3D HAIR DESIGN AND KEY FRAME ANIMATION IN REAL TIME

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MASTER OF SCIENCE

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July, 2008

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ABSTRACT

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Computer generated animations of humans, animals and all other kinds of objects have been studied extensively during the last two decades. The key for creating good animations has been to correctly imitate the behaviors of real objects and reflect these into computer generated images. With the rapid development of computer technology, creating realistic simulations has become possible, and the most striking components of these realistic animations happen to be the most dynamic (moving) parts; hair, in the case of human animations.

With the development of high quality hair animations, the concern is not only creating physically correct animations, but also controlling these animations. An implementation of a key frame hair animation creation system, supported by a hair design tool, helping to model and animate hair easily, and provide these functionalities in real time is the aim of the proposed system.

This work reviews several hair animation and sketching techniques, and proposes a system that provides a complete level of control (capable of controlling even the individual hair strands) of key frame animation and hair design in real time.

Keywords: hair simulation, sketching, key frame.

ÖZET

3 BOYUTLU ÇİZİM İLE GERÇEK ZAMANLI SAÇ MODELLEMESİ VE ANAHTAR KARELERLE SİMÜLASYON

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Bilgisayar tabanlı animasyonlar (insanlar, diğer canlılar ve her türlü nesneler) uzun seneler boyu üzerinde araştırma yapılmış konulardır. Bu animasyonların başarıya ulaşmasında en önemli rol, nesnelerin hareketlerinin doğru şekilde taklit edilebilmesi olmuştur. Bilgisayar teknolojisinde yaşanan hızlı ilerlemeler sonucu, son derece gerçekçi animasyonlar üretilmeye başlanmıştır. Animasyonlarda en çok dikkat çeken öğelerse, tahmin edilebileceği gibi en hareketli bölgelerdir. Bu hareketli öğeler insan ve yüz animasyonlarında genellikle saçlardır.

Yüksek kaliteli animasyonların yapılmasında, sadece fiziksel gerçekçi harekete ve görüntüye sahip animasyonlar yapmaktan ziyade, bu animasyonları gerçek zamanlı olarak kontrol edebilme gereksinimi de oluşmuştur. Bu tezde tartışılacak sistem, yüksek kalitede bir animasyonun sıfırdan oluşturulup, anahtar kareler kullanılarak hareketlendirme problemine bir çözüm önermektedir. Saçın gerçek zamanlı olarak tasarlanıp, anahtar kareler aracılığıyla animasyonu amaçlanmaktadır.

Bu çalışmada daha önce saç animasyonu ile ilgili yapılmış diğer sistemlerden bahsedilecek ve söz konusu sistemler dışında nasıl bir şekilde bu animasyonların oluşturabileceğine dair çözümler getirilecektir.

Anahtar sözcükler: saç simülasyonu, çizim, anahtar kare.

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Chapter 1

Introduction

Hair has been one of the most striking aspects of any kind of computer generated character animation. The vast amount of hair strands on a head, and the weakness of these strands against any kind of physical forces makes it a relatively complex phenomenon to animate. To target its difficulty, physically-based and key frame animation techniques have been proposed.

Physically-based techniques allow creation of realistic and high-quality animations. Unfortunately this is not adequate for animators who aim to design the hair style from scratch, and also pre-define paths that the hair will travel through.

Under the influence of physical forces, the control over hair is none or too small. It is possible to exert pre-calculated forces to lead the hair strips into shapes and positions defined beforehand, but this is an inefficient and cumbersome task requiring lots of calculations. Furthermore, the results might be unsuccessful due to the nature of hair strands constrained by physical rules. However, with key frames and the free manipulation mechanisms this provides, the animator can decide the motion, the shape of the hair (as well as an individual hair strand) with total control in real time.

This total control gives the animator the chance to create physically-correct (sufficiently realistic to trick our perception) animations, as well as animations without any constraints (not bound by any physical rules), such as totally chaotic, cartoon type animations, showing that there are no limits of the types of hair animations that can be produced, since the results are not bounded by physical constraints.

In this system, which is not bound by constraints, hair can be curled, elongated, twisted etc. without difficulty. These are animations that would stretch the limits of the powerful physically based animation systems, and translate the results to graphical animations.

Even when such systems do succeed in producing the intended animations, the results do not usually satisfy the requirements of the animator fully. The main aim of this thesis is to introduce a tool for creating hair styles with the use of a sketching interface; creating key frames using this interface (with or without the support of physical constraints); animating them and performing all the tasks in real time.

1.1 Previous Work

Different hair modeling techniques have been proposed to serve for different purposes. Individual particle-based methods [6][12][13], real-time animation solutions [2][15][16], representing detailed interactions of the hair strands with each other [14] and interactive hairstyling systems [1][11] have all addressed different parts of the hair modeling and animation problem. Our proposed tool deals with three different aspects of the problem: Modeling the hair along with its stylistic properties through a sketching interface; creating the flow of the animation by defining key frames and controlling the animation of the hair model during and before the animation; and performing these tasks in real time with a direct manipulation interface. Therefore, it would be appropriate to examine the previous work relevant to our method, classified with respect to these different aspects.

1.1.1 Hair Modeling and Animation

In spite of the easy definition and usage of individual hair strands, wisp based techniques are becoming widely used since they provide an efficient and collective way to represent hair. In their work Choe et al. [1] use a wisp based hair representation technique. They represent wisps with parameters like fuzziness that defines the wavy nature of the strands, deviation radius function which affects the distribution of the hair strands and length distribution which defines the lengths of the hair strands all together forming static hairstyles. This statistical model is supported by a styler used by employing constraints to the formed hairs. The styler is proposed to model artificial features that affect the natural flow of hair under gravitational forces, such as a hairpin. With the constraints and the statistical wisp model, realistic hair styles can be formed but due to excessive amount of calculations, results cannot be obtained in real time. In his paper Oshita [2] presents a method for real-time hair animation. He combines a dynamic hair generation technique and a conventional particle-based dynamic simulation. The movements of the coarse model (small amount of hair strands) are simulated using a dynamic simulation at the beginning. Then a fine model is generated from the coarse model using a dynamic wisp model. The velocities of the particles in the coarse model define the shape of a wisp and the individual strands in the fine model during the simulation. The method is designed to work on GPU and works on real time simulating hair to hair interactions between hair strands in the same wisp.

1.1.2 Controlling Animations and Key Frames

From the animators point of view, animation creation has two important aspects: the quality of the animation, and the controllability of the animation. Sophisticated physical calculations and graphical calculations can be done in very short time intervals so that high quality animations can be created, fulfilling the first requirement of the animators, but controlling these animations is still a problem to solve. In Shi and Yu's work [3], external force fields are applied to control the shapes of the liquids. Regular objects' shapes are defined as target shapes, and the liquids are controlled by applying forces to match these changing target shapes. A gradient force field is defined by the shape of the target object combined with a feedback force field and both are applied to the liquid. In their work, Fattal and Lischinski [4] drive the smoke towards a given sequence of target smoke states. This control is achieved by two extra terms added to the standard flow equations that are (i) a driving force term used to carry smoke towards a target and (ii) a smoke gathering term that prevents the smoke from diffusing too much. Popovic et al. [5] use a continuous quasi-Newton optimization to solve for wind-forces to be applied to the underlying velocity field throughout the simulation to match the user-defined key frames. Their system is based on the algorithm presented in work of Stam [19]. In this framework, smoke simulation has states. A state consists of a grid r of densities and a grid v of velocity vectors. Animator controls the animation with smoke density and velocity key frames (Figure 1.1).

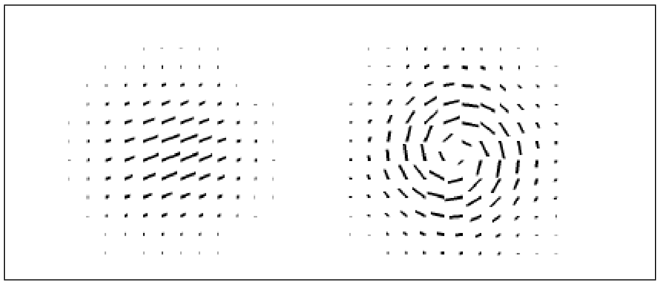

Figure 1.1: Smoke density and velocity key frames. (Smoke Simulation, Treuille et. al)

Simulation is computed from a start state q_0. The latter states are then calculated recursively via step function S for time t, $q_t = S(q_t - 1)$. The simulation starts with an initial state and repeatedly the subsequent states are calculated. These calculated sequence of states form the simulation. An optimization process is used to produce the best matching states.

Physically-based hair animation has also been a subject of animation control. In Petrovics work [6], hair is represented as a volume of particles. To control hair, this method employs a simulation force based on volumetric hair density difference between current and target hair shapes, which directs a group of connected hair particles towards a desired shape. Petrovic et al. use a mass-spring system in their hair structure and the forces are exerted to the strands through this structure. They create density grids for both the starting shape and the target shape (Figure 1.2).

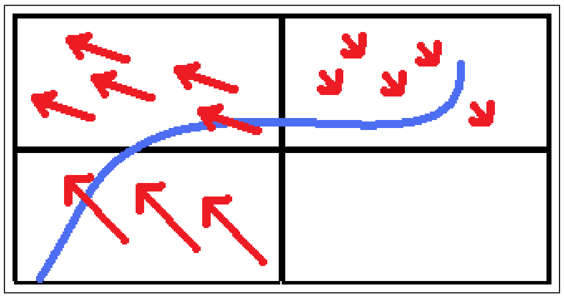

Figure 1.2: Example drawing of density grids and force fields.

To match the density of the starting shape to the density of the target shape, they create a gradient force between the grids, pushing the hairs to their target shapes. Although the technique is successful to reach the target key frames when they are physically reachable key frames (under physical constraints, they can be reached via the use of forces), it cannot imitate the behavior of chaotic, non-physical hair styles.

1.1.3 Sketch Based Interaction

In a computer generated 2D environment, it is straight forward to map the inputs of the well-know input devices to the computer environment. The challenge is being able to map the 2D input data into a 3D computer generated space. In a previous work [20] a 3D input device for direct mapping to the 3D computer generated space is presented. The device consists of a stiff piece of paper which is tracked by a digital video camera. The piece of paper and its location represents a virtual plane in the 3D space. By drawing on the paper, the user can specify points in 3D space. But most of the time, the input devices are simple 2D devices. Being able to create 3D content via these input devices in an intuitive way is an active research area.

In their work Wither et al. [7] present a sketching interface for physically-based hair styling. The sketching interface does not involve 3D input, but a side view of the model is shown on the screen and the user inputs are reflected to this side image. The elastic parameters and the geometric parameters are extracted from the drawn hair strands. For inferring the strand parameters from a sketched 2D strand, the method detects the inflection points along the 2D stroke input by the user (to the side image), and uses them to cut the stroke into sections representing a half turn of a helix (Figure 1.3). Then the method fits these half helixes to segments. A volume stroke that is input by the user is used to set the hair volume. After this input, other strands are interpolated according to the volume stroke. Although, visually satisfying results are obtained by this technique, there exists a drawback. In this technique, the user input cannot be reflected correctly to the model. Bound by physical forces, the strokes of the users cannot always be transformed to the created hair strands as they imagined. Users eventually observe different hair strands than they input.

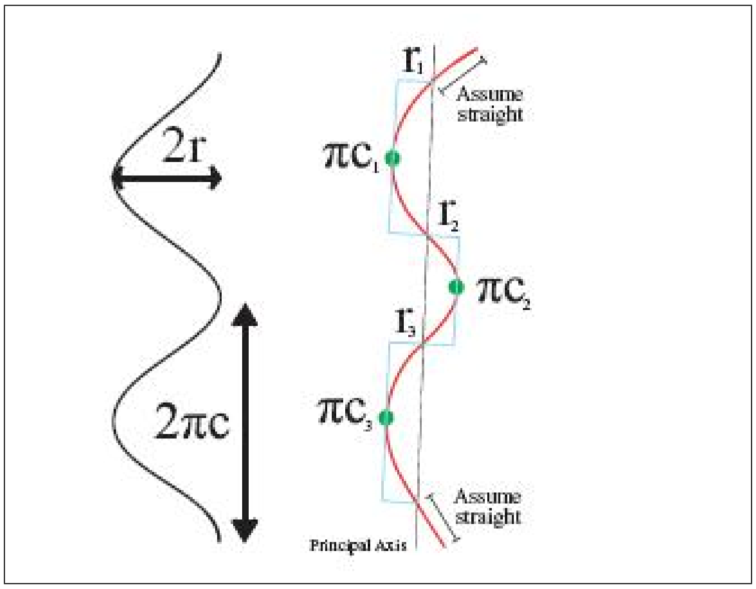

Figure 1.3: Half turn of a helix. (Super-Helices for Predicting the Dynamics of Natural Hair, Bertails et. al)

Another physically-based hair creation technique is proposed by Hernandez et al. [8]. They propose a paint tool to determine a set of gray scale images that allow them to establish hair length values and hair density values. For animations they use a simplified physically-based method that computes physics on basis hairs and distributes these calculations to other hair strands. Fu et al. [9] proposes a non-physically based hair design system equipped with a sketching interface and a fast vector solver. Users manipulate the global shape of the hair style via the sketching interface. Local control is not possible in this system in real time. Another non-physical hair design system was proposed by Malik [10]. He proposes a hair sketching interface manipulated via a tablet, to create hairstyles that are not bound by physical constraints. Hair is represented by wisp structures in his work. The wisp structure is defined by a number of parameters such as twist, density and frizziness. He also provides virtual tools such as combs or hair pins to change the hair style interactively via the help of gesture recognition algorithms.

