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A Survey of Image-Based Techniques for Hair Modeling

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ABSTRACT With the tremendous performance increase of today's graphics technologies, visual details of digital humans in games, online virtual worlds, and virtual reality applications are becoming significantly more demanding. Hair is a vital component of a person's identity and can provide strong cues about age, background, and even personality. More and more researchers focus on hair modeling in the fields of computer graphics and virtual reality. Traditional methods are physics-based simulation by setting different parameters. The computation is expensive, and the constructing process is non-intuitive, difficult to control. Conversely, image-based methods have the advantages of fast modeling and high fidelity. This paper surveys the state of the art in the major topics of image-based techniques for hair modeling, including single-view hair modeling, static hair modeling from multiple images, video-based dynamic hair modeling, and the editing and reusing of hair modeling results. We first summarize the single-view approaches, which can be divided into the orientation-field and data-driven-based methods. The static methods from multiple images and dynamic methods are then reviewed in Sections III and IV. In Section V, we also review the editing and reusing of hair modeling results. The future development trends and challenges of image-based methods are proposed in the end.

INDEX TERMS Hair modeling, image-based hair modeling, orientation field, hair editing and reusing.

I. INTRODUCTION

Hair is a vital component of a person's identity, which can provide strong cues about age, background and even personality [1]. Hair modeling is important for creating convincing virtual humans for many computer graphics and virtual reality applications. In digital games and movies, the virtual characters have lifelike hair models, which not only provide rich visual characteristics, but also describe human characteristics and emotions in a specific language. In addition, there are a large number of application requirements for modeling hair in the fields of makeup, advertisement and so on. However, hair modeling is a difficult task primarily due to the complexity of hair. A human head typically consists of a large volume of hair with over 100,000 hair strands. Each individual hair strand is quite small in diameter. Therefore, it has important theoretical significance to carry out 3D hair modeling.

Parametric geometric properties [2]–[6] had been used for early hair modeling. These parametric representations involve parametric surface, wisp, and generalized cylinder. Using 2D surfaces to represent groups of strands had become a common approach to modeling hair [7]–[9]. Clusters, wisps, and generalized cylinders had been used as intuitive methods to control the positioning and shape of multiple hair strands in groups [10]–[14]. Complex hair geometry can also be represented with a hierarchy of generalized cylinders [15], [16], allowing users to select a desired level of control in shape modeling. Although parametric modeling methods can be used to quickly generate hair models, hairstyles that can be modeled are limited due to the representation of hair.

Unlike earlier hair modeling methods, there are currently two main ways to generate hair models. One way to reconstruct a hair model is running physical simulation based on physical equations [17]–[19]. According to those complex physical models, users can generate realistic 3D hair models. But it is really hard to simulate a desired hair model since there are too many parameters to determine in these physical models. Another way to reconstruct a hair model is image-based hair modeling, which can achieve higher quality with lower effort. In recent years, researchers have paid more attentions to this hair modeling method, and many research results are presented. Image-based hair modeling incorporates a great deal of techniques in computer vision. The relevant methods focus on reconstructing a hairstyle that approximates the real image. Currently, the image-based hair modeling is still a hot research topic. There are many scientific problems that are urgently needed to be solved, including: realistic surface modeling results, true hair strand distribution, efficient dynamic hair modeling, and the editing and reusing of hair modeling results.

In this survey, we will discuss the primary challenges involved with image-based hair modeling and limitations of methods presented in the past for handling these complex issues. The remainder of this paper is organized as followed. Single-view hair modeling techniques are reviewed in Section II. Methods for static hair modeling from multiple images are presented in Section III. Section IV describes the video-based dynamic hair modeling methods. The editing and reusing of hair modeling results are reviewed in Section V. Finally, Section VI presents the prospects facing image-based hair modeling research.

II. SINGLE-VIEW IMAGE-BASED HAIR MODELING

Recently, researchers have proposed a way of generating hairstyles only based on single-view image. The single-view image-based hair modeling can be divided into two types according to the different ways of reconstruction. One way is orientation-field based hair modeling method, and the other is data-driven based hair modeling method.

A. ORIENTATION-FIELD BASED HAIR MODELING

Generally, the steps of the orientation-field based hair modeling are as follows: a 3D orientation field is firstly generated from a single-view image, then the hair strands are traced from hair roots based on this orientation field. Constructing a realistic 3D orientation field is the key core point of this method.

Kong *et al.* were the first who used one 2D image to generate a 3D hair model [20]. Their method analyzes and recognizes hair strands by image processing, which provides valuable data, particularly hair outline and the flow direction of the hair. Chai *et al.* [21] used a portrait image to reconstruct a 3D hair model. They focused on applications related to portrait manipulation. As shown in Figure 1, their method could produce a strand-based 3D hair model, which is visually resemble with the original image. Their single-view hair modeling enabled a number of interesting applications which were previously challenging, including hairstyle transfer and hair editing. However, the hair model generated by this method is not physically plausible. The hair model consists of hair strands floating in the hair shell rather than tracing from the scalp. Chai *et al.* [22] improved the physical plausible by solving an unambiguous 3D vector field explicitly from the image and adopting an iterative hair generation algorithm. Similar to the orientation estimator in [21], this

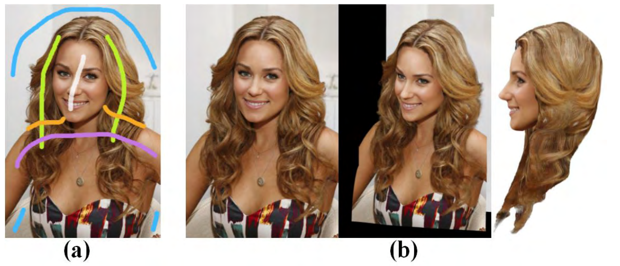

FIGURE 1. The input image overlaid with the strokes the user has drawn (a), and the portrait pop-up rendered in different views (b) [21].

method uses 32 even-symmetric Gabor kernels to estimate the orientation. A 2D Gabor filter is constructed by modulating an oriented sinusoidal plane wave by a Gaussian envelope. The real component of an even-symmetric Gabor filter is given as:

$$G(u, v) = \exp\left(-\frac{1}{2}\left[\frac{\tilde{u}^2}{\sigma_u^2} + \frac{\tilde{v}^2}{\sigma_v^2}\right]\right)\cos\left(\frac{2\pi\tilde{u}}{\lambda}\right), \quad (1)$$

where $\tilde{u} = u\cos\varphi + v\sin\varphi$ and $\tilde{v} = -u\sin\varphi + v\cos\varphi$. The parameter φ and λ determine the orientation and period of the sinusoidal plane wave respectively, while σ_u and σ_v control the standard deviations of the Gaussian envelope. Since the strand roots are fixed on the scalp, the physical plausibility enables them to manipulate hair in many new ways that were previously very difficult with a single image, such as interactive hair shape editing. However, their method can only ensure that the modeling result is approximately true under original single-view point. Yeh *et al.* [23] constructed hair in a given cartoon image with consistent layering and occlusion. Since the generated hair model is 2.5D, the authenticity of the hair modeling and editing cannot be guaranteed.

