Virtual Hair Handle: A Model for Haptic Hairstyling

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Abstract

The process of styling virtual hair is a tedious task for 3D artists, who would significantly profit from more natural and intuitive ways of creating virtual hairstyles - such as, for example, the possibility to simply comb virtual hair using a haptic device. However, despite significant advances in hair simulation during the last decades, physically based haptic interaction with hair is still an unresolved problem. In this paper, we propose a real-time simulation framework allowing to interactively style virtual hair and feel a force-feedback through a haptic device. Unlike previous approaches, we adapt our hair simulation model to fulfil the requirements of haptic interaction. Our model reproduces, on a physical basis, hair behaviour and interaction forces arising when touching hair.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual Reality

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1. Introduction and Previous Work

A hairstyle decidedly influences a person's look. Likewise, virtual hair plays a fundamental role in the appearance of a digital human within a virtual reality environment. However, the process of styling virtual hair is a tedious task for 3D artists, who would significantly profit from more natural and intuitive ways of creating virtual hairstyles, like simply combing virtual hair using a haptic device.

Haptic-based hairdressing techniques have been explored in recent years to enhance user interaction in simulation frameworks. In their system for interactive hairstyling, Ward et al. [WGL06] obtained interesting results extending their previous research on level-of-detail in hair simulation [WLL*03] to handle haptic interaction. To improve performance, the hair hierarchy is coupled with a simulation localization scheme around the contact area. Haptic interaction facilities, however, are mainly used as a means of 3D manipulation, since the force-feedback is not computed on the basis of physical interaction. Moreover, the model controlling the skeleton of the hair simulation is derived from projective dynamics [AUK92]. A drawback of this approach is its inefficiency in properly handling strong curliness. It is therefore not the optimal choice for simulating a complete range of different hairstyles.

Another system for interactive virtual hairdressing has been proposed by Magnenat-Thalmann et al. [MTMGV06, MTMBG07]. Their framework provides an easy interface for haptic-based hair cutting, brushing, curling and grasping. This approach builds on the real-time free-form deformation lattice model of Volino and Magnenat-Thalmann [VMT04]. 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 doesn't explicitly model individual hair strands, and is thus not optimal for interactive haptic hairstyling.

So far, haptic-based hairstyling has been mainly understood as an extension of 3D interaction modalities within existing hair simulations. But physically based haptic interaction with hair is mostly unexplored and still an unresolved problem. Contrariwise, many a model for simulating the dynamics of individual hair strands has been proposed over the last 15 years, including simple mass-spring systems, projective dynamics, chains of rigid bodies and helical strands. A comprehensive survey on hair simulation is given by Ward et al. [WBK*07]. Among the most recent physically based formulations expressing the nonlinear behaviour of individual hair strands are *Dynamic Super Helices* [BAC*06], piecewise helical rods animated with Lagrangian mechanics. A super-helix represents a discretization of the Kirchhoff model, which relies on the Cosserat theory of elastic rods originally introduced to the computer graphics community by Pai [Pai02]. It properly handles the dynamics of curls by modelling bending and twisting deformations and allows to simulate a vast variety of hairstyles. Despite its complexity, the *Super-Helix* approach meets the requirements of both computer graphics and human-computer interaction and allows to explore physically based haptic interaction with hair.

2. Virtual Hair Handle

"Hair handle" refers to the overall sensation experienced when touching and handling hair. The concept of hair handle is used in the cosmetic research and industry, where studies matching the physical properties of hair with specific tactile sensations such as softness or smoothness have proved particularly useful for developing new hair care products. Hair handle can be defined through a systematic comparison of objective quantitative hair fibre measurements with subjective qualitative assessments of hair. This correlation gives an insight about which physical properties can be considered more relevant on a perceptual level. In spite of the relevance of hair handle in hair science, there has been no application of this complex property in computer simulation so far. Our approach is to define a *virtual* hair handle - i.e. to model only those physical parameters which can be considered relevant during haptic interaction with hair.