Chapter 2

Hair and Head Structure

A persons head skin contains tens of thousands of individual hair strands, which, despite their large numbers, all share the same structure underneath. As a result, human head can be defined as a surface where there are very large numbers of hair strands that share exactly the same structural properties with each other; only located at different positions all around the head, with slight variations in shape. This allows us to create single hair strands and duplicate them.

2.1 Hair Strands

Hair strands consist of a number of control points (Figure 2.1). Each hair strand has a root control point that defines its location on the skull and does not change its location under any circumstance. Other control points define mainly the shape of the hair strand. These control points are input using the sketching interface. This process will be discussed in detail in the sketching section, further below.

After establishing a number of control points, according to their input sequence, the first control point is defined as the root control point. The other control points are connected to each other with lines, to and from the structure of the strand (Figure 2.1). Directly connecting these control points results in lines

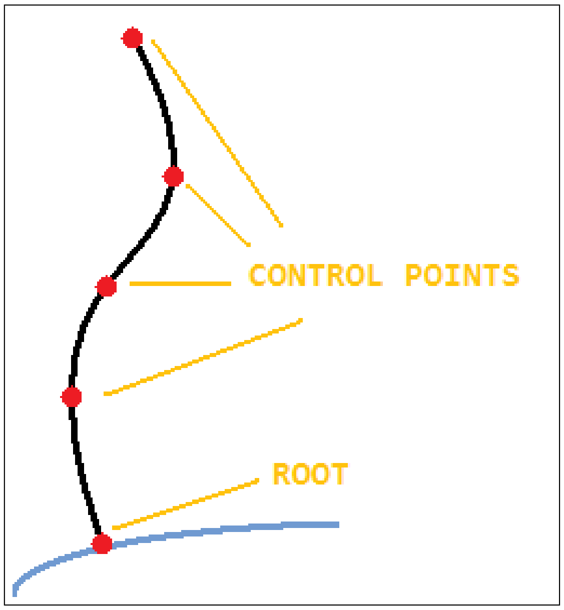

Figure 2.1: Structure of a hair strand.

with many corners (looking zigzag-like line). To smooth out the corners in the lines we use a combination of Bezier and Catmull-Rom splines [21], as explained below.

The nature of Catmull-Rom splines requires us to provide four control points C_1, C_2, C_3 and C_4 to create a spline between C_2 and C_3. As the user gives n inputs to our system, we need $n+2$ control points to form a Catmull-Rom spline passing through these n control points. Therefore, at the beginning of spline formation, we extrapolate two control points, one to the beginning and one to the end.

To form a Catmull-Rom spline passing through many control points, we form groups of four control points iteratively. For a strand containing n control points, $(n+1)-4$ groups are formed. For example a strand containing 6 control points will have the following groups C_1, C_2, C_3, C_4; C_2, C_3, C_4, C_5; C_3, C_4, C_5, C_6 where C_i means the i^{th} control point. From these control points, Bezier control points are calculated according to Equation 2.1.

$$
\begin{aligned}
BC_0 &= C_0 \\
BC_1 &= C_1 + ((C_2 - C_0)/6) \\
BC_2 &= C_2 - ((C_3 - C_1)/6) \\
BC_3 &= C_2
\end{aligned} \tag{2.1}
$$

These Bezier control points are calculated via GPU [22] saving important clock cycles of the CPU for other operations. Then these Bezier control points are fed into the Bezier Equation 2.2 to form the part of the Catmull-Rom spline, which will then be combined with the previously created splines to form the final Catmull-Rom spline.

For $0 \leq t < 1$,

$$B(t) = BC_0(1-t)^3 + 3BC_1t(1-t)^2 + 3BC_2t^2(1-t) + BC_3t^3 \tag{2.2}$$

2.2 Hair Wisps

A hair wisp is a cluster of hair strands placed together, which has a leader hair strand in it. A number of hair strands are located around the leader hair strand, sharing the same properties such as length, number of control points (or mass nodes), curl, and color, with it. These are named imitator strands. They are evenly distributed around the leader strand, all having the same distance to it. During the style recording stage, the user creates the leader strand. Once the creation of the leader strand is completed, its identical copies are produced and wisp formation begins. With the formation of many wisps, the head is filled with hair. These wisps can have different styles than each other.

These different styles are represented by the following style parameters: closeness $c_{i,j}$, fuzziness $f_{i,j}$ and the number of strands in a wisp n_i, where i is the id of a particular wisp and j is the number of recorded control points on that wisp.

Closeness parameter is used for the purpose of defining how distant the imitator strands are placed. According to the closeness values obtained from the wisp parameters, the root points of the imitator strands are determined in a two dimensional u,v coordinate system with a circularly layered arrangement (Figure 2.2). Each circular layer consists of eight imitator strands, closeness of these layers to each other are also the same with the closeness parameter. The value eight was chosen in order to be able to achieve an arrangement that is close to a circular shape. The imitator strands can be thought as placed in *North*, *South*, *East*, *West*, *North-East*, *North-West*, *South-East* and *South-West* directions.

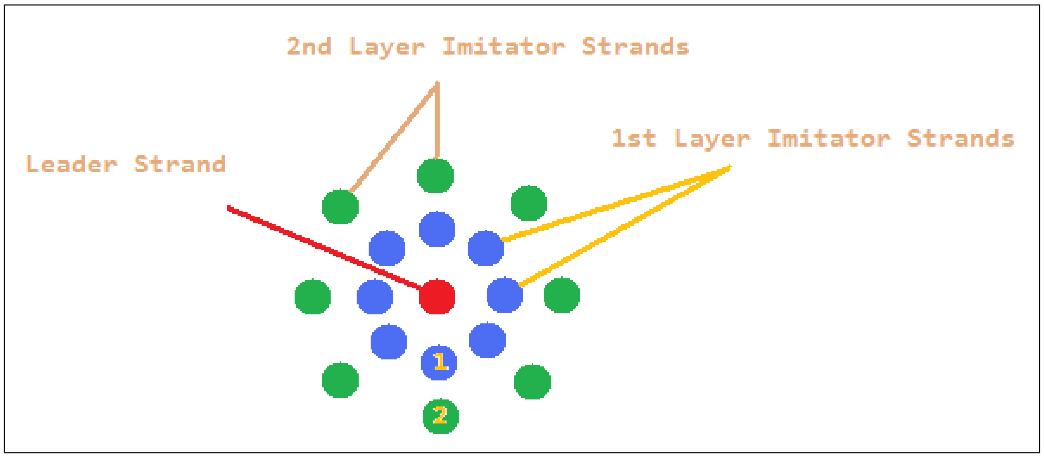

Figure 2.2: Distribution of imitator strands.

The closeness value d fed to the system, is used to calculate the coordinates of each one of the eight imitator strands. The main four coordinates (*North,South,East,West*) are calculated on the basis of the coordinates of the leader strands (Figure 2.3) on 2D u,v coordinate system as:

$$u + d, v; u - d, v; u, v + d; u, v - d; \tag{2.3}$$

The root points of the imitator strands are distributed around the root point of the leader strands uniformly (with the same distance), using the employed patch structure defined in the following section.

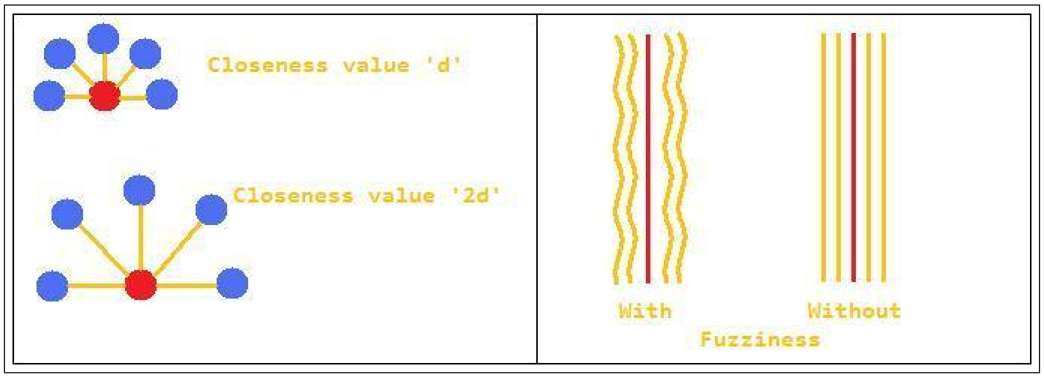

Figure 2.3: Closeness value effects how distant the imitator strands are placed. Fuzziness value gives a wavy look to the hair wisp.

The closeness values are used along the imitator strands. In other words, when root points are placed at a distance from the root point of the leader strand using the closeness value, the upper level control points are placed in the same manner. Similar to the root points, they are placed around their corresponding control point of the leader strand. This creates duplicate imitator strands, spaced from the leader strand by a distance determined by the closeness value. In order to create more realistic, uneven looking wisps, a fuzziness parameter is used. This is a random value between 0 and 1 and is used to change the location of the control points in small increments, so that the imitator strands, instead of being an exact copy of the leader strand, would have their own characteristics and wavy appearances, but still obey the movements of the leader strand (Figure 2.3).

2.3 Head Structure

The head model appearing on the animations is created using AutoDesk 3ds Max [18] software. The model is defined by a triangular dataset. Instead of using the triangular head dataset as the base for the hair strands, we define and fit an invisible patch structure under the scalp and use it as the base for the hair strands.

Using the mesh representation of the 3ds Max model for root point positioning might seem reasonable, as it would provide us with an easy way of placing the root points on the mesh points, since all the coordinates of these points are already calculated and available. However, there are some drawbacks of using this approach, such as:

- The first drawback is related to obtaining neighborhood information. As we have discussed before, we are using a wisp structure that contains a leader strand and neighborhood strands. In order to find the root point positions of the neighboring imitator strands, unlike in patch structures, additional computations would be required since the calculations are done in 3D space.
- The second and most important drawback is the problem of triangle edges. A root located near an edge of a triangle might require one of its neighbors to reside on another triangle (which might happen to have a different normal than the current one). Thus imitator strands will exist that cannot actually imitate the direction of their leader strands (Figure 2.4).

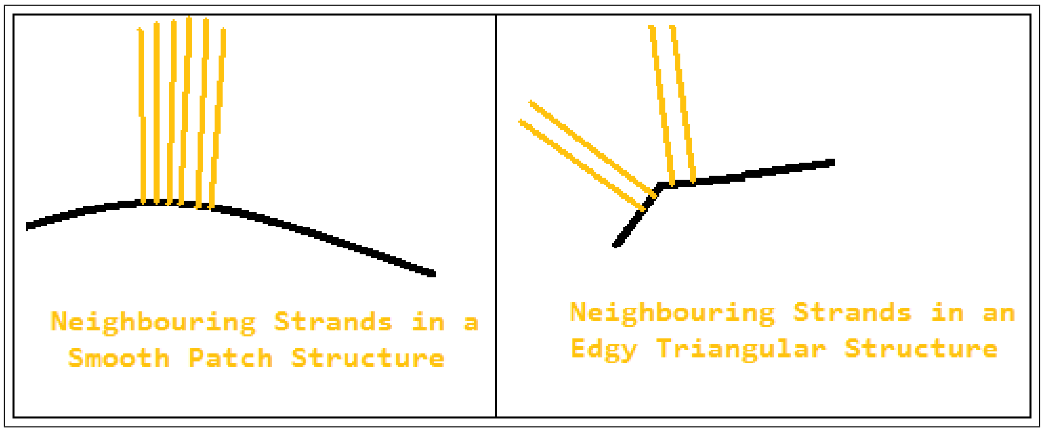
Neighbouring Strands in a Smooth Patch Structure
Neighbouring Strands in an Edgy Triangular Structure

Figure 2.4: An example of a possible drawback of using triangular dataset rather than a patch.

Because of these drawbacks we use a patch structure under the scalp (Figure 2.5). Reducing the three dimensional head structure into a two dimensional space, finding neighboring information becomes a relatively easy and efficient task. Also, the problem of having dramatically different slopes between an imitator strand and leader strand is prevented.

The patch structure under the scalp is formed by using a combination of Catmull-Rom splines, forming a grid-like structure. The reason for using a Catmull-Rom patch is to be able to create a patch that is very similar to the head shape. Since Catmull-Rom patch has a property that the patch structure always passes from the control points; by selecting a set of control points on the head structure, we guarantee that the patch will fit to the head. We used a 6 by 6 (total 36 control points) Catmull-Rom patch underneath the head structure. These control points are distributed evenly on parts of the head structure that normally contain hair.

However employing a Bezier patch would be an easier decision from an implementation point of view. The reason that makes Catmull-Rom patches a more difficult option is the nature of Catmull-Rom patches that require us to extrapolate the control points we provide (Figure 2.6). While creating a Catmull-Rom spline, it is obligatory to provide 4 control points. If not possible, extrapolation shall be done. Same requirements also exist for closed shapes.

