International Journal of CAD/CAM Vol. 9, No. 1, pp. 93~102 (2009)

Interaction Metaphors for Modeling Virtual Hair using Haptic Interfaces

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Abstract – Shaping realistic hairstyles for digital characters is a difficult, long and tedious task. The lack of appropriate interaction metaphors enabling efficient and simple, yet accurate hair modeling further aggravates the situation. This paper presents 3D interaction metaphors for modeling virtual hair using haptic interfaces. We discuss user tasks, ergonomic aspects, as well as haptics-based styling and fine-tuning tools on an experimental prototype. In order to achieve faster haptic rates with respect to the hair simulation and obtain a transparent rendering, we adapt our simulation models to comply with the specific requirements of haptic hairstyling actions and decouple the simulation of the hair strand dynamics from the haptic rendering while relying on the same physiochemical hair constants. Besides the direct use of the discussed interaction metaphors in the 3D modeling area, the presented results have further application potential in hair modeling facilities for the entertainment industry and the cosmetic sciences.

***Keywords*: Haptic Interaction, hair simulation, 3D modeling**

1. Introduction

Hair animation and rendering methods have impressively progressed over the last two decades. The 3D interaction techniques and interfaces to model virtual hair, however, have received comparably little attention [1]. Most of the current approaches for creating digital hairstyles suffer from an overly complex and long modeling process. As a result, 3D artists require up to several hours to design a virtual hairstyle. An advanced interface for digital hairdressing which allows to intuitively reproduce well-known styling actions, such as e.g. combing, by means of appropriate virtual tools, has therefore a significant innovation potential allowing to unleash the creativity of 3D artists and designers.

The niche domain of hair modeling is particularly relevant because of the fundamental role virtual hair plays in characterizing the unique identity and the personal physical appearance of digital humans. Hence, easy and time-efficient modeling facilities allowing to create a broad variety of hairstyles can increase productivity and quality, bringing strong benefits to all industries displaying virtual hair. This concerns most prominently the video games and movie sectors, but also applies to the areas of cosmetics and fashion, where such methods could foster the virtual prototyping of hairstyles and related care products.

Realistic, natural interaction with hair has been prohibitive to achieve in real-time so far. Consequently, intuitive and physically plausible hairstyle editing is still almost unexplored in VR. Open challenges concern the physically based simulation of a high number of hair strands, the handling of collisions occurring among them and with an interacting tool, as well as the computation of a compelling force-feedback during 3D interaction. However, another reason for the unavailability of efficient and simple, yet accurate hair modeling interfaces is the lack of appropriate interaction metaphors enabling efficient real-time hairstyling functionalities. Most of the state-of-the-art hair modeling systems have failed in specifying an exhaustive, yet simple set of tools which provide an intuitive access to the needed styling operations. We aim to fill this gap and propose appropriate tool-based interaction metaphors for digital hairstyling. This paper extends our previous work on haptics-based interaction metaphors for tool-mediated hair modeling [2] and is organized as follows: Section 2 surveys previous work related to hair modeling techniques and interfaces. The shortcomings of current state-of-the-art methods and requirements to intuitive-yet-accurate hairstyling interfaces are discussed in Section 3. In Section 4 we present our interaction metaphor design for haptics-based hairstyling interfaces taking into consideration ergonomic aspects, styling tools and fine-tuning operations. Section 5 presents a prototype implementation of the proposed tools and validates the functionality of selected interactions. The paper ends with Section 6 discussing conclusions and future work.

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2. State of the Art in Hair Modeling

The creation of 3D hairstyles commonly bases on off-line techniques affecting static hair at its rest state.

Well-known approaches include explicit hair modeling techniques, fluid-flow and vector-field systems, sketch-based interfaces and photorealistic capturing methods. More recently, there have been attempts to enhance user interaction in hair simulation frameworks allowing dynamic hair modeling. The latter approach calls for hair simulation methods which are capable of animating hair strands at interactive rates - which most of the time is achieved at the cost of motion realism.