As we known, there is a growing trend of design and fabrication personalized figures, which created by scanning real person. The resulting mesh is often processed with artist interaction, and the figurine is printed using a 3D printer. The reproduction of figurines without hair is a severe limitation of current systems, since the hairstyle contributes so substantially to the person's identity. Currently, many researchers focus on 3D-printed hairstyle reconstruction. Echevarria *et al.* [24] introduced an approach constructing 3D hair models using feature-preserving color filtering and abstract geometric details. Their method could produce appealing 3D-printed hair models, as illustrated in Figure 2. The hair model generated by their method can preserve the structural details. Their method is suitable for manufacturing personal figurines. But it cannot generate strand-level precise hair models. Ding *et al.* [25] introduced an approach constructing hair models based on orientation and helix fitting. As shown in Figure 3, this method could generate more realistic hair models. However, the generated hair model is not physically correct since the hair strands are not fixed on the scalp. Chai *et al.* [26] developed a hybrid system dedicated to modeling high-quality hairstyles. The system

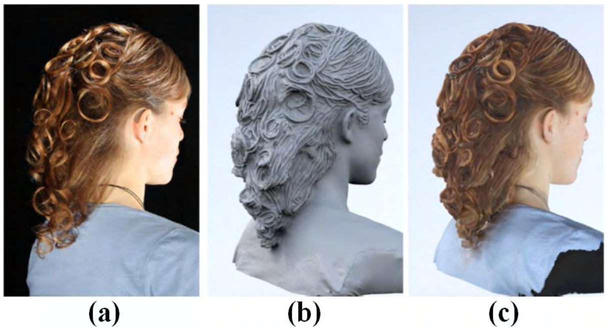

FIGURE 2. **Input image (a), and the final hair modeling results generated by Echevarria *et al.* [24]. The result of geometry stylization without color (b), and the final result with both color and geometry stylization (c).**

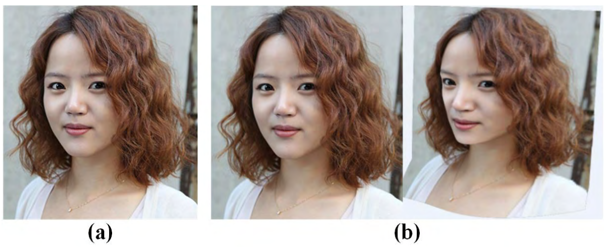

FIGURE 3. **A real image (a), and the hair modeling results in different views (b), which are generated by orientation and helix fitting method [25].**

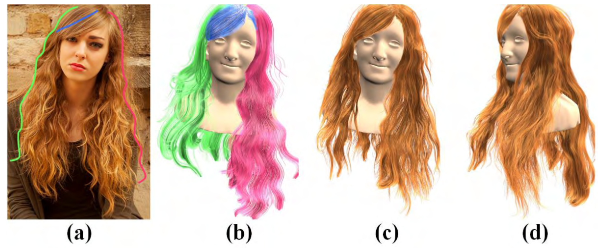

FIGURE 4. **Single-view hair modeling using a hairstyle database [27]. Input image with the user strokes (a), colored visualization of the hairstyle combination result (b), and the final hair strands shown from two different views (c) (d).**

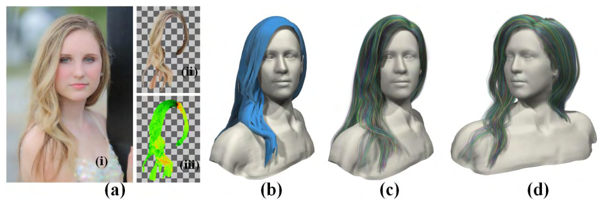

FIGURE 5. **Fully automatic hair modeling from a single image [28]. A single portrait image (a)(i) as input, this method computes a hair segmentation (a)(ii) and a hair growth direction (a)(iii). A matching hair shape (b), and the generated 3D hair model rendered from two views (c) (d).**

combined the base shape, the normals estimated by shape from shading, and the 3D helical hair prior to reconstruct high-quality 3D hair models. The final depth map was calculated by minimizing an energy function, which contains the energies of the base shape, shape from shading normals, and the helical hair prior. The reconstructed 3D hair models can be used for high-quality portrait relighting and 3D-printed portrait reliefs. But they don't have physical authenticity. These methods [24]–[26] generate hair as a closed-manifold surface, yet contains the structural and color elements stylized in a way that captures the characteristics of a hairstyle.

B. DATA-DRIVEN BASED HAIR MODELING

Recent hairstyle generation approaches have proposed a way of generating hairstyles based on the automatic reconstruction of hair from databases. The use of an existing shape database can significantly speed up the modeling process compared to building a new shape from scratch. Data-driven based hair modeling approaches mostly rely on crucial clues in order to search a 3D target hair model from the database.

Hu *et al.* [27] introduced a data-driven framework that can digitize complete and highly complex 3D hairstyles from a single-view photograph. Given a reference photo of the target hairstyle and a few user strokes as guidance, they can automatically search for multiple best matching examples from the database, and combine them consistently into a single hairstyle to form the large-scale structure of the hair model (see Figure 4). It is the first data-driven method generating a complete 3D hairstyle from single image. Though this method can be used for fast hairstyle generation, the different hairstyle types it can model are limited by the ones included in the reference database and the quality of input strokes. Chai *et al.* were the first who used fully automatic technique for 3D hair modeling from a single portrait image [28]. Their method consisted of automatic hair segmentation and hair growth direction estimation by hierarchical deep neural network, an automatic data-driven hair matching and modeling algorithm, and a large set of 3D hair exemplars. Figure 5 shows the pipeline of this method. Compared with the previous hair modeling methods [21], [22], [26], [27] that require user interaction, this method could achieve fully automatic hair modeling results. However, due to the reliance on face alignment technology, this method is not suitable for faceless images. The quality of the modeling results also depends on the size of the hair model database.

More recently, Hu *et al.* [29] proposed a fully automatic framework that digitized a complete 3D head with hair from a single image. Their method generates hair based on 3D-model and texture retrieval, shape refinement, and polystrip patching optimization. To accelerate hairstyle retrieval, a deep convolutional neural network is used for semantic hair attribute classification. Figure 6 shows three states of the pipeline in this method. The quality of hair models generated by this method also depends on the size of hairstyle database. Since the cartoon's hair is expressed in polystrip rather than strand, it is not suitable for strand-based hair simulation.

The data-driven framework for modeling hairstyles from a single-view image mainly includes three parts:

TABLE 1. A comparison of the orientation-field and data-driven methods for single-view image-based hair modeling based on the user control, modeling speed, degree of automation and the reality of hair modeling.