The extrapolated coordinate values $C_{i,j}$ (Figure 2.6) of the extra control points are calculated according to their locations around the grid. In a grid with $n+1$ rows and $n+1$ columns, if the extrapolated control point is along the first row ($C_{0,j}$) or the last row ($C_{n,j}$), extrapolated coordinates are calculated via Equation 2.4.

$$\begin{aligned} C_{i,j} &= C_{i+1,j} * 2 - C_{i+2,j}; \\ C_{i,j} &= C_{i-1,j} * 2 - C_{i-2,j}; \\ & i \neq j; \end{aligned} \tag{2.4}$$

If the extrapolated control point is along the first column ($C_{i,0}$) or the last column ($C_{i,n}$), extrapolated coordinates are calculated via Equation 2.5.

$$\begin{aligned} C_{i,j} &= C_{i,j+1} * 2 - C_{i,j+2}; \\ C_{i,j} &= C_{i,j-1} * 2 - C_{i,j-2}; \\ i &\neq j; \end{aligned} \tag{2.5}$$

The final extrapolation calculations are performed to form the control points at the corners of the grid. To calculate extrapolated control points located at the four corners $C_{0,0}$, $C_{0,n}$, $C_{n,0}$ and $C_{n,n}$, Equation 2.6 is used.

$$\begin{aligned} C_{0,0} &= C_{1,1} * 2 - C_{2,2}; \\ C_{0,n} &= C_{1,n-1} * 2 - C_{2,n-2}; \\ C_{n,0} &= C_{n-1,1} * 2 - C_{n-2,2}; \\ C_{n,n} &= C_{n-1,n-1} * 2 - C_{n-2,n-2}; \end{aligned} \tag{2.6}$$

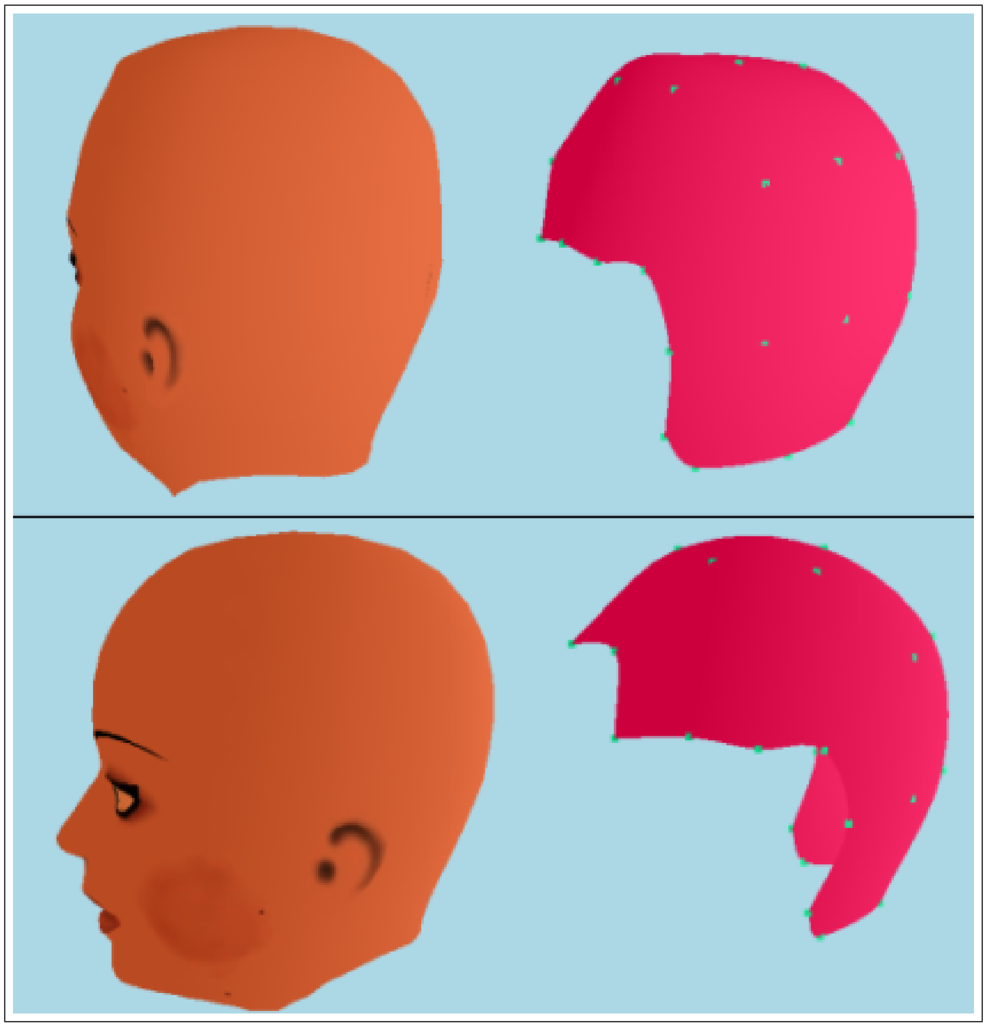

Figure 2.5: The head model and the Catmull-Rom patch structure representing it.

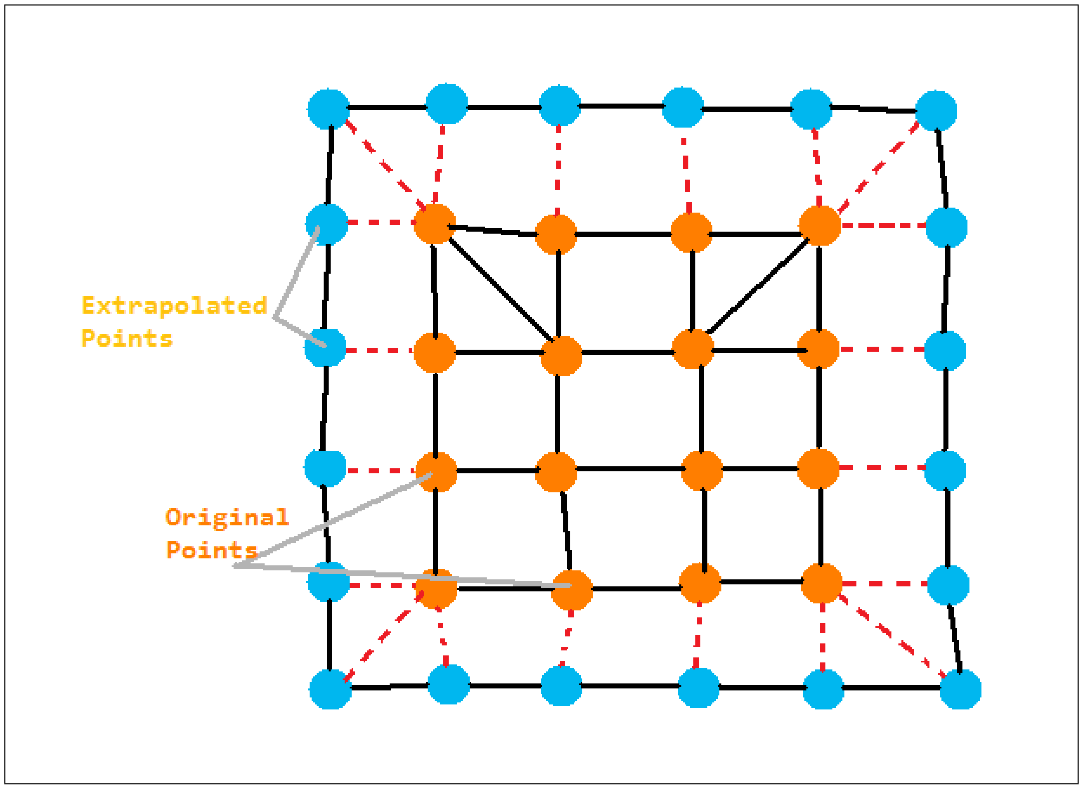

Figure 2.6: Extrapolation of control points is needed since we are using a Catmull-Rom patch structure. Grid in the figure contains 6 rows and 6 columns.

Chapter 3

Sketching

We propose a sketching interface for direct manipulation of hair strands. The head model lies inside a 3D space. The user, by using an input device (a mouse, a stylus pen etc.) directly draws the hair strands on the 3D head (Figure 3.1). Each movement of the input device is recorded and reflected to the head model and hair is created. The movements are mapped into 3D space and the control points are recorded in uniform time steps. The details are explained in the following subsections.

3.1 Input Mapping

The input devices used to interact with the computer are usually two dimensional devices. In order to be able to draw hair strands on a head that is located in a 3D space, these two dimensional input coordinates should be correctly mapped to the world coordinates of the 3D space. To correctly reflect what is inputted through our devices and draw the hair strands into a 3D world, two important steps should be achieved. These are: (i) create a 2D plane on which these inputted values will be drawn parallel to the computer screen, and (ii) find the depth of this plane. This plane is called the drawing plane.

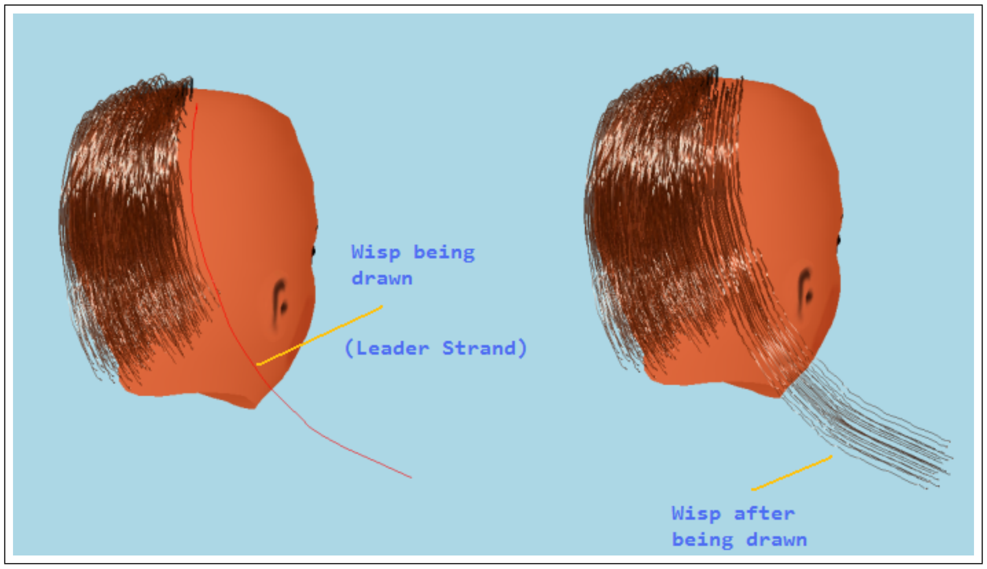

Figure 3.1: A wisp being drawn through the sketching interface.

3.1.1 Drawing Plane

The hair strands are created on a two dimensional plane (since inputs are 2D). To be able to correctly define the location and slopes of the drawing plane, we have to find the depth of the plane and its slope.

The slope of the drawing plane is calculated by the angle of the viewing vector of the camera. Thus the screen of the computer is actually the drawing plane of the user. Drawing experience of the user is aimed to be similar to drawing to a regular painting program.

If the system was working on a 2D space, the drawing task could have been easily accomplished. The drawing plane would be located right behind the screen, parallel to it without any depth. But, in a 3D space, we also have to calculate the depth of this plane. We should decide whether the user is drawing the strand on the top of the head, or to the forehead etc. To calculate the exact point where the user is drawing, we use the depth buffer. The task is accomplished as follows:

1. When an input is received, the depth buffer is cleared.

2. After the depth buffer is cleared, the patch is rendered filling the depth buffer by its coordinates.
3. When the user clicks on the screen, we use OpenGL's [23] *glReadPixels* function in order to get the clicked pixel and search the depth buffer for that pixel to find out if it is containing an object.
4. If the result is a hit (it hits a rendered location in the depth buffer) the coordinates are projected to world coordinates by OpenGL's *gluUnProject* function. Then, a drawing plane which is parallel to the screen and passing through that point is created. As the drawing continues, the control points are drawn on this plane with the same methodology, after the patch is rendered, the invisible plane is rendered and its position is read from the depth buffer so that the drawn control points are located on this plane.

3.1.2 Root Positioning and Wisp Formation

The first input on the screen after an idle state is always assumed to be a candidate root point of a hair strand. The point is checked whether it belongs to the patch structure or not. If it is on the patch, the control point is created there and as the drawing continues the inputs are converted to the drawing plane and visualized there. Once the user stops input, all the collected control points are fed into the GPU and a Catmull-Rom spline is created, forming the structure of the hair as we defined on Chapter 2. Lastly the rendering effects are applied such as spline creation for smooth appearances, supported by Kajiya and Keys illumination model which is defined further below, to complete the final touch [24].

3.1.3 Gesture Recognition

As we have mentioned before, the drawing interface provides a 2D invisible drawing plane which is parallel to the screen. The movements of the mouse or digital pen are reflected directly onto this plane. Since it is 2D, occasionally some intersections will occur (on the drawings), especially if the user is drawing a long hair strand with lots of curves. These intersections, or loops, should be detected and taken care of. Instead of just avoiding these intersections, or preventing the users from being able to create such conditions, we take a different approach and provide the intersection situations as a means of interface; an interface for creating curly 3D hair drawn on the 2D plane.

In order to avoid self intersecting hair strand creation during the hair drawing process, and also provide a chance for creating 3D curling hair, we detect the intersections occurring in the strand. To detect if the hair is intersecting with itself, we divide it into imaginary hair segments. We assume that each two consecutive mass points are connected with a linear segment and all intersection calculations are done on these. We use formulas (3.1) and (3.2) to detect intersections between two segments n and m where x_{n1}, x_{n2}, y_{n1}, y_{n2} are x and y coordinates of the beginning point and ending point of segment n, and x_{m1}, x_{m2}, y_{m1}, y_{m2} are x and y coordinates of the beginning and ending points of the segment located after segment n (segment m).

$$\begin{aligned} u_1N &= ((x_{m2} - x_{m1}) * (y_{n1} - y_{m1})) - ((y_{m2} - y_{m1}) * (x_{n1} - x_{m1})); \\ u_1D &= ((y_{m2} - y_{m1}) * (x_{n2} - x_{n1})) - ((x_{m2} - x_{m1}) * (y_{n2} - y_{n1})); \\ u_2N &= ((x_{n2} - x_{n1}) * (y_{n1} - y_{m1})) - ((y_{n2} - y_{n1}) * (x_{n1} - x_{m1})); \\ u_2D &= ((y_{m2} - y_{m1}) * (x_{n2} - x_{n1})) - ((x_{m2} - x_{m1}) * (y_{n2} - y_{n1})); \\ & u_1 = u_1N/u_1D; u_2 = u_2N/u_2D; \end{aligned} \tag{3.1}$$

According to these calculations, if both u_1 and u_2 lye within the range 0-1; these two segments are intersecting with each other. Intersection detection is performed between all segments satisfying the condition $m > n$. Each segment is tested for intersection for the segments after them. This is a precaution preventing double calculations. After detecting the intersections we take the following approach to create a 3D curling hair model. The intersections that have a potential to form curly hair are selected if they satisfy the following two constraints:

1. A hair segment might be intersected by more than one segment. If such a

condition occurs, the segment that is nearest is ($m-n$ value is the smallest) chosen and the others are discarded. The curly hair partition is formed via only one intersection point.