2.1 Static Hair Modeling

Users of explicit hair modeling systems manually define the shape, position and orientation of individual hair strands or wisps by manipulating control curves using the mouse. A number of research papers have presented or refined this technique (e.g. [3], [4]), which is also used by commercial software such as 3DS Max plug-ins (e.g. Hair & Fur, shag:hair) or Maya Hair. Although this process allows a high precision in positioning strands and defining hair shapes, creating a full hairstyle is very time consuming even for skilled users. The hair modeling pipeline in the feature film industry, which traditionally follows this explicit approach, additionally uses a number of different pre- and post-processing steps to improve the final rendering results. Still, many workarounds are required when creating complex hairstyles and the lack of mature styling tools, the inaccurate visual feedback and the unreliable simulation results are strongly felt [5]. Moreover, the steep learning curves for new hires along with the low chances to reuse previously modeled styles (due to the necessity of simultaneously using multiple software packages to obtain the desired results) decidedly motivate the improvement of the intuitivity and efficiency of hair styling facilities in this sector.

Another option for modeling hair consists in defining the flow of hair strands through mathematical and physical parameters. Hadap and Magnenat-Thalmann proposed an elegant solution for defining static hair shapes using streamlines of fluid flow [6]. A method for creating complex hairstyles by defining vector fields and trajectories was further developed by Choe and Ko [7]. Despite the impressive results obtained through these techniques, their ease-of-use is somewhat limited by the employed constraint-based styling methods (i.e. using trajectories, streams or vortices as modeling primitives), which can only be fully exploited by experienced users.

Sketch-based interfaces [8] provide a more user-friendly interactive hair modeling facility. This very quick approach to hair modeling, however, has very limited styling functionalities. The intuitivity of sketch-based interfaces comes at the cost of a lack of accuracy and displays poor styling results.

An attractive approach for creating hairstyles is scanning photographs of real hair and converting it to virtual 3D models [9]. The hair shape is captured from multiple images through dedicated computer vision techniques which provide impressive photo-realistic results. The capturing process, however, is time-consuming, and has problems in correctly interpreting complex hair patterns and styles (e.g. braids or ponytails). Moreover, these techniques require additional post-processing, and efficient interactive tools could enhance the editing of the captured styles.

While these techniques significantly differ from each other, they all share the approach of modeling static hair, i.e. the hairstyle is not animated during the styling process. On one hand, this reduces the complexity of the modeling process: designers do not need to consider head-hair, tool-hair and hair-hair interactions, and the possibility that modifications might indirectly affect other parts of the hairstyle is ruled out. On the other hand, it is exactly these mutual interactions which can increase the realism and intuitivity of innovative 3D hair modeling applications, allowing the designer to reproduce hairstyles more easily according to real styling gestures while seeing the corresponding hair motions in real-time.

2.2 Dynamic Hair Modeling

Dynamic hairdressing techniques have been explored in recent years to enhance user interaction in simulation frameworks. In their system for interactive hair modeling, Kim and Neumann extended the use of generalized cylinders into a multi-resolution control structure allowing the user to edit the hair geometry at global and local levels [10]. In this system, however, the hair is not animated in a physically based way, resulting in less natural motions. Moreover, the only means of interaction is the mouse, which limits the modeling ease.

In order to enhance user interaction, Ward et al. [11] integrated the use of a haptic device in their interactive virtual hair salon. To improve performance, the hair hierarchy of their previous research on level-of-detail hair simulation [12] is coupled with a simulation localization scheme around the contact area. Allowed interaction modes include cutting, grasping, wetting/spraying and drying, but do not support combing or brushing, which however are essential tools to quickly define the shape and position of hair wisps throughout their length. Applying water, mousse or spray to the hair is an interesting option with significant potential application in the cosmetics industry. However, these actions are not truly physically based, but they rather apply arbitrary modifications to spring constants of the simulation model. The lack of appropriate physically based parameters also applies to the haptic interaction facilities, which do not return a force-feedback according to a haptic rendering algorithm considering hair properties, but are mainly used as a means of 3D manipulation instead. Furthermore, although the hair is displayed using a hierarchy of visualization primitives (individual strands, clusters, and strips), its motion follows a unique base skeleton animated through a model derived from projective dynamics as originally proposed by Anjyo et al. [13]. A drawback of this approach is its inefficiency in properly reproducing the dynamics of curls and handling bending-twisting discontinuity effects. It is therefore not the optimal choice for simulating the modeling interaction with a complete range of different hair types.