2.1. Mechanical Properties of Hair

Chemical and physical behaviour of human hair has been extensively reported in the literature along with descriptions of the human hair morphology, composition and mechanical properties. The mechanical behaviour of single hair fibres is strongly influenced by elastic deformations which include tensile, bending and torsion properties, as well as relaxation in each of the different modes.Moreover, important characteristics of single hair fibre include friction properties, cross-sectional area/diameter, static charge, lustre/shine, and cohesive forces [Rob02]. While these single hair fibre properties have been widely studied, there has been less attention to the understanding of hair collective properties influencing hair-hair interactions. A scientific analysis of the collective properties can be significant for rating consumer assessments such as combing ease or manageability and define the contribution of mechanical properties towards hair handle and feel. To this aim, the cosmetic industry identified three most relevant categories of hair properties sensed when touching real hair [WFJ06]:

- **Geometrical properties** of single hair fibres: cross-sectional geometry, ellipticity, diameter and length
- **Bending properties** of single fibres in a fibre collective
- **Frictional properties** of hair fibres arising during hair-hair interactions

The main design guideline for our hair simulation model is the possibility to express these properties.

2.2. Objective Measurement vs. Subjective Assessment

Physical parameters of hair are obtained through objective measurements providing e.g. diameter or frictional properties of hair fibres. These measurements can be performed through devices such as optical fibre diameter analyzers and tensile testers. Bending properties can be derived from the hair's cross-sectional geometry [WFJ06]. In this context, there is good evidence that the hair's cross-section is elliptic rather than perfectly circular, thus single fibres will only bend over their cross-section's major axis [Swi95]. This consideration allows us to neglect bending over the minor axis.

Hair Type	**Positive Ratings (%)**	**Maj. Axis Diameter (μ m)**	**Ellipticity**	**Bending Stiffness (10^{-9}Nm)**	**Frictional Force (cN)**
H1	41	93.1	1.36	7.59	0.64
H2	69	96.1	1.33	9.25	n/a
GA1	94	89.5	1.45	5.23	0.65
GC3	94	89.3	1.42	5.66	0.79

Table 1: *Correlations between objective measured data and subjective rating of different hair types. Source: [WFJ06].*

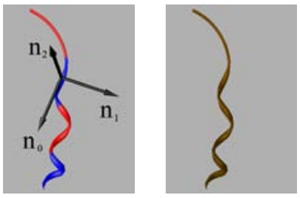
The properties described in section 2.1 are fundamental for the subjective qualitative assessment of hair samples [WFJ06]: experts associated "good handle" with the adjectives "smooth", "soft" and "flexible", which is the case for hair with a low bending stiffness, low diameter, and high ellipticity. Negative adjectives determining "bad handle" were typically "coarse" and "blunt", with higher bending stiffness and diameter, as well as lower friction in root-to-tip direction. Table 1 shows these correlations.

3. Physical Simulation for Haptic Hairstyling

Our physical model for hair is based on *Super-Helices* as discussed in sec. 1. A hair strand is modelled as an elastic rod composed of one or more helical *segments* (see figure 1). The degrees of freedom of the model proposed by [BAC*06] are the twist and two curvatures of each segment. As discussed in section 2.2, however, we assume hair doesn't bend over the minor axis of its cross-section.Therefore we model just two degrees of freedom per segment, *twist* and *bend*. This brings a significant speedup by reducing the number of equations to solve by one third compared to the full model. We consider a strand of length L, divided into N helical segments. The twist and bend of segment S_Q $(1 \leq Q \leq N)$ depends on time and it is written $q_{i,Q}(t)$ for $i = 0, 1$ respectively. The numbers $q_{i,Q}(t)$ together form a vector of size $2N$ denoted $\vec{\mathrm{q}}(t)$. Curvature for the whole strand is then given as

$$\kappa_i(s, \vec{\mathrm{q}}, t) = \sum_{Q=1}^{N} q_{i,Q}(t) \chi_Q(s)$$

for $i = 0, 1$, where $\chi_Q(s)$ is the characteristic function of segment S_Q.