2. After the intersecting segment is chosen, if the segments between the chosen pair do not produce a convex polygon, this means that the loop does not represent a curling hair and shall be discarded (Figure 3.2).

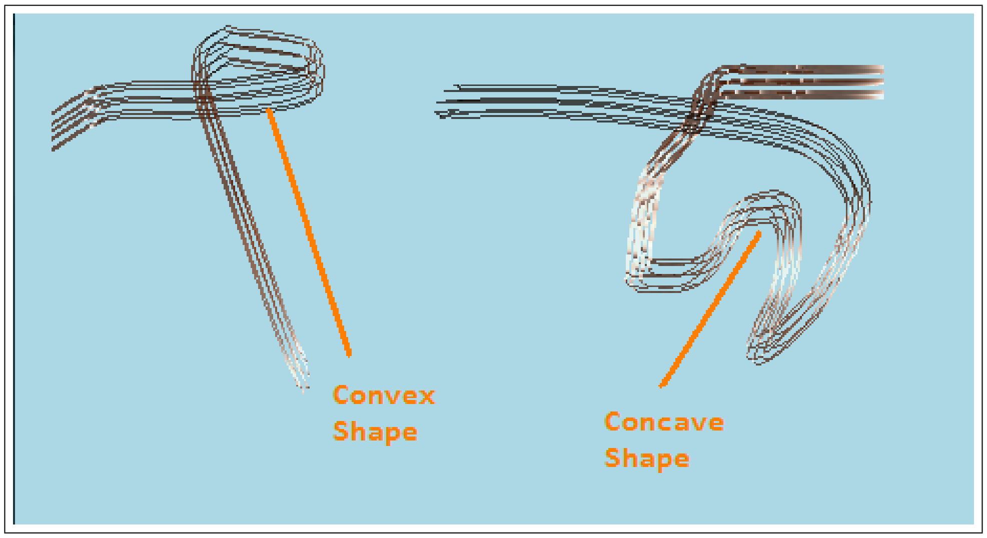

Figure 3.2: Two different self intersecting wisps. One forming a convex shape (circular) the other one a concave shape (will be discarded).

If all these constraints are satisfied, the drawing is detected as a loop. The two dimensional loop should be converted into a 3D helix-like shape in order to achieve a curly hair look. Three steps for forming the helix structure are as follows:

1. The focal point of the loop has to be found. Each of the segments lying between the intersecting segments (between n and m) are examined one by one and their center of gravity coordinates are calculated. The mean value of these segments is defined as the focal point of our loop.

$$C_{xn} = x_{n+1} - x_n/2, C_{yn} = y_{n+1} - y_n/2, C_{zn} = z_{n+1} - z_n/2; \tag{3.2}$$

$$F_x = sumC_{xn}/totalsegments;$$
$$F_y = sumC_{yn}/totalsegments;$$
$$F_z = sumC_{zn}/totalsegments;$$

Where C_{xn}, C_{yn} and C_{zn} are the coordinates of the center point of segment n. Average of all the center points are calculated and one focal point F is found. A rotation axis defined by the beginning of segment, intersected segment, and the end of intersecting segment is formed.

2. The axis is then translated to the focal point of the loop, which will be the rotation axis that turns the two dimensional loop into a helix. The rotation amount must be 360 degrees along the loop. The last control point has to connect to the other segment naturally. According to the number of segments on the loop, the rotation amount is calculated. A loop containing n segments will have $2n - 1$ points to be rotated (every segment has two control points). Each of these points will be rotated according to their index i on the loop (Figure 3.3) according to formula:

$$Rot = (360/(n * 2 - 1)) * i; \tag{3.3}$$

3. After the rotation finishes, the mass nodes in this loop are mapped to a helical structure, thus producing a 3D curly hair.

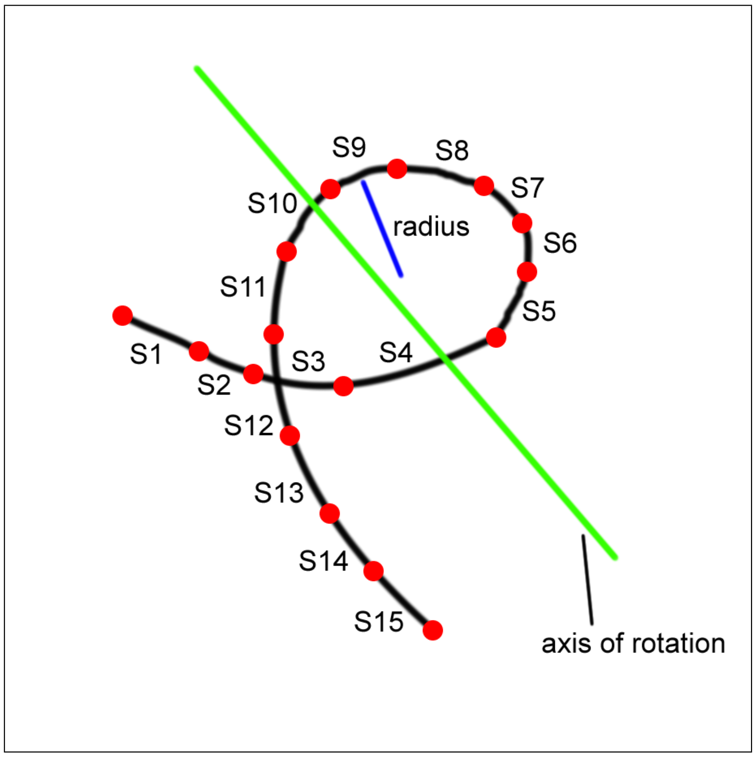

Figure 3.3: The control points lying between the intersecting segments are rotated around the axis of rotation.

Chapter 4

Key Frame Animation and Rendering

Being able to provide an intuitive interface both for styling and creating hair led the way for key frames. With the sketching interface, it is possible to define key fames, edit and combine them, to form a real time hair animation.

Hair wisps are drawn on the 3D head model and their positions are recorded as key frames. After key frame creation is finished, in-betweening stage starts. The in-betweening stage is responsible for calculating the transition functions and mapping of wisps between the key frames. The whole key framing stage consists of the following steps.

1. 3D Key frame recording via the sketching interface,
2. Switch to in-betweening stage with wisp matching, wisp mass sampling, path function creation stages,
3. Animation stage consisting of running the correctly formed in between frames with the ability to provide a touch of randomness with viscous air noise force,
4. For efficient transitions slow in, slow out methods.

5. Collision detection.

4.1 Key Frame Recording

The drawing interface is used as the key frame recording tool. User can draw any type of hair through this interface. Once the drawing of a key frame is finished and it is recorded; the skull is cleared for the next key frame and user starts drawing the next frame. This way, sequentially the key frames are defined. For each key frame, once hair drawing is finished, the coordinates of the hair strands are recorded for later usage. So for each key frame, the previous frame's root locations, and complete 3D view are still available, giving a better key frame definition process. After drawing again the key frame is recorded and the skull is cleared for further key frame drawing. Any number of key frames can be created with any number of hair strands on them this way.

Once the key frame definition process is finished (after the last key frame is recorded); the in-betweening stage starts operating. Having the key frames in hand, we need to create in between frames (Figure 4.1).

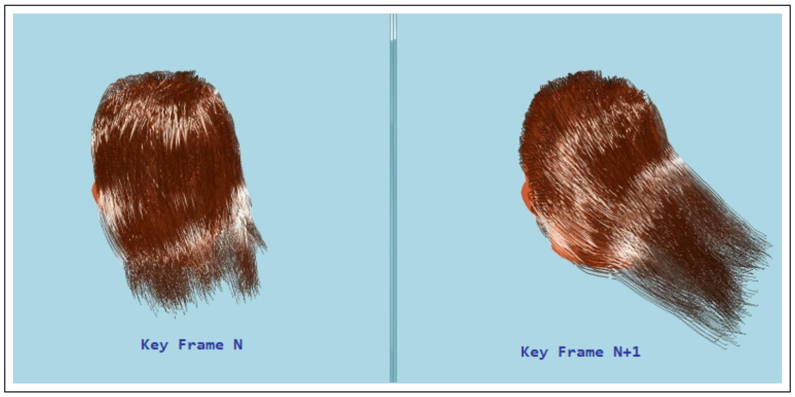

Figure 4.1: Two consecutive key frames.

4.2 In-Betweening Stage

The key frames are snapshots of the animations most dramatic moments. The frames lying between them are usually regular frames (changing regularly). These regular frames should be created successfully. The in-betweening stage is the most crucial stage of key frame based hair animation, since it fills the gaps between the key frames provided to the interface, with correctly calculated in-between frames (The number of in-between frames, for each two consecutive key frame, is defined by the user before key frame creation). The stage consists of the following main steps, *Wisp Matching*, *Wisp Mass Sampling*, *Path Function*.

4.2.1 Wisp Matching Between Key Frames

Since there are no limitations on the animation length, there can be any number of key frames provided to the tool. Each of these key frames might potentially contain hundreds of hair wisps. A mapping between two consecutive key frames has to be done in order to decide which wisp in the current key frame should aim which wisp in the latter one (Figure 4.2). One solution might be forcing the user to draw each wisp on the exact same location on the skull for each frame. Accomplishing this purely by the user is very difficult; also forcing the user through the system to do this takes the freedom away. So the wisps can be drawn to any location on the skull and these hair wisps of each key frame should be correctly mapped to the hair wisps on the next key frame to achieve a realistic simulation. For instance, a hair wisp located above the right ear in a key frame should be mapped to a hair wisp again located above the right ear on the next key frame. Without this constraint, the effect would be similar to mapping the right leg to left leg in a walking animation. This might not cause very dramatic effects if the animator chooses to create regular animations, i.e. animations in which all the strips are uniformly swing to one place (doing same kind of movements). But once some irregularity is introduced via key frames (for example a twisting hair, or separately swinging hair wisps), irrelevant movements might occur.

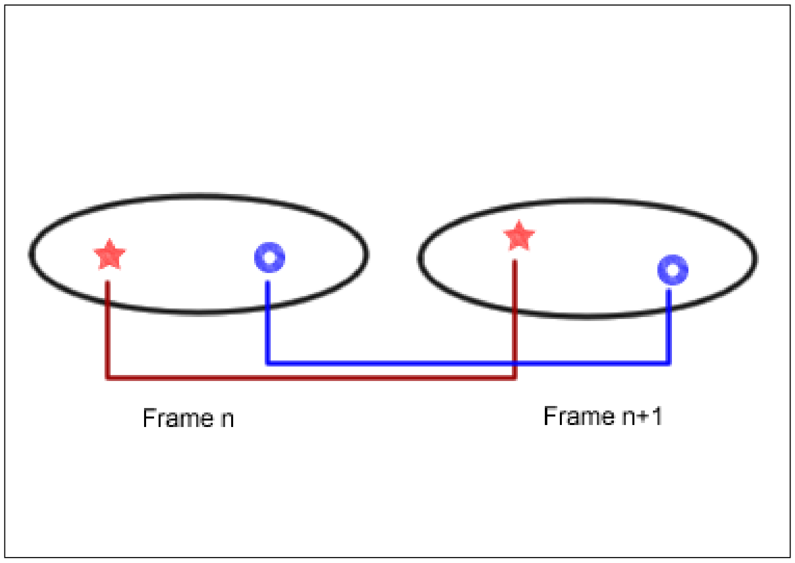

Figure 4.2: Mapping of the wisps between two consecutive are done according to the locations of the roots on the patch structure.

To prevent this unwanted effect to occur, we carefully map each wisp to one in the next key frame. The in-betweening stage controls each two consecutive key frames and all of the wisps created during these key frames. As we have defined before, the skull is parameterized as a 6x6 3D Catmull-Rom patch. All hair wisps have their roots on this patch, and their root coordinates are located as a 2D point in u, v coordinates on this patch. To find the most suitable wisps (the ones that have the closest root locations) in consecutive key frames, we calculate the distances of the root locations of each wisp with others. Since they all have their roots on the same patch, and the patch is in 2D space; it is easy and fast to calculate these values. The wisps having the closest 2D Euclidian distance in parametric space are mapped to each other. As a summary; root position of the current wisp is taken and it is compared to the wisp root locations on the next key frame. The closest one is found and selected as the target wisp.

Through the interface on the surface of the skull, the locations of the previous key frames root locations are shown on demand, reminding the user how the previous key frame was drawn (Figure 4.3). Even if the roots are drawn to completely unrelated places, good animations can still be produced, but the achieved animation might have some differences with the key frames provided to the system (since the roots of the wisps are different while drawing). Thus the usage of previous frames snapshots gives a chance to further enhance user input.