Method	User Control	Modeling Speed	Automatic	Reality	Typical References
Orientation-Field Based Methods	Low	Slow	No	Most 2.5D Models	[21] [26]
Data-Driven Based Methods	High	Fast	Medium	Full 3D Models	[27] [28]

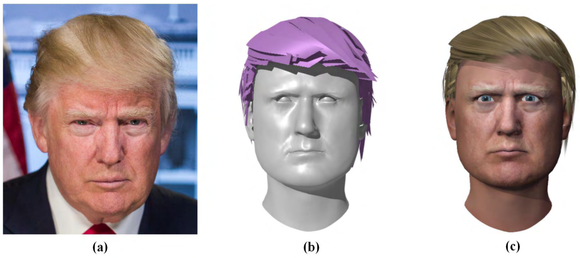

FIGURE 6. Three states of the pipeline in [29]. Input image (a), hair polystrips with face mesh (b), and final result of 3D avatar (c).

constructing a database of hairstyles, generating example strand for searching, and combining hairstyles. The number of samples in database is one of the most important factors for final results. A database containing complete example hairstyles can be used to model a wide range of target hairstyles. The common way to generate an example strand for searching is from user strokes. To measure the differences between a 2D user stroke $\mathcal{U}$ and a 3D hair strand $\mathcal{S}$, it first projects the 3D strand onto the image plane using the transformation matrix. Then it finds the closest sample s_j on the projected strand for each sample s_i on the user Stroke $\mathcal{U}$, and computes the differences as follows:

$$D(\mathcal{U}, \mathcal{S}) = \sum_{s_i \in \mathcal{U}} \min_{s_j \in \mathcal{S}} \left| \mathbf{p}(s_i) - \mathbf{p}(s_j) \right|, \tag{2}$$

where $\left|\mathbf{p}(s_i) - \mathbf{p}(s_j)\right|$ is the distance between the positions of s_i and s_j on the image plane. To combine these retrieved hairstyles, a 3D direction volume is usually used for combining orientation field to obtain the target hairstyle.

C. EVALUATION

Each of the single-view image-based hair modeling methods described in this section is appropriate for modeling hair under different circumstances. Table 1 shows a comparison of two single-view image-based hair modeling methods in user control, modeling speed, degree of automation, reality of hair modeling results, and the typical references. The level of user control is important in order to facilitate placing exact details where desired in hair. Moreover, while some single-view image-based hair modeling methods can reconstruct a hair shape quickly through automatic processing, others require time-consuming manual setup or input by its user. The more reality of hair shapes that can be modeled by an algorithm, the broader its applicability in practice is.

As Table 1 indicates, single-view image-based hair modeling techniques, such as through orientation field, customarily give the user a small degree of control over hair; however, the manual segmentation of hair can be a tedious, time-consuming task due to the complicated interaction with hair. The hair modeling methods based on orientation field are less automated. The modeling speed is relatively faster while the modeling result is not complete three-dimensional. The data-driven based hair modeling methods customarily give the user a large degree of control over the hair. These methods are highly automated, and they can get a fully 3D hair model with less time. Controlling the shape of strokes drawn by user in [27] typically requires less tedious input by the user; however, the retrieved hairstyles can closely match the local details of the reference photo.

III. STATIC HAIR MODELING BASED ON MULTIPLE IMAGES

Generally, the static hair modeling based on multiple images can be divided into two types. One way is orientation-field based method, which generates hair models by constructing orientation fields. Another way is data-driven based method, which constructs hair models from a hairstyle database. Next, we will explain and evaluate these different approaches.

A. ORIENTATION-FIELD BASED STATIC HAIR MODELING

Orientation-field based static hair modeling approaches mostly rely on the pipeline of capturing multiple hair images, generating orientation field or interior field, constructing 3D hair models based on the constraints of sample hair and hair tracing algorithm.

Ming *et al.* [30] were the first who used real hair images to automatically construct hair models. Their method consists of building a 3D hair volume from various viewpoints of the subject's hair. Hair strands are then generated inside this volume using a heuristic way that does not ensure faithfulness in hair directionality. This approach is merely geometric and suited for simple hairstyles. In order to capture local orientation from hair images, Grabli *et al.* [31] proposed an approach of hair modeling exploiting hair illumination. Their method works by studying the reflectance of the subject's hair under various controlled lighting conditions. By considering various viewpoints as well as several filters, Paris *et al.* [32] extended prior method [31] to a more accurate one. As shown in Figure 7, this method captures local orientation of the visible part of hair, and thus produces visually faithful results with respect to original hairstyles.

FIGURE 7. Hair capture from multiple images [32]. One view of input image (left) and the reconstructed results (right).

FIGURE 8. One of the captured input images (left), and the recovered hair rendered in different two views (right) using triangle-based hair modeling method [34].

Mao *et al.* [33] developed a sketch-based system dedicated to modeling cartoon hair models. This sketch-based system generates a silhouette surface representing the boundary of the hairstyles. Paris *et al.* [32] improved the flexibility of the method by exploiting the geometry constraints inherent to multiple viewpoints. They introduced a technique to create hair strand models from the visual hull constructed from many views. The strands are grown constrained by the orientation consistency across the views (see Figure 8).

With the continuous focus on image-based static hair modeling methods, more and more researchers start to use sophisticated and specially designed acquisition equipments to capture hairstyles. Paris *et al.* [35] presented *Hair Photobooth*, a complex system made of several light sources, projectors, and video cameras that capture a set of data to extract the hair geometry and appearance. Figure 9 shows the outcome of the modeling process. This work uses the method in [32] to analyze the direction in captured images, following by transforming the direction into a 3D orientation field [34]. The acquisition system designed by them can directly access the triangular surface of hair. They construct the whole hair model by combining the hair tracing from the orientation field and the surface hair. In recent years, Luo *et al.* have introduced multi-view [36] and wide-baseline [37] based static hair modeling methods (as illustrated in Figure 10 and Figure 11 respectively). They captured hairstyles using multiple cameras and reconstructed the geometry of hair shell from orientation fields. The hair geometry reconstructed by these methods has a good visual effect, but they only reconstruct the surface of a hairstyle.

In order to generate fiber-level hair models, Jakob *et al.* [38] presented a method for capturing the small-scale structure

FIGURE 9. Outcome of the *Hair Photobooth* system [35]. Reference photograph (left) and reconstructed results rendered from different viewpoints (right).

FIGURE 10. The input reference images (left), and the final results (right) reconstructed using orientation field method [36].

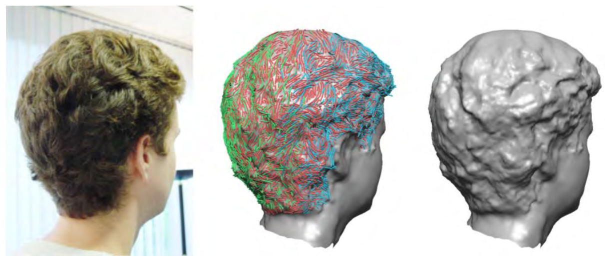

FIGURE 11. Surface construction of hairstyle using wide-baseline [37]. Input image (left), refined strands (middle), and reconstructed surface (right).

of hair using large sets of macrophotographs that isolate individual fiber using shallow depth of field. The shallow depth of field helps isolate the fibers and reduce occlusion. It is the only existing method for fiber-level hair modeling. A plurality of filters (see Figure 12) are used to determine the direction of points on the image. However, it is difficulty to collect the hair of a real person directly because of the complex acquisition equipment. Herrera *et al.* [39] reconstructed a high-quality hair model by sidestepping anisotropic hair reflectance and complicated segmentation among skin and hair. However, it is not suitable for long hair strands far away from head because it relies on the thermal emission from head scalp. Beeler *et al.* [40] presented an algorithm to detect and trace hair in the captured images, and reconstructed hair strands using a multi-view stereo approach. Their method could deliver the best result in the presence of short, sparse hair. But they could not reconstruct dense hair because of occlusion.