Another system for interactive virtual hairdressing has been proposed by Magnenat-Thalmann et al. [14]. Their framework provides an easy interface for haptics-based hair cutting, brushing, curling and grasping. This approach builds on the real-time free-form deformation lattice model of Volino and Magnenat-Thalmann [15]. Hair is attached through viscoelastic forces to the lattice, which is deformed as a particle system. Although being characterized by high performance and versatility, this volumetric approach tends to create uniform deformations because it does not explicitly simulate the motion of individual hair strands, and is thus not optimal for displaying the typical behavior of wisps during styling actions such as combing. In order to overcome this problem while keeping the advantages of the volumetric approach, Bonanni et al. recently proposed a bi-layered visuo-haptic hairstyling framework, which handles user interactions at a local and global level [16]. While the large-scale dynamics of the full hairstyle are still defined as a volume, the behavior of single strands around the tool-hair contact region during haptic interaction is modeled by individual hair strand mechanics based on appropriately simplified super helices [17]. Although the multi-layered visuo-haptic approach provides some advantages with respect to previous work, such as the distinction between large- and small-scale hairstyling tools, its inherently heterogeneous definition of the global and local simulation models makes it difficult to efficiently synchronize the two layers in a smooth way.

3. Requirements to 3D Hairstyling Interfaces

Reviewing the state of the art in hair modeling clearly shows how each technique has its own strengths and weaknesses. While some of the discussed methods put more emphasis on the possibility to add geometrical details and so increase the modeling precision, but also its complexity, other focus on simplicity and ease-of-use, at the cost of the styling accuracy. The amount and sheer variety of these approaches is justified by the fact that they aim at different targets. It is therefore difficult to objectively define the superiority of one technique with respect to the others, since the most suitable approach can only be defined with respect to a specific goal. The previous section also shows that a strong limitation of the majority of current 3D hair modeling techniques concerns their tedious and long styling procedures. This translates into a lack of intuitive styling tools allowing the quick creation of hairstyles.

We aim at defining a modeling interface which fills this gap. At the same time, we require the styling method to be also accurate enough to represent a variety of different shapes and types of hair. This section presents the requirements to 3D hairstyling interfaces which need to be satisfied to achieve our goal of enabling intuitive, quick and accurate hairstyling. To this aim, we first define what users need to be able to do with a 3D hairstyling application and then discuss the appropriateness of existing modeling approaches to accomplish these tasks.

3.1 User Tasks

Users should be able to model new hairstyles from scratch and access basic functionalities allowing to load/save/export the created hairstyles. Due to the high complexity involved in hair simulation, we assume a level-of-detail (LOD) simulation scheme, or the use of a method which defines the exact time-space evolution only of a limited number of guide strands. The steps required to model new styles (to be reiterated as necessary) can then be roughly summarized as follows:

1) define the growing regions, i.e. the areas on the head on which hair grows;

2) define the required degree of modeling accuracy by adjusting the simulation LOD;

3) define the hair type through easily identifiable high-level parameters related to physiochemical hair properties;

4) interactively model the hair shape through effective styling tools;

3.2 Modeling Approach

The fundamental requirement to the modeling approach is its appropriateness to make the process of virtual hairstyling:

- **intuitive and easy**, allowing to model the hair shape through real styling gestures with no prior knowledge of the interface, and to define the hair type by tuning simple parameters such as hair curliness, volume, or color/texture;
- **quick** as it can potentially be in reality, where entirely different styles can be done with a few movements in a few minutes.
- **accurate** enough to allow the modeling of the overall hair shape through precise strand positioning and the creation of a variety of hair styles with different geometrical and physical properties;

With these criteria in mind, we rated the specific characteristics of state-of-the-art hairstyling approaches discussed in Sec. 2. Table 1 summarizes to which extent these existing methods allow for an intuitive, quick and accurate styling of virtual hair.

3.3 Discussion

Haptics-based hairstyling techniques seem to promise the best results in terms of "intuitivity" due to their ability to simulate the use of virtual tools with force-

Table 1. Different hair modeling approaches rated after the likelihood of their styling procedures to be intuitive, quick and accurate.