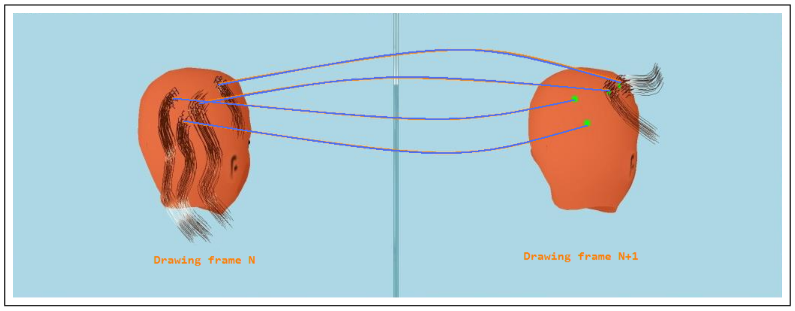

Figure 4.3: Roots of the previous key frame are shown on the sketching screen.

Key Leader Strand. Hair animations that involve similar movements of hair strands is a usual situation. Swinging hair, become electrified, grow from short hair to long hair are all animations that involve hair strands that share similar motion characteristics. For these kinds of animations, to ease the usage of sketching tool, the user can take the advantage of using key hair strands. Instead of drawing each hair wisp through the interface, it is possible to define a key leader strand, and map the actions of all hair wisps to it so that all hair wisps will follow the guide of the leader strand(Figure 4.4).

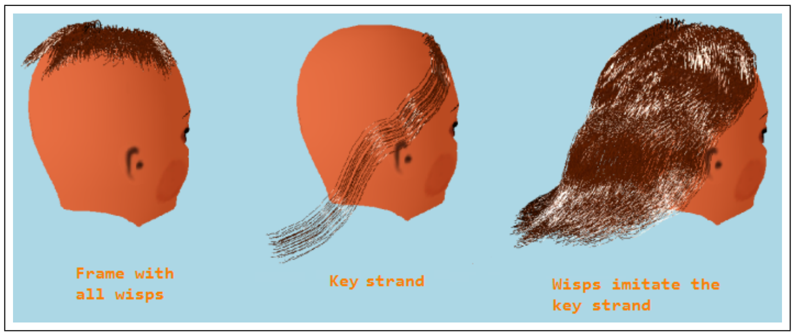

Figure 4.4: The wisps are following the lead of the key strand.

4.2.2 Wisp Mass Sampling

After the wisp mapping stage is completed, each wisp on each key frame has a specific target wisp on the next key frame but their structures might have differences. Hair wisp lengths can be different than the mapped hair wisp and they most certainly will be since they are created by user inputs. Irregularities of this should be supported since any kind of hair animation can be created by the system such as growing hair, or hair that is shortening. Having different number of mass nodes between two mapped hair wisps causes the problem of extra mass nodes having no target location. To be able to overcome this problem, wisp mass sampling methodology is used. The number of mass nodes of the mapped wisps that are different should be made equal to each other. A wisp consisting of n mass nodes mapped to a wisp on the latter key frame having $n+m$ nodes will require the wisp sampling stage to introduce it m new mass nodes and distribute these evenly throughout its structure (Figure 4.5).

The mass sampling stage operates through the following three steps:

1. Numbers of mass nodes m_1, m_2 of the two mapped hair wisps are compared. If they have the same value, no sampling is required. If they have different values, the difference d is calculated ($d = m_2 - m_1$ if $m_2 > m_1$ AND $d = m_1 - m_2$ if $m_1 > m_2$). This value will be used in stage 2 as the number of extra mass nodes.

2. After calculating the number of the needed number of extra mass nodes d, the issue about distributing these evenly between the existing mass nodes (i.e. on segments connecting the control points) should be solved. Distribution task is operated iteratively. For each segment we have a value n indicating the number of extra control points that were added to that segment, which is zero at the beginning. On each iteration we add 1 extra control point to each segment and decrement the value d by 1. Once we reach the last segment, we begin a new iteration from the beginning. When value of d reaches 0, i.e. the number of control points of the two mapped wisps match with each other, step 3 begins.

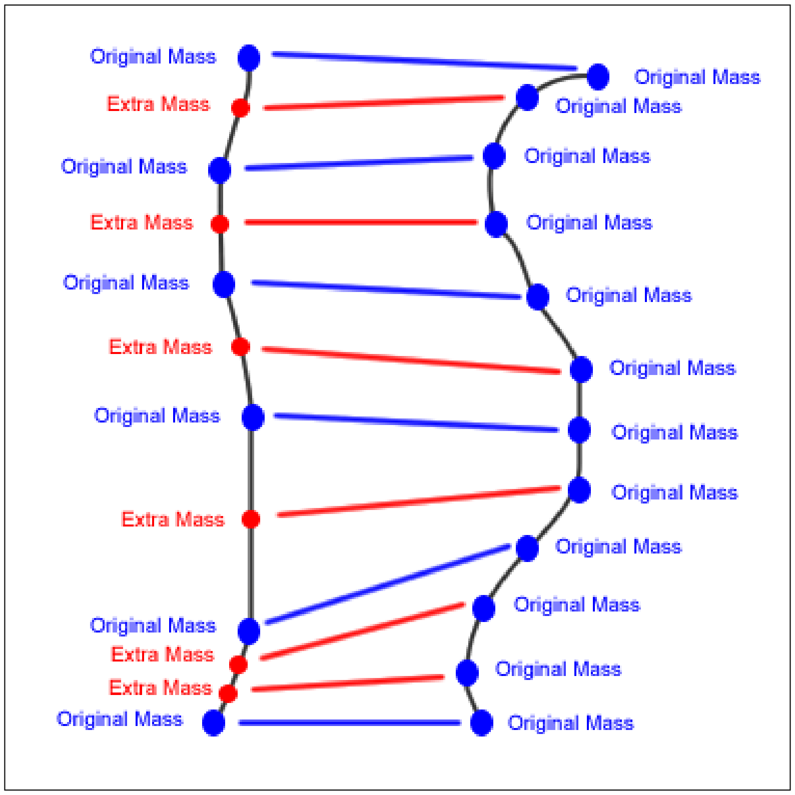

Figure 4.5: The strand having less number of control points (6) is sampled to higher dimension to match the wisp with higher number of control points (12). 6 additional control points are added.

3. To adapt the new control points into the structure, the extra control points should be distributed evenly on each segment in 3D space. This is required to preserve the structure of the hair wisp (it shall not change after the sampling stage). To achieve this aim, the extra control point numbers (n) of the segments are used. A segment having n extra control point is divided into $n + 1$ equal sub-segments, and the control points are placed on the end points of these segments. Since the newly added points lye on the same segment, and they are distributed evenly on it, hair wisp preserves its structure and shape.

Now the animation between these two hair wisps can be processed. Extra mass nodes are added to the line connecting the older mass nodes uniformly so that their addition does not cause any change in hair wisps shape.

4.2.3 Path Function Creation

After matching the wisps between key frames and sampling their control points to fit each other, definition of the path they will take between two key frames should be defined. During animation, each hair wisp will follow the path created in this stage to reach its target shape and location. Since each hair wisp consists of control points, the paths are actually defined for each of these control points. During the in-between frames, these control points traverse the linear path assigned to them, and once the next key frame is reached, they have to be in the correct position.

Path function creation requires two inputs; the current wisp, the target wisp and the number of in-between frames between key frames. Then the following calculations take place separately for all wisps:

1. The coordinate values of each control point belonging to the current wisp and the target wisp are gathered. For each control point on the current wisp, in order to find out how much distance should they travel, the distance to the target wisps corresponding control point is found (control point having the same index on the wisp). Distances for each coordinate axis are calculated separately where $d_x = x_t - x_c$, $d_y = y_t - y_c$ and $d_z = z_t - z_c$ where d stands for distance and x, y, z values represent coordinates. Subscripts t and c stand for target wisp and current wisp respectively.

2. According to the calculated distance values, how much distance should each control point travel is known. Dividing these values by the number of in-between frames input by the user, the distance that should be traversed by each control point in each in-between frame is calculated. $d_x = d_x/n$, $d_y = d_y/n$ and $d_z = d_z/n$

After the calculations, on each in-between frame, the control points translate their locations gradually according to the calculated path function. On each in-between frame, the n^{th} control point of wisp m moves, $d_{xn} - m$ on x axis, $d_{yn} - m$ on y axis and $d_{zn} - m$ on z axis. These 3 values are actually the speeds of the control points along the coordinate axes. In each time frame (in-between), they traverse the distance according to their speeds (Figure 4.6). This is a linear interpolation methodology where the time to translate from one frame to the other is defined by the number of in-between frames. The path functions are created during drawing phase, so once the animation starts, no calculations regarding the positions of the wisps and their control points are made. This aspect helps us achieving the real time animation goal.

The path function data are kept in memory. The number of path functions that will be created throughout the recording stage is directly proportional to the number of wisps, number of control points of each of these wisps and the number of key frames. Total amount can be calculated by the formula:

$$Total_{path} = k_n * w_n * c_n \tag{4.1}$$

where k_n, w_n and c_n stands for number of key frames, number of wisps and average number of control points for each wisp, respectively. For an animation consisting of 5 key frames, 50 wisps and an average of 10 control points of each wisp, there should be 5 * 50 * 10 = 2500 path functions.

Being able to access this large amount of data needs an indexing scheme. We record each wisp into the memory in an array using the drawing order of them. The order they are drawn is assigned to them as their index. For each key frame, a separate array of wisps are recorded with the same indexing methodology. After the wisp mapping stage concludes, each wisp has a pointer to the target wisp. The same recording strategy is used for path functions, so that these two arrays are mapped to each other. Later on during animation, by the use of indexes, path functions are reached.

During animation stage, a real-time viscous air drag noise is reflected to the animating hair strip. Its aim is to give the hair a wavy look while it is being

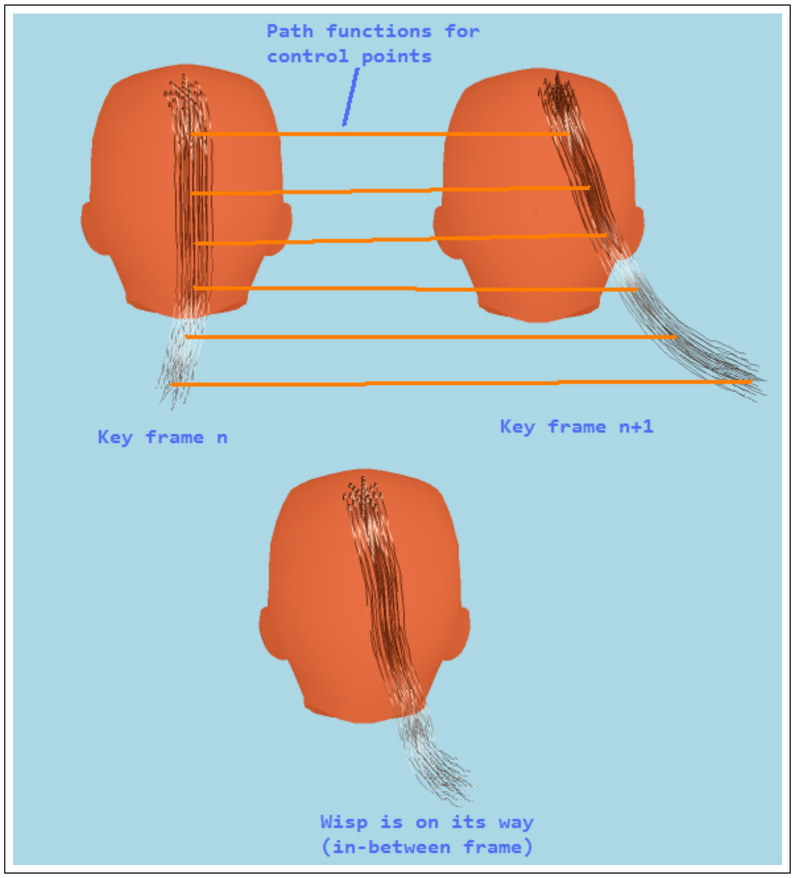
Path functions for control points
Key frame n
Key frame n+1
Wisp is on its way (in-between frame)

Figure 4.6: Path function created for a wisp. Below is an in-between frame following the path created by the function.

animated. To further enhance the quality of animation and provide smooth and realistic transitions, slow-in and slow-out systems are introduced, defined below.

4.2.4 Slow-in Slow-out and Viscous Air Drag Noise

The number of in-between frames input by the user defines how sensitive the animation will look. Having a large number of in-between frames means the control points will translate by little amounts (high sensitivity). This also defines the speed of the animation. The number of in-between frames is inversely proportional with the speed of the animation.

The speed of key frame animation can be defined by changing the number of in-between frames, but since the speeds of hair wisps are constant between each key frame, non-natural movements of the hair wisps can be encountered.

We introduce a slow-in / slow-out scheme for individual control points for more natural interpolation. Slow-in / slow-out alters the speeds of the control points according to the index of the in-between frame (the in-between frame they currently are shown on). The method aims to achieve the following task:

- As the new frame begins, the hair wisps are motionless
- Gradually they start accelerating until the half way of the control points path is traversed
- Then gradually decelerate until reaching the next key frame and stop there

Speeds are calculated according to Equation 4.2. The in-between frame at the middle (i.e. on an animation defined with n in-between frames; the frame number $n/2$) frame has the highest speed ($normalspeedx2$), while the beginning and end in-between frames have the lowest (Figure 4.7).

$$\begin{aligned} s_i &= (n_f/(n_{ib}+1)) - n_f/(n_{ib}+1); \\ speed_{new} &= speed_{old} * (2 - abs(s_i)); \end{aligned} \tag{4.2}$$

Where s_i is the index of the current in-between frame, n_f is the number of frames so far, and n_{ib} is the number of in-between frames chosen between two key-frames.