With the great development of computer vision in point cloud reconstruction, Luo *et al.* [41] proposed a multi-view hair reconstruction method capable of reconstructing the

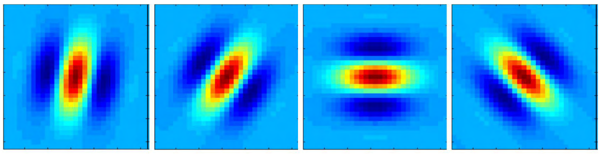

FIGURE 12. Gabor filter in estimating orientation.

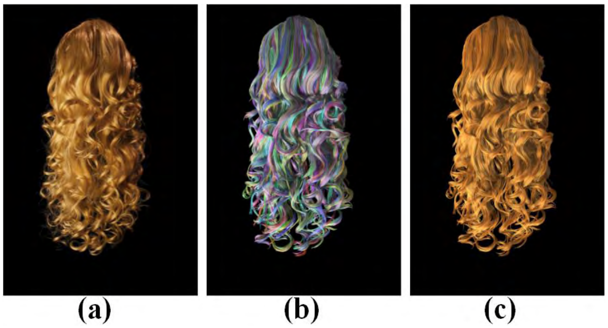

FIGURE 13. An image of captured hairstyle (a), color-coded reconstructed wisps (b) and synthesized hair strands (c), which are generated by structure-aware hair capture method [41].

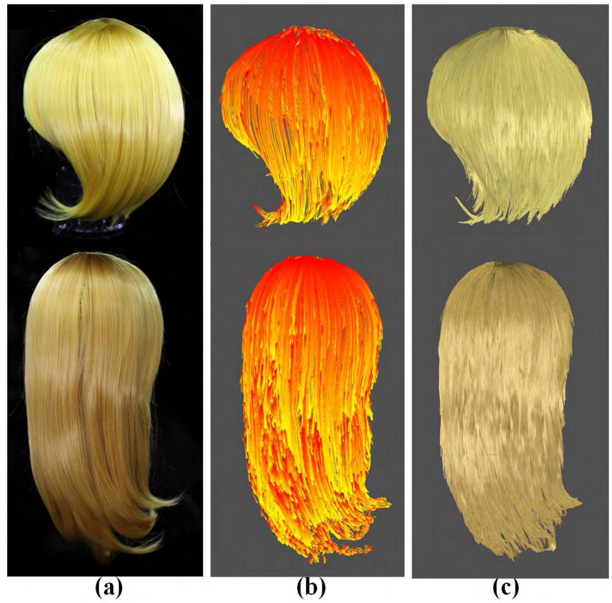

FIGURE 14. The final results of two hairstyles reconstructed by hybrid orientation field method [42]. Input images (a), directed 3D strand segments (b) and modeling results (c).

strand-level hair geometry. As shown in Figure 13, this method can reconstruct coherent and plausible wisps aware of the underlying hair structures from a set of still images without any special lighting. However, the reconstructed results cannot preserve the internal characteristics of hair, and the distribution of hair roots and interior hair are quite different from the real distribution. Bao and Qi [42] introduced a realistic hair modeling method from a hybrid orientation field, which was composed of multiple orientation fields. This method takes into account the distribution of interior hair and the structural details of exterior hair. The final modeling results are shown in Figure 14. This method can reconstruct a realistic 3D hair model in both interior distribution and exterior structure compared with those methods [34], [41] which only consider surface structure of a hairstyle. Vanakittistien *et al.* [43] generate guide-hair-strand models for real-time applications. It differs from most previous methods [41], [42] which aim to create realistic hairstyles. This method takes photos in 8 views of one hairstyle using a smart phone camera and segments images with some easy to use tools. The generated hair model is imported to HairWorks [44] for real-time simulation and rendering.

B. DATA-DRIVEN BASED STATIC HAIR MODELING

Recently, data-driven based static hair modeling methods from multiple images have been rapidly developed. The procedure of this method mainly includes two steps: constructing a database and searching hair models from this database via fitting algorithm. According to the representation of hair model in database, there are three types of hair database, namely strand-based database, patch-based database and hairstyle-based database.

Hu *et al.* [45] developed a data-driven hair modeling framework based on example strands generated through hair simulation. From a set of images, the user first reconstructs a point cloud as well as a 3D orientation field, followed by a local growing step that generates the cover strands. This method then generates a database of example strands through hair simulation constrained by the input hairstyle. Finally, this strand-based database is used to discover clustered strands from the covered strands with structurally plausible configurations via strand fitting algorithm. This method does not require any clean-up on the captured input data and can directly produce faithful hair models. However, the constructed models do not provide any significant qualitative improvement compared with the results of [41]. Yu *et al.* [46] introduced a hybrid image-CAD based hair modeling system, which could reconstruct many hairstyles. But the reconstructed results are not as realistic as captured hair images.

Fitting algorithm is the central to the searching of a hair model. In this type of strand-based database, the fitting algorithm considers each pair of strands $\{S_c, S_e\}$ and computes the optimal transformation to align S_e with S_c. Specifically, it minimizes the matching cost via Iterative Closest Point algorithm with point-to-point constraints:

$$\varepsilon\left(S_c, \mathbf{T}(S_e)\right) = \sum_i \left|\mathbf{p}(s_{c,i}) - \mathbf{T}\left(\mathbf{p}(s_{e,i})\right)\right|^2, \tag{3}$$

where $\left\{\mathbf{p}(s_{c,i})\right\}$ are the positions of all the samples in S_c, $s_{e,i}$ is the closest sample of $s_{c,i}$ in S_e, and $\mathbf{T}\left(\mathbf{p}(s_{e,i})\right)$ is the position of $s_{e,i}$ under the rigid translation and rotation specified by $\mathbf{T}$.

In order to reconstruct the braided hairstyles, Hu *et al.* [47] proposed the first framework that enables the acquisition of wide range of different braided hairstyles. They introduced

TABLE 2. A comparison of the orientation-field and data-driven methods for multi-view image-based static hair modeling based on the input image number, user control, time consumption and the reality of hair modeling results as well as typical references.

Method	Input Image Number	User Control	Time Consumption	Reality	Typical References
Orientation-Field Based Methods	More	Medium	More	Realistic	[35] [41]
Data-Driven Based Methods	Less	High	Less	Not Real Enough	[47] [48]

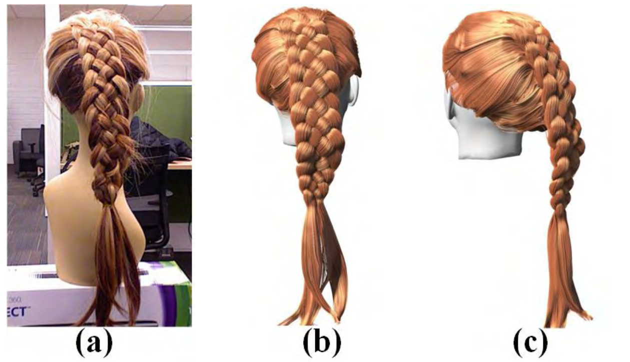

FIGURE 15. The input photo (a), and the output strand model rendered in different two views (b) (c). The final results are generated by capturing braided hairstyles method [47].

a data-driven method to automatically reconstruct braided hairstyles from input data obtained from a single consumer RGB-D camera. This method first generates a patch-based database and uses a robust random sampling approach for patch fitting. It then recovers the input braid structures using a multi-label optimization algorithm. The reconstruction results is shown in Figure 15. Similar to the method in [41], this method also needs to manually separate the hair region from the captured images as a preprocessing in advance. And this method is only suitable for reconstructing braided hairstyles.