Approach	Intuitive	Quick	Accurate
Explicit (static)	•	•	•••
Photo-realistic	••	•	••••
Fluid flow / Vector fields	••	••	••
Explicit (interactive)	••	••	•••
Sketch-based	•••	••••	•
Haptics-based	••••	•••	••

feedback in a 3D modeling scenario, allowing to perform real styling gestures within the given haptic workspace. This also positively affects the time required to create a style. Their accuracy, however, is still limited because of the challenges linked to the effective realization of this approach. Displaying a physically based simulation of a hairstyle with real-time animated hair strands in contact with a styling tool returning haptic interaction forces is a very ambitious endeavor which calls for a highly efficient and accurately synchronized multithreaded application.

Fundamental requirements to the visuo-haptic hair simulation models underlying a 3D styling application include the ability to define the precise placement of hair strands, the handling of both interaction forces and torques, and an appropriate force/torque accumulation and propagation mechanism synchronizing the visual and haptic modalities in a consistent way. The efficient implementation of these requirements, however, is far from being trivial, and has not been satisfactorily achieved for the interaction with a full hairstyle so far.

Additional difficulties stem from the lack of previous experience in the definition of adequate 3D interaction metaphors in the field of haptics-based hairstyling. Previous approaches in this area (e.g. [11] and [16]) have emulated the setting of a real hairdresser's shop. Such an explicitly true-to-detail, 1:1 reproduction of real hairstyling actions in a VR environment could presumably find application e.g. in the training of hairdresser apprentices, or in the entertainment sector. We do not believe, however, that it suits to the professional 3D modeling arena, where the detailed reproduction of real hairdressing techniques is only of advantage if it improves the efficiency of virtual tools. This is the case, e.g., when *combing* hair with a brush – an extremely powerful styling action which finds no equal in traditional modeling techniques. But in other situations, e.g. when reducing the hair length, it is questionable whether enforcing cutting through the use of virtual scissors is more effective than alternative methods. It is therefore important to research appropriate tool-based hairstyling metaphors defining the essential interactions and functionalities which need to be implemented by a haptics-based hairstyling interface in order to guarantee both user-friendliness and styling efficiency.

4. Interaction Metaphors for Haptics-based Hairstyling

In this section we present an analysis of interaction metaphors for haptics-based hairstyling. We discuss ergonomic aspects, interaction modes, styling tools and fine-tuning operations. Clearly, additional modes might be added according to specific necessities. Our focus however is to define a basic toolset which allows the creation of a hairstyle while keeping a balance between ease-of-use and functionality.

4.1 Ergonomics

The adoption of a haptics-based approach allows to both take advantage of the use of styling gestures and perform accurate tuning operations. On the other hand, using a force-feedback device in a 3D modeling environment requires considering end-user ergonomics.

Haptic stylus and mouse are typically operated with the same hand. In order to ensure a smooth interaction and avoid being obliged to switch from one device to the other, the styling interface should allow to perform all supported operations through the haptic device. Hence, we prohibit the simultaneous use of mouse and haptic device, and require all modes (selecting, styling and fine-tuning, as defined in Sec. 4.2, below) to be operated directly from the haptic device. A typical setup of a haptics-based hairstyling interface is shown in Figure 1. When modeling, the user operates only haptic device and keyboard, without the need of reaching

Fig. 1. Typical setup of a haptics-based hairstyling interface with the application being controlled through the keyboard selectors with the left hand and the haptic interface with the right hand. This prototype implementation allows to haptically interact with wisps of hair strands.

to the mouse.

While most of the required standard functionality (e.g. New/Load/Save/Export hairstyle) can be easily integrated in the virtual environment through appropriate panels which can be reached by a haptically controlled 3D selection tool, the switch between interaction functionalities provided by the interface requires a more direct approach. To this aim, we integrate two keyboard shortcuts which we call selectors. The user can press these keys with the free hand to choose between different interaction modes and operations. Having one hand on the keyboard, selecting the desired functionality, and the other on the haptic stylus, performing the operation, increases the modeling efficiency and avoids the need to use the mouse. A right-handed user will typically operate the haptic device with the right hand, while keeping the left hand on the keyboard. In such a case, the combination of the TAB and SPACE keys provides a good support for the selection of the desired interaction.

