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Measuring realism in hair rendering

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Abstract

Visualisation of hair is an extremely complex problem within the field of Computer Graphics. Over the last 10 years, huge strides have been made in the area of physically-based hair rendering, giving rise to many applications in various fields other than the graphics industry. Given the number of models for hair rendering, there is no well defined evaluation process to measure the realism in the hair models in use today. For this work-in-progress paper, we propose an evaluation process not only to evaluate the realism in hair rendering models, but also examine the various effects that contribute to its realistic perception. This builds an index of realism based on experiments with computer generated models, and then proposes comparing the results with values obtained from computational tomography, optical imaging and goniophotometer readings.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture; Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism—Virtual reality; Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism—Raytracing

1. Introduction

Modelling hair is core in computer graphics for a variety of applications. Rendering and modelling hair realistically is essential to visualise people and animals, especially in recent years when virtual characters have become increasingly present in video games, cartoons and advertisements. In this context, photo-realistic characters can only be created by solving some diverse problems. This includes the generation of convincing hair-styles, the simulation of hair dynamics, as well as hair rendering [WByK*06].

The complexity of this process is due to the huge number of interactions within and between hair fibres. Also, the comparatively long and thin structure of the fibre and its highly nonlinear deformation under external forces, makes modelling a hair fibre highly complex and very sensitive to the physical model chosen. The anisotropic nature of light scattering from hair fibres, known as single scattering, along with reflections and refractions within the hair coupe, known as multiple scattering, have to be considered as they both contribute to the right visual perception of the colour.

Representing this scattering of light in hair is the key to achieving realism. The evaluation mechanism to detect the extent of realism in hair models has mainly depended on visual perception in the graphics industry, even as models become more physically realistic. Physically realistic optical simulations of hair are also gaining relevance in the cosmetic and materials science industries. In the cosmetic domain, emphasis is placed on hair colour under different illuminations and hairstyles, whereas in the materials science domain, hair research demands a physically accurate simulation to observe the interaction of hair fibres with light and in the prediction of coatings and ethnic differences. In order to validate these models, a scientific evaluation process is required which can help determine the realism in the hair models and create an index thereof. Also, with advances in computational-tomography, microscopic imaging and other optical technologies, the internal structure of hair can be uncovered in greater detail.

2. Background

A human head typically consists of a large volume of hair with over 100,000 hair follicles and the cross section of hair is more or less elliptical ranging from 45 to 100 μm [SG77] (cross section axis ratio is defined and shown in figure 1 as

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a:1). A hair fibre is composed of three main parts: the cuticle, the medulla and the cortex. The cuticle consists of scales which are overlapping cells surrounding the central core of the hair fibre. They are arranged like shingles on a roof, with their surfaces tilted toward the root end of the fibre by approximately 3° (defined as α in figure 1). The medulla is the coloured central cone-like structure of the fibre. The cortex is the major part of the fibre mass of hair and consists of cells and binding material. These spindle-shaped cells are usually 1 to 6 μm thick and approximately 100 μm long with a refractive index of $\eta = 1.55$. Extensive details are available in various texts including [SG77,Rob02].

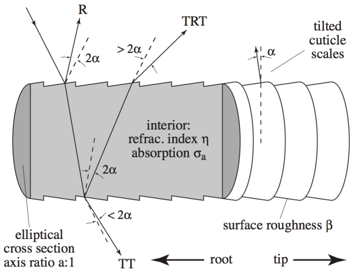

Figure 1: *Illustration of the Marschner model, adapted from [MJC*03]*

3. Models

There have been many models used in hair rendering and they are well documented in the survey by Ward et al. [WByK*06]. For our study, we have chosen four of the most prominent models for hair rendering which address different aspects of scattering of light in hair.

3.1. Kajiya-Kay model

This model [KK89], treats every individual hair fibre as an opaque cylinder with a circular cross-section and assumes that all incident light is reflected from the hair fibre to a cone. A highlight of constant intensity is placed at the centre of that cone, which captures the linear highlight running perpendicular to the fibre direction and is modelled using a Phong Lobe. The reflection of light within the fibres is modelled by an overall diffuse component whose radiance is proportional to the cosine of the incident angle. The Kajiya-Kay model is a phenomenological model as it has no real physical foundation. The most obvious features of light reflecting from hair are captured by the model but it fails in several respects, most notably in its assumption that a hair fibre is opaque.