More recently, Zhang *et al.* [48] propose a four-view image-based hair modeling method. Their method first estimates the rough 3D shape of the hairstyle using a predefined database of 3D hair models. It then synthesizes hair texture on the surface of the shape, from which the hair growing direction information is calculated and used to construct a 3D direction field in the hair volume. Thanks to the multi-source hair texture synthesis algorithm [48], this method does not require all input images are captured from the same hairstyle. It can reconstruct most of the long straight hairstyles except constrained hairstyles such as buns and braids. In addition to selecting the best hair model from a predefined 3D hairstyles database, the most important step for this method is to optimize the hair model to be as close as possible to the input images.

C. EVALUATION

Each of the static hair modeling methods based on multiple images is appropriate for modeling hair under different circumstances. In most cases, the orientation-field based methods could reconstruct most unconstrained hairstyles from an orientation field. However, it cannot handle special hairstyles (e.g., the classical Marilyn Monroe hairstyle or constrained by dreadlocks). Since it is difficult to precisely represent the direction of these hairstyles on a regular grid. Although some methods [41] reconstruct complex hairstyles with plausible hair structure. But their methods cannot guarantee that hair roots and interior hair strands are consistent with actual distribution. Compared with orientation-field based methods, the data-driven based methods can generate a desired hairstyle in less time. However, the quality of hairstyles generated by this method is limited by the number and type of hairstyles in a database.

Table 2 shows a comparison of two types of static hair modeling methods based on multiple images in the areas of input image number, user control, time consumption, the reality of hair modeling results, and the typical references. The image number of input reflects the complexity of preprocessing. The time consumption indicates the performance of hair modeling. The realism of the output model reflects the quality of final modeling results.

As Table 2 indicates, static hair modeling methods based on multiple images, such as through orientation field, customarily need a large number of input images. The user control degree in this method is relatively lower, and the modeling speed is slower. But the reality of modeling results is more realistic. On the other hand, the data-driven approaches require less input images and more user control. The hair modeling speed is faster, but the modeling quality is not real enough. In the future, the static hair modeling methods based on data-driven and orientation-field analysis may significantly improve the quality of reconstruction results.

IV. VIDEO-BASED DYNAMIC HAIR MODELING

Current researches on hair modeling from multiple images mainly focus on static hair geometric modeling. Dynamic hair capture from videos is much less explored. The central challenge is to ensure temporal coherence while retaining the hair details in spatial domain.

A. CONTINUOUS IN TIME DOMAIN

Early video-based dynamic hair modeling methods mainly ensure the correspondence and coherence among adjacent frames in the time domain without considering the correspondence among hair strands in the spatial domain. Ishikawa *et al.* [49] were the first who proposed a dynamic hair modeling method based on captured data. Given a 3D

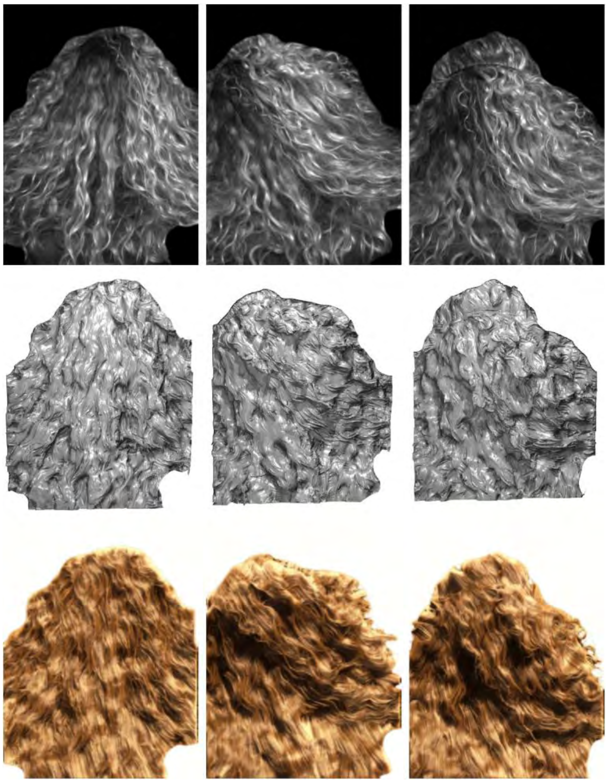

FIGURE 16. A temporally coherent set of hair fibers is generated by dynamic hair capture algorithm [51]. A sequence of input video (top), reconstructed envelope surface (middle), and the synthesized hair strands (bottom).

hairstyle, the user first attaches small reflective markers to a few guide hair strands. The user then uses a motion capture system to reconstruct the motions of these guide hair strands, followed by an interpolation scheme to generate a full sequence of dynamic hair models. But this method is limited by very coarse hair motions, as the details are smeared out by the interpolation of guide hair strands. Yamaguchi *et al.* [50] extended an early work [34] to video-based modeling of dynamic hair. It captures dynamic hairstyles using an array of synchronized cameras. The hair structure and motion are modeled using an algorithm that grows each hair in segments from the root to the tip. This method only works for straight hairstyle with limited motion due to excessive restrictions on the direction of hair growth. Luo *et al.* [51] developed a system for passive capture of dynamic hair performance using a set of high-speed video cameras. The final output of this method is a set of hair strands for each frame, grown according to per-frame reconstructed geometry and orientation field (see Figure 16). This method computes multi-view correspondence from 2D orientation maps for dynamic hair capture, but still has artifacts of temporal incoherence in the results.

To capture and reconstruct more natural hair motion, Fukusato *et al.* [52] proposed a method of capturing hair motion using hair extensions instead of markers. But this method can reconstruct the motion of hair extensions instead

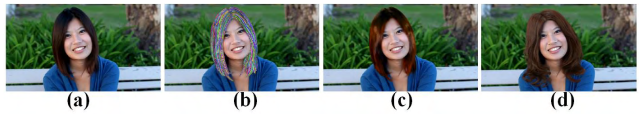

FIGURE 17. One frame of input video (a), reconstructed 3D hair strands (b), appearance editing (c) and hair replacement (d) [22].