4.2 Interaction Modes

We define three main interaction modes which can be used for accomplishing the user tasks defined in Sec. 3.1:

- **selecting** parts of the scalp and of the hair;
- **styling** through the supported tools;
- **fine-tuning** the given parameters;

These modes correspond to the first navigation level. The user can switch mode with the chosen first-level selector at any time. All modes lead to a second navigation level offering further options accessible by pressing the chosen second-level selector. The system automatically remembers the second-level option selected before switching first-level. This enables quick changes between frequently used second-level options on different interactions modes (e.g. brushing and curling). Figure 2 shows an overview of the first- and second-level navigation options. These are detailed in the following subsections.

4.2.1 Selection

The "selecting" mode allows to define:

- **growing regions** on the scalp;
- **individual hair strands** or wisps, according to the chosen LOD.

The styling and fine-tuning operations performed after the selection are applied to the chosen areas only. If no strands are selected, then fine-tuning affects the whole hairstyle.

4.2.2 Styling Tools

The "styling" mode activates the following modeling tools:

- **brush**: allows to interactively model and position hair strands according to the natural hair behavior (i.e., hair can fall back and assume another rest state after combing according to gravity and head position);
- **clip**: allows to pick and attach strands to the hairstyle. The attached part of the strand is constrained to a fixed position, while the rest is still subject to physically based dynamics;
- **gel**: allows to force hair strands to follow the defined path, but unlike clip, it makes the affected strands entirely static;
- **trimmer**: allows a straight cut in a plane, trimming the strands to the same relative length.

Styling tools can be directly operated through the haptic stylus within the 3D workspace provided by the

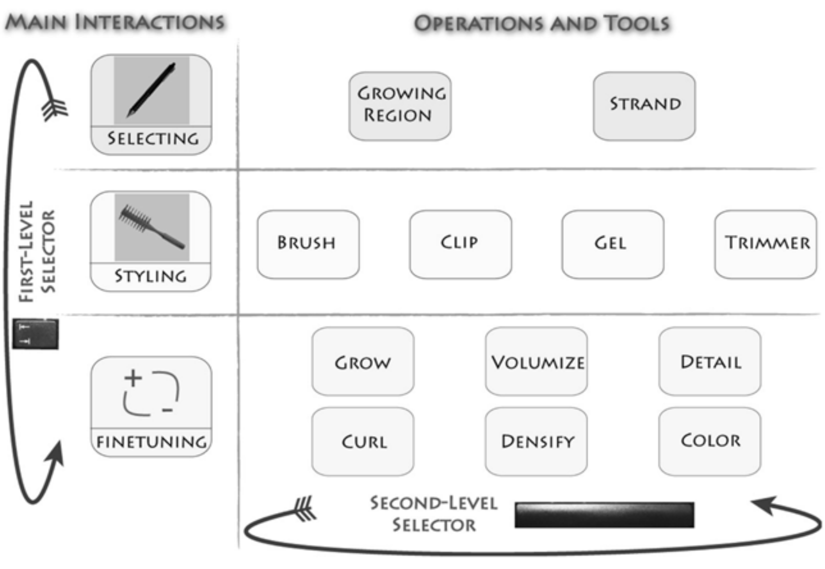

Fig. 2. Selecting the proposed functions and tools is easily done pressing two keyboard shortcuts, which allow navigating through the main interaction modes and the corresponding operations and tools.

device. All operations can be performed interactively and results are visualized in real-time. Pressing the stylus button inverts the tool action where appropriate (e.g. remove clip), while a dedicated keyboard shortcut allows to "undo" modifications. Because force-feedback significantly enhances the use of such tools, appropriate haptic rendering mechanisms return forces in accordance to the performed operation and the type of hair.

4.2.3 Fine-tuning Operations

Similarly to the way in which styling tools are chosen, pressing the second-level selector in "fine-tuning" mode allows to choose between the following actions:

- **grow**: increase/reduce the absolute hair length;
- **curl**: straighten/curl the hair;
- **volumize**: increase/decrease the hair volume;
- **densify**: increase/decrease number of strands;
- **detail**: increase/decrease level of detail;
- **color**: select the hair color.

Fine-tuning takes place by inducing a horizontal torque on the haptic stylus, which increases or decreases the affected parameters on the strand selection (if no selection, on the whole hairstyle) according to the torque magnitude and sign.