(a) (b)

Figure 1: *Segments with material frame (a) and rendered (b)*

3.1. Strand reconstruction

The vector $\vec{q}$ allows us to compute the 3D position of the centreline of the super-helix, denoted $\vec{r}(s,\vec{q},t)$. Each point on the centreline has an associated material reference frame, an orthonormal basis given by the orientation of the cross-section at that point. We denote the vectors of this basis as $\vec{n}_i(s,\vec{q},t)$. $\vec{n}_0$ is the tangent to the centreline. $\vec{n}_1$ and $\vec{n}_2$ are the directions of the cross-section semimajor and semiminor axes, respectively (see figure 1). As the frame is orthonormal, there exists a Darboux vector $\vec{\Omega}(s,\vec{q},t)$, such that for each $i=0,1,2$:

$$\frac{\partial \vec{n}_i(s,\vec{q},t)}{\partial s} = \vec{\Omega}(s,\vec{q},t)\times\vec{n}_i(s,\vec{q},t)$$

In the local material frame, the coordinates of the Darboux vector $\vec{\Omega}(s,\vec{q},t)$ are defined as the strand's twist and bend:

$$\vec{\Omega}(s,\vec{q},t)=\sum_{i=0}^{1}\kappa_i(s,\vec{q},t)\vec{n}_i(s,\vec{q},t)$$

Let us now consider one segment S_Q, given by $\langle s_L^Q, s_R^Q\rangle \subseteq \langle 0,L\rangle$. Recall that each segment of the strand is a plain helix. This means that on S_Q, $\kappa_i(s,\vec{q},t)=q_{i,Q}(t)$ and is therefore constant with respect to s. So the norm of the Darboux vector $\vec{\Omega}(s,\vec{q},t)$ is also constant. We denote it $\Omega(\vec{q},t)$. We further introduce the following notations ($\vec{a}$ stands for an arbitrary vector):

$\vec{\omega}(\vec{q},t)=\frac{\vec{\Omega}(\vec{q},t)}{\Omega(\vec{q},t)}$	the unit vector parallel to $\vec{\Omega}(\vec{q},t)$
$\vec{a}^{\parallel}=(\vec{a}\cdot\vec{\omega}(\vec{q},t))\cdot\vec{\omega}(\vec{q},t)$	projection of $\vec{a}$ parallel to $\vec{\omega}(\vec{q},t)$
$\vec{a}^{\perp}=\vec{a}-\vec{a}^{\parallel}$	proj. of $\vec{a}$ perpendicular to $\vec{\omega}(\vec{q},t)$
$\vec{n}_{i,L}^{Q}(\vec{q},t)=\vec{n}_i(s_L^Q,\vec{q},t)$	material frame at segment start
$\vec{r}_L^{Q}(\vec{q},t)=\vec{r}(s_L^Q,\vec{q},t)$	centreline position at segment start

The position of the centreline can then be expressed as:

$$\begin{aligned}\vec{r}(s,\vec{q},t) = {} & \vec{r}_L^Q(\vec{q},t)+(s-s_L^Q)\vec{n}_{0,L}^{Q\parallel}(\vec{q},t)+\\ & +\frac{\sin((s-s_L^Q)\Omega(\vec{q},t))}{\Omega(\vec{q},t)}\vec{n}_{0,L}^{Q\perp}+\\ & +\frac{1-\cos((s-s_L^Q)\Omega(\vec{q},t))}{\Omega(\vec{q},t)}\left(\vec{\omega}(\vec{q},t)\times\vec{n}_{0,L}^{Q\perp}\right)\end{aligned}$$

A straight, untwisted segment presents a special case. For such a segment, $\Omega(\vec{q},t)=0$ and the above formula is replaced by:

$$\vec{r}(s,\vec{q},t)=(s-s_L^Q)\vec{n}_{0,L}^{Q}(\vec{q},t)$$

Nevertheless, all derivatives required in the dynamic equations (see section 3.2) can still be expressed.