Slow-in / slow-out system might have a possible drawback. While it is increasing the quality of animations involving hair wisps that change their directions frequently (for example swinging), they can lead to unrealistic results in regular animations. A hair wisp falling down from the top of the head, or continuing

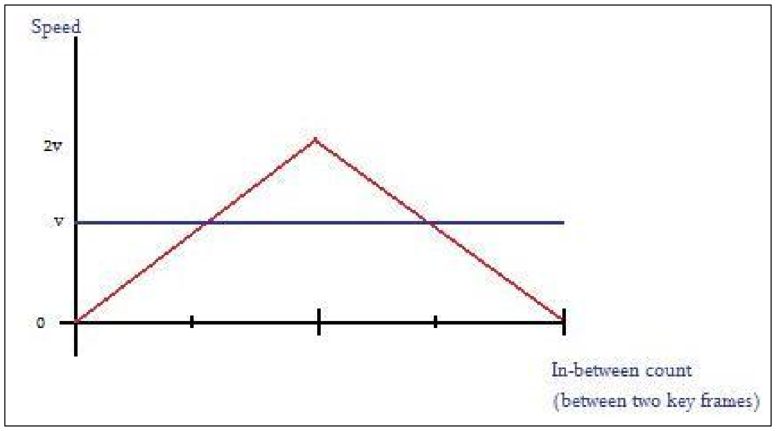

Figure 4.7: Hair strands reach their maximum speed during the in-between frame lying at the middle of two consecutive key frames. Speeds are always 0 at the beginning of key frames.

its movement along the same direction on two consecutive key frames should not slow down and stop during the movement. These kinds of movements should be continuous. We introduced a direction check constraint in our tool. The slow-in / slow-out method checks the general direction of the hair strands mass nodes in 3D space. The directions of each control point are their velocities on x, y and z axes. General direction of the hair wisp is the average value of these velocities again on x, y and z axes. After finding the general direction of each wisp, the same calculations are done for the corresponding hair wisps on the next frame. Then these general direction values are compared by examining their signs (negative or positive). A sign change means a directional change on that axis. If a direction change is detected on x, y or z component slow-in/slow-out operates on the axes that have direction change. Thus, if a hair is swinging to the left and then to the right, its x direction component is changing its direction leading to a slow-in / slow-out effect performed on its x direction speed whereas if the hair is swinging to right and is continuing this motion on the next frame, no slow-in / slow-out effect is produced for the x axis.

Besides slow-in slow out, to improve the quality of the animation; a touch of randomness should be introduced into the system as well. In real life situations, since all of the elements around encounter a resistive force (friction), we should

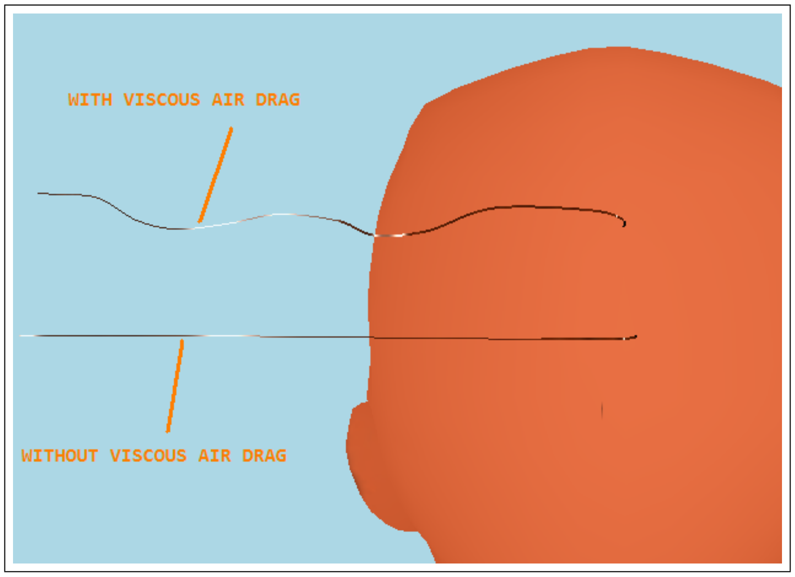

Figure 4.8: Two individual hair strands. One is under the influence of viscous air drag, the other one is not.

also include this into our animation system. The force is viscous air resistance force, which in our application is the force that gives our hair a wavy randomly moving simulation look. To be able to reflect this into our key frame interface, we add an extra randomized noise value to our path function that edits the positions of each mass node during run time. From root to top, this noise is introduced to the control points of the hair wisp but the values are different for different mass nodes. If the node is near to the surface, the viscous air drag force is not too effective, but once we reach to the top parts of the hair, it becomes more apparent, preventing the stick like effects during hairs motion (Figure 4.8).

To provide a wavy look, for each coordinate axis, the direction to apply the noise is again randomly calculated. This random value decides whether to apply the noise in the negative or the positive direction. As control points continue moving on each in-between frame, the noise values are applied to their coordinates to deviate their locations on a small scale. The magnitude of the random values can be scaled during run-time by the user through the keyboard.

4.2.5 Collision Detection

The excessive amount of hair strands that are being animated have a high potential of penetrating inside the head model during animation. Even though the key frames are collision free, during the in-between frames, hair wisps might intersect with the head model, leading to unrealistic animations. We are representing the head model and the hair wisps with spherical volumes to detect hair to head collisions which is an efficient method requiring low amounts of calculations. Hair to hair collisions are not taken into consideration to fulfill the real time requirements of the animations.

The head model is represented by three spheres; located and sized manually. Hair wisps are represented by $n-1$ spheres having radii r_i where n is the total number of control points (centers) and i is the index of the control point. Radii of these spheres are calculated according to the closeness value and the number of layers of imitator strands. A control point having a closeness value x, with m layers of imitator strands will be represented by a collision sphere having a radius $x*m$. At each in-between frame, collision check is performed between each sphere (representing the hair wisp) against head model spheres. If the distance between the center points of the two spheres d, is less than the sum of their radii r_1+r_2, then a collision is detected. Penetration amount is calculated as r_1+r_2-$d$and the control point is translated to the outside of the head sphere according to this value along the vector c_1-c_2 (Figure 4.9).

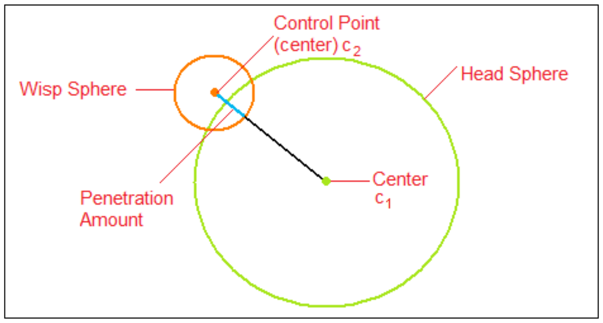

Figure 4.9: Sphere representing a hair wisp control point and a sphere representing the head model, during collision.

4.2.6 Rendering and Lighting

In most of the hair animation systems, the lighting of the hair is done using Kajiya and Kay illumination model [24] The reason for its common usage is that it supports anisotropic light effects. This illumination model enabled us to form stripes of lights over the hair groups. The most important aspect of Kajiya and Key that differs from other illumination models is the usage of the tangents of the hair strands in the lighting equations instead of the normals. In the graphics rendering pipeline, after the vertex shader program manipulates the input vertices, then these vertices and their tangent values are fed into a fragment shader program, where the calculations Kajiya and Kay lighting takes place according to Equation 4.3.

$$l_p = k_d sin(T, L) + k_s * ((T.L)(T.V) + sin(T, L)sin(T, V)) \tag{4.3}$$

Where T is the tangent value of the hair segment, L is the light vector and V is the viewing vector and $sin(T, L)$ is the angle between T and L vectors. Along with the Catmull-Rom spline and patch creation calculations, Kajiya and Kay rendering and lighting calculations are also done in GPU for each frame saving important clock cycles of CPU for other operations. For each frame, each hair strand should be illuminated and rendered. Position calculations, collision detection, slow-in and slow-out calculations etc. are all done in CPU which is already under heavy calculations. Performing the rendering related calculations such as illumination and spline creation on GPU leads to a more efficient workload both on CPU and GPU.

Chapter 5

Results

5.1 Usability Tests

The Usability tests are applied to sixteen people (Usability Testers) from various educational backgrounds. They were assigned two different tasks. One of the tasks was hair design and the other one was a key frame design. The characteristics of the persons taking the tests are shown in Table 5.1.

In the hair design task the usability tester was asked to create a hair style similar to his own, using a mirror and the sketching interface of the software. In the Key frame design, on the other hand, the Usability Tester was first required to create a hair style with long wisps and then swinging them to the right using three key frames (Table 5.2). The main aim of these usability tests are understanding how new users react to this completely new design environment and how much time does it take for them to adapt to it. By measuring the time it takes for them to create their own hair styles, we are investigating how they reflect their drawing abilities through the sketching interface and how long it takes. By measuring the time it takes for them to create an animation consisting of a swinging hair, we aim to investigate how the new users make use of the key frame animation system and how fast they are able to use it.

Table 5.1: Characteristics of Usability Testers.

Testers	Occupation	Age	Drawing Exp.?	Computer Graphics Exp.?
T1	Computer Engineer	24	YES	NO
T2	Computer Engineer	25	YES	NO
T3	Manager	31	YES	NO
T4	Industrial Engineer	25	YES	NO
T5	Mine Engineer	23	YES	YES
T6	Computer Engineer	24	YES	YES
T7	Civil Engineer	24	YES	NO
T8	Manager	35	YES	NO
T9	International Relations	24	YES	NO
T10	Lawyer	25	YES	NO
T11	Electric-Electronic Engineer	25	YES	NO
T12	Industrial Engineer	23	YES	NO
T13	City Planner	29	YES	NO
T14	Industrial Engineer	24	YES	NO
T15	Computer Engineer	25	YES	YES
T16	Computer Engineer	23	YES	NO

Table 5.2: Test Tasks.

Tasks	Details
Task1	Develop own hair using sketching interface
Task2	Develop long hair, swing to right with 3 key frames

Table 5.3 gives the completion times of this test.

It took an average of 2 minute 05 seconds for a first time user to sketch his hair style on the computer, while creation of animation with key frames took an average of 5 minutes 05 seconds. The completion times do not include the time spent in explaining the test procedure. During the performance of the Usability tests the following observations were made.

Hair Styling Design. The Usability Testers were all capable of creating the desired hair styles following a brief explanation of what they should be doing. After creating a few wisps, they all started creating their own hair styles. This

Table 5.3: Task Completion Times.

Usability Tester	Task 1 Completion Time	Task 2 Completion Time
T1	1 minute 45 seconds	4 minutes
T2	1 minute 45 seconds	3 minutes 50 seconds
T3	2 minutes 5 seconds	5 minutes 15 seconds
T4	2 minutes 15 seconds	4 minutes 35 seconds
T5	1 minute 25 seconds	3 minutes
T6	2 minutes 30 seconds	4 minutes 20 seconds
T7	1 minute 40 seconds	4 minutes 45 seconds
T8	3 minutes	7 minutes 5 seconds
T9	2 minutes 5 seconds	4 minutes 35 seconds
T10	1 minute 55 seconds	4 minutes 55 seconds
T11	1 minute 30 seconds	4 minutes 10 seconds
T12	2 minutes 55 seconds	5 minutes 35 seconds
T13	2 minute 05 seconds	5 minutes
T14	2 minutes	3 minutes 55 seconds
T15	1 minutes 50 seconds	4 minutes 10 seconds
T16	1 minute 40 seconds	4 minutes 10 seconds

indicated the simplicity of the interface used. Especially the testers that had prior experience on drawing applications adopted easier. The created hair styles were usually more successful when the tester had long and straight hair, whereas testers with short hairs had a bit more difficulty compared to the others. The main reason for this can be; since the long haired users usually start with a long hair wisp, that wisp helps the user to visualize the general hair shape that will be achieved. Thus, for the following strokes the user has an idea about how to continue. This is a bit more difficult for a tester with short hair, having more minor details to take care of.

Key Frame Design. In this test, the learning process took slightly longer, as it involved the understanding of the key frames and their usage. We explained to the Usability Testers that the key frames are designed using the sketching interface, in the same manner as the design of the hair styles, using the sketching interface. The creation of the key frames involves two steps; designing the hair strands; recording. Once a key frame is created, clicking on the record button saves the key frame and the screen is cleared for the creation of the next key frame. It is also possible to view the previous key frame instantly. The Usability Testers all found this feature convenient.

Wisp style definition. The parameters such as fuzziness, closeness and in-between count are passed to the system through the console before sketching process. The Usability Testers indicated they would like to be able to edit these parameters during runtime.

Viscous Air Drag. We can increase or decrease the air drag by the use of the keyboard easily. The Usability Testers did not encounter any difficulties changing the air drag parameters. The result of the change in the parameter was immediately observable. This interactive behavior helped the Usability Testers anticipate the results of their actions after a short while.

Development Time. The Usability Testers were able to develop rapidly the hair styles for each key frame. Spending, at an average, 1-2 minutes for each key frame development, they were able to create a fairly detailed animation, involving growing complete hair and then swinging to the sides, within 5 minutes. At each key frame, the head is to be repopulated with hair. In other words, the hair created in the previous key frame is lost and the hair creation is to be redone. The Testers felt that this feature could be improved. Recalling the hair created in the previous key frame, and then manipulating it for the current key frame under development, would result in considerable time saving, and the animation would look even more natural. The Testers liked working with wisps, and liked not having to draw each hair strand, as this would be too time consuming.