5. Implementation and Validation

Our prototype VR environment displays a virtual styling tool controlled by the user through a haptic interface, and wisps of real-time animated hair (see Fig. 1). Our simulation model represents individual hair strands as simplified superhelices [18] subject to gravity, air friction, and external forces and torques. In order to define a simulation level-of-detail, we divide hair strands into leaders and followers. At each simulation step, the motion of the leaders is computed by the mechanical model, while the position of the followers is interpolated according to the area of influence of neighboring leaders.

5.1 A Multi-Rate Approach

We base our application on a multi-rate approach which defines a visual thread computing the hair simulation (typically at 40-60 frames per second), and a haptic thread running at a significantly higher frequency (reaching 1 kHz). This architecture is depicted in Fig. 3.

The significant difference of the visual and haptic rendering speed is motivated by the need to adapt to the human perception: while the successive repetition of tens of static images per second is enough for our sense of vision to interpret it as a dynamic sequence, our sense of touch requires several hundreds of stimuli per second to perceive a force cue as continuous and steady. This makes the achievement of a so-called transparent haptic rendering particularly challenging, especially in conjunction with physically based simulation of deformable bodies computed in real-time (i.e. in the very moment in which the interaction takes place, without precomputations). The related complications arising from multimodal integration are important aspects which a haptics-based 3D user interface must take into consideration.

The development of effective interaction metaphors can significantly avoid additional sources of instability and complexity by clearly differentiating the requirements of the provided tools in terms of applicable deformations and force-feedback.

- At application start, the relevant physiochemical hair constants for the simulated hairtype are read into the system. These properties affect both the hair dynamics and haptics.
- Beginning from a non-contact state, the user is able to freely move the tool in the virtual space, and the hair is animated according to its simulation model.

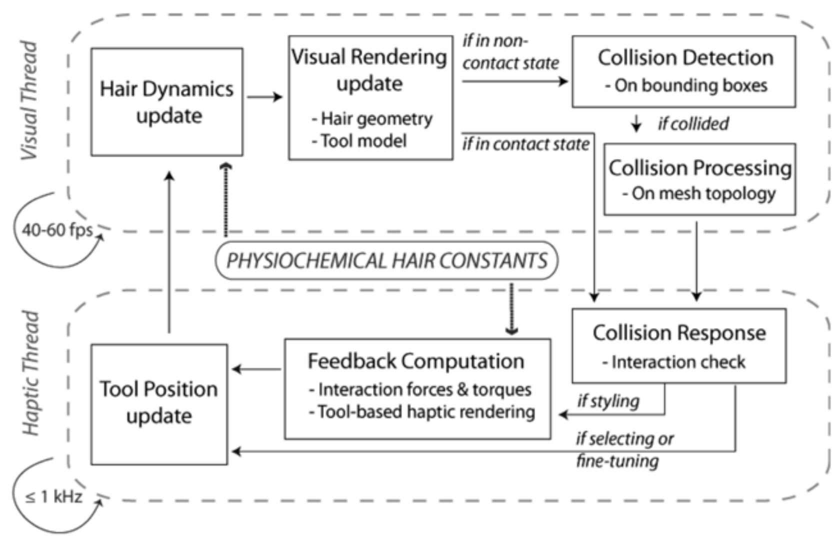

Fig. 3. Overview of the processes running in the virtual and haptic threads of our multirate architecture.

The tool position, the hair dynamics and the visual rendering are updated.

- The contact state is entered when a collision is detected by the bounding box enclosing the hit strand, and the collision is processed on the mesh of the strand.
- A collision response is then computed according to the user movement. An interaction check is performed to evaluate whether the performed movement should perform a styling action, e.g. comb the hair or drag it in space.
- Once combing, the tool-hair collision area slides down in the combing direction and a force-feedback is returned through the haptic device. If instead the hair is dragged, no force feedback is computed due to the neglectable weight of hair. In both cases, however, the interaction forces are accumulated at each haptic step and then propagated back to the leader strand by the dynamics update process of the following visual thread call.
- The contact state is active until the hair wisp is combed over its whole length, or the haptic brush is explicitly detached through the device button. The haptic interaction loop can then start over from the beginning.