3.2. Marschner model

Marschner et al. [MJC*03] took observations made by two cosmetic groups [SG77, BS91] about scattering properties of hair fibres and approximated it into a realistic model. It considers an individual hair fibre to be a coloured dielectric cylinder of elliptical cross-section. Light scattered through a hair fibre has three components as shown in figure 1: R, TT, and TRT components. The R component refers to the reflected component off the hair surface. The TT component refers to the transmission of light through the fibre (which is visible when hair is lit from behind) and the TRT component refers to the internally reflected component off the opposite side of the fibre. The scattering geometry of the Marschner model is illustrated in figure 1. Here θ_i and θ_r represent the inclinations with respect to the normal plane and ϕ_i and ϕ_r refer to the azimuths. The direction of illumination is ω_i and the direction in which the reflected ray is computed is ω_r. The scattering model can be represented by:

$$\begin{aligned} S(\phi_i,\theta_i;\phi_r,\theta_r) &= M_R(\theta_h)N_R(\eta'(\eta,\theta_d);\phi)/\cos^2\theta_d \\ &+ M_{TRT}(\theta_h)N_{TRT}(\eta'(\eta,\theta_d);\phi)/\cos^2\theta_d \\ &+ M_{TT}(\theta_h)N_{TT}(\eta'(\eta,\theta_d);\phi)/\cos^2\theta_d \end{aligned}$$

The M functions represent the 3 longitudinal scattering functions which account for the effect of the cuticle scales and the N functions represent the azimuthal scattering components where η' is the effective refractive index to accommodate for the approximation of the elliptical cross-section of the hair fibre.

The model is a good approximation of the scattering of light from a single hair fibre, but does not handle multiple scattering. It also assumes that the light source and the observer are far away from the hair fibres, and therefore, does not function well with closeups.

3.3. Zinke model

Zinke et al. [ZSW04] built a near-field scattering model which approximates the local hair-hair interaction and adds attenuation factors for indirect illumination. In case of indirect illumination, the effects of local scattering from hair geometry are approximated due to statistical reasons. The attenuation coefficients of light scattering from the hair into the viewing direction are averaged out and it assumes that indirect illumination is locally constant and it works well for closeups and blonde hair. The new outgoing radiance is:

$$L_o(h_o,\phi_r,\theta_r) = \int_0^{2\pi}\int_{-\pi/2}^{\pi/2} f_{nearfield} L_i \cos\theta_i d\theta_i d\phi_i$$

The averaged attenuation coefficients are called $AFS^{avg}_{R,TT,TRT}$ and depend on outgoing inclination θ_r, index of refraction and relative absorption coefficients (F refers to the fresnel coefficients and S' is the scattering function after approximating for local hair-hair interactions)

$$AFS^{avg}_{R,TT,TRT} = \int_0^1 A_{R,TT,TRT} F_{R,TT,TRT} S'_{R,TT,TRT}$$

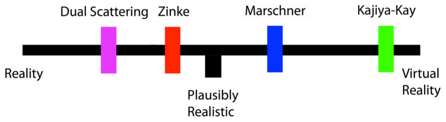

Figure 2: *Index of realism for the 4 models according to hair experts*

3.4. Dual Scattering model

The ‘dual scattering’ model [ZYWK08] splits multiple scattering into local and global components. The global multiple scattering component (ψ^G) is responsible for approximating the light that reaches the neighbourhood of any shading point after it travels through the hair volume. It is computed by approximating the overall density of the hair volume and computing the scattering, mostly forward scattering, of a single light path to the source, known as the shadow path. The local multiple scattering component (ψ^L) accounts for the scattering events, usually backscattering, that occur within the neighbourhood of the shading point. The complete multiple scattering component is thus derived as:

$$\psi(x, w_d, w_i) = \psi^G(x, w_d, w_i)(1 + \psi^L(x, w_d, w_i))$$

where w_d represents the direction of the incident light entering the hair volume and w_i represents the direction of the multiple scattering component/light as it reaches the shading point represented by x. The illumination is considered to be only a single directional light source such that w_d remains constant. The model, however, approximates the effect of the geometry of the hair volume by using only an estimate of the density of hair fibres. This makes the analytical model possible and assumes that the geometry of the hair/hairstyle has no effect on the multiple scattering except for the shadow path. Therefore, this model will not give realistic results for hairstyles which can break this assumption.