3.2. Dynamic equations

To derive equations of motion for our model, we use Lagrangian mechanics, with the vector $\vec{q}$ used as generalized coordinates of the model. This gives us the following system of $2N$ equations:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_{iQ}}\right)-\frac{\partial T}{\partial q_{iQ}}+\frac{\partial U}{\partial q_{iQ}}+\frac{\partial D}{\partial \dot{q}_{iQ}}=\int_0^L\frac{\partial\vec{r}(s,\vec{q},t)}{\partial q_{iQ}}\cdot\vec{F}(s,t)\mathrm{d}s$$

for $i=0,1$ and $1\le Q\le N$. The dot accent denotes differentiation by time: $\dot{q}_{i,Q}(t)=\frac{\mathrm{d}}{\mathrm{d}t}q_{i,Q}(t)$. T, U and D stand for the kinetic, potential and dissipation energy of the strand, respectively. $\vec{F}(s,t)$ is external force acting on the strand. In our current model, this consists of gravity, viscous drag from surrounding air (which is considered immobile) and haptic interaction force:

$$\vec{F}(s,t)=m(s)\vec{g}-\nu\dot{\vec{r}}(s,\vec{q},t)+\vec{F}_{\mathrm{hap}}$$

where $m(s)$ is hair strand mass, $\vec{g}$ is gravitational acceleration, ν is air drag coefficient and $\vec{F}_{\mathrm{hap}}$ is interaction force.

The potential energy U and the dissipation energy D of the elastic rods are computed in a similar way as in [BAC*06]. Instead of computing the kinetic energy directly, however, we calculate only the derivatives needed, as given in [Tor84]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_{iQ}}\right)-\frac{\partial T}{\partial q_{iQ}}=\int_0^L m(s)\ddot{\vec{r}}(s,\vec{q},t)\cdot\frac{\partial\vec{r}(s,\vec{q},t)}{\partial q_{iQ}}\mathrm{d}s$$

We used the symbolic math toolbox of the Matlab program to obtain the equations of motion as functions of $\vec{q}$, $\dot{\vec{q}}$ and $\ddot{\vec{q}}$. These are then integrated using DASPK, a differential algebraic equation solver [BCP96].

Figure 2: *Several frames obtained from haptic interaction in our preliminary implementation*

3.3. Haptic Rendering

During haptic hairstyling, the user operates a tool (represented by a brush model, see figure 2) to interact with the hair. The first tool-hair collision constrains the tool to stick to the hair until it has *combed* the hair over its whole length or is explicitly detached. With the previously described model, interaction forces can be computed from the tool velocity $\dot{\vec{t}}$:

$$\vec{F}_{hap} = \dot{\vec{t}}^{\perp}\beta + \dot{\vec{t}}^{\parallel} f(\gamma)$$

where β is directly related to the bending stiffness and f is a function of the internal frictional coefficient γ. $\parallel$ and $\perp$ denote projections parallel and perpendicular to the strand tangent $\vec{n}_0$, respectively.

We tested the described system with a Force Dimension Omega haptic device. Our implementation is based on CHAI3D [CBMS05]. This allows us to supports most commercial haptic devices based on impedance control.

4. Conclusions and Future Work

We presented a model for visuo-haptic interaction with virtual hair carried by a scientific analysis of physical properties relevant for hair handle and feel. Although our virtual hair handle model is still work in progress, a preliminary implementation confirms that our new method is capable of rendering haptic interaction forces during virtual hairstyling (sec. 3.3, see also figure 2) according to differences in the hair's physical attributes (sec. 2.1) and style. Before performing a comprehensive visuo-haptic evaluation of the differences between simulated and perceived hair properties, however, several improvements need to be addressed. These include, among others:

- Hair type definition by interactively adjusting high-level parameters for both visual and haptic rendering (e.g. "curliness" and "combing ease", respectively) which influence multiple physical properties and haptic feedback;
- Extension of haptic tools exploring adequate haptic rendering algorithms and enabling multipoint feedback;
- New formulation of collective hair properties to be used in a multiresolution approach;
- "Fixing hairstyle" facilities modelling the transition between interactively modelled and static hairstyle.

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