5.2 Dynamics and Haptics

We consider a strand of length L, divided into N helical segments. We extend our previous work on the haptic interaction with one-dimensional structures [19] to handle force and torque interactions with *wisps* of hair modeled as *leader* strands (simulated) and *follower* strands (interpolated). Interpolation is performed on the basis of a pre-defined area of influence of neighboring leader strands. Allowed deformation modes of leader strands include twisting about the tangent to the centerline ($i = 0$) and bending about the cross-sectional major axis ($i = 1$). Thus, we model only two degrees of freedom per segment and reduce the total amount of equations to solve by one third with respect to the original model, as proposed in [18]. Accordingly, the twist and bend values of segment $S_Q (1 \le Q \le N)$ depend on time and are expressed with $q_{i,Q}(t)$ for $i = 0,1$ respectively. The numbers $q_{i,Q}(t)$ together form a vector of size $2N$ denoted $\vec{q}$ (t). The computation of the hair dynamics consists in solving, for each guide strand, the corresponding equations of motion expressed in Lagrangian mechanics:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_{i,Q}}\right) - \frac{\partial T}{\partial q_{i,Q}} + \frac{\partial U}{\partial q_{i,Q}} + \frac{\partial D}{\partial \dot{q}_{i,Q}}$$

$$= \int_0^L \left(\frac{\partial \vec{r}(s,\vec{q},t)}{\partial q_{i,Q}} \cdot \vec{F}(s,t) + \vec{\tau}(s,t) \cdot \vec{n}_i(s,\vec{q},t) \right) ds \qquad (1)$$

The resulting system of $2N$ equations relates the kinetic, potential and dissipation energies (T, U and D) acting on the strand to the centerline's space-time evolution $\vec{r}(s,q,t)$, with the vector $\vec{q}$ used as generalized coordinates of the model. We further define user-induced force and torque interactions which are accounted for in the hair dynamics. $\vec{F}(s,t)$ is external force acting on the strand, consisting of gravity, viscous drag from surrounding air and haptic interaction force. $\vec{\tau}(s,t)$ is the external torque influencing the orientation of the strand's cross section at the interaction point. This orientation is given by the strand's material reference frame, an orthonormal basis denoted as $\vec{n}_i(s,\vec{q},t)$.

5.3 Selecting

The selection modality is symbolized by a pen which allows to select the desired areas by painting mesh triangles of the head model, and to choose individual hair strands for performing individual modeling operations on selected areas without affecting the whole hairstyle. Fig. 4 shows the selection process of the area on which hair is due to "grow". The hair strands are evenly distributed over the selected polygons according to the defined hair density.

5.4 Styling

Styling tools are used to directly interact with hair as discussed in Sec. 4.2.2. From an implementation viewpoint, different tools inherit the basic functions of the generic tool and are treated in a similar way. They share the collision detection, but not the response, nor the resulting haptic feedback. We detect tool-hair collisions against axis-aligned bounding boxes placed around each hair strand. For brush and hair clips, which need the definition of contact models describing the hair-tool interactions, we explicitly require the strands to stick to the tool after the first tool-hair contact, as it can be observed in real-life scenarios. When a contact occurs, the styling tool influences the dynamics of the leader strand which is closer to the collision point, and consequently all his interpolated followers. Hence, the

Fig. 4. Selecting the growing area on the scalp.

leader-follower interpolation mechanism accounts for the propagation of forces and torques induced by brush movements and turns towards the whole contact area. Collision response is computed at haptic rates according to the performed interaction and appropriate force rendering schemes, which are tool-dependent. Interaction forces and torques are accumulated at each haptic step and then propagated back to the leader strand by the dynamics update process of the following visual thread call.

When using the brush, the tool-hair collision area slides down in the combing direction and a force-feedback is returned through the haptic device. If instead the load exerted on the tool-hair contact point is not high enough to determine the start of a combing action, the hair is dragged, and no force feedback is returned due to the neglectable weight of hair. The tool stays in contact with the hair until the hair wisp is combed over its whole length, or the haptic brush is explicitly detached through the device button. The haptic interaction loop can then start over from the beginning.

5.5 Fine-tuning

The hair type is defined according to physiochemical hair constants which affect both the dynamic hair behavior as well as the haptic interaction. In order to ensure an improved usability of the interface, we have combined the physical properties of hair fibers into tunable high-level parameters.

The derivation of the tunable parameters, however, is inherently model-dependent, and subject to strong variations even with little modifications of the implementation. The curliness factor is one of the proposed high-level parameters which, as we believe, plays a fundamental role in hair styling, and is at the same time very difficult to define. With our current model, the hair strand curliness is dependent on the bending and twisting rigidity, as well as bend and twist values per segment, with increasing values towards the strand's end. Curliness can be fine-tuned on each leader strand.