4. Reality v/s Virtual Reality

Physical realism is the easiest way to define and quantify the accuracy of any result. If the spectral irradiance values at all points in both the real and the virtual scenes match, then we can assume to have achieved physical accuracy. To obtain such a result, the complete scene including the geometry, materials and light of the scene has to be modelled without any approximations [CF10]. However, the complete light scattering model of hair is too complex to be used in hair rendering. Hence, in this study, we work on certain approximations in order to mimic the effects of physical phenomena in hair scattering. Thus, in order to build a predictive system in materials science research, we must be able to define an index of realism. We used two methods of evaluation of realism: Visual perception of a random audience and evaluation of realism from a hair expert. The four models were blindly cross compared across a range of participants(33 in number) mostly from the University of Manchester who were asked to rate the models on a scale of 1 to 10; 1 for no realism or completely virtual, 5 for a plausibly realistic image and 10 for a completely realistic image. The images presented to the participants included all the four hair models implemented on four separate hair meshes obtained from the dual-scattering experiment within [ZYWK08]:

1. Straight hair: 50,000 fibres;1,250,000 total vertices
2. Curly hair: 50,000 fibres; 3,441,580 total vertices
3. Wavy hair: 50,000 fibres; 2,450,000 total vertices
4. Thin Wavy hair: 10,000 fibres; 872,756 total vertices

Images of each model were shown to the participants varying different factors such as frequency, position and colour of incident light, position of camera, position of highlights, colour and geometry of hair strand. The results were then averaged across inputs for each of the varying factors and plotted to scale along with the standard deviation shown in figure 3. The dual-scattering model [ZYWK08] performed the best amongst all the models and most of the participants ranked the model quite close to a realistic image with most of the ratings falling in the range of 8-9 on the realism scale. The higher the number of vertices in the geometrical model, the better the realistic perception was, with the Curly hair model giving the best results as shown in figure 3. The experiments on colour, seen in figure 4, showed that for lighter shades, the dual scattering model performed better than the other models; and for darker shades, the Marschner [MJC*03], Zinke [ZSW04] and dual scattering models [ZYWK08] displayed a similar amount of realism. Therefore, the ratings on the Marschner model have a high standard deviation in figure 3 as participants rated the model high for darker shades but quite low for lighter ones, leading to a large spread of values.

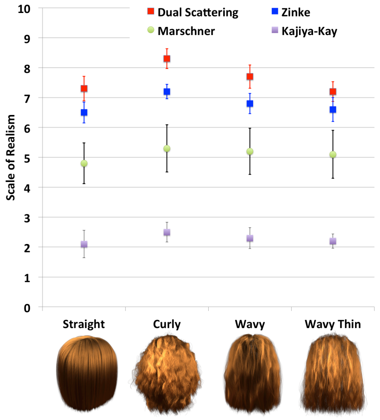

Figure 3: *Index of realism for each of the geometric hair meshes*

The images were also examined by expert practitioners from the School of Materials Science (University of Manch-

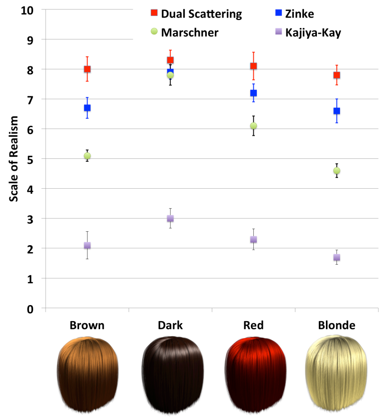

Figure 4: *Index of realism for different hair colours*

ester) and the results of their evaluation was plotted to scale in figure 2, suggesting that the models developed so far may show plausible realism, especially the dual scattering model. However, there is a long way to go to bridge the gap between reality and computer generated virtual reality.

5. Results

Along with this initial evaluation of the various models, the results in terms of computational cost through offline ray-tracing were also compared. Since the Kajiya-Kay model does not have a pre-computation phase, its computational cost is negligible. The Marschner model renders in around 15 mins and the Zinke model takes an enormous time (≈ 50 mins) to compute due to numerical integration and a huge recursion depth to handle multiple scattering. The dual scattering model performed the best in terms of computational cost and realism taking around 12 mins on average.

6. Future Work

This is a work-in-progress paper and a more concrete analytical model based on hair geometry, thickness, eccentricity of hair fibres, shadow smoothness, lighting conditions and other environmental and structural factors will be developed and tested experimentally. The aim is to better capture the factors that determine the realism of a hair model precisely [RLCW01]. The results of the study will be presented to a range of participants and using techniques such as logistic regression, we propose to find the correlation between any change in factor with the binary output - real or virtual. The models and techniques used over the years will be reviewed to form a more detailed index for realism in hair rendering. Using techniques like the visible difference predictor [Dal93] and perceptually based metrics [RBR*97], we propose to build an index of models and categorise them into believable, not believable, physical and not physical techniques [CF10]. We also propose to explore the simulation of hair dynamics to examine it's realism, using global illumination techniques to simulate natural lighting environments.


(a) Kajiya-Kay (b) Marschner (c) Zinke (d) Dual Scattering

Figure 5: *Images of all the four models*

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