FIGURE 18. The full swinging motion of two kinds of hair [53]. The left two columns is straight hair, and the right two columns is long hair. Input sequences of video (top), and the corresponding hair model (bottom).

of strand-level hair models. Chai *et al.* [22] demonstrated a dynamic hair modeling technique based on single-view input. To ensure temporal coherence, it generates a 3D hair model from a user-specified reference frame using image-based modeling algorithm, and deform that model based on the motion estimated from the video so that it matches the hair in each frame (as illustrated in Figure 17). But the combination of optical flow with sparse features for tracking hair motion is limited by simple hairstyles and motions. Zhang *et al.* [53] introduced a simulation-guided approach for dynamic hair capture. Given an initially reconstructed sequence of hair strand models, this method develops a hair dynamic refinement system using particle-based simulation and incompressible fluid simulation. The system can be used to improve reconstructed hair strand motions and generate missing strands caused by occlusion or tracking failure. The simulated hair motions are used to ensure temporal coherence, but this method is limited by an over-smoothed hair geometry. Figure 18 shows the four-frame results of its dynamic modeling process. The hair geometry of each frame is very smooth, and most of the geometric details are lost (see Figure 18).

B. CONTINUOUS IN TIME DOMAIN AND COHERENT IN SPATIAL DOMAIN

To reconstruct the dynamic modeling results with continuous in time domain and coherent in spatial domain, Xu *et al.* [54] developed a dynamic hair capture system using spacetime optimization. Given multiple synchronized video sequences, the user can recover hair strands' temporal correspondence by a motion-path analysis algorithm which can robustly track local hair motions in input videos. Figure 19 shows four frames of dynamic hair modeling results using this method. This dynamic hair capture system is able to reconstruct hair

FIGURE 19. Four frames of an input head shaking video (top), and the corresponding hair model (bottom) reconstructed by space-time optimization method [54].

dynamics, which can closely match video recordings both in terms of geometry and motion details. The types of dynamic hairstyle that this system can reconstruct are limited by the geometry of the hair subject. This method also fails to handle hair interactions with an object because it does not take into account the material or physical properties of hair fibers. More recently, Hu *et al.* [55] present a framework to automatically determine optimal parameters of hair models from video footage, such that the simulated sequence matches the motion of real hair. However, on the one hand, their method is time-consuming, since a full dynamic simulation must be solved for every particle evaluation. On the other hand, the re-simulated animations with the optimized parameters may not perfectly match the inputs.

To ensure the spatial and temporal coherence of the dynamic capture, this type of method formulates the global hair reconstruction as a spacetime optimization problem solved iteratively. It introduces an EM-like algorithm for optimizing the final shape of each strand. In the *E-step*, let $\xi_{t+\Delta,t}$ denote a strand warped from frame $t + \Delta$ to t, for each strand ξ_t, it calculates a weighted average of all warped strands:

$$\xi_t^* = \sum_{\Delta=-3}^{3} \omega_\Delta \xi_{t+\Delta,t}, \tag{4}$$

where ω_Δ is normalized Gaussian weight, and $\xi_{t,t} = \xi_t$. In the *M-step*, it aligns each average strand ξ_t^* computed in the *E-step* with the local spatial constraints. It selects the aligned strand ξ_t' by iteratively minimizing the following energy function:

$$E = \sum_i \left\| \xi_t'(i+1) - \xi_t'(i) - \epsilon \mathbf{V}_t(\xi_t(i)) \right\|^2 + \left\| \xi_t'(i) - \xi_t^*(i) \right\|^2, \tag{5}$$

where $\mathbf{V}_t$ is the 3D direction field in frame t, and ϵ is the step length for initial hair tracing.

C. EVALUATION

Researchers have done a lot of work on video-based dynamic hair modeling methods in terms of temporal continuity and spatial similarity. However, due to the occlusion among hair, these dynamic hair modeling methods can only deal with relatively simple hairstyles. It cannot accurately construct a dynamic motion sequence of complex hairstyle. The main disadvantage of dynamic hair modeling methods is time-consuming. To generate a motion sequence of ten seconds for one hairstyle, the state-of-the-art dynamic hair modeling method [54] takes more than ten hours in total, computed by a shared computer cluster whose available cores vary from several dozens to a few hundreds.

Table 3 shows a comparison of static hair modeling methods based on multiple images and video-based dynamic hair modeling methods in the areas of modeling hairstyle, complexity, time consumption, reality and typical references. The large the range of hairstyles that can be modeled by an approach, the boarder its applicability in practice is. The level of complexity is important in order to facilitate modeling desired hairstyle. The degree of reality reflects the quality of hair modeling methods. Moreover, while some static hair modeling methods can reconstruct a real hairstyle quickly through automatic processing, other dynamic hair modeling methods require time-consuming manual setup or preprocessing by its user.

As Table 3 indicates, static hair modeling methods based on multiple images customarily give the user a less time consumption, a lower complexity and a realistic modeling result; however, these methods can only reconstruct static hair models. The video-based dynamic hair modeling methods can only reconstruct simple hairstyles such as straight ones. Since these methods not only reconstruct each frame of the hairstyle, but also ensure the coherence of each frame in the time and space domains. These methods give the user a high complexity and a longer time consumption.

V. EDITING AND REUSING OF HAIR MODELING RESULTS

The editing and reusing of hair modeling results can be divided into two types according to the different modes of editing. One way is geometry-based method, which constructs new hairstyles by editing the appearance of the hair model. Another way is physics-based method, which generates new hairstyles in the form of physical simulation.

A. GEOMETRY-BASED HAIR EDITING AND REUSING

1) SKETCH-BASED APPROACH

Generating hairstyles from the sketch-based approach is an early common way to edit hairstyles. Choe *et al.* [11] introduced an approach for interactive hairstyle generation using a statistical wisp model and pseudo physical method. Their method is utilized to achieve intricate hair shapes such as braids, buns, and ponytails. Manual input is considered as the most time-consuming part in the process of generating virtual hairstyling. Malik [56] proposed an interaction technique for modeling and editing hairstyles with a user-friendly sketching interface. Using a pressure-sensitive table, one user makes strokes to mimic a number of real-world hairstyling

TABLE 3. A comparison of the multi-view image-based static and video-based dynamic hair modeling methods based on the hair shapes, complexity, time consumption and the reality of hair modeling results.

Method	Hair Shapes	Complexity	Time Consumption	Reality	Typical References
Static Hair Modeling Methods	Various Hairstyles	Medium	Less	Realistic	[35] [41] [47]
Video-Based Dynamic Hair Modeling Methods	Limited to Straight One	High	More	Not Real Enough	[53] [54]

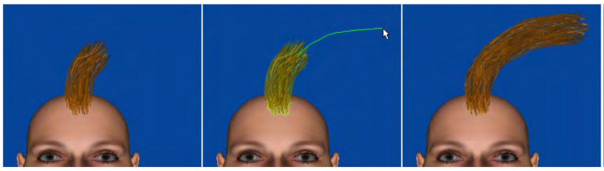

FIGURE 20. Sketching interface for editing hairstyle [56].

operations, such as cutting, combing, implanting, and lengthening hair strands. However, the results generated by this method are relatively unrealistic (see Figure 20).

Some research work later began to extract hair growth information from the user input. It first builds a parametric hair model or an orientation field from the growth information, and then edits it to generate a final hair model. Chen and Zhu [57] proposed a generative sketch model for human hair analysis and synthesis. To edit hair, their method first computes sketches with directions from input images, and then provides a user interface to edit the sketches. A vector field is generated from the sketches. After diffusing the orientation field, it traces a novel hairstyle from this dense orientation field. However, it can only generate 2D hair models. Wither *et al.* [58] explored a sketch-based interface for creating visually realistic hair models. Their method extracts the parameters of a physical model from the input sketches, and then generates the corresponding hairstyle based on the physical model. This method can be applied to generating relatively complex hairstyles. However, the final editing results are not satisfactory enough. Fu *et al.* [59] presented an intuitive sketching interface for interactive hairstyle design. Figure 21 shows a hairstyle created using their system. Their system is equipped with a sketching interface and a fast vector field solver. But it is only suitable for relatively simple hairstyles such as straight ones.

