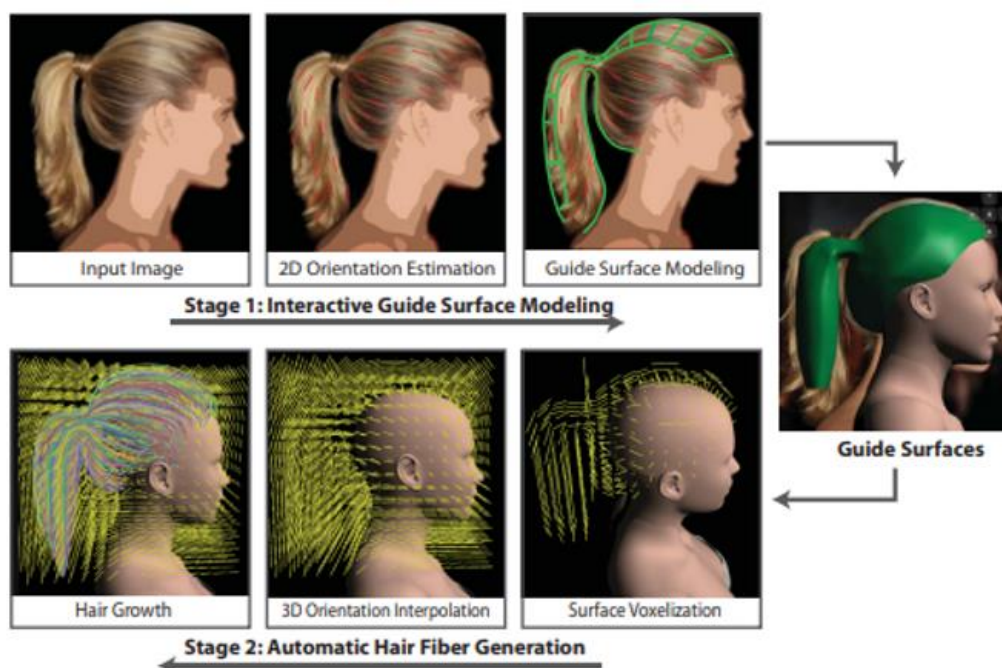


Figure 17. The hair modeling module in [78]

3. Discussion

The seven approaches to hair modeling in computer graphics, including generative models, physics-based simulations, interactive editing, deep learning, 3D modeling and reconstruction, geometric and graphical modeling, as well as image processing and computer vision methods, each possess distinct advantages and limitations. Generative models efficiently generate high-fidelity 3D hair structures but rely heavily on training data. Physics-based methods capture realistic hair dynamics but demand significant computational resources. Interactive editing tools offer intuitive control but can be computationally intensive. Deep learning techniques automate hair modeling with high-resolution outputs but are constrained by data diversity. 3D modeling and reconstruction methods facilitate full automation but may struggle with limited view data. Geometric and graphical methods ensure efficient rendering but face challenges in scattering theory. Image processing and computer vision approaches enable real-time performance on mobile GPUs yet are bound by device capabilities. Each method contributes unique strengths, shaping the landscape of hair modeling in diverse applications (Table 1).

Table 1. Advantages and limitations of different types of methods

Types of Methods		Advantages	Limitation
Generative Model Methods	Hair-GAN [1]	Hair-GAN excels in efficient single-view modeling, enabling high-quality 3D hair reconstructions that are generalizable across diverse hairstyles.	Hair-GAN's performance is limited by its dependency on training data, requiring substantial training time, and lacks support for multi-keyframe animations and partial control.
	HAAR [3]	Smooth Trajectories, style-and-physics awareness, global consistency, simplicity & online usability	Physically biased, long training time, limited keyframe support, motion discontinuities, lacks partial keyframe control
Physics-Based Methods	Multiscale modelling of human hair [9]	Comprehensive multiscale understanding, experimental validation, insight into complex Behavior, design and optimization	Computational complexity, model assumptions and limitations

	Lighting hair from the inside [12]	Illumination Independence, simplified reconstruction, robustness to material properties, applicability to real scenarios	Resolution limitations, sensitivity to environmental factors, data interpretation complexity, cost and availability
	Inverse dynamic hair modeling with frictional contact [13]	Physical consistency, frictional contact handling, inverse dynamics approach, user-friendly interface, improved stability	Input data requirements, model complexity, dependency on initial conditions
Interactive and Editing Methods	HairCLIP [15]	Multi-modal input support, disentangled editing capabilities, high-quality editing results, user-friendly interaction	Dependence on pre-trained models, loss of fine details, computational resource requirements, data dependency
	MHM [17]	Multi-resolution modeling and editing, efficient performance, easy integration, preservation of global hair structure	Steep learning curve, dependency on hardware, model complexity, lack of scalability
Deep Learning Methods	RGBD Images [18]	Intuitive user interaction, leveraging CLIP's representation capability, high-quality editing results, unified framework	Computational complexity, limited dataset bias, scalability, domain adaptation
	HairStep [19]	Comprehensive intermediate representation, high-resolution and detailed results, scalable to different hair types, effective transfer from synthetic to real	Dependence on high-quality input images, sensitivity to occlusions, limited by training data diversity
	MonoHair [21]	High fidelity reconstruction, flexibility in input, staged approach, efficient reconstruction	Challenges with complex hairstyles, limitations of data priors, computational resources, sensitivity to input quality
3D Modeling and Reconstruction Methods	AutoHair [37]	Fully automated process, high efficiency, scalability, high-quality results	Dependency on facial alignment, limited information from single view, training data annotation cost, limited support for complex hairstyles
	GaussianHair [40]	Innovative representations, efficiency, versatility, ease of use	Approximation of the scattering model, limitations of the dataset, calculate resource requirements
	Automatic 3D hair visual effect modeling method [57]	High realism, easy operation, strong applicability	limited style diversity, computational complexity, and limitations of texture mapping,
Geometric and Graphical Modeling Methods		Seamless LoD transitions, consistent hair appearance, efficient rendering, support for animation	Limitations of dual scattering theory, challenges with glints, dependency on guide hairs
Image Processing and Computer Vision Methods	Real-time hair segmentation and recoloring on mobile GPUs [72]	Real-time performance, high accuracy, efficient architecture, scalable and adaptable hair recoloring, seamless integration	Manual effort for LUT creation, dependency on good segmentation, limited by mobile GPU capabilities, generalizability
	2.5D cartoon hair modeling [70]	Efficient 2.5D modeling, automatic layering, hair completion, simplified fluid simulation	Limited to well-segmented hair, no hair-hair interaction, local layering limitations, sensitivity to segmentation accuracy
	Hair modeling from a single anime-style image [80]	Broad viewing angles, simulation of artistic workflow, dynamic hair modeling, automatic layering and overlap resolution	Limitation to simple hairstyles, collision with facial features, inability to reconstruct fully occluded hair

4. Conclusion

Hair modeling techniques have witnessed remarkable progress, encompassing generative models, physics-based simulations, deep learning, and interactive editing methods. Each approach offers unique strengths and application scenarios. Future research may focus on generating even higher-resolution and more realistic hair dynamics, enhancing real-time rendering capabilities, and developing more intelligent interactive editing tools. With advancing computational power and algorithm optimization, hair modeling promises to become even more realistic, efficient, and widely applicable in fields like film, gaming, and virtual reality.

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