5.2 Performance Evaluation

Graphic tasks, and especially animations, require considerable processing power. A proper distribution of processing requirements between the CPU and the GPU is necessary to shorten the processing time. Our system makes use of both the CPU and the GPU for calculations. Using both these processing units in parallel enables us to increase the frame rates during animations and sketching.

The computer system we used for the tests was a PC with Intel Core2 Duo T7500 @ 2.20Ghz laptop with NVIDIA GeForce 8600M GT graphics card. We recommend this as the minimum configuration as the system has a high demand on processing power.

Wisp sampling, wisp matching, and path function creation tasks require calculations to be done by the CPU. Performing these operations during sketching reduces the number of calculations to be performed during the animation, resulting in a smoother motion. Table 5.4 shows the performance results with different strand and wisp combinations.

Table 5.4: Performance Results.

Number of Wisps	Number of Strands	fps
120	3600	21
50	1250	32
50	5000	19
60	3600	21
2	3600	20

The results were obtained while slow-in slow-out is in progress and real time viscous drag was being applied. The table shows that the number of strands has a direct impact on the fps of the animation. As the number of strands increases, the number of frames per second decreases. The change in number of key frames and in-between frames does not affect the real time performance. Users can define any number of key frames, and any number of in-between frames without noticing any difference in the performance.

The number of in-between frames affects only the values in the path function, and it does not change the frame rate during animation. Wisp parameters, such as fuzziness and closeness again have no effect on the animation performance, since they actually are local parameters changing appearance, which do not require calculations during runtime.

A dynamic hair simulation system, built on top of the same sketching interface is developed by R. Aras [25]. In his work Aras provides tools for applying forces to the hair wisps with changing magnitudes and directions in real-time. The hair strands can be animated under different force fields with different properties. Unlike our key frame system, users can not control each individual hair wisp, but users can interact directly during animation through the sketching interface by changing the force fields. With the same number of hair strands, and the same number of mass nodes (on average) the comparison of the performances of the two simulation methods can be seen in Table 5.5.

Table 5.5: Performance Comparison with the dynamics hair simulation.

Number of Wisps	Number of Hair Strands	Fps (Key-Frame)	Fps (Dynamics)
50	1250	32	36
50	5000	19	24
100	2000	24	25

Hair design takes the same time in both systems that share the same basic structure. But the complete design stage of dynamic hair simulation system is faster than the key frame system since it requires the hair model to be sketched only once. For the key frame system, design stage takes more time since each key frame should be defined separately. For an animation consisting of n key frames, n designs should be done (without the usage of key hairs). On the other hand, only one hair design is sufficient for the dynamic system. The length of the created animations are different in these two systems that share the same infrastructure. The animation time is bound by the number of key frames defined and the in-between frame count chosen by the user in key frame animation system whereas animation time is without boundaries; letting the user to interact with the hair continuously in the dynamic hair simulation. Combinations of these two systems is published in 2008 [26].

5.3 Visual Results

Figure 5.1 shows the visual result for key frame development. This animation consists of 3 key frames, which were developed within 1 minute 45 seconds, 2 minutes

10 seconds and 1 minute 10 seconds, respectively. The completed animation runs for a total of 15 seconds with 250 in-between frames.

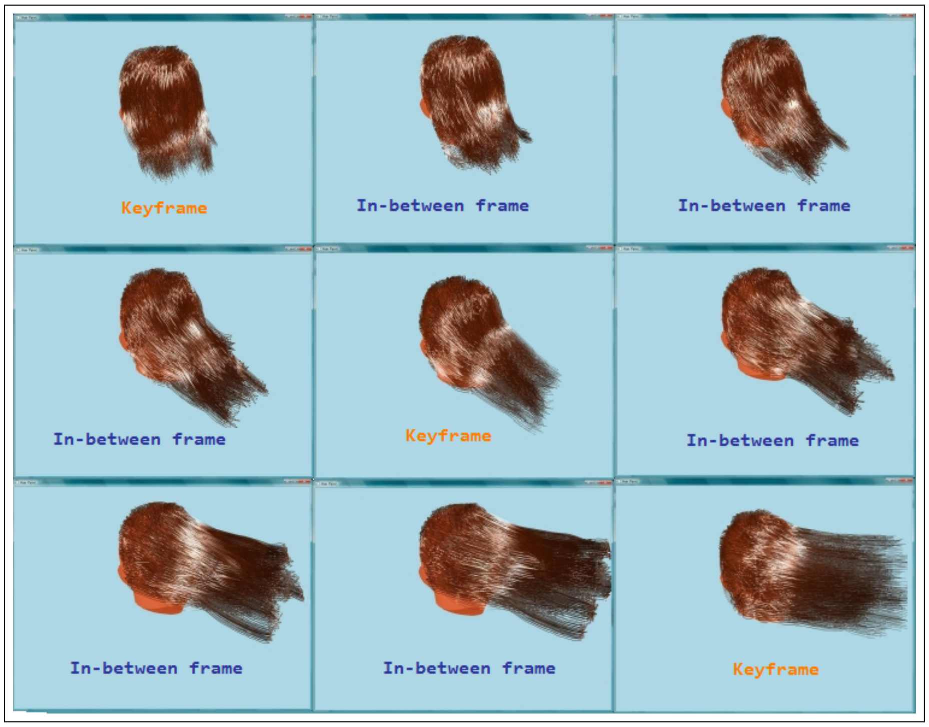

Figure 5.1: A sequence of screenshots showing the in-between frames filling the gaps between 3 previously created key frames.

Figure 5.2 shows a hair style which was developed within just 1 minute and 55 seconds using the sketching interface.

Figure 5.3 shows a screen shot of the middle in-between frame in an animation with 2 key frames consisting of 60 hair wisps, created in 4 minutes.

Figure 5.4 shows a hair style developed in just 35 seconds using the sketching interface. The users do not have to fill the skull completely with hair unless they want to. In this case, only the right part of the head is filled with hair.

Figure 5.5 shows a hair style developed by a first time user. The user was trying to imitate his hair style, and after several trials, he achieved a good result.

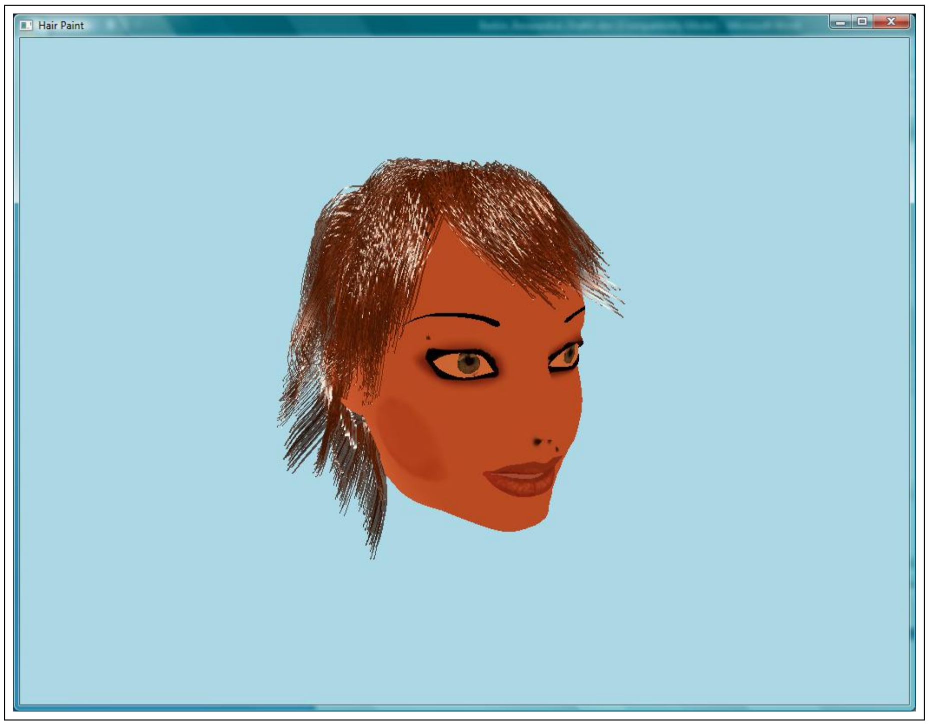

Figure 5.2: Front view of a modern hair style created with the sketching interface.

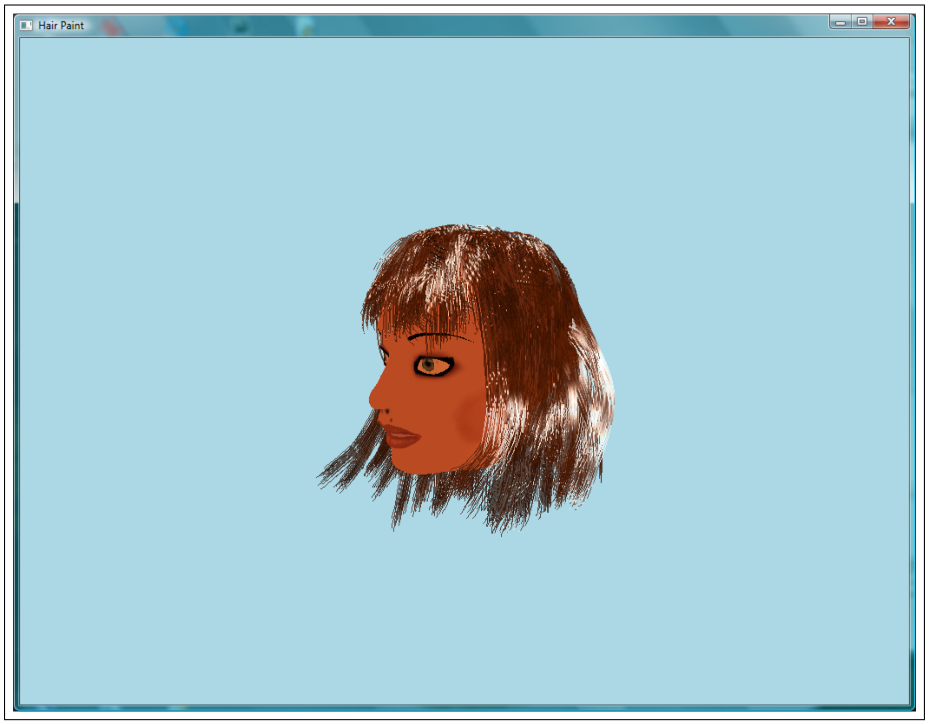

Figure 5.3: Screenshot of an in-between frame during an animation.

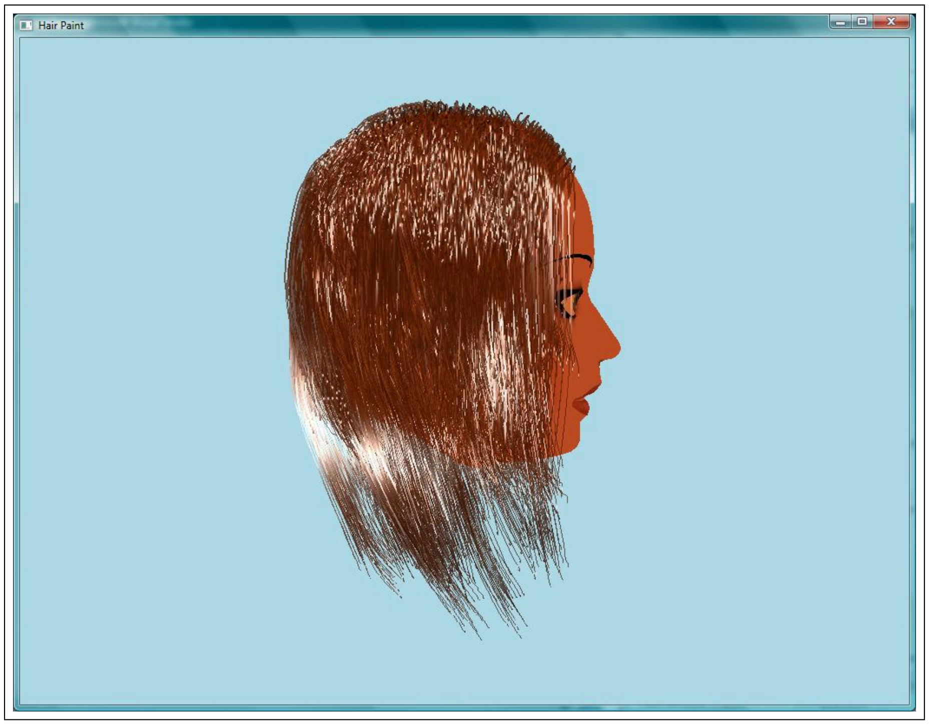

Figure 5.4: A hair style created using the sketching interface.