2) STRAND-BASED APPROACH

Creating hairstyles either manually or through image-based acquisition is a costly and time-consuming process. This motivates an example-based methodology that creates novel hairstyles with reference to existing ones. A hairstyle consists of thousands of hair strands. Some work generates new hairstyles from the strand-based approaches. Wang *et al.* [60] presented an example-based approach to hair modeling. A hierarchical hair clustering algorithm is developed for detecting wisps in example hairstyles. Traditional 2D texture synthesis techniques are used to synthesize the

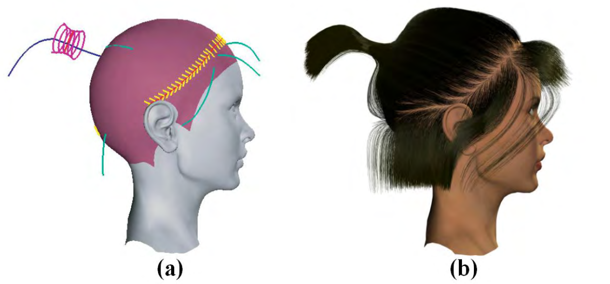

FIGURE 21. Editing orientation hairstyle by sketching [59]. Input sketches (a), and generated hair model (b).

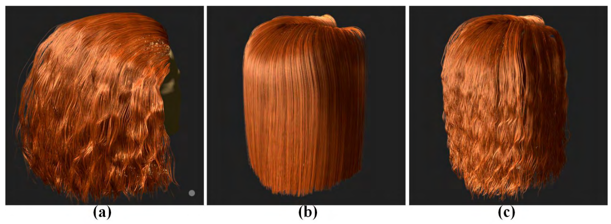

FIGURE 22. Example-based hair geometry synthesis [60]. The synthesized hairstyle (c) from the input hairstyles (a) (b).

coarsest level of the output hairstyle. Synthesizing finer levels of the hierarchy is based on cluster oriented detail transfer. As illustrated in Figure 22, the details from the hairstyle in (a) are transferred to the coarsest level of the hairstyle in (b) to produce the final result in (c). Their method can be used for user-controlled synthesis and editing techniques, including feature-preserving combing as well as detail transfer between different hairstyles. But it is not directly applicable to draped long hairstyles. Bonneel *et al.* [61] introduced a method for estimating hair appearance parameters using a single flash-lit photo. Their method achieves this by recasting the process as an image retrieval problem. The image is captured indoors with a flash and a grayscale card. This method generated a hairstyle that is visually similar to the input photo. The hairstyle can be edited to achieve the desired modeling result. However, due to the restrictions on input photo, their method cannot process portrait photos.

Chai *et al.* [21] reconstructed a hair model from a single-view portrait image. The single-view hair modeling enables a number of interesting applications. But the hair model generated by this method is not a full 3D model of the entire hair volume. The hair that is originally invisible in the input image is hallucinated and incorrect. With the development of hair

FIGURE 23. A random sampling of the portraits (bottom) generate from three input portrait images (top), which are generated by portrait morphing [62].

interpolation, Weng *et al.* [62] proposed an automatic hair interpolation method for portrait morphing. Their method calculates a many-to-many strand correspondence between two or more given hair models, takeing into account the multi-scale clustering structure of hair. A random sampling of the portraits are generated from three input portrait images (see Figure 23). Compared with other previous method [60], this method allows the user to continuously interpolate multiple hair models in real time. However, the hair modeling results are still not in line with the physical reality.

B. PHYSICS-BASED HAIR EDITING AND REUSING

The physics-based methods first convert one given hairstyle into a physics-based model, they then edit dynamic hair model by solving complicated physical equations.

1) PHYSICS-BASED HAIR MODEL

The physics-based hair editing and reusing methods edit hairstyles based on physical models. Physical models have been proposed and used for simulating the dynamics of hair strands. One of the first attempts to animate individual hair strands was presented by Rosenblum *et al.* [2]. They used a mass-spring model, well-suited for animating dynamic hair movements. Other approaches [63]–[65] used a constrained mass-spring model, well-suited for animating extensible wisps such as wavy or curly wisps. Choe *et al.* [17] proposed a hybrid model, which took advantage of both mass-spring models and rigid multi-body serial chains. Selle *et al.* [19] extended the mass-spring model [2] to a new altitude-spring model that can model torsion. Parameters for this model are easy to set up. This physical model is suitable for simple hairstyles, such as straight hairstyle (see Figure 24). This model has recently been widely used in [22], [53], and [66].

In order to handle more complex hairstyles, Bertails *et al.* [18] introduced a new parametric method using a mechanically accurate model for static elastic rods (the Kirchhoff model). This method can automatically generate the fine geometry, including waves or curls of natural hair.

FIGURE 24. Hair simulation results by mass-spring model [19]. Long straight hair (a), medium straight hair (b), and long curly hair (c).

FIGURE 25. Dynamic simulation of natural hair of various types by super-helices model [67]. Wavy (a), straight (b), and curly (c) (d).

They further exploited the Kirchhoff's theory for accurately predicting the motion of individual hair fiber [67]. The resulting mechanical model for one individual hair strand is called a super-helix model. This model is animated using the principles of Lagrangian mechanics. The simulation results are shown in Figure 25. The hair movement sequences generated by this method can show rich details, but the calculation time is relatively long.

2) HAIRSTYLE EDITING AND REUSING

The super-helix model has been widely used in hairstyle editing and reusing [45], [68]–[71], since it can be used to represent a variety of complex hairstyles. Derouet-Jourdan *et al.* [72] used the super-helix model [67] to simulate the collision forces and frictional contacts among hair. They further generated fidelity motion sequence of this hairstyle. In their method, a given hair geometry is first converted into a physics-based hair model. Then the force analysis is performed on this model to calculate the physical parameters of it under a static equilibrium configuration. Finally, hair motion sequence is generated from this model. By changing the physical properties of the dynamic hair model, Ward *et al.* [73]–[75] edited the hairstyle to achieve specified effects, such as wetting, wind blowing and trimming. Yuksel *et al.* [76] introduced hair meshes, a new method for modeling hair, which aimed to bring hair modeling as close as possible to modeling polygonal surface. This method allows the user to create complex hairstyles by providing explicit control over the overall shape of the hair surface. Derouet-Jourdan *et al.* [77] converted hair geometry into super-helix model using floating tangent algorithm. Their method solves the problem of hair sagging at the beginning of simulation.

Currently, dynamic hair interactive technologies have been further developed, which could be used for editing hairstyles.

TABLE 4. A comparison of the geometry-based and physics-based methods for hair editing and reusing based on the constructing way, time consumption, the reality of editing results, difficulty level and the typical references.