5.6 Implementation Details

The implementation is done in standard C++. The equations of motion of the hair simulation model are integrated using DASPK, a differential algebraic equation solver [20]. In order to support most commercial haptic devices based on impedance control, part of the implementation of the haptic interaction handling is based on CHAI3D [21]. The application allows six degrees-of-freedom (6-DOF) interaction and 3-DOF force feedback. We tested the described system with different haptic devices, such as a Force Dimension Omega, a Sensable Phantom Desktop and a Novint Falcon. All devices provided a good response and similar results. We noticed slight differences in the feedback due to hardware-related stiffness rendering capabilities. The overall impression, however, was that all devices could provide a good enhancement of the hairstyling facilities with respect to the same interactions without haptic feedback.

6. Conclusions and Future Work

We discussed the state-of-the-art in hair modeling and identified the specific problems which currently limit the creativity and efficiency of digital artists working in this area: the lack of intuitive and quick, yet accurate 3D styling facilities. We rated to which extent existing methods comply with these requirements, emphasizing the high innovation potential offered by haptics-based approaches.

Instead of relying on 2D pen tablet or mouse, this truly three-dimensional modeling approach allows to reproduce real styling gestures, which results in a more intuitive use. The large degree of motion freedom of the 3D workspace and the return of a force-feedback to the user has the potential to significantly enhance the design of virtual characters' hairstyles. Nonetheless, there are several unsolved problems in the domain of visuo-haptic simulation which severely hamper the efficient implementation of this approach. Besides many technical difficulties, the lack of adequate interaction metaphors enabling efficient styling functionalities represents an obstacle to the successful realization of haptics-based modeling applications. Hence, we presented a set of tool-based hairstyling metaphors for a haptic modeling

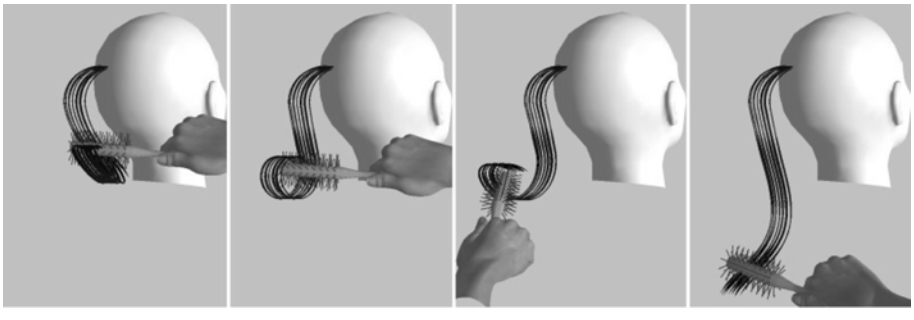

Fig. 5. Modeling the hair through a styling tool.

interface taking into consideration ergonomic aspects, interaction modes, styling tools and fine-tuning operations, with the intent to keep a balance between ease-of-use and functionality. We further validated our approach on a prototype implementation of the proposed interface.

The presented design paves the ground for further research and can provide meaningful insights for developing novel haptics-based hairstyling interfaces. Furthermore, the clear definition of the essential requirements to the targeted functionality can help identifying flaws at early stage.

Prospects for future work include the application of the proposed interaction metaphors to a complete hairstyling interface relying on a simulation model enabling the explicit positioning of arbitrary centerline nodes, which could allow for an improved punctual handling of strong external forces. A good candidate for this enterprise is given by the discrete elastic rods model [22], which is currently subject of our investigation for application in the haptics-based hairstyling context [23]. The efficient adoption of such a model, together with appropriate parallelization schemes exploiting multicore architectures, could lead to a more robust implementation of haptics-based hairstyling applications and a breakthrough in 3D hair modeling.

7. Acknowledgements

The authors would like to thank Nedjma Cadi-Yazli and Marlène Arévalo-Poizat for their collaboration to the design of the 3D models. This research is funded by the Swiss National Science Foundation (SNSF), grant nr. 200020-121780. The second author is further supported by GA UK (Grant Agency of the Charles University in Prague, Czech Republic), project nr. 100209.

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