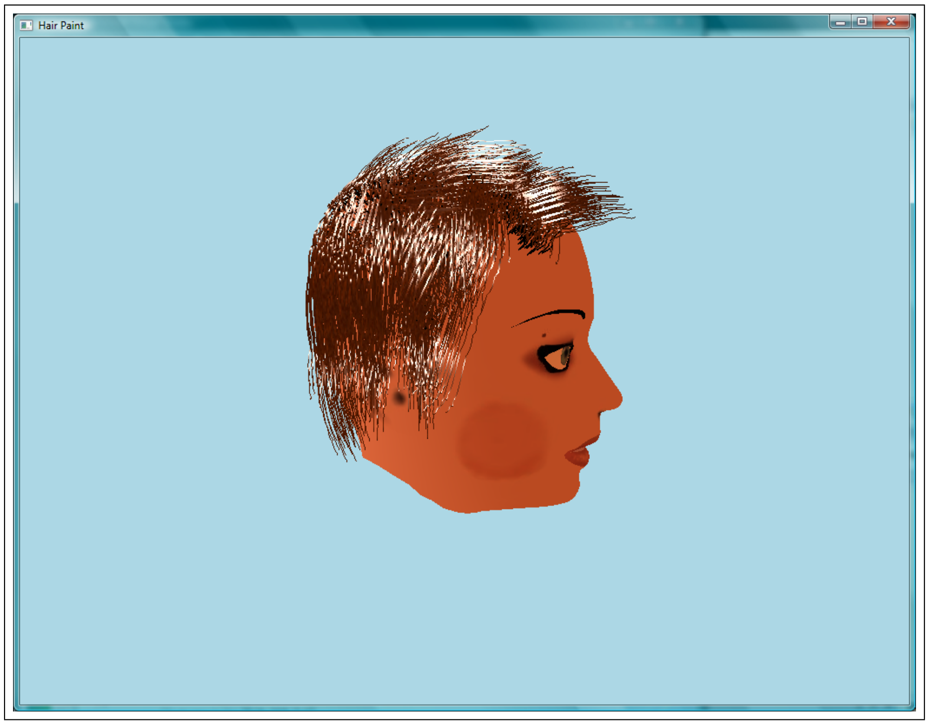

Figure 5.5: A hair style created by a beginner user in approximately 4 minutes.

Chapter 6

Conclusion

In this thesis, we propose a system that gives the user the opportunity to use directly all three main stages of a computer generated hair animation, which are hair structure design, animation flow design, and direct manipulation during animation. By providing tools for manipulating all three stages, a totally controllable animation system is created. In order to be able to provide these tools and use them in real time, the difficulties and problems regarding different aspects of hair animations are solved. Hair and hair wisp structure, sketching interface, key frame definition with in-betweening and rendering are all different aspects that are considered.

The main aim of the system is to give the animator total control over the animation creation, through all stages. To achieve this, an intuitive user interface is used, which is able to map the 2D inputs into 3D space. The problem of mapping 2D inputs to 3D space is solved using a combination of viewing vector of the camera and the root location of the wisp to be drawn. An invisible plane which passes through this root location and has a normal vector, parallel to the viewing vector of the camera, is defined as a drawing plane. The root location of the wisp to be drawn is calculated by the help of OpenGL and depth buffer. This solution results in a familiar drawing experience, making the user feel like he is drawing on a piece of paper instead of a 3D space.

The structure of the hair strands is defined by the control points input by the users. The control points are connected to each other via Catmull-Rom spline, so, once the hair is created, it has a smooth appearance. Regardless of the distance between the control points, and their deviation from a straight line, a smooth spline passing through all the points are created. This gives the user total freedom in the input of control points and creates hair strands that are not bound by physical laws. In their work, Wither et al. [7] provides a sketching interface for creating physically based hair strands. Bound by physical forces, the strokes of the users cannot be reflected to the created hair strands. Users eventually observe different hair strands than they input. Our sketching interface guarantees that the inputs will be reflected to the hair strands without being deviated.

The examination of real life situations shows us that the hair strands that are in close proximity of each other generally share the same structure and motion characteristics. To take advantage of this, we employ a wisp structure that contains a single leader strand input by the user, and imitator strands located around it. This speeds up the hair creation design dramatically. Unnecessary drawing of hair strands is avoided. This is especially important in long animations where there must be a large number of key frames created. With a wisp structure containing n imitator wisps, drawing time reduces n times during the key frame definition. The structures of these wisps are defined by the users input through a console, giving a complete control to the user.

Key frames are drawn through the sketching interface and recorded one after another. Once a key frame drawing finishes, users can immediately switch to next key frame by clearing the skull. Feedback from the users shows that defining key frames is rather intuitive and recording and switching between key frames is very smooth and efficient. Following the key frame definition phase, in-betweening stage operates on these key frames to match the wisps between key frames, sample their control points to make their structures equal and then calculate paths for the control points to be used in animation stage, in order to move them to their target locations. For smooth and natural interpolations between key frames and the in-between frames, we use slow-in/slow-out method that alters the speeds of the control points throughout their journey. Key frames provided to the system can be nearly achieved completely during the animation since the path functions created are leading the hair strands to them. In their work Petrovic et al. [6] use forces to deviate the hair strands to their target locations, which cannot be completely successful as there exist key frames that cannot be reached like chaotic hair styles.

During runtime, a random viscous air drag noise can be introduced into the system by the users for more natural animations. Objects moving through atmosphere on earth have different behavior than they have on the moon. The viscous air drag force is the cause of this difference. The effect is more noticeable on light objects. Introducing this drag force into our system helps create more natural animations. The air drag force can be varied by the users, via keyboard during runtime.

In order to achieve these tasks in real time, instead of depending on the CPU only, we made use of the highly developed GPU programming technology. Hair strand spline creation, and hair wisp illuminations are calculated on GPU, freeing valuable clock cycles of the CPU for other calculations. In short, we developed a system capable of creating and editing hair animations in real time with an easy and efficient sketching system.

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Berlin / Heidelberg. Computer Graphics International Conference (CGI), Istanbul. ISSN: 0178-2789 (Print) 1432-2315 (Online) (Jun. 2008).

Appendix A

User manual for Sketching Interface

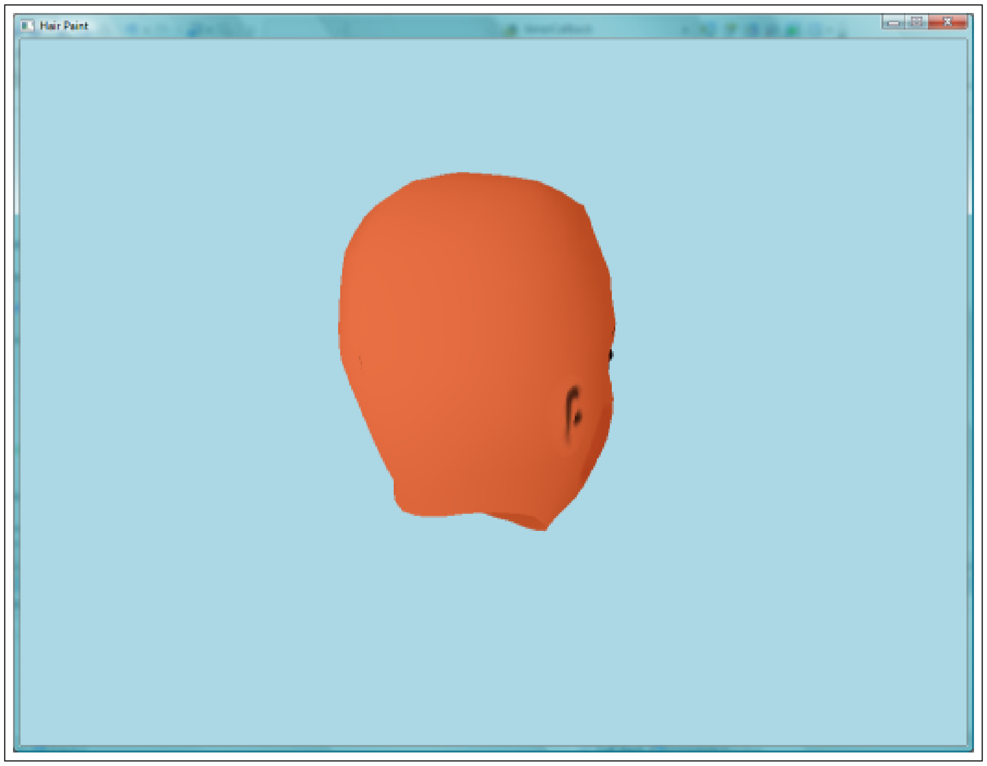
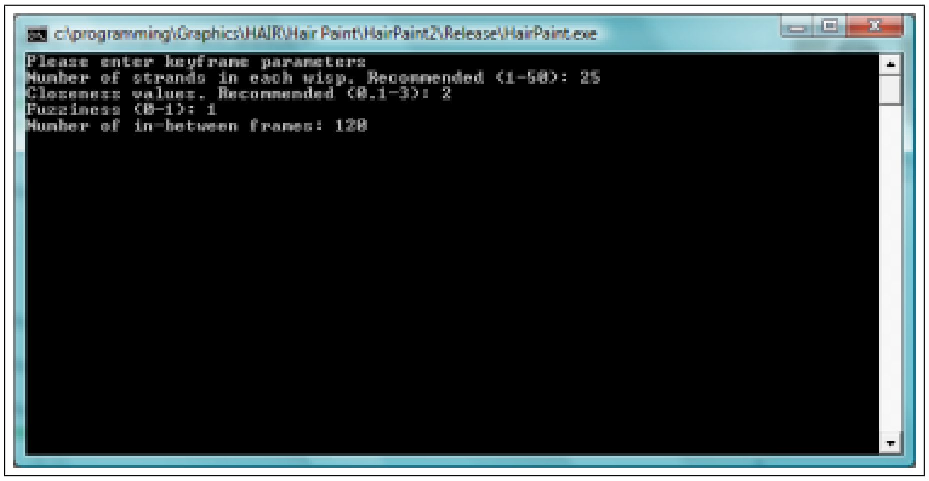


Figure A.1: Sketching interface appears with a bald head model.

Inputs defining the animation parameters must be provided before each animation creation. The number of strands on each wisp, closeness values, enabling fuzziness and defining the number of in-between frames are done via the console, (Figure A.2). After these values are input, the sketching interface becomes ready for key frame design (Figure A.1).


c:\programming\Graphics\HAIR\Hair Paint\HairPaint2\Release\HairPaint.exe

```
Please enter keyframe parameters
Number of strands in each wisp. Recommended (1-50): 25
Closeness values. Recommended (0.1-3): 2
Fuzziness (0-1): 1
Number of in-between frames: 120
```

Figure A.2: Parameters are passed via a Console Screen.

Sketching interface has a natural and intuitive usage. Users that have previous experience with any drafting program find it easy to interact with the sketching interface. Using the mouse (or a stylus pen), the user clicks on any location on the head. This action defines a hair strand root point on that coordinate, on the patch. As the user drags the mouse, a line following the drag pattern is drawn on the screen, like a painting program. As the user continues dragging, the hair strand grows longer. Once the mouse button is released, the hair strand is formed between the beginning point (root), and the end point; the release point. Users are actually interacting with a 3D space, through a 2D space.

Key frame definition process is a sequence of hair strand drawing processes. User can draw any number of hair strands at any location on the head, (Figure A.3). To define a key frame, user simply clicks the record button, which is mapped to r character on the keyboard. When this button is pressed, the key frame and all its related data are saved; the skull is cleared; and the sketching interface gets ready for the next frame to be drawn.

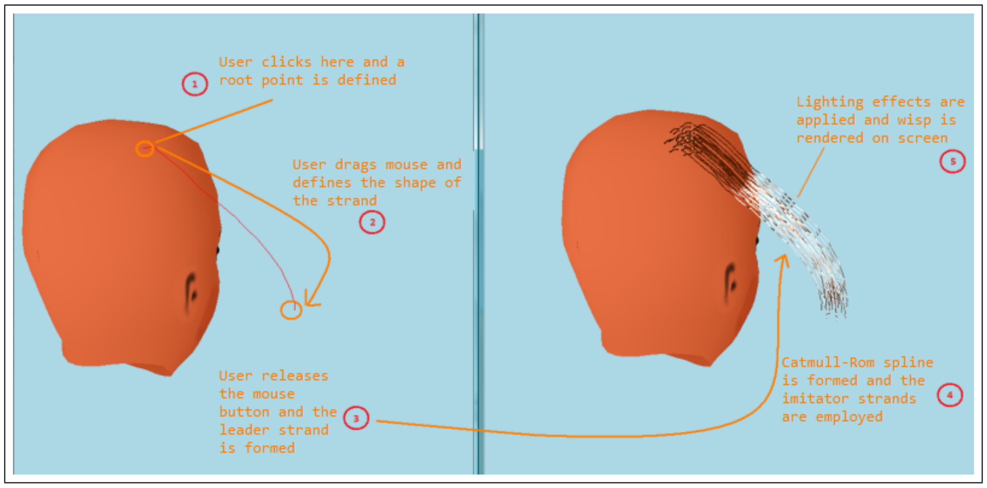

1 User clicks here and a root point is defined
2 User drags mouse and defines the shape of the strand
3 User releases the mouse button and the leader strand is formed
4 Catmull-Rom spline is formed and the imitator strands are employed
5 Lighting effects are applied and wisp is rendered on screen

Figure A.3: Drawing through the sketching interface.

At this stage the user can see the previously drawn frame to be reminded about the relative locations of the hair strands, on the previous frames, so that the new strands can be drawn on the locations observed from the previous frame. This button is currently mapped on the keyboard to m button as a shortcut. Pressing it once shows the root locations whereas pressing it twice shows the entire image of the previous frame. One more pressing closes the previous frame reminders.

Key leader strand is a method to decrease key frame development time during animation creation. In animations where all the hair strands have the same motion characteristics (swinging right, left, becoming electrified etc), drawing each wisp, one by one is not necessary. By drawing only one wisp, which will be the key leader wisp, and mapping the actions of all the other wisps to that wisp they can all be controlled together.

A gesture recognition algorithm acting like an interface for drawing curly hairs is also provided. Users can define and create curly hair by drawing loops on the hair strands they create. The intersecting parts are rotated in 3D space to create a helix like shape, forming a curly hair. During animation, users can input viscous air drag noise into system easily via the keyboard input device. By pressing '+'

button sequentially they can increase the drag force, or by pressing '-' button, they can decrease it.

Wisp mapping, sampling, slow-in slow-out, path creation are all operations done by the system on background, and the user has no control over them.