Method	Constructing Way	Time Consumption	Reality	Difficulty Level	Typical References
Geometry-Based Methods	Editing Hair Geometry Models	Less	Not Real Enough	Medium	[60] [62]
Physics-Based Methods	Calculating Physical Equations	More	Physical Reality	Hard	[66] [72]

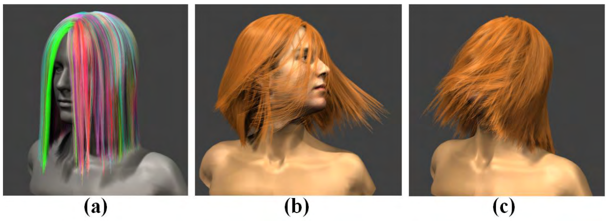

FIGURE 26. Visualized guide hair (a), two of the simulation frames are shown in (b) and (c), which are generated by a reduced model for interactive hair [66].

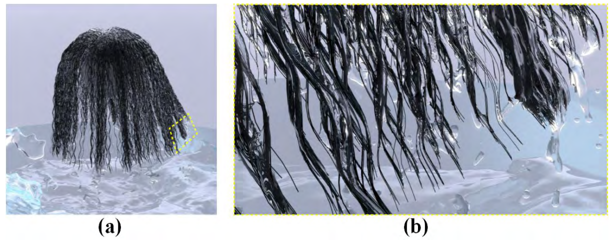

FIGURE 27. Simulating liquid-hair interaction (a) by multi-scale model [81], (b) showing details of part (a).

Aras *et al.* [78] described a sketch-based tool to generate hair models with different styling parameters. It could produce motion sequence of these hair models using physical properties and key-frame techniques. But this method is cumbersome for a large number of hair. Chai *et al.* [66] proposed a data-driven solution for realtime hair motion sequence generation. This method can produce realistic results by full simulation (see Figure 26). Wu and Yuksel [79] presented a hair simulation method using hair meshes. They introduced a volumetric force model and position correction method for incorporating hair interactions inside the hair mesh volume. However, the topological structure of the hair must remain intact throughout the simulation. Chai *et al.* [80] introduced an adaptive hair skinning method for interactive hair simulation with hair-solid collisions. Their method can generate hair motion sequence in real time by simulating the collision among guide hair strands and the solid. The diverse interactions between hair and liquid are central to the appearance of humans and animals in many situations. Fei *et al.* [81] therefore proposed a multi-component simulation framework that treats many of the key physical mechanisms governing the dynamics of wet hair. Their method can yield an effective wet hair simulator (see Figure 27). To generate hair motion sequences from static hair modeling results, Bao and Qi [82], [83] introduced an adaptive floating tangents fitting algorithm that converts the hair geometry model into a physics-based hair model. Dynamic hair motion sequences are then generated by simulating this model.

C. EVALUATION

Geometry-based hair editing and reusing methods directly edit the hair geometry represented in points and lines. These methods can get the desired hairstyle in a short time. However, the generated hairstyle cannot be in line with physical reality. In physics-based methods, a given hairstyle first needs to be converted into a physics-based hair model. Physics-based hair editing and reusing methods then edit dynamic hair model by solving complicated physical equations. The modeling results can be controlled by the boundary conditions in physical equations. One disadvantage of this method is that the process of editing hair models is not intuitive enough. Another disadvantage is that it is difficult to directly obtain the hair motion sequences corresponding to the real hairstyles, since there are too many parameters to determine in these physical equations.

Table 4 shows a comparison of geometry-based and physics-based hair editing and reusing methods in the areas of constructing way, time consumption, the reality of editing results, difficulty level and the typical references. The constructing way reflects how to get the editing and reusing models. The degree of reality reflects the quality of hair editing and reusing methods. The level of difficulty refers to the computational complexity and the difficulty of parameter setting. It is one of the important factors for speeding up editing hairstyles. As Table 4 indicates, geometry-based hair editing and reusing methods give the user a less time consumption, a medium difficulty level and not real enough editing results. Conversely, the physics-based hair editing and reusing methods can achieve physical reality results. But they need a time-consuming setup for parameters choice.

VI. PROSPECTS

As we all known, image-based 3D modeling technologies have been widely applied in the fields of computer graphics and virtual reality. As an important part of 3D modeling, image-based hair modeling techniques have attracted many research's attention. However, there are many challenges mentioned above need to be solved. Therefore, image-based hair modeling will still be a hot research topic in the future, and there are some research prospects in the future are shown as follows.

1) FIBER-LEVEL HAIR GEOMETRY RECONSTRUCTION

Currently, most hair models reconstructed by image-based hair modeling methods are not visually consistent with the captured image data at the fiber level. The reconstructed results are only approximate with captured data in the overall shape and characteristics. The only existing fiber-level hair modeling method [38] relied on sophisticated precise acquisition equipment. Therefore, how to achieve realistic hair modeling results under multi-view image acquisition is one of the main problems to be solved in the future. The appearance of reconstructed hair models should be consistent with captured images at the fiber level.

2) REALISTIC HAIR MODELING FOR HAIR GROWTH AND DISTRIBUTION

One hairstyle of real person generally has the following characteristics, such as evenly distributed hair roots on the scalp, continuous growth direction of interior hair strands, uniform growth direction of adjacent hair, smooth transition of hair curvature, and the dense and evenly distributed hair in its occupied space. However, at present, the best result of static hair modeling methods is that the appearance of the model is similar to the captured image. But the hair roots and interior hair strands are not consistent with actual distribution. The future researches should focus on realistic hair modeling. They could reconstruct hair models with exterior hair strands similar to images as well as interior hair strands growing in line with real distribution.

3) SINGLE-VIEW IMAGE-BASED HAIR MODELING

Most of the existing single-view image-based hair modeling methods can only generate 2.5D hair models because of the large amount of information missing. Many data-driven based hair modeling methods could reconstruct hair models in a short time. However, due to the limited number of samples in a database, the generated hair model may lack authenticity. In the future, we need to focus on the hair model searching and combining method to generate a complete 3D hair model, and to ensure that the modeling results are basically in line with the input image.

4) EDITING AND REUSING OF HAIRSTYLES

Currently, there exists little research on these hair modeling results. Most researchers only compare the hair modeling results with the captured hairstyles. However, there are few methods for shape editing or motion simulation. Only a few work attempts to generate new hairstyles through editing or reusing hair models. How to convert the static hair geometry into physics-based hair model is still an open problem. The key issues that need to be solved in the future include the research of adaptive floating tangent fitting algorithm, the construction of physical hair model, as well as hair motion conforming to physical reality. In addition, there are some scientific problems need to be solved in the future, including editing hair geometric features, hairstyle transformation, and the time editing and motion reusing for dynamic hair models.

VII. CONCLUSION

In conclusion, this paper presents a comprehensive review on image-based hair modeling techniques. The classical and current popular image-based hair modeling methods have been summarized, with the analysis of their advantages and shortcomings. Also, the challenges of various methods proposed by many researchers have been pointed out. Some research results of image-based hair modeling have been applied to the fields of games, film, advertisement and so on. We believe that with continuous developments in computer graphics research field and the progress of computer hardware performance, the existing problems can be solved step by step and image-based hair modeling results will be widely applied in the future to promote the development of interactive applications in movies